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Partnering with industry and the community for innovation and impact through modelling

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The Modelling and Simulation Society of Australia and New Zealand Inc. has been active since 1974, and has run the previous 20 MODSIM Congresses in Australasia.

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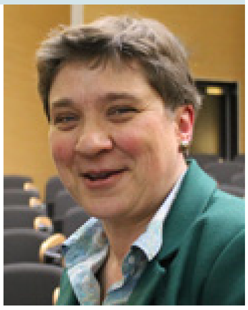
Associate Professor Mary Myerscough

University of Sydney, Australia



Why do hives die? Using models to explore the mechanism of honey bee colony collapse.

Mary Myerscough received her first degrees in Applied Mathematics from the University of Sydney and then completed her D.Phil (the equivalent of a PhD) in mathematical biology at Oxford University.

She returned to Sydney to take up a research position in the School of Chemistry at Macquarie University where she studied the mathematics of exothermic chemical reaction kinetics. She became interested in honey bees when her boss dropped a paper on her desk which suggested that a stationary honey bee swarm was very similar to a smouldering lump of coal and its temperature could be modelled in a similar way.

Since then, Mary has been working on problems in honey bee and termite behaviour in collaboration with biological scientists at Sydney University, Macquarie University and CSIRO. She has also works with biomedical scientists at the University of Sydney on models for cancer and vascular disease.

Mary is an Associate Professor in the School of Mathematics and Statistics at the University of Sydney.

Professor Kerrie Mengersen

Queensland University of Technology, Australia

You Say, I Hear: Case studies of academic-industry engagement

Kerrie Mengersen is a statistician whose research interests are in Bayesian and other modern methods for statistical modelling and computation. She currently holds a Chair in Statistics at Queensland University of Technology, Australia, with previous appointments at Siromath Pty Ltd, Bond University, Central Queensland University, Colorado State University and the University of Newcastle. Kerrie has maintained an active collaborative and consultancy profile in both the development of statistical methods and in their application to a wide variety of problems in environment, health and industry. She is a Deputy Director of the ARC Centre of Excellence in Maths and Stats Frontiers, which aims for research excellence and its translation to collaborative domains in healthy people, sustainable environments and prosperous societies. For the past decade Kerrie has led the Bayesian Research and Applications Group (BRAG) which aims to engage in world-class, relevant fundamental and collaborative statistical research, training and application through Bayesian and other modern methods.

Dr Rob Vertessy FTSE

Bureau of Meteorology, Australia

How modelling propels environmental intelligence at the Bureau of Meteorology

Dr Rob Vertessy is the Director of Meteorology and CEO of the Bureau of Meteorology – a position he has held since September 2012. Prior to this appointment he was head of the Bureau's Climate and Water Division which included responsibility for the National Climate Centre, the national flood forecasting and warning service, and the agency's new water information function.

Rob has a PhD in fluvial geomorphology from the Australian National University and spent the first 20 years of his career as a researcher in CSIRO specialising in catchment hydrology. During this time Rob served as Chief Executive of the CRC for Catchment Hydrology (2002–2004) and Chief of CSIRO Land and Water (2004–2007).

In late 2006, Rob was seconded to the Department of Prime Minister and Cabinet to advise on the establishment of a national water information strategy. He later joined the Bureau of Meteorology to lead implementation of a new national water information function awarded to that agency.

Rob is Australia's Permanent Representative to the World Meteorological Organization. In 2013 he was elected a Fellow of the Australian Academy of Technological Sciences and Engineering.

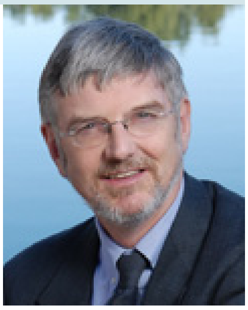
Dr Christina Burt

University of Melbourne, Australia
(Mid-career plenary speaker)

Hybrid approaches for challenging scheduling problems in open pit mining

Christina Burt completed her PhD in Operations Research at Curtin University of Technology in 2008 with a Chancellor's commendation. Since then, she has collaborated on several industry research projects in Perth (Curtin University), Melbourne (University of Melbourne) and Vienna (Austrian Institute of Technology), including projects with industry partners Rio Tinto Iron Ore, Strabag, Hubaer and SatNetCom. Christina specialises in modelling and mathematical programming solution methods for transportation and scheduling problems.

Professor Howard Wheater



The University of Saskatchewan, Canada

Modelling hydrological extremes in a data sparse environment – experience from Western Canada

Howard Wheater holds the position of Canada Excellence Research Chair in Water Security and Director, Global Institute for Water Security at University of Saskatchewan, Canada, and Distinguished Research Fellow and Emeritus Professor of Hydrology at Imperial College London, UK. He is Fellow of the Royal Academy of Engineering, UK, and of the American Geophysical Union. His various national and international prizes include the Prince Sultan bin Abdulaziz International Prize for Water. He has a distinguished research record in hydrological processes and modelling and has advised various governments and international agencies on issues of flood, water resource and water quality management. He has represented Hungary and Argentina at the International Court of Justice, and recently was a member of a Court of Arbitration in a dispute between Pakistan and India concerning the Indus Waters Treaty.

Associate Professor Jason Evans

University of New South Wales, Australia (Mid-career plenary speaker)

High-resolution climate change projections over Australia: producing policy-relevant information

Jason Evans is an Associate Professor and ARC Future Fellow in the Climate Change Research Centre at the University of New South Wales. He received his PhD in hydrology and regional climate science from the Australian National University before spending several years as a research scientist at Yale University in the USA. He is the co-Chair of the Global Energy and Water Exchanges (GEWEX) projects Hydroclimate Panel, and a coordinator of the Coordinated Regional Climate Downscaling Experiment (CORDEX) AustralAsia domain. Both are projects of the World Climate Research Programme (WCRP).

Jason's research is aimed at understanding regional climate processes and regional climate changes. He works on problems concerning land-atmosphere coupling and water cycle processes over land. His focus is at the regional (or watershed) scale and includes processes covering river flow, evaporation/transpiration, water vapour transport and precipitation. The main tools of his research are models including regional climate models, land surface and hydrology models.

We of the meta meta: is Australia developing a transparent and reproducible approach to transparency and reproducibility?

N.J. Car [a]

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Abstract: Many sessions in this conference bear witness to the amount of effort now being put into data management, process modelling, model run reproducibility and specialised sub areas of them, such as provenance. Additionally, many large data holders and science organisations in Australia now have data management strategies and principles that state their intentions for process openness. Is all of this coordinated? Does it need to be? Can we measure claims by efforts to increase transparency and reproducibility in uniform way? Is such measurement itself transparent?

This address will review Australia's attempts towards data and process transparency and reproducibility as indicated by papers in MODSIM conferences from 2007 to 2015 as well as the presenter's knowledge of relevant work. A pitch will be made to Australia's data holders and science organisations that these attempts need to apply some of the very principles and methods that they advocate to the overall process they are part of.

Keywords: *Transparency, reproducibility, data management, meta modelling, provenance*

Zooplankton Foraging induces Chaos in Dynamic Green Ocean Models

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Abstract: The exchange of important greenhouse gases between the ocean and atmosphere is influenced by the dynamics of near-surface plankton ecosystems. Marine plankton ecosystems are modified by climate change creating a feedback mechanism that could have significant implications for predicting future climates, for example, the collapse or extinction of a plankton population may push the climate system across a tipping point. Dynamic green ocean models (DGOMs) are currently being developed for inclusion in climate models to predict the future state of the climate. These models are often complicated, commonly with 5-10 competing phytoplankton and several omnivorous zooplankton (Le Quéré et al., 2005). Complicated dynamics including chaos are readily found even in unforced forms of the relatively simple nonlinear plankton ecosystem ordinary differential equation models that underpin DGOMs (Cropp et al., 2014). The appropriate complexity of the DGOMs is an ongoing issue, with models tending to become more complex, and perhaps an increasing propensity for chaos (Fussmann and Heber, 2002).

The complexity of DGOMs means that most attempts to confer them with "desirable" properties proceed by numerical experimentation and/or model inter-comparison projects such as the MARine Ecosystem Model Inter-comparison Project (MAREMIP, Sailley et al., 2013). Some recent investigations into DGOMs have considered the role of zooplankton predation functional forms in determining model properties (for example, Anderson et al., 2010; Visser and Fiksen, 2013; Vallina et al., 2014). The functional forms considered in these experiments are generally based on the classic Holling Type II or III forms (Holling, 1959) with modifications to represent zooplankton strategies such as the specialised or generalised feeding strategies described by Koen-Alonso (2007) and prey switching (Gentleman et al., 2003). However, little consensus has been reached on the most useful form of grazing function for plankton systems that underpin both green ocean models and fisheries ecologies (Le Quéré et al., 2005).

We consider a relatively simple (three-population) DGOM of two phytoplankton and a zooplankton where the interacting plankton populations compete for a single limiting nutrient. We find chaotic dynamics are possible in this low trophic order ecological model with a specialist foraging strategy as we vary the zooplankton mortality. This suggests that chaotic dynamics might be ubiquitous in the more complex models, but this is rarely observed in DGOM simulations. The physical equations of DGOMs are well understood and are constrained by conservation principles, but the ecological equations are not as well understood, and are often constructed without explicit consideration of conserved quantities as closed model domains are considered unrealistic by some ecologists (Loreau, 2010, p 16). The work we present here utilizes a theoretical framework constructed on the fundamental principles of conservation of mass, finite resources and explicit resource limitations to growth. Our results, when considered in the context of the paucity of the empirical and theoretical bases upon which DGOMs are constructed, raises the interesting question of whether DGOMs would represent reality better if they include or exclude chaotic dynamics.

Our analysis of this simple, but representative, plankton system suggests that apparently innocuous choices of grazing terms, varying from indiscriminate to discriminate types which do not appear significantly different, and which may be equivalent up to observational/experimental accuracy, can predetermine the emergent properties of the systems. We observe that the indiscriminate grazer appears to have more reliable and steadier shares of the ecosystem biomass in contrast to the discriminate grazer's very strongly fluctuating biomass share. Indiscriminate grazing functions for zooplankton are commonly used in the current generation of GCMs, where the emphasis is to maintain biodiversity and to represent the dynamics of large groups of plankton functional types (PFTs). However, future generations of GCMs may wish to resolve more detailed dynamics, such as bloom succession, and we suggest that for these models introducing discriminate grazing functions for the marginal populations may be more appropriate.

Keywords: *Chaos, plankton model, CN framework, zooplankton foraging, zooplankton mortality*

EXTENDED ABSTRACT ONLY

The Diversity of New Zealand's Defence Operations Analysis

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Abstract: The Defence Technology Agency (DTA) is the principal advisor to the New Zealand Defence Force (NZDF) on Science & Technology matters. As a small organization DTA has a particular focus on providing expert systems-analytic advice to our military sponsors. DTA's Operations Analysis (OA) section forms a leading part of these efforts and we describe here some of the challenges that this area faces and how they are being met.

Operations Analysis work at DTA was originally focused on Army requirements, with particular foci on field experimentation and modelling & simulation. It has since moved into supporting requirements across all services and warfare domains, and whilst the staffing numbers increased the requirements for support increased more.

Current areas covered include:

- strategic level analysis;
- support to capability acquisition;
- support to operations; and
- analytic support within DTA to technology programmes.

The team is diverse, covering staff with physical sciences, engineering and psychology backgrounds. This diversity gives us strength to deal with a range of problems that may arise.

Such a range of foci would typically be covered by multiple and substantial analytic groupings overseas so we must adopt strategies for dealing with our resourcing limitations, which include:

- Strong linkage with sponsors at all levels of NZDF so that the most pressing support requirements can be discerned and fully understood.
- Prioritization based upon the technical complexity of the project/work area concerned.
- Prioritization based upon likely impact to NZDF should the study area fail to be adequately supported. Factors such as overall breadth of impact, risk to life and financial impact are some of those considered.
- Recognition that many analytic techniques can be used across military services and analytic application levels, from operations through to strategic level.
- Strong use of collaborative links such as through TTCP and bilaterally.
- Carefully considering the strengths of the current OA team so that work is shaped around that.

A recent successful initiative has been to encourage other traditionally more technology focused areas at DTA to become more analytically focused so that they can cover areas that OA would have historically covered. DTA's size and its lack of geographic distribution facilitates such cross-lab efforts.

In terms of quality and impact our strategies have included:

- Direct access to decision making fora so that layers of interpretation are avoided.
- Direct access to experimentation activities and Operators so that advice can be provided at the point of use. This allows compromises to be assessed and advised on in real time.
- International liaison (e.g. through TTCP) in order to exchange expert advice, data and tools; including for the purposes of peer review. These links are especially critical given the sensitive nature of our work.

The presented paper will provide practical instances from our work programme that illustrate these points. It will show that even with a relatively small effort one can be effective and make a difference.

Keywords: *Operations Analysis, prioritisation, New Zealand*

What core integrated modelling skills should we teach future environmental planners, managers and decision makers?

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Abstract: Teaching in our higher education system is traditionally based around single-disciplinary Schools or Departments. This means that environmental modelling units are typically taught from a particular disciplinary perspective, such as hydrology, geology or ecology. Such a single-disciplinary perspective can create problems when students are introduced to multi-faceted socio-environmental problems - which require multi-disciplinary solutions. Students are often not sufficiently equipped to consider such complex problems from different perspectives. However, the labour market increasingly requires environmental scientists, natural resource managers, spatial planners and policy makers to effectively collaborate with each-other, and with other disciplines and stakeholders. In addition, they are expected to work with computerised decision support tools to make better resource management decisions that account for multiple perspectives. How can we strike a balance between teaching in disciplinary degrees and this identified need for developers and users of interdisciplinary models? This paper addresses this question by presenting the practical experiences from modelling units taught at the University of Western Australia, augmented by data about modelling units taught in universities around the world.

I collected details about environmental modelling units from online university syllabi. Courses in GIS Modelling or Environmental Engineering were not included in the analysis because their specific unit objectives varied significantly from other environmental modelling units. Fourteen undergraduate and postgraduate units as well as two postgraduate degrees on Environmental Modelling were further reviewed to assess from what disciplinary perspective they were taught and whether interdisciplinary modelling played a role in the unit/degree.

The units reviewed are all taught from very different disciplinary perspectives: hydrology, ecology, economics, engineering, geography, and others. Core skills that are taught in most units are: (1) Assessing the model development process (i.e. steps involved in designing and building models); (2) System conceptualisation (conceptual modelling); (3) Analysing model structures, assumptions, and results; (4) Model calibration, verification and validation; and (5) Sensitivity analysis. The software packages that are used most are Microsoft Excel, R, and MATLAB. Nearly all units emphasise skills development to construct simple models and/or to be able to use and apply computer models to various environmental systems. This is particularly relevant for natural resource managers and other decision makers who will most likely be using, rather than developing, integrated decision support tools. One of the surprising findings of the review is that only three units and both MSc degrees included “integrated modelling” or “interdisciplinary expertise” in their course objectives (for example, “developing skills in modelling ecological, hydrological, agricultural and economic systems and the relationships between them”). While a unit syllabus may not completely represent the unit content, interdisciplinary modelling skills do not seem to be a focus of university teaching in Environmental Modelling. This could be problematic given the need for interdisciplinary model developers and users. I suggest that we should better train our students in assessing an environmental problem from different perspectives (be they different scientific disciplines or multiple stakeholder views). While the five core skills identified above are absolutely fundamental, I propose that a sixth core skill must be included in any Environmental Modelling unit: teaching our students critical multi-disciplinary thinking skills, so that they are able to assess whether a model adequately considers the different perspectives relevant to addressing the environmental problem under consideration. To demonstrate the challenges and advantages of integrated environmental modelling, instructors are advised to use real-world examples, drawn from a wide range of environmental issues (e.g. climate change, air and water pollution, agricultural land management, conservation planning, biodiversity and natural resource management).

Keywords: *Decision support tools, integrated modelling skills, multi-disciplinarity, teaching and learning, university education*

Evaluation of financial sustainability of the Japanese medical system: Analysis of the length of hospital stay for diabetes patients

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Abstract: As Japan's population continues to age, the total medical expenditure is rapidly increasing, becoming a serious financial concern. In fiscal year 2012, the medical expenditure was 39.217 trillion yen, compromising 8.30% of the GDP (Ministry of Health, Labour and Welfare, 2014). Since Japan instituted a mandatory public health insurance system in 1961, the public expenditure and the amount of health insurance premiums reached 15.146 trillion and 19.120 trillion yen, respectively. The direct payment by patients was just 4.619 trillion yen or just 11.9% of the total medical expenditure. Hence, the financial sustainability of the system is now a very serious question, and controlling medical expenditures by limiting the length of stay (LOS) in hospital has become a controversial issue. In this paper, we evaluate the LOS of diabetes patients. The medical expenditure for diabetes was 1,209 billion yen, compromising about 3% of the total medical expenditure, and diabetes was the third-most costly disease, after malignant tumor (cancer, 3,327 billion yen) and renal insufficiency (1,490 billion yen). Moreover, various researchers have pointed out that comorbid diabetes increases the risk of fatality and prolongs LOS, such that the true cost of diabetes might be much higher than the direct one. A large part of the medical cost of diabetic patients is determined by the LOS. However, the LOS for diabetes patients has not been widely studied, and only a few studies have been done in Japan.

In this paper, we analyze the LOS of type 2 diabetes patients by the Box-Cox transformation model (BC MLE) when variances of error terms vary among different hospitals. The maximum likelihood estimator (BC MLE) which maximizes the likelihood function under the normality assumption is used for the estimation of the BC model. However, Showalter (1994) reported large biases of the BC MLE when heterogeneity exists in variances. Heteroscedasticity is a very important problem in the BC model, as mentioned even in the original paper of Box and Cox (1964). For LOS in particular, variances are often very different among hospitals even after controlling for the characteristics of diseases, treatments and patients. We propose a new estimator which is consistent even under heteroscedasticity. We then analyze the LOS of type 2 diabetes patients using the data set of 1,571 patients collected from 17 general hospitals in Japan by the proposed method. Finally, we evaluate the financial effects on the Japanese medical system based on the obtained results. In Japan, a new inclusive payment system based on the Diagnosis Procedure Combination (DPC) was introduced in April 2003, and the system is now referred as the DPC/PDPS (per diem payment system). As of April 2014, a total of 1,585 hospitals had joined the DPC system and an additional 278 hospitals were preparing to join the DPS/PDPS (hereafter DPC hospitals). The DPC hospitals comprise about 25% of the 7,483 general hospitals in Japan. The DPC hospitals have 511,439 beds (474,981 beds for already joined hospitals and 36,458 for soon-to-join hospitals), which represents 57% of the total number of beds (897,749 beds) of all general hospitals. The DPC hospitals are required to computerize their medical information, and thus it has become possible for us to use large-scale data sets consisting of many hospitals and patients.

The variables found to affect the LOS were the purposes of hospitalization, numbers of secondary diseases and complications, acute hospitalization, and principal disease E117. We found surprisingly large differences in LOS among hospitals, even after eliminating the influence of patient characteristics and principal disease classifications. There were also large differences among estimates of the variances, and the feasibility of the proposed model was strongly suggested. We finally evaluated the effects of shortening the LOS and found that as much as 50 billion yen could be saved by reducing LOS for type 2 diabetes patients.

Keywords: *Cox-Box transformation, heteroscedasticity, length of hospital stay, diabetes*

Guidelines for the admissibility of farm and catchment models in the New Zealand environment courts

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Abstract: Mathematical and computer models are useful as environment policy tools in environmental management, and appear everywhere from climate science to economic impact assessments. Because modelling tools are useful for determining environmental policy, this also means that internationally, mathematical scientists are increasingly entering debates concerning environmental policy. As a result, courts are becoming a public forum for scientific debate. Models are being used more and more in legally binding international protocols and environmental reporting, to the point where some models are prescribed as standards that all countries must adopt. This paper discusses some concerns regarding use of catchment and farm systems models in the environment court. The OVERSEER® nutrient budget model, as a case in point, is used as compliance tool and by councils to assess impacts in specific resource consent application processes. It is also a model used widely as a sub-model in several New Zealand catchment models, such as CLUES. It is probably the only model used in New Zealand for regulatory purposes.

This paper explores the qualities a model must have for regulatory purposes, in order to be admissible in the legal arena. *Daubert* standards, used to assist courts overseas in assessing the admissibility of scientific evidence, are explored for their relevance to scientific modelling. These standards, or a variant, could present one way forward out of the current quagmire.

Daubert standards for a theory or technique are related to:

1) Testability: whether the theory or technique is falsifiable, refutable, and/or testable,

2) Peer review: whether it has been subjected to peer review and publication,

3) Uncertainty: the known or potential error rate,

4) Protocols: the existence and maintenance of standards and controls concerning its operation, and

5) Acceptance: the degree to which the theory and technique is generally accepted by a relevant scientific community.

Models such as OVERSEER® are tested to see if they meet the above criteria. This work is of great importance for progress within the farm systems and catchment modelling sector in New Zealand.

Keywords: *Farm models, catchment models, admissibility, environment courts, Daubert standards*

Data farming: what it is, and why you need it!

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Abstract: Simulation models are integral to modern scientific research, national defense, industry and manufacturing, and public policy debates. These models tend to be extremely complicated, often with large numbers of factors and many sources of uncertainty, but recent breakthroughs help analysts deal with this complexity. Data farming is a descriptive metaphor that captures the notion of generating data purposefully in order to maximize the information "yield" from simulation models. Large-scale designed experiments let us grow the simulation output efficiently and effectively. We can explore massive input spaces, uncover interesting features of complex simulation response surfaces, and explicitly identify cause-and-effect relationships. Data farming has been used in the defense community for over a decade, and has resulted in quantum leaps in the breadth, depth, and timeliness of the insights yielded by simulation models.

Data farming draws on tools and techniques from data mining and "big data" analytics—but goes a step further. Numerous big data success stories are touted regarding the interesting patterns that are found by sifting through massive volumes of data, and then treated as actionable information. However, a key drawback to the big data paradigm is its reliance on observational data—causality remains unprovable. With data farming, we can leverage techniques developed for big data while retaining the ability to determine cause and effect. Expanding on the "3 V's" of observational big data (*volume*, *velocity*, and *variety*), the "3 F's" of inferential big data are *factors*, *features*, and *flexibility*. A "big factor" view embraces a broad exploration of the inputs (or functions of inputs) that, when varied, increase our understanding of the simulation responses. A "big feature" view refers to the simulation responses—we are typically interested in many, and they may be of different types. A "big flexibility" view captures the need to answer a wide variety questions from our experiments, even if we don't know *a priori* all the questions that might be asked—so our simulation study must be designed accordingly.

I will give an overview of the principles of data farming, and describe some recent applications in defense and homeland security. The bottom line: once you have invested the time and effort to develop a simulation model, it's time to let that model work for you!

Keywords: *Data farm, experiment design, data analytics*

Can models be used to determine if the hydrologic cycle is intensifying?

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Abstract: Whether the hydrological cycle is intensifying in response to climate change is a key question with relevance to impact assessment, feedbacks with climate, and policy-making. With global warming, the expectation is that droughts will intensify and last longer, and precipitation will become more intense with knock-on effects to flooding. Observational data show some evidence that this is happening for some variables in some regions, but data limitations, human influences and natural variability ensure that a definitive picture has not emerged globally. We show how land surface modeling can be used to address some of the observational limitations to provide global, long-term estimates of the terrestrial hydrological cycle. We focus on drought as a global natural hazard in an increasingly connected world and present recent updates on global and regional drought changes. Despite our ability to provide continuous and consistent estimates of the terrestrial hydrological cycle, there are multiple sources of uncertainty that ensure that the derived changes in the hydrological cycle, and drought in particular, are dependent on the modeling and data choices that we make. We discuss where and when these are important.

Keywords: *Hydrological cycle, intensification, drought, global, uncertainties*

Numerical modelling of wildland fire spread on the windward and leeward sides of a ridge

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Abstract: Wildland fires are occasionally observed to spread rapidly across steep leeward slopes, in a direction that is approximately transverse to the background wind. Laboratory experiments and remote sensing of wildland fires suggest that this atypical lateral fire spread can occur regardless of whether the fire is ignited on the leeward slope or advances onto it from the windward slope. The lateral rate of fire spread is typically greatest on the leeward slope close to the ridge, and can considerably affect the subsequent development of the fire, particularly through spotting downwind of the slope. Until now, numerical modelling of this atypical lateral fire spread has considered only the scenario in which a wildland fire is ignited on the leeward slope, with no fire initially present on the windward slope. However, such a scenario will not always occur in reality, and it is fairly common for a wildland fire to cross over from a windward slope to a leeward slope, due to the combined effects of the slope and background wind on the fire spread. It is therefore of interest to establish how a wildland fire can behave as it crosses from a windward to a leeward slope, for a variety of different fire environment conditions, in particular the background wind speed and terrain slope.

The aim of this study is therefore to conduct a series of idealised numerical simulations of wildland fire spread, starting from an ignition on a windward slope and with the fire subsequently crossing onto a steep leeward slope. In particular, the analysis focuses on the occurrence of lateral widening of the fire front as it progresses from the windward to the leeward slope, and the relationship of this lateral widening to the background wind speed. As in previous numerical modelling of atypical lateral fire spread, the WRF numerical weather predicition model is used in a large eddy simulation configuration and coupled to the WRF-Fire wildland fire physics module, allowing for direct modelling of the two-way coupled atmosphere-fire interactions. However, in contrast to previous modelling efforts, we amend the way the combined effects of wind and slope on fire spread are modelled in WRF-Fire. This amendment is made to better account for downslope fire spread in particular, though it also offers advantages in other respects.

It has previously been demonstrated that to resolve the fire whirls and turbulent atmospheric eddies that are predominantly responsible for driving the atypical lateral fire spread, is necessary to implement the simulations at high spatial and temporal resolution. In this study we use a spatial resolution of 30 m and a time step of 0.04 seconds. Simulations were conducted with the fire to atmosphere coupling enabled and disabled to examine the relative effect of coupled fire-atmosphere feedbacks on the lateral fire spread.

The non-coupled simulations failed to produce any significant lateral spread on the windward or leeward slope for any of the background wind speeds considered. In contrast, the coupled simulations exhibited significant lateral spread as the windward slope fire crossed the ridge onto the leeward slope for background wind speeds above 10 m s^{-1}. In the coupled simulations the occurrence of lateral spread was strongly associated with the formation of pyrogenic vortices, otherwise known as fire whirls. This is in accordance with previous results concerning the modelling of atypical lateral spread of leeward slope fires.

The modelling results were used to examine the relationship between lateral enhancement of fire spread on the leeward slope and the background wind speed. Raposo et al. (2015) found a power law relationship between the lateral spread enhancement on the leeward slope and the background wind speed in a series of laboratory experiments, as well as in three wildland fire cases. The coupled simulations exhibited a general increase in the lateral enhancement of fire spread for all but the highest background wind speed, though no obvious power law relationship was evident. A number of reasons for the differences in these findings with previous work are briefly discussed.

Keywords: *Lateral fire spread, wind-terrain effects, WRF-Fire*

Unlocking development in northern Australia: have we found the key?

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Abstract: Agriculture was northern Australia's first major industry. Within three years of the Burke and Wills Expedition (1865) more than 200,000 cattle and 1.3 million sheep were living in Australia's north. By 1880 cattle numbers exceeded 3 million, and today >9 million cattle occupy >60% of the northern landscape. The development of substantial intensive agriculture occurred later and took longer. Amongst the wide range of crops tested in northern Australia from the 1880s only peanuts, tobacco and sugar persisted through to the 1940s. It rapidly became apparent that irrigation was, in most of the north, a critical ingredient for success. But providing water for cropping businesses has posed its own challenges. Of the nine major irrigation schemes established in northern Australia since the 1940s only three have met their own expectations, attaining an irrigated area of 146,000 ha or less than 0.5% of the north's landscape. The remainder achieved less than 13% of their planned areas, and most persisted for <5 years. The harsh northern environment poses challenges, but it has mainly been farming systems introduced at too ambitious a scale without an adequate "learning" phase, and planning of finances, especially overcapitalising early, that has caused irrigation schemes to fail.

In most of the north irrigation is required for crops to reliably achieve break-even yields. Today, we know that the north has soil sufficient to potentially support >16 million ha of intensive agriculture, and water sufficient to irrigate about 10% of that area. Where water is available, the north is capable of growing a wide range of food or fodder crops, and could feed 7.5 million people.

The available evidence suggests that profitable supply chains, rather than the quantum of physical resources, is the major constraint to development of the north's intensive agricultural industries. Transport costs are high with nearly all of the supply chains drawn to southern Australia through existing transport infrastructure and logistics because of undeveloped and cost-ineffective transport routes to the north. Use of tools such as the recently developed TRANSIT model are being used to optimise use of the north's existing infrastructure and also to inform strategic investment to reduce transport costs.

CSIRO continues to drive an integrated program of research designed to reduce the risks and costs associated with development of northern Australia's agriculture, so that it might reach its full potential.

Keywords: *Water resources assessments, northern Australia, agriculture, integrated water management*

Adopting Lean Six Sigma to AnyLogic Simulation in a Manufacturing Environment

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Abstract: The aim of this paper is to illustrate the use of the Lean Six Sigma (LSS) methodology in a manufacturing environment by adopting the simulation software Anylogic®. In doing so, we present an innovative approach that implements simulation as a decision-supporting tool in the management of Six Sigma quality improvement projects. We intend to demonstrate how the LSS improvement process, "Define, Measure, Analyse, Improve & Control" (or DMAIC) can be applied in the Anylogic® environment so as to enable us to validate a manufacturing system's existing state and its subsequent improvement. LSS has become the de-facto method for process performance improvement in manufacturing sectors and LSS has been progressively increasing its acceptance in industrial manufacturing that confronts challenges, such as, how to decrease waiting time, maximise capacity, best use resources etc. Determining what alterations and changes to make is not simple and it is not easy to forecast the effect of proposed changes precisely. Coping with complicated systems composed of several interacting components poses the risk of generating s unacceptable decisions. This paper explains how the simulation program Anylogic®, with its powerful predictive and visualization capabilities reduces the risk of making undesirable process improvement decisions and assists in ensuring the best possible solutions are found and executed. Consequently, the quality of any process may be enhanced by utilising Lean Six Sigma in an Anylogic Simulation environment and it has the potential to offer a useful approach in term of improving quality and reducing costs. This approach enables evaluation of the performance of the manufacturing process after the proposed and recommended solutions for waste reduction have been implemented. Anylogic® can confirm improvements in yield, Defects Per Million Opportunities (DPMO) and six sigma levels.

Keywords: *Lean Six Sigma (LSS), Simulation, Anylogic®*

A simple population model with a stochastic carrying capacity

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Abstract: Many ecosystems are subject to external perturbations such as pollution, land clearing and sudden shocks to their environment. However, most current models used do not take the changing environment into consideration. In cases where the changes in the environment are taken into account this is usually done by specifying some time-dependent function for the carrying capacity that reflects the observed behaviour of the changing environment.

Here we employ an alternative approach where the carrying capacity, a proxy for the state of the environment, is used as a state variable in the governing equations. Thereby, any changes to the environment can be naturally reflected in the survival, movement and competition of the species within the ecosystem.

In this paper a simple ecosystem consisting of a single species and its variable environment is studied. Specifically, a logistic population model that incorporates a stochastic carrying capacity is investigated. The carrying capacity is treated as a state variable and is described by a stochastic differential equation. The statistical properties of the carrying capacity and the population are analysed using the Monte Carlo method giving; the expected time evolution of the population and its variance, the probability distribution of the population and the mean-time to extinction.

Keywords: *Logistic equation, Ornstein-Uhlenbeck process, stochastic differential equation, Monte Carlo simulation, carrying capacity*

Filtration Efficiency of Bubble Scrubbers

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Abstract: The passing of air through a column of water results in streams of bubbles rising through the chamber. Such a device has been used in science and industry, as a filtration mechanism to remove pollution particulates and gases from exhaust streams. Models of the individual processes inherent in the device have been developed over time. However, there are problems when attempting to match these theoretical results with the observations from experimental work that measures the efficiency of removal of the pollutants. There are some inconsistencies in determining the best operating conditions for the bubble chambers. For example, even researchers from the same research facility have provided inconsistent advice on the ideal operating conditions.

We use input-output analysis to model the bubble chamber as a complete system and incorporate existing individual process models as parts of the whole. The independent variables in the model are the water volume and the pollutant mass inside the scrubber chamber. The ensuing model is a set of two ordinary differential equations whose complexity depends on which individual process models are selected. The output processes include the “film” and “jet” droplets which are formed when the air bubble bursts at the water surface in the bubble chamber. Some of these droplets can be entrained and exit the chamber with the cleaned gases.

The equation for the water volume becomes redundant when the water volume in the chamber is held constant. Using the results from Fuchs, for particle absorption with in the column, and typical models for the generation of jet and film drops, the equation for the pollutant mass simplifies to a single linear ordinary differential equation. The outcomes are the existence of an equilibrium point and time varying exponential expressions for the efficiency of the chamber.

Measuring the efficiency of the scrubber is also compounded by the effects of measuring points and lengths and curvature of piping, and the expulsion of water droplets from the outlets. Some measurements of the deposition of particles in lengths of piping were made. Results show that the deposition depends on pipe length, curvature and flow rate. This effect needs to be accounted for in both the inlet and outlet piping and measurement points. Outgoing water droplets will also influence the size distribution and particle count at the outlet measuring point. The model suggests that the best way of measuring efficiency is to monitor the particle count in the water column, possibly by sampling and then taking a particle count in the sample. The sampling point should not be too close to the water surface.

The results provide guidance for operating the scrubber so that a desired efficiency is met including estimating time for maintenance. Monitoring the particle mass in the water is a better option than monitoring the input and outputs. Timing of the measurements is also important when performing experimental work and comparing with theoretical results, due to the time varying nature of the efficiency.

Keywords: *Bubbles, nanoparticles, filtration efficiency*

Dynamics of a discrete population model with variable carrying capacity

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Abstract: The carrying capacity is assumed to be constant in population growth models used for resource assessment and management. However, changes to the carrying capacity do occur due to both exogenic and endogenic processes. The need to treat the carrying capacity as a function of time has long been recognised in order to model population dynamics in an environment that undergoes change. Most populations experience fluctuations in their environment due to seasonal change.

The simplest approach is to specify some time-dependent function for the carrying capacity that reflects the observed behaviour of the changing environment. To date these models are deterministic with overlapping generations, the kind that are best described using continuous equations. However, the dynamics of some populations may not be appropriately described with continuous equations. Populations with non-overlapping generations are better described by discrete (difference equation) models.

In this paper, by considering the carrying capacity as a proxy for the state of the environment, we analyse a population whose growth is governed by a discrete logistic model and whose carrying capacity is modelled by a separate difference equation. The existence of fixed points is established and the stability of fixed points is discussed. Aperiodic behaviour is also shown to exist.

Keywords: *Population dynamics, carrying capacity, difference equation, discrete model*

Effective Method for Locating Facilities

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Abstract: There has been an increasing interest in the problem of effective facility location over the past five decades. The location of these important facilities arises in the service and manufacturing industries. The fundamental questions that arise concern the number and location of facilities such as: schools; hospitals; ambulances; warehouses; factories; department stores; police stations; waste material dumps; fire stations; needed to achieve a prescribed level of service and output. The main concern of many location problems is to place facilities to optimize some spatially dependent objectives such as: minimize average travel time or distance between demand points and servers; minimize a cost function of travel or response time. These optimization problems are complicated with the need to meet a number of specified constraints that relate to safety, demand, available resources, level of service and time. Indeed, the optimization problems that arise in practice are computationally difficult (NP hard) to solve by exact methods.

An important problem is the ***p*-median problem** which is to find the location of *p*-facilities so as to minimize the average weighted distance or time between demand points and service centers. Many heuristic algorithms have been proposed for this problem due to the difficulty in obtaining solutions by the exact methods. We discussed below a reduction concept applied to *p*-median problem as follows.

Consider a weighted *p*-median problem with a distance matrix given as $D = (d_{ij})$. Note that each row (column) of *D* is associated with a demand (facility) location. We say that **column *k* dominates column *l*** if $d_{ik} \le d_{il}$ for all $i \ne k$. We use the term **strongly dominates** in the case of strict inequalities. Observe that locating a facility at a dominated location *l* would provide no advantage to locating a facility at *k* except possibly in serving the demands of customers in location *l*. Further, strongly dominated columns would only be used for 'self-serve'. Consequently, dominated column can be dropped to generate a feasible solution and the location can later be considered as a possible 'self-service' facility.

We extend the concept of dominance somewhat further as follows. We say **columns *k* and *l* dominate column *j*** if $d_{ij} \ge \min\{d_{ik}, d_{il}\}$ for all $i \ne j$. In this case there is no advantage in using location *j* (except for serving customers in location *j*) when locations *k* and *l* are used. So again we can drop the dominated column *j* if columns *k* and *l* are used. The term strongly is used as before.

We further extend this concept of dominance as follows. We say that **column *k* partially dominates column *l*** if $d_{ik} \le d_{il}$ for at least half or more of the entries for which $i \ne k$. Similarly, we say **columns *k* and *l* partially dominate column *j*** if $d_{ij} \ge \min\{d_{ik}, d_{il}\}$ for at least half or more of the entries for which $i \ne j$. Partially dominated columns correspond to nodes which may be assigned 'self-serve' facilities in the original and the reduced matrix.

In this paper, we developed a new greedy algorithm based on a concept known as dominance to obtain solutions for the *p*-median problem. This concept reduces the number of columns of a distance matrix by considering potential facilities that are near and those that are far from the population or demand. We illustrate our ideas and the algorithm with an example. We further applied the new algorithm to effectively locate additional ambulance stations in the Central and South East metropolitan areas of Perth to complement the existing ones. We also compare the performance of our new Greedy Reduction Algorithm (*GRA*) with the existing greedy algorithm of the *p*-median problem.

Keywords: *Facilities, reduction, greedy algorithm, dominance*

Investigating Flame Fronts in Competitive Exothermic Reactions

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Abstract: The phenomenon of combustion is undoubtedly one of the most important physiochemical processes in nature and industry. Combustion theory has played a significant role in the advance of human civilization and provided an understanding of natural phenomena such as energy production from burning fossil fuels, the synthesis of advanced materials (e.g. the steady travelling wave is extremely important in the combustion synthesis via the Self-propagating High-temperature Synthesis process) and bushfire (the combustion models can be utilized to give correct predictions or even effective control over mountainous or grassland bushfires). However, there are still many aspects of combustion that are still not understood. Hence, there is a great value in understanding the process of combustion through mathematical modelling.

In this work, we consider travelling wave solutions of a one-dimensional reaction-diffusion system corresponding to two competitively exothermic reactions with the inclusion of Newtonian heat loss. We suppose all reactions occurring during the combustion may be lumped together as two different paths. The two exothermic reactions compete for the same reactant and both reactions are well described by the Arrhenius law. Such a reaction scheme has been shown to represent the combustion of titanium–carbon–hydrogen and zirconium–carbon–hydrogen experimentally. The model presented considers a general case of there being volumetric heat loss transferring heat to the surroundings in the reactions.

Properties of travelling wave fronts, particularly wave speed, are determined numerically by solving the governing partial differential equations (PDEs). The speed of the combustion wave is analysed for different values of the heat loss parameter with other parameter values fixed. We point out that as the heat loss coefficient increases with other parameter values fixed, the flame speed decays gradually before the front ceases to exist. This is expected as increasing the heat loss would result in less energy being available to sustain the propagation of the flame fronts. We also determine how the extinction limit depends on the heat loss parameter as well as the exothermic parameter. Numerical solutions show that there is no travelling wave when we choose the parameter values of the exothermicity and heat loss parameter above threshold values. All numerical solutions were obtained using the Method of Lines approach to solve the governing PDEs and were independently verified using a commercial finite-element package, $\mathrm{FlexPDE}^{\mathrm{TM}}$.

Keywords: *Combustion, two-step competitive exothermic reactions, heat loss, travelling wave, wave speed*

Internal versus external complexity: how organizations react

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Abstract: This paper investigates the effects of environmental complexity on organizational performance by means of computational modeling. There are few works that prepare a bottom-up, mechanism-based account of organization-environment interactions. Rather, a lot of top-down, statistical models have been developed which fall short of explaining how an organization can handle uncertainties. The theoretical foundation of this paper is based on the concept of learning, which is a running thread linking organization science with the agent-based modeling paradigm. The definition of environmental complexity is based on Shannon's famous information entropy which represents a good conceptualization of complexity. The definition contains appropriately all facets of environmental uncertainty including degree of uncertainty, number of decision elements, and interdependence or interrelatedness among decision elements. In this paper, the process conception of learning is considered, because it is consistent with behavioral theory of organizational learning and can be modeled as a learning algorithm. Organizational learning is modeled as a Reinforcement Learning (RL) algorithm that operates as a trial-and-error search with delayed reward. The appropriateness of RL comes from the fact that the overall objective of managers is to align organizations towards environmental requirements and thus the environment feedback plays a key role in the decision making process within any organization. Among various conceptualizations of organizations, they are viewed problem-solving entities in this paper. The question considered is how environmental complexity affects organizational performance.

To examine the effects of environmental complexity, an organization is exposed to different levels of environmental complexity, represented as decision rules. The requirements to accommodate environmental complexity have some counterintuitive effects on productivity. The results of the model show that the complexity of environment requirements has positive effects on organizational performance. In other words, if the organization can learn from the complexity of the environment, it can improve its performance. The computational model developed can be used to investigate other questions like the effects of internal complexity or organizational memory on performance.

Keywords: *Agent-based simulation, multi-agent systems, complexity, learning*

Rational function approximations in a response surface methodology

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Abstract: Scenario analyses of complex dynamic systems, such as environmental and economic systems, can be very computationally demanding and can generate large amounts of data. To efficiently process and summarize the results from such a scenario analysis, a response surface methodology (RSM) has been proposed. The RSM has originally been used to support efficient experimentation, but extensions towards efficient numerical experimentation have been widely accepted (Kleijnen, JPC (2008) Design and Analysis of Simulation Experiments, Springer Verlag, pp. 216). After sampling the factor space and subsequently conducting the (numerical) experiments, the resulting responses form the so-called response surface that is typically approximated by a multivariate polynomial function.

Polynomial models are frequently used for curve fitting, as these models have a simple form, have well-known properties, have moderate flexibility of shapes, are a closed family and computationally easy to use. However, polynomial models have poor interpolatory and extrapolatory properties, have poor asymptotic properties and exhibit a poor trade-off between shape and degree. Nevertheless, second-order polynomial models are popular, as these allow nice interpretations, even for high-dimensional factor spaces. For instance, an eigenvalue decomposition of the matrix weighting the second-order terms provides the orientation of the main axes and corresponding lengths of the semi-axes of the approximate ellipsoidal surfaces.

Rational functions for approximate modelling of a response surface will, in general, give better fits than polynomial functions. A rational function is simply the ratio of two polynomial functions. Rational function models have a moderately simple form, are a closed family, can take on an extremely wide range of shapes, have better interpolatory and extrapolatory properties than polynomial models and have excellent asymptotic properties. As for the polynomial model, the coefficients of a rational model and their statistical properties can, after a linear parametrization, be estimated using ordinary least-squares methods. Refer to Doeswijk, TG, Keesman, KJ (2009) Linear parameter estimation of rational biokinetic functions. Water Research 43 (1), 107 – 116) for further details.

The objective of this work was to introduce rational function approximations in RSM and, in particular, to present some properties of a rational function composed of two second-order polynomials. A truncated two-dimensional Gaussian function (Figure 1), typically found in solving diffusion problems, will be presented to demonstrate the advantage of using a rational instead of a polynomial approximation.

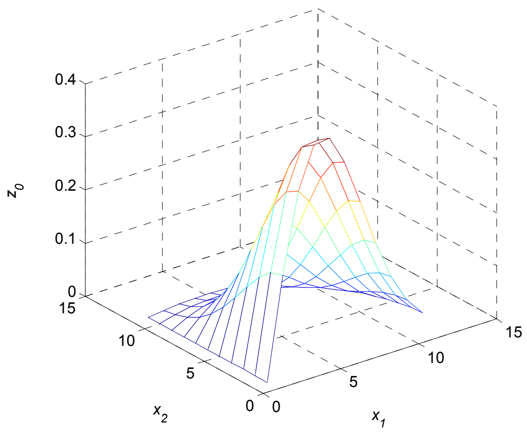

Figure 1. Example response surface.

Keywords: *Response Surface Methodology (RSM), rational functions, least-squares methods*

Multi-objective optimization of thermal comfort and energy consumption in a typical office room using CFD and NSM-PSO

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Abstract: With ever increasing energy costs, finding an optimal design to strike a balance between thermal comfort, indoor air quality and energy consumption has become a constant challenge for engineers. A number of research works have been carried out to develop a computational design optimization method for the indoor environment where design indices such as predicted mean vote (PMV), percentage dissatisfied of draft (PD), age of air, CO_2 concentration and energy cost were considered. Nevertheless, previous studies mainly focused on single objective optimization procedures where artificial weighting factors were introduced to combine all design objectives into one single objective function. It is well known that the optimal design may be sensitive to the weighting factors. Different weighting factors could result in substantially different optimal solutions.

In attempting to resolve the aforementioned problem, this paper provides some preliminary results on the development of a multi-objective optimization algorithm, which could be integrated into generic computational fluid dynamic (CFD) packages. A nondominated sorting-based multi-objective particle swarm optimization (NSM-PSO) algorithm has been developed to perform design optimization for a typical office room based on CFD predictions. The supply air temperature and velocity are the design parameters selected to optimize against the predicted mean vote (PMV), CO_2 concentration and energy consumption as objective functions. The results show that the optimal design temperature ranges from 290.15K to 294.15K, and the velocity ranges between 0.15m/s and 0.44m/s where a 3D Pareto-optimal front is given within the range. Based on the given Pareto-optimal front, designers could then choose the optimal design which is well-balanced between thermal comfort, air quality and energy consumption.

Keywords: *Multi-objective optimization, computational fluid dynamics (CFD), nondominated particle swarm optimization (PSO)*

Texture-Based Identification of Inert-Maceral Derived Components in Metallurgical Coke

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Abstract: As part of a comprehensive approach to understanding the relationship between the properties of metallurgical coke and its microstructure, we present methods and techniques for the identification of inert-maceral derived component (IMDC) grains in metallurgical coke. Detecting the presence of IMDC grains, delineating their extent and quantifying their density and spatial distribution assist in predicting the quality of the bulk coke. In order to overcome the inadequacy of the more common image analysis techniques, our methodology tackles visual texture in 3D. It is centred on mimicking human visual inspection of the mineral texture from two or more angles, and as such is based on a biologically inspired approach. In this paper we briefly describe the methodology as well as associated processing techniques that play a support role. Preliminary results are presented for a range of cokes produced from different coals. The methods have been incorporated into our overall approach to analysis of the quality of coke from its microstructure. We are working towards a framework in which 3D image analysis constitutes an integral part of the assessment of the quality of coke made from specified coals under given processing conditions.

Keywords: *Metallurgical coke, image analysis, Gabor filter*

Effects of climate, objective function and sample size on global sensitivity in a SWAT Model

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Abstract: Environmental models typically possess large uncertainty due to contributions from model structure, assumptions, parameterization, and data errors, not to mention lack of consideration of problem framing and the associated choice and justification of objective function. Sensitivity analysis (SA) is a fundamental tools to help identify uncertainties relevant to the modelling objectives. It provides information on the impact on model outputs from inputs and parameters and can contribute to simplifying models to make them more identifiable. However, sensitivity analysis can produce different results in accordance with several sources, such as input forcing, objective function, and the sampling undertaken.

The Sobol' method of SA is applied here to the Soil and Water Assessment Tool (SWAT). The method is based on variance decomposition, is categorized as a global sensitivity analysis (GSA) and is known to be model independent. It is able to handle non-linearity and non-monotonic functions and models. This study illustrates its findings using the total sensitivity index which includes the main effect and parameter interactions. Quasi Monte Carlo is invoked as the sampling method.

The SWAT model can be regarded as an example of a complex, dynamic, over-parameterized environmental model, albeit in the hydrology domain. It has been used to simulate both water quantity and quality. It represents catchment processes based on spatially distributed soil type, weather variables, topography and land use. Multiple modules in SWAT handle hydrologic processes, weather conditions, erosion and nutrient processes. The SWAT model used here is based on previous studies by Leta et al. (2015) and Zadeh et al. (2015) for the Senne river basin in Belgium. This paper investigates how individual sources affect the results of a Sobol' global sensitivity analysis of the SWAT model. Sensitivity analyses are performed with different weather conditions and multiple objective functions, and the stability of the ranking of parameter sensitivity is discussed.

The objective functions used as illustration in this study are: the Nash-Sutcliffe Efficiency (NSE), the modified NSE (NSE*), NSE*Log, and NSE*combined. The study analyses the sensitivity indices and rank of the parameters for different weather conditions, using wet and dry calendar years selected from the five-year observation period. In case of the selected wet year, NSE and NSE* produce the same rank for parameter sensitivity. The objective functions NSE*Log and NSE*combined both return different sensitivity indices and rankings to NSE and NSE*, as they emphasize low flows and mid flows more than high flows. The SWAT parameter *Cn2* (runoff curve number) becomes more influential in drier conditions whereas *Ch_K2* (effective hydraulic conductivity), for example, yields lower sensitivity indices for the dry year.

In addition, the study presents a visual comparison of the stability of relative sensitivities with the different sources using the estimated confidence intervals for different numbers of sampling runs. The SWAT model is generally insensitive to most parameters indicating that some of these parameters may require other conditions (i.e. a different catchment/climate) in order to be calibrated. This emphasises the need for GSA to determine which parameters are important for a given catchment when using very heavily parameterized models.

Keywords: *Sensitivity analysis, SWAT, model parameters, Sobol' method, environmental modelling, identifiability*

Linking Crime to Spatial Distribution of Urban Variables using Geospatial Discriminative Patterns and Geographic Information System Models

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Abstract: Crime is one of the indicators for measuring the quality of life in Malaysia. Crime incidents tend to cluster spatially. Models are used to explain the influential factors of crimes patterns. The aim of this study is to locate hot spots of crimes and to understand reasons such crimes occur on that location. Two major data will be used in this study that is detailed land use activities and location-based crime variables. The study area is the Penang Island, a recently declared a city, which is located on the northern region of Malaysia. Geographical Information System (GIS) will be used in the data analysis. GIS can visualize the spatial patterns of crimes, correlate activities of crime with the built environment and correlate the different types of crime and its related attributes. In this study Geospatial Discriminative Patterns (GDP) is applied to detect the significant difference between the hotspots area and areas outside the hotspots areas based on the dataset. GDP and GIS can also insight meaningful information from the visualized patterns and thus can be used in the allocation of resources as well as the deployment of police forces. The implications of the hot spot areas on the social environment and urban planning system will also be discussed.

Keywords: *Crime spatial patterns, urban land use, GIS mapping and Geospatial Discriminative pattern*

A continuous genetic algorithm for the calibration of a sedimentation model

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Abstract: In this contribution we consider the problem of flux identification in a scalar conservation law modeling the phenomenon of sedimentation. The experimental observation data used for the calibration consist of a solid concentration profile at a fixed time. The identification problem is formulated as an optimization one, where the distance between the profiles of the model simulation and observation data is minimized by a least squares cost function.

The direct problem is approximated by a monotone finite volume scheme. The numerical solution of the calibration problem is obtained by a continuous genetic algorithm. Numerical results are presented in order to validate the efficiency of the proposed algorithm. The optimization by a continuous genetic algorithm turns out to be more robust than previous calibration attempts with a gradient method.

The calibration of the model uses a set of measurements along the column at a fixed time $t = T$. The n measurement locations are denoted as $\overline{x}_i$ The solids concentration values measured in these points are $\overline{\phi}_i$ which means that the data set for the calibration is specified as

$$\Big\{(\overline{x}_i, \overline{\phi}_i) \in [0,H] \times [0, u_{\max}] \;:\quad 0 = \overline{x}_0 < \overline{x}_1 < \cdots < \overline{x}_{n-1} < \overline{x}_n = H\Big\}.$$

In practice, the data are represented by a curve, i.e. one defines $u^{\exp} : [0,H] \to [0, u_{\max}]$ such that $u^{\exp}(\overline{x}_i) = \overline{\phi}_i$. In terms of this experimental information, the inverse problem of determining the flux function is formulated in an abstract setting as the optimization problem

$$\text{minimize} \qquad J(u,f) := \frac{1}{2}\sum_{i=0}^{n}\Big|(u - u^{\exp})(\bar{x}_i)\Big|^2, \tag{1}$$

where u is the solution of the direct problem for the given parameter set, and $f = f(u)$ is the flux function of the governing equation

$$u_t + f(u)_x = 0, \quad \text{for} \quad x \in (0,H), \qquad f(u) = 0 \quad \text{for} \quad x \in \{0,H\}. \tag{2}$$

To handle the problem (1) it is reduced to a parameter identification problem, where one assumes that the flux function f is parametrized having a parameter vector $\mathbf{e} = (e_1, \ldots, e_d) \in \mathbb{R}^d$, which means $f(\cdot) = f(\cdot; \mathbf{e})$. In consequence, the parameter identification is formulated by the following optimization problem in several variables:

$$\text{minimize} \qquad \mathcal{J}(\mathbf{e}) := J\Big(u(\mathbf{e}), f(u(\mathbf{e}); \mathbf{e})\Big) \tag{3}$$

The search of the minimum of the cost function (3) follows the first-discretize-then-optimize paradigm, using a standard finite-volume scheme for solving the direct problem.

Keywords: *Continuous genetic algorithm, calibration, parameter identification, sedimentation*

Estimating the unit hydrograph and effective rainfall from observed output

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Abstract: The high uncertainty in estimated areal rainfall and potential evapotranspiration, as well as the observed streamflow means that it is difficult to identify an appropriate model structure and calibrate the parameter values. Improvements in model identification requires minimizing the impacts of the uncertainty in these quantities. This paper presents recent work on using observed streamflow and rainfall data to gain insight into the shape of the unit hydrograph (impulse response function), as well as estimating both the unit hydrograph and effective rainfall.

The first method looks at the potential information available from using a Fourier deconvolution approach for estimating the unit hydrograph. While it would be normal to take a straight forward approach to deconvolution (using the rainfall and streamflow timeseries as the inputs), the inputs in this case were the correlation function of streamflow with rainfall and the autocorrelation of rainfall (Croke et al, 2011, Hydrology Research, 42(5), 372-385). The advantage of this approach is that most of the temporal variation in the response signature is averaged before undertaking the convolution, resulting in reduced noise in the resulting deconvolved response curve. The resulting impulse response function includes the unit hydrograph response curve as well as the impact of wetting/drying of the catchment. The signal at negative lags is entirely due to the wetting/drying processes, while the signal for positive lags is a combination of the two sources. This allows investigation of both parts of the catchment response to be explored. Examples of the approach applied to salt transport as well as streamflow generation will be presented.

The second approach uses an iterative constrained deconvolution method, where the effective rainfall is constrained to be less than or equal to the rainfall (Croke, 2010, Proceedings BHS International Conference, Newcastle upon Tyne, UK, 494-499 (ISBN 1 903741 17 3). While such an approach would normally be extremely ill-posed, the fact that most days have zero rainfall puts a significant constraint on the problem, enabling convergence to a plausible solution. In one part of the iteration, the approach uses an estimate of the unit hydrograph, and runs through the time series of streamflow data, asking the question at each time step: given the result so far, what would the effective rainfall (with maximum permitted value being the areal rainfall) need to be in order to reproduce the observed flow. The second step in each iteration is to use the effective rainfall to estimate the parameter values of the unit hydrograph. This process is continued until the total absolute change in the parameter values of the unit hydrograph is less than 10^{-6}.

There are two modes this approach can be used in: simulation and forecasting. In the simulation mode, the previous modelled flows are used as an input to the calculation of the current effective rainfall. In forecasting mode, the observed flows are used as the input for calculating the effective rainfall. The simulation mode mimics the simulation of flow by a rainfall-streamflow model, and sets an upper limit on the possible performance of such a model using the adopted form for the unit hydrograph. The forecasting mode mimics a 1 timestep forecast model, and gives a better estimate of the effective rainfall at low flows, as well as a clear indication of timing errors in the data (either due to incorrect time stamps, or a variable delay in the rainfall-streamflow response). Examples of the application of these methods will be presented, and their limitations will be discussed.

Keywords: *Unit hydrograph, effective rainfall, rainfall-streamflow model, deconvolution*

Multi-Fidelity Surrogate-Based Parameter Estimation for a Sailing Yacht Hull

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Abstract: Given a numerical simulation $m : \boldsymbol{\xi} \mapsto \boldsymbol{y}_{\mathrm{num}}$, the objective of parameter estimation is to provide a joint posterior probability distribution $p(\boldsymbol{\xi}|\boldsymbol{y}_{\mathrm{exp}})$ for an uncertain input parameter vector $\boldsymbol{\xi} \in \mathbb{R}^d$, conditional on available experimental data $\boldsymbol{y}_{\mathrm{exp}} \in \mathbb{R}^q$. However, exploring the posterior requires a high number of numerical simulations, which can make the problem impracticable within a given computational budget.

A well-known approach to reduce the number of required simulations is to construct a surrogate, which — based on a set of training simulations — can provide a inexpensive approximation of the simulation output for any parameter configuration.

To further reduce the total cost of the simulations, we can introduce low-fidelity as well as high-fidelity training simulations. In this case, a small number of expensive high-fidelity simulations is augmented with a larger number of inexpensive low-fidelity simulations. We investigate the scaling of the computational cost with the number of parameters, as well as the optimal ratio of the number of low-fidelity and high-fidelity training simulations.

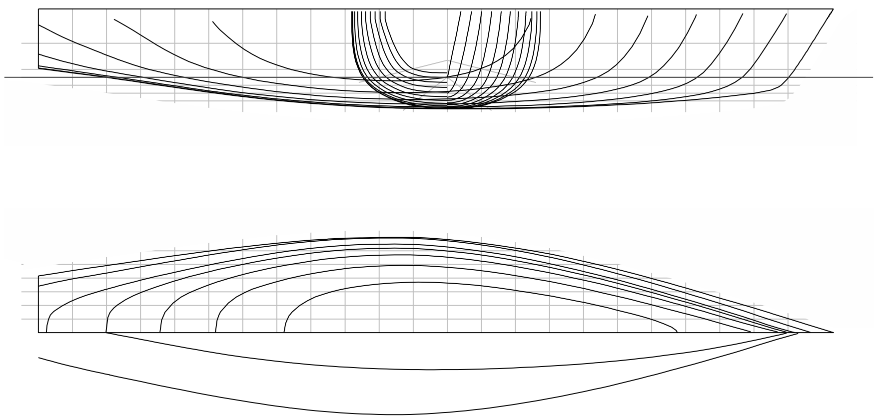

Figure 1. Lines plan of the sailing yacht hull used for multi-fidelity surrogate-based parameter estimation, showing the sections, buttocks, waterlines and diagonal cuts.

As an application we consider a towing tank experiment of the sailing yacht hull shown in Figure 1. The high-fidelity and low-fidelity simulations m_{HF} and m_{LF} solve the free-surface Reynolds-averaged Navier-Stokes equations on high and low-resolution grids, respectively. Experimental data $\boldsymbol{y}_{\mathrm{exp}}$ are available for the resistance, sinkage and pitch over a range of Froude numbers. The uncertain parameters $\boldsymbol{\xi}$ are the tank blockage, the mass and the centre of gravity. As a result we conclude that the centre of gravity is very close to the value provided by the laboratory, and that the tank blockage and mass are negatively correlated.

Keywords: *Parameter estimation, inverse problem, surrogate, multi-fidelity, free-surface, Reynolds-averaged Navier-Stokes*

Reduced Basis Model Reduction for Statistical Inverse Problems with applications in Tsunami Modelling

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Abstract: Tsunami modelling involves the problem of forecasting the effect that a tsunami has on a coastal area, given the recordings of the water height at several buoys. This forecast has two consecutive steps: (1) estimating the initial condition from the buoy data, and (2) propagating that initial condition to forecast the effect on the coast. In order to be effective, the forecast should be completed within reasonable time. This is challenging, as the first step involves solving a high-dimensional inverse problem, at significant computational cost. Therefore, there is a need to search for methods that accelerate the solution of the inverse problem.

One approach is to reduce the number of dimensions of the inverse problem through parameter reduction. This involves determining a reduced parameter basis, which enables us to approximate the model data to a high level at accuracy while reducing the dimensionality of the inverse problem. This approach introduces an 'offline' and an 'online' stage: during the offline stage, before a tsunami occurs, we allocate significant computational cost to determining the reduced basis. As soon as a tsunami occurs and buoy data arrives, we address the inverse problem, which is now lower-dimensional as a result of our efforts of determining the reduced basis in the offline stage.

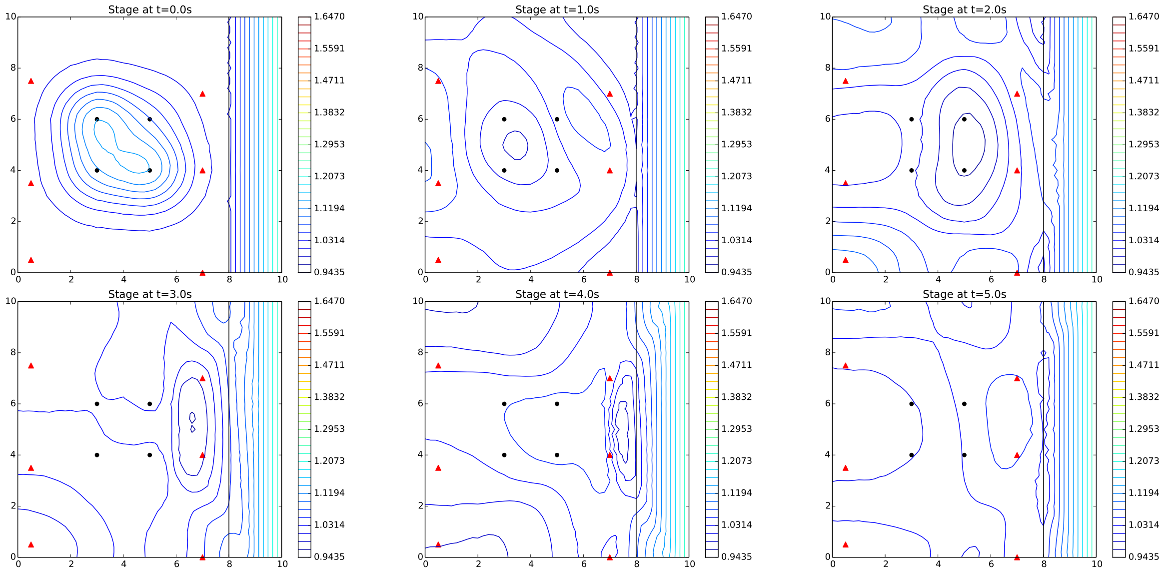

Figure 1. Time evolution of a model tsunami problem, with a coast line on the right-hand side.

In this work, we consider the model tsunami problem illustrated in Figure 1, which shows how the water height evolves over time, starting from an arbitrary initial condition. The initial condition is parameterised by the input parameters $\mathbf{p}$, which result in the buoy output $\mathbf{y}(\mathbf{p})$. We focus on finding a reduced basis, such that the reduced model $\mathbf{y}(Q_k\mathbf{p})$ is an accurate estimate of the full model $\mathbf{y}(\mathbf{p})$, with Q_k an orthogonal projection corresponding to the reduced basis. We use a greedy algorithm to approximate the optimal reduced basis.

We add a novel element to the greedy algorithm by quantifying how well the reduced model approximation $\mathbf{y}(Q_k\mathbf{p})$ can recover the full model $\mathbf{y}(\mathbf{p})$ for arbitrary $\mathbf{p}$. Results for up to $N = 25$ input parameters show that we can efficiently approximate the full model by using a reduced number of parameters. We find that the relative amount of parameters that we need for an accurate approximation decreases when the number of input parameters increases.

Keywords: *Statistical inverse problems, model reduction*

Toward A Generic Framework for the Multi-physical Inversion of Large-scale Geophysical Data Sets

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Abstract: Inversion is a key method for processing geophysical data sets and widely used in research in Earth Sciences as well as in industrial applications including hydrology, mining and oil and gas exploration. The objective of inversion is to built a three-dimensional model of the Earth's subsurface from data collected on or near the surface. Over the last decades the collection of geophysical data has dramatically changed delivering data sets with higher spatial and temporal resolution over larger areas but also for several physical observable over the same surface region. This enhancement is attributed to significant cost reductions in sensor technology and for data storage as well as to a free and open data access policy which is more and more applied to geophysical data sets.

The inversion problem can formulated as an optimization problem minimizing the defect of measurements and corresponding model predictions subject to physical constraints in the form of partial differential equations (PDEs). Regularization is introduced in order to select the 'simplest' feasible instantiation of the unknown physical parameters during optimization. It is common practice to solve the inversion problem using a 'first discretize then optimize' approach which - typically in combination with analytic solutions of the PDE constraint - transforms the problem into a discrete quadratic programming problem. Although being very efficient for small to medium size problems the approach reaches serious computational limitations for large-scale data sets and spatial extents as required to be processed today. Multi-physical inversion is also difficult to perform firstly due to computational limitations and secondly due to incompatibilities in the way individual inversion problems are tackled.

In the talk we will present an alternative mathematical and computational framework to perform geophysical inversion following the 'first optimize then discretize' approach. The framework is particularly suitable for solving multi-physical inversion problems and is tailored for the finite element method (FEM) using structured and unstructured meshes. The problem is solved using a quasi-Newton method (BFGS method) in an appropriate Hilbert space leading to a sequence of PDEs that are numerically solved on individual FEM meshes. We will illustrate the usage of the framework for some application scenarios, demonstrate its computational scalability for large spatial grids in parallel across thousands of processor cores and discuss results from various field data sets.

Keywords: *Geophysical inversion, finite element method, parallel computing*

Interpolatory Inequalities for First Kind Convolution Volterra Integral Equations

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Abstract: We consider the problem of computing a function $u(t)$ which satisfies the equation

$$k * u = \int_0^t k(t-s)u(s)\,ds = f(t), \quad 0 \le t < \infty, \tag{a}$$

where $k(t)$ is a given kernel and the right-hand side $f(t)$ is only known through some observations which contain observational errors. This problem arises in the study of the rheology of linear viscoelastic materials. It is well known that solving this first kind Volterra integral equation is ill-posed and thus special regularisation techniques are required to solve it in a stable fashion.

An important property of many kernels occurring in rheological applications is that they admit solutions $h(t)$ of the *interconversion equation*

$$\int_0^t k(t-s)h(s)\,ds = t, \quad 0 \le t < \infty. \tag{b}$$

In such situations, the solution of the Volterra equation takes the following form

$$u(t) = \frac{d^2}{dt^2}\left\{\int_0^t h(t-s)f(s)\,ds\right\}. \tag{c}$$

Problems where the interconversion equation can be solved explicitly includes

$$k(t) = 1 + \sum_{j=1}^n a_j \exp(-t/\tau_j)$$

with the $\tau_j > 0$. A characterisation of the solutions $h(t)$ for such $k(t)$ will be given below.

Even when the solution $h(t)$ to the interconversion equation is known, the problem of computing the solution of (a) as (c) is still ill-posed. A consequence is that regularisation techniques are required to compute $u(t)$. Even then for data containing errors, one can at best get error bounds of the form

$$\|u_\epsilon - u\| \le \eta(\epsilon)\,\epsilon$$

for some unbounded $\eta(\epsilon)$. The form of such error bounds based, on interpolatory inequalities, will be discussed for the first kind Volterra equations considered here.

Finally, a numerical technique to solve such Volterra equations, when the data is sampled and contains errors, will be discussed. The method is obtained from equation (c) by explicit differentiation, it evaluates

$$u(t) = h'(0)f(t) + \int_0^t h''(t-s)f(s)\,ds \; + h(0)\frac{df(t)}{dt}, \tag{d}$$

where the prime in (h') denotes the derivative of the function h etc. Instead of having to perform the numerical differentiation of the kernel k in equation (a) and then solve the resulting second kind Volterra integral equation, or the numerical differentiation of equation (c), the solution can be obtained, when h is known, through the direct evaluation of the right hand side of equation (d).

Keywords: *Interconversion equation, Volterra convolution integral equations, variable Hilbert scales*

Total variation method for computed tomography using filtered back-projections

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Abstract: The computed tomography is widely used in medical imaging. Its objective is to determine the density of cross sections of human body by measuring the attenuation of X-rays as they propagate through the biological tissues. This problem can be modelled by the linear equation of the form

$$Rf = g$$

where R denotes the Radon transform, g is the observed image, and f is the image to be reconstructed. This is an ill-posed equation. Because g always contains noise in practical applications, the reconstruction of images from projections is a challenging subject.

The current method used in hospitals is the prominent filtered backprojection (FBP) algorithm which is based on an explicit inversion formula and the fast Fourier transform and therefore can be implemented very fast, (*F. Natterer, The Mathematics of Computerized Tomography, 2001*). However, the FBP algorithm is not robust with respect to noise and is difficult to incorporate a prior information, its accuracy requires patients to be over-exposed to X-rays. In this talk we will propose a method based on the filtered backprojections, the total variation and the iterative techniques. More precisely, let Q denote the backprojection, and let $\Theta(f) = \mu\|f\|_{L^2}^2 + |f|_{TV}$, where $\mu > 0$ is a small number and $|f|_{TV}$ denotes the total variation of f. We then consider the iterative method

$$\begin{aligned} \xi_{k+1} &= \xi_k - t_k Q(Rf - g), \\ f_{k+1} &= \arg\min_{f \in C} \{\Theta(f) - \langle \xi_{k+1}, f \rangle\} \end{aligned}$$

with suitable step size $t_k > 0$, where C denotes the constraint on the sought solution. Numerical simulations on computed tomography are given to illustrate the performance of this method (*Jin and Wang, Inverse Problems, 29 (2013), 085011*).

Keywords: *Computed tomography, back-projection, total variation*

Calibration of hydrological models allowing for timing offsets

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Abstract: A central activity in hydrological modelling and simulation is the construction of predictors of extreme events, such as floods and droughts, on the basis of available historical observational data. For a given extreme event, the construction involves not only the choice of an appropriate parametric model for the predictor but also the identification of the key feature of the extreme event to be predicted, since it determines the focus for the associated parameter identification. For example, in flood forecasting, though the peak size of the flood represents a crucial aspect, the key feature is the accurate prediction of the timing of the arrival of the flood peak and its shape, after a rainfall event. The arrival time's importance relates not only to its practical significance from a community perspective but also to its theoretical significance in that the accurate prediction by the model of the size and shape of the flood peak depends crucially on the accurate prediction of the arrival time. On the other hand, in drought prediction, the key features are the duration and intensity of the drought.

However, the protocols that are commonly used to perform the associated parameter identification only focus on minimizing, with respect to some appropriately chosen error measure such as least squares, the *amplitude offset* discrepancy between the modelled and observed data at a representative set of time points. Such approaches can lead to significant errors in the identified parameters when the prediction, relative to the observed, contain (small) *timing offset* errors, reflected in the fact that the predicted flood peak arrival and shape does not accurately match the observed peak arrival and shape. In such situations, the parameter identification protocol has failed to successfully match the predicted flood peak arrival and shape with the observed.

The paper presents a new approach to overcome this problem by estimating jointly the amplitude and timing offsets. For a given flood event, it is based on comparing the difference between the cumulative sums of the predicted and observed flood, in order to assess the extent to which timing and/or amplitude offsets have occurred and how to correct for them. The method is applied to a synthetic case study where known amplitude and timing errors are introduced in the rainfall time series, and a simple hydrological model is fitted to perturbed data.

Keywords: *Timing errors, amplitude errors, rainfall-runoff modelling, non-linear storage model*

Rainfall Simulation from an Inverse Problems Perspective

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Abstract: The recovery of information from indirect measurements is the paramount goal that underlies the solution of inverse problems. The indirect measurements, both practical and theoretical, come in a wide variety of disparate forms from histology, tomography, pathology, preventive medicine, geophysical exploration, rheology, financial management, etc. Often the information recovered is used to answer quite specific practical questions such as ”Are cancer cells present?”; ”Is the bone density normal?”; ”Are minerals present in the surveyed area?”; ”What is the risk associated with investing in this type of option?”; ”What is the molecular structure of this type of polymer?”; ”How does the DNA chromatin folded in response to a drought event?”.

In many situations involving experimentally determined indirect measurements, the recovered information is the answer, because the experimental protocol being utilized has been designed to simply test for the presence or absence of some specific feature. Such situations arise in pathology where body fluids are used to test for the presence of infections or cancer.

In other situations, such as in stereology and in rheology, the answer is obtained directly from the indirect measurements without the need to formulate and solve a model relating the required information to the indirect measurement. Such *“direct use of the indirect measurements”* is based on the use of mathematical results that have established an equivalencing of the information to be recovered with some specific formula defined on the indirect measurements. A popular strategy for performing the equivalencing is the *“linear functional strategy”*.

The underlying *“modus operandi”* is modelling, in that some model which relates the indirect measurements to the information to be recovered has been formulated and solved using some appropriate form of regularization.

Equally important, yet not so common, is the recovery of information for the construction of a simulator, which will be used to test various scenarios. A prototypical example considered here is the construction of a synthetic rainfall simulator to test urban drainage design or to assess flood mitigation measures.

Here, the indirect measurements are the historic records of rainfall at various locations $\{\ell_k\}$ $(k = 1,\ 2,\ \cdots,\ K)$ in the region Ω of interest, such as a new suburb being designed or the catchment of a river upstream from a dam. The information to be recovered is the structure of the simulator. A popular design for such a simulator is a multivariate (cumulative) probability distribution $J(u_1,\ u_2,\ \cdots,\ u_d)$ which is a function of the rainfall intensities $\{r_i\}$ $(i = 1,\ 2,\ \cdots,\ d)$ for the d (successive) months of interest. The corresponding indirect measurements are the d monthly rainfall intensities $\{r_i\}$ modelled as the marginal distribution functions $u_i = J_i(r_i)$ of $J(u_1,\ u_2,\ \cdots,\ u_d)$.

Without additional assumptions, there is a continuum of possibilities for $J(u_1,\ u_2,\ \cdots,\ u_d)$ with respect to the given marginals $\{u_i\}$. When it is appropriate to conclude that the marginal are independent, it follows automatically that

$$J(u_1,\ u_2,\ \cdots,\ u_d) = \Pi_{i=1}^{d} u_i.$$

However, this often represents a gross simplification of the situation since it is known that, in the rainfall situation, successive monthly rainfalls tend to be correlated. In order to take the nature of such correlation into account in the recovery of a suitable approximation for $J(u_1,\ u_2,\ \cdots,\ u_d)$, a popular strategy is to use an appropriate *copula* to perform a regularized recovery.

Other questions such as spatial correlation and modelling rainfall intensities at shorter timescales is not inlcuded in this paper. In this paper, the focus is on the various *inverse subproblems* that must be solved in implementing a copula recovery strategy.

Keywords: *Rainfall simulation, copulas, inverse problems*

On the efficient use of satellite data to improve volcanic ash dispersion modelling

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Abstract: Volcanic ash poses a hazard to aviation, with ubiquitous jet powered aircraft being particularly vulnerable to its effects. Consequently, information about the location of ash and its predicted dispersion pattern is crucial to aviation stakeholders during eruption events. The Australian Bureau of Meteorology performs this function over a region that includes Australia, Indonesia, Papua New Guinea, and the southern Philippines. In current practice, information about the location of ash is obtained mainly from satellite imagery. Apart from the difficulty of identifying ash reliably by remote sensing, other properties of the ash cloud such as its altitude are still subject to significant uncertainties even when ash is successfully detected. On the other hand, the future location of ash is predicted by the use of dispersion models. In Lagrangian versions of these models, such as that used operationally by the Bureau, model particles, representing atmospheric pollutants such as ash, are released at specified locations and transported by gridded atmospheric winds and sub-grid turbulence. Information obtained from satellite retrievals of ash, such as its altitude, is frequently used to initialize the dispersion model. However, this is not in general done in a self-consistent and efficient manner by also taking into account how the simulated and observed ash distributions compare at a given analysis time. In this paper, we demonstrate how information about the ash distribution may be optimally integrated within the dispersion model. This is done by running a suite of dispersion model simulations with different values of the altitude of the initial ash cloud in the analysis phase of the algorithm. Pattern correlations are used to compare the simulations with the observed ash cloud. The altitude values which provide the best matches between simulations and observations are then used to initialize the dispersion model in the forecast phase of the algorithm. In this paper, we use the eruption of the Puyehue-Cordon Caulle volcanic complex, located in Chile, which occurred in June 2011 as a case study. Ash from this eruption circumnavigated the globe and caused significant disruption to aviation services in the southern hemisphere mid-latitudes, including southern parts of Australia. We demonstrate that the altitude estimates obtained from the method presented in this paper are consistent with the altitude measurements obtained from lidar instruments and superior to estimates obtained from satellite imagery alone. We also demonstrate the utility of satellite derived probabilistic forecasts of ash dispersion in the presence of significant uncertainty in the ash cloud altitude, as opposed to deterministic forecasts currently in use.

Keywords: *Volcanic ash, dispersion model, data assimilation, inverse modelling*

Propagation of measurement uncertainty in spatial characterisation of recreational fishing catch rates using logistic transform indicator kriging

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Abstract: Geostatistical estimation techniques (such as kriging) have been widely accepted and applied to characterise the spatial distribution of natural phenomena. In fisheries science, these techniques have been applied for computing indices including catch per unit effort (catch rate) used for stock assessment. The nonparametric kriging approach, known as indicator kriging, is particularly helpful for the estimation of catch rates using data observed from recreational fishing surveys because it can also handle other features of the data distribution such as zero-inflation, high skewness and class-specific spatial patterns. The problem considered in this paper is the use of indicator kriging for estimation of catch rates associated with an uncertainty due to multiple measurements observed at some locations. This measurement uncertainty is often non-negligible and needs to be propagated to produce accurate estimates. In addition, the uncertainty might be spatially autocorrelated and correlated with the data and so will restrict the use of a parametric approach of uncertainty propagation. Using catch rate data for Australian herring (*Arripis georgianus*) from a recreational fishing survey, this study presents a soft indicator kriging approach that uses a logistic function transformation to allow the propagation of measurement uncertainty in the estimation. The performance of the uncertainty propagated model was evaluated based on the leave-one-out cross-validation method. The accuracy plot and goodness statistic indicate agreement between the expected and empirical proportions of the observed catch rates falling within probability intervals of increasing size. These suggest a good estimation performance of the approach for Australian herring catch rate data. The spatial distributions of catch rate estimates with propagated uncertainty can be used for quantifying location-specific patterns to assist stock assessment or validation of policy supporting stock assessment models. The measurement uncertainty is considered to be potentially valuable for estimation of catch rate.

Keywords: *Logistic transform, soft indicator kriging, catch rate, spatial characterisation*

Evaluating Ecological Niche Modelling Techniques

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Abstract: Ecological niche modelling is an important method for predicting the range of a species or genus. In this paper we examine a particularly challenging case of niche modelling where:

- the number of samples is small (in our case, 12, not including "background" datapoints);
- samples are taken not from an individual species, but from a group of related species within a genus (in our case, Vietnamese frogs from species within the *L. applebyi* group of the genus *Leptolalax*); and
- the predicted distribution is required to generalise to other species within the group, which are not part of the training dataset (because we hope to identify regions where undiscovered species may be found).

Of necessity, such modelling will be imprecise, and dependent on the choice of training samples. However, even an approximate predicted distribution will support conservation efforts and guide the search for additional specimens (including those of undiscovered species within the group).

Figure 1 maps the samples used in our study, while Figure 2 illustrates our experimental process. Figure 3 shows some of the frog species used. We conducted niche modelling using the Generalised Linear Model (GLM), Maxent, Random Forest, Domain, and Bioclim methods.

Our experiments showed that, for the small training datasets used in our study, GLM outperformed the other methods used. With appropriate parameters, the predicted distribution produced by GLM always included at least half the independent test samples. Similar performance was obtained with GLM even when the size of the training dataset was reduced to just four samples (plus "background" datapoints).

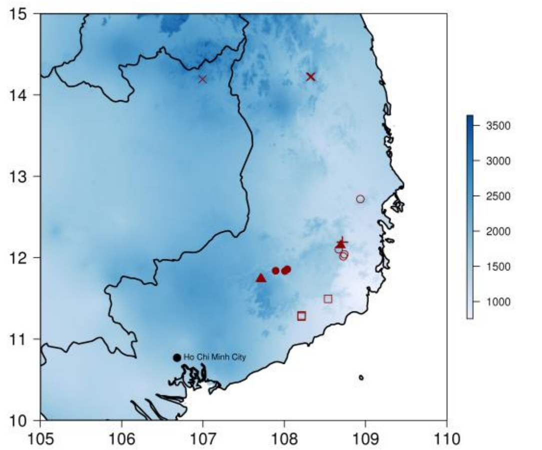

Figure 1. The 24 *Leptolalax* samples used in our study, marked on the map of central Vietnam. Map colouring indicates annual precipitation in mm, which is one of the 19 bioclimatic variables used.

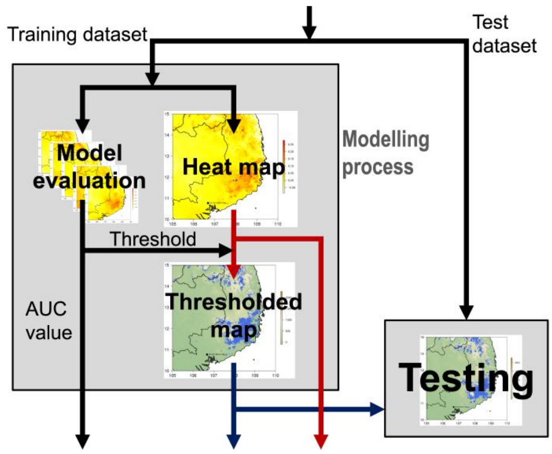

Figure 2. Our experimental process. The 24 *Leptolalax* samples are partitioned into a training dataset and an independent test dataset, which is used to assess the performance of the modelling process.

Figure 3. Some of the frogs in the study (L to R): *L. melicus*, Lineage 3, *L. bidoupensis* (photos: J. Rowley).

Keywords: *Ecological niche modelling, species distribution modelling, generalised linear model, frogs*

Maximal autocorrelation factors for function-valued spatial/temporal data

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Abstract: Dimension reduction techniques play a key role in analyzing functional data that possess temporal or spatial dependence. Of these dimension reduction techniques functional principal components analysis (FPCA) remains a popular approach. Functional principal components extract a set of latent components by maximizing variance in a set of dependent functional data. However, this technique may fail to adequately capture temporal or spatial autocorrelation.

Functional maximum autocorrelation factors (FMAF) are proposed as an alternative for modeling and forecasting temporally or spatially dependent functional data. FMAF find linear combinations of the original functional data that have maximum autocorrelation and that are decreasingly predictable functions of time. We show that FMAF can be obtained by searching for the rotated components that have the smallest integrated first derivatives. Through a basis function expansion, a set of scores are obtained by multiplying the extracted FMAF with the original functional data. Autocorrelation in the original functional time series is manifested in the autocorrelation of these scores derived.

Through a set of Monte Carlo simulation results, we study the finite-sample properties of the proposed FMAF. Wherever possible, we compare the performance between FMAF and FPCA. In an enhanced vegetation index data from Harvard Forest we apply FMAF to capture temporal or spatial dependency.

Keywords: *Autocorrelation operator, Functional time series, Spatially dependent functional data, Linear dimension reduction technique*

Predicting the spatial distribution of seabed hardness based on multiple categorical data using random forest

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Abstract: Seabed hardness is an important character of seabed substrate as it may influence the nature of attachment of an organism to the seabed. Hence, spatially continuous predictions of seabed hardness are important baseline environmental information for sustainable management of Australia's marine jurisdiction. Seabed hardness is usually inferred from multibeam backscatter data with unknown accuracy and can be inferred from underwater video footage or directly measured at limited locations. It can be predicted based on two-class hardness data derived from video footage and environmental predictors, but no study has been undertaken for predicting multiple-classes of hardness data.

In this study, we classified the seabed hardness into four classes based on underwater video images that were extracted from the underwater video footage. We developed an optimal predictive model to predict the spatial distribution of seabed hardness using random forest (RF) based on the point data of the hardness classes and spatially continuous multibeam bathymetry, backscatter and other derived predictors. A novel model selection measure that is the averaged variable importance (AVI) was used based on predictive accuracy that was acquired from averaging the results of 100 times replication of 10-fold cross validation. Finally, the spatial predictions generated using the most accurate model were visually examined and analyzed in comparison with previously published predictions based on two-class hardness data.

This study confirmed that:

1) seabed hardness of four classes can be predicted into a spatially continuous layer with a high degree of accuracy (i.e., with a correct classification rate of 86.27%);
2) model selection for RF is essential for identifying an optimal predictive model in environmental sciences and AVI selects the most accurate predictive model(s) instead of the most parsimonious ones, and is recommended for future studies;
3) caution should be taken when using the correlation coefficient to select predictors for RF in marine environmental sciences;
4) RF is an effective modelling method with high predictive accuracy for multi-level categorical data and can be applied to 'small p and large n' problems in the environmental sciences;
5) the spatial predictions for four-class hardness data were similar with the predictions based on two hardness classes, with high match rates; and
6) RF and AVI are recommended for generating spatially continuous predictions of categorical variables in future studies.

In summary, this is the first attempt to predict the spatial distribution of seabed hardness of four classes. AVI shows its effectiveness in searching for the most accurate predictive models and is recommended for future studies. This study further confirms the superior performance of RF in marine environmental sciences. RF is an effective modelling method with high predictive accuracy not only for presence/absence data but also for multi-level categorical data. RF and AVI are recommended for generating spatially continuous predictions of categorical variables in future studies.

Keywords: *Machine learning, model selection, cross validation, multibeam backscatter and bathymetry, spatial prediction*

A surface cover change detection method based on the Australian Geoscience Data Cube

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Abstract: We describe a surface cover change detection method based on the Australian Geoscience Data Cube (AGDC). The AGDC is a common analytical framework for large volumes of regularly gridded geoscientific data initially developed by Geoscience Australia (GA), the National Computational Infrastructure (NCI) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). AGDC effectively links geoscience data sets from various sources by spatial and temporal stamps associated with the data. Therefore, AGDC enables analysis of generations of consistent remote sensing time series data across Australia.

The Australian Reflectance Grid 25m is one of the remote sensing data sets in the AGDC. The data is currently hosted on the high performance computational cloud at the National Computational Infrastructure. Our change detection method takes advantage of temporally rich data in the AGDC, applying time series analysis to identify changes in surface cover.

The aim of this study is to develop a modelling framework addressing these issues, and to improve the efficiency and effectiveness of data modelling processes for the AGDC. The framework adopts a modular design, taking advantages of standardisation of data structures provided by the AGDC. The basic unit in the framework is a modelling module, which applies generic statistical functions or machine learning algorithms on a spatial-temporal partition of remote sensing data. Under the framework, a typical workflow of a modelling process consists of a sequence of connected modules. Such modular design offers both flexibility and reusability.

To detect change we apply a series of modules, which are independent of each other. The modules include:

- a pixel quality mask and time series noise detection mask, which detects and filters out noise in data;
- classification modules based on a random forests algorithm, which classifies pixels into specific objects using spectral information;
- training modules, which create classification modules using known surface cover data;
- time series analysis modules, which model and reduce time series data into coefficients relevant to change detection targets;
- temporal and spatial classification modules, which classify pixels into predefined land cover classes.

This paper summarises development of the work flow and the initial results from example applications, such as reforestation / deforestation detection and coastal zone mapping.

Keywords: *Surface cover, time series analysis, change detection*

A Multiple-point Geostatistics Method for filling gaps in Landsat ETM+ SLC-off images

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Abstract: The Scan Line Corrector (SLC), which compensates for the forward motion of Landsat 7, failed on May 31, 2003. The lack of SLC resulted in data gaps in the observed images, affecting the spatially continuous fields that were usually provided. Fortunately, the observations acquired by Landsat 7 are highly geometrically and radiometrically accurate compared with many other sensors, allowing the opportunity to develop gap-filling approaches to address the problem. How best to do this remains an open question. A variety of simple and effective methods based on different ideas have been proposed. Most of these can be classified into two categories: deterministic interpolation or geostatistical estimation. Deterministic interpolation approaches calculate the values of the unknown pixels based on an assumed continuity with the values of neighbouring data points. Geostatistical approaches formulate a spatial model of variability that is used to estimate the missing values as well as to quantify the uncertainty of these missing values. Most current approaches are only applicable for relatively homogeneous areas. For example they cannot satisfactorily predict the presence of narrow or small objects such as roads or streams. As a result, such objects can be truncated after interpolation. This problem may drastically constrain the application of filled SLC-off images. In this study, a multiple-point geostatistics approach, the Direct Sampling method, is adopted as a solution to fill Landsat 7 images. The Direct Sampling method uses a conditional stochastic resampling of known areas in the observation image to simulate the unknown locations. This approach can reuse the complex patterns present in the incomplete image, and has the capacity to simulate narrow or small objects. Moreover, being a geostatistical method, it allows for the generation of multiple interpolations to compute uncertainty bounds on the interpolated values. Here, the Direct Sampling method is applied to both univariate and multivariate cases to demonstrate its application. Numerical experiments indicate that the Direct Sampling method is able to fill the gaps satisfactory, especially when combining the target image with a temporally close image. The results are satisfactory for filling narrow objects like roads or streams. Compared with other gap filling method, the Direct Sampling method is relatively simple and easily employed. However, it also has limitations, such as the appropriate selection of parameters, which can greatly influence the simulation effect and computation time. Further research advancing the optimisation and providing guidance on parameter selection is required.

Keywords: *Landsat ETM+, Gap filling, Multi-point geostatistics, Direct Sampling*

Estimation of Near Ground PM10 Concentrations using Artificial Neural Networks

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Abstract: The impacts of atmospheric aerosols on public health, climate and atmospheric composition are currently among the most widely studied topics in environmental science research. Of most interest to its inhabitants, near-ground atmosphere (up to 1km AMSL) is most likely to influence the activities of our world. Short-term forecasting of air quality can help to avoid excessive medication, reduce the needs for hospital treatments and even prevent premature deaths by placing restrictions on traffic and industry and reducing unnecessary trips in contaminated areas. Artificial Neural Networks (ANNs) with the development of computer sciences have provided a powerful platform for different fields including air pollution modelling.
This paper aimed at predicting maximum PM10 concentrations for the next day using the meteorological parameters of the next day and day before. In this study an Artificial Neural Network was used to estimate maximum PM10 concentrations one day ahead in Timaru, New Zealand. Despite having a low population, Timaru is known to suffer from degraded air quality during the winter. Meteorological and PM10 data were obtained from Environment Canterbury((Ecan, 2015) air quality monitoring stations located at Anzac Park as well as industrial suburb of Washdyke in the north of Timaru (6 Km apart). The data set used in this study contains mean and max of wind direction (°) and speed (m s^{-1}), mean temperature at 2 and 6 meters (° C), mean humidity and mean and max of PM10 of the day before and mean wind direction and speed and mean temperature at 2 and 6 meters (° C) of the next day. The input and target variables were normalized scaling (0.1-0.9) and then presented to the network.

Table 1. PM10 descriptive statistics

Site	Year	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max
Washdyke	2012-2014	712	17.557	0.3507	9.357	1.2752	10.969	15.7864	22.5244	59.7062
Anzac Park	2012-2014	717	25.6432	0.6516	17.447	2.3247	14.3644	21.2981	31.446	125.713

Site specific ANN were established for each site in a way which PM10 is forecasted with the best accuracy. The model parameters were set to an input layer of thirteen neurons, an output layer of one neuron and one hidden layer of seventeen neurons. The dataset was divided into training (70%), validation (15%), and test sets (15%) randomly. Feed-forward back propagation neural networks and hyperbolic tangent sigmoid function were used during the training of networks, setting the maximum of epochs at 1000. The Levenberg–Marquardt optimization and Bayesian Regularization training algorithms were applied to update the training weights and bias values. The performance of both algorithms were evaluated using MSE performance function. In this study the Bayesian Regularization outperformed the Levenberg–Marquardt algorithm. The neural networks were implemented with MATLAB neural network toolbox. Statistical descriptors reveal that the selected inputs appeared to have a significant contribution to forecast PM10 one day in advance. The overall agreement between modelled and observed values for individual sites are presented in (Table3). Regression plots of site specific NN are presented in Figure 1.

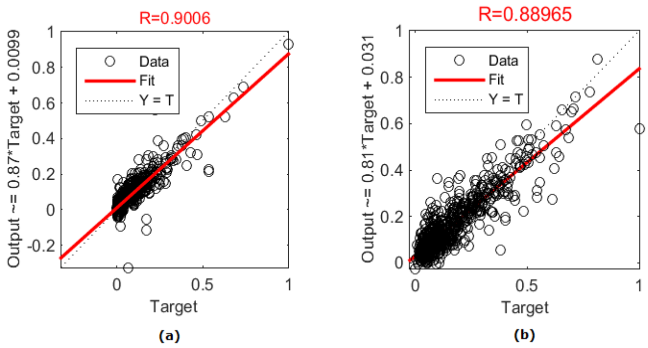

Figure 1: Regression plot: (a): Washdyke, (b): Anzac Park

Table 2. Overall agreement between output and target values for each site

Site	MSE	Correlation Coefficient (R)	Epoch
Washdyke	0.0020	0.90	865
Anzac Park	0.0043	0.889	287

Keywords: *Air pollution estimation, PM10 concentration, Artificial Neural Network*

Predicting potential spatial distribution of Toothed Leionema (*Leionema Bilobum* sub sp. *Serrulatum*) using Weights-of-Evidence modelling with GIS

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Abstract: This paper presents a study on predicting the potential spatial distribution of Toothed Leionema (*Leionema Bilobum* sub sp. *Serrulatum*) using Weights-of-Evidence (WofE) predictive modelling with GIS. Toothed Leionema is one of four subspecies of *Leionema bilobum* from the Rutaceae family. It is a poorly investigated species which is considered rare in Victoria, Australia. WofE is a statistical method based on Bayesian theorem, which applies a log-linear form of Bayes' rules and uses the prior probability distribution, calculated based on the observed presence of the modelled species, to produce a posterior probability distribution of the species. This study aims to use WofE as a tool coupled with GIS to identify key environmental factors associated with the habitat of Toothed Leionema, based on field observations and to determine the potential spatial distribution of this species in the Strzelecki Ranges, part of the Great Dividing Range, located in the West Gippsland region of Victoria.

The integration of WofE with GIS allowed the distribution of the species to be predicted based on geographically referenced observation data. It involved combining a set of evidence themes representing environmental predictor variables with the known distribution of the species to generate a response theme representing the probabilities of occurrence of the species at every location. The evidence and response themes were represented as raster map layers. This research used Arc-WofE to implement WofE.

The modelling results indicate that elevation, aspect, distance to water and distance to plantation areas are significant factors associated with the spatial distribution of Toothed Leionema. The model shows that areas with elevations between 336m and 555m and a dominant south-western aspect that are close to plantation areas (within 710 m), and to water (between 1000-1250m), provide potentially suitable habitat for Toothed Leionema in the region.

The effectiveness and validity of the tool for predicting the likely distribution of the species for which there is little knowledge about their physiology and habitat requirements was also assessed. Both model validation with training and control sites and ground truthing suggest that the modelling results are valid and the predicted spatial distribution provides a useful indication of potentially suitable habitat for Toothed Leionema. The results not only offer some understanding of the habitat requirements of the species, but also provide a new set of data about the species for developing strategies for their conservation and management, particularly when forest plans are formulated or reviewed.

Keywords: *Species distribution modelling, Weights-of-Evidence, GIS, Toothed Leionema*

An augmented level set model for the propagation of bushfire fronts

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Abstract: Based on the model of Rothermel (1972), during several decades, the spread of bushfires has been studied by empirical, quasi-empirical and physical models, in order to increase the knowledge on this phenomenon and its relevant characteristics, and to deliver timely information for fire extinction. In Chile, since 1976, the UNESCO has proclaimed in total 9 Biosphere Reserves within its 'Man and the Biosphere' program (Gedda, 2014). This program emphasizes the importance of protection measures and the relevance of scientific research in the area.

Recently, in March 2015, a large forest fire in the 'China Muerta' National Park in mid-southern Chile devastated some 8,000 hectares of native Araucaria araucana-Nothofagus forest, as firefighters had a hard job to extinguish the fires. This study is motivated by the need of a better understanding of forest fire dynamics in order to allow for improved prediction and prevention measures.

Propagating fronts or interfaces in general can be described by the Hamilton-Jacobi equation

$$\frac{\partial \phi}{\partial t} + v\frac{\partial \phi}{\partial x} + w\frac{\partial \phi}{\partial y} = 0, \tag{1}$$

where $\phi = \phi(t, x, y)$ represents the front implicitly as level-set where $\phi = 0$. This implicitly defined front is propagated by the convection velocities v and w in x and y direction, respectively. The propagation direction is normal to the front, pointing to the side where $\phi > 0$. Propagating fronts can be observed in different situations such as the interaction of gas and liquid in improved oil recovery, medical image segmentation and object tracking.

In the application of the Hamilton-Jacobi equation to bushfire propagation, the sign of ϕ distinguishes whether the corresponding area is burned ($\phi < 0$) or unburnt ($\phi > 0$), thus implicitly characterising the location of the fire front as $\phi = 0$.

In this contribution, an augmented propagation model based on the Hamilton-Jacobi equation is developed by introducing additional variables such as combustion and heat. The evolution of these variables is described by differential equations. The goal is to couple the equation for front evolution with a heat equation and an equation that corresponds to the local combustion process. The model dynamics is demonstrated by numerical simulations.

Keywords: *Hamilton-Jacobi equation, level set method, bushfire front propagation*

Effectiveness of automated fuelsticks for predicting the moisture content of dead fuels in *Eucalyptus* forests

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Abstract: The fuel moisture content (FMC) of forest litter strongly affects fire ignition and behaviour, and is a key factor in planning when and where to burn. Planned burns are safest and most efficient when FMC lies within a narrow range (9 % - 17 %). Drier fuels (<9% FMC) can burn too intensely and fires may be difficult to control, while wetter fuels (>17% FMC) may fail to ignite and/or burn poorly. Planned burning is associated with real risks of escape, and large annual operational costs (e.g. in the order of several $100M's per year in several Australian states), but in the absence of reliable estimates of FMC, fire behaviour predictions are compromised, and many burning opportunities may be missed, leading to the inefficient allocation of resources and compromising strategic burn planning.

The aim of this research is to quantitatively evaluate the performance of Campbell Scientific 10-hour fuel moisture sticks for the prediction of the FMC of dead surface and elevated fuels in a wide variety of *Eucalyptus* forests. Fuelsticks can be installed and monitored remotely, providing continuous real-time information to fire managers on fuel conditions. The performance of the sensors was evaluated in the context of the needs of planned burn managers, specifically, i) *daily FMC* trend information to assist in the efficient scheduling and resource allocation in the weeks and days prior to the burn, and ii) *hourly FMC* prediction to build an understanding of how FMC is responding to current conditions. The primary research objectives were to, a) quantify the relationship between Campbell 10-hour fuel moisture stick readings and the *in situ* gravimetric FMC of surface and elevated fuels collected from 40m x 40m plots, b) use the collected data to develop site-specific corrections to improve fuelstick FMC predictions, and c) evaluate the capacity of the uncorrected and corrected fuel moisture stick FMC readings to improve operational planned burning decision making. The fuelsticks were installed in eight contrasting forested locations across south east Australia and evaluated from December 2014 to June 2015.

The results showed that the uncorrected 10-hour fuelstick readings resulted in prediction errors of sufficient magnitude (RMSE of 8-17% FMC) that limits the utility of this method (as applied in this study) for planned burning decision making at the scale of days to weeks, resulting in correct planning decisions only about 50% of the time. However with site-specific corrections and the use of addition microclimate data the fuelsticks enabled correct planning decisions 75% of the time at the scale of days to weeks. Additional fuelstick replication and the use of fuelsticks with shorter response times could further improve the predictive ability of this method. At sub-daily scales the 10-hour fuelsticks were poorly suited predicting current FMC conditions, as the FMC of fuels changed more rapidly than FMC of fuelsticks. The results also indicated that the use of EMC type models to predict the FMC of the surface and profile litter is likely to be unsuccessful due to slow response time of the fuels relative to the rate of change of the atmospheric forcing during the day, and due to the lack of representation of recent precipitation on FMC.

Overall, these initial results indicate that locally-calibrated remotely monitored fuelsticks can be used to identify FMC trends which substantially improve planned burning decision making in the weeks and days prior to burning. However the 10-hour fuelsticks tested were unsuited to prediction at sub-daily scales, and more generally, further refinement of the fuelstick and microclimate FMC monitoring methodology is recommended in order to fully exploit the potential of this technology to improve operational decision making.

Keywords: *Fuel moisture content, Campbell's fuel moisture sticks, fire, planned burning*

Estimating Grassland Curing for Wildfire Danger Assessment from Satellite Based Microwave Data

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Abstract: During an extreme summer in Australia, wildfire can become a catastrophic natural hazard. Multiple meteorological and geographical elements can determined the severity level of fire, ranging from small scale bushfire to uncontrollable fire. There are various types of fire danger level assessment systems, where the most common systems used here are McArthur's Forest Fire Danger Index (FFDI) and Grassland Fire Danger Index (GFDI). The degree of curing is one of the important factors, as a fuel moisture representation, in determining the fire danger level in GFDI for the grassland environment. It is a measurement of how dry the grass is in percentage, where a completely dry grass field is indicated by a 100% cured value. Since it is very tedious and costly to accurately and consistency obtain curing field measurements, the degree of curing for calculating grassland fire risk is usually assumed constant.

The aim of this study is to accurately estimate the degree of curing using a passive microwave based satellite product referred to as vegetation optical depth (VOD). VOD illustrates the vegetation dynamics at a continental to global scale and acts as a proxy for vegetation water content. It is a unit-less measurement of vegetation water content with a value ranging from 0 to 1.3, where 0 indicates that there is no above ground biomass present or it is completely dry and 1.3 indicates a dense, fully saturated above ground biomass. VOD used here is the most recent version with a 10 kilometres spatial footprint and an 8-day temporal interval. Note that the VOD retrieval is usually accompanied with top layer soil moisture retrieval at a same spatial and temporal resolution.

By correlating the observed degree of curing with VOD, a significant relationship can be found. However, it should be noted that the VOD values for each observation site across Australia are very site-specific with a distinct base value, such that VOD value at one site may range from 0.7 to 0.9, and another may range from 0.4 to 0.6. Since this study is aiming for a continental scale prediction model, site classifications and additional remote sensing data were used to supplement VOD. For instance, using the MODIS MCD12C1 land cover type map, the sites located in the forests were removed, since at a 10 kilometres spatial resolution, if the majority area within the pixel where the observation were taken is classified as forest, then the data interpreted from the satellite signal is not going to be a good representation of the grass or cropland site data; it is usually found that the forest sites have a much higher minimum VOD value, because the total moisture in above ground biomass is much more higher in forest than grassland.

An additional satellite reflectance data for determining the vegetation greenness called Normalised Difference Vegetation Index (NDVI) is also used as a supplement data in the multiple linear regression model for estimating curing, since NDVI has a more normalised range across all sites and a resolution of 500 metres. Major drawbacks of NDVI are that they are prone to cloud cover interferences and a rapid saturation in dense vegetation. NDVI used during this study is computed from MODIS MOD09A1 reflectance dataset.

After several site selection criteria and multiple linear regression models were tested, the optimal models for estimated curing data can be derived based on the curing and VOD with NDVI multiple linear regression. The computed estimated curing data is then evaluated with the observed curing data again to ensure the robustness of model performance. Note that the observed data that were used for evaluation phase also contains data that were omitted during the calibration phase. The results suggested that the observed overall temporal trend in curing across various sites can be reproduced with estimated curing models. By utilising the estimated curing models, the curing dataset for Australia can be vastly expanded spatially and temporally.

Keywords: *Curing, Grassland Fire Danger Index (GFDI), remote sensing, Vegetation Optical Depth (VOD), wildfire*

Inter-Comparison of Land Surface Model Soil Moisture Data with Traditional Soil Dryness Indices

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Abstract: Australia has a long history of frequent forest fires, owing to its hot and dry climate. The McArthur Forest Fire Danger Index (FFDI; McArthur, 1967) was introduced in 1958 for operational fire warnings over Australia and is still used operationally, albeit with continuous development. The formulation of FFDI is based on air temperature, wind speed, relative humidity, and a component representing fuel availability called the Drought Factor (DF). The DF is defined on the assumption that the fuel moisture content (FMC) is affected by both long term and short term drying effects. The short term drying effects are based on the time since recent rain and past 20 days rainfall amount. The long term drying effects are based on either the Keetch-Byram Drought Index (KBDI; Keetch and Byram, 1968) or Mount's Soil Dryness Index (MSDI; Mount, 1972). KBDI and MSDI are estimates of the cumulative soil moisture deficit (SMD) and represent the degree of drought in the landscape. Studies show that the occurrence of large destructive fires corresponds to very large SMD values. SMD therefore is a key variable in the FFDI calculations with accurate estimates of soil moisture crucial for effective wildfire management, rating and warning. The KBDI is widely used in the Australian states of Victoria, New South Wales and Queensland while MSDI is used in the states of Tasmania, South Australia and Western Australia (Finkele et al., 2006).

KBDI and MSDI are simple water balance models that do not take into account the majority of physical factors which affect soil moisture dynamics such as soil type, vegetation type, terrain or aspect. They over-simplify the evapotranspiration and runoff processes, which are critical in calculating accurate soil moisture states, leading to large errors. Recent progresses in the remote sensing of soil moisture, data assimilation techniques and physically based land surface models has led to the development of new soil moisture products. Two examples of such datasets are the soil moisture analyses produced from the Bureau of Meteorology's operational Numerical Weather Prediction (NWP) system and remotely sensed soil wetness measurements from the Advanced Scatterometer (ASCAT; Wagner et al., 2013) instrument. This study undertakes an evaluation of the latter two datasets along with KBDI, MSDI and another simple water balance model called the Antecedent Precipitation Index (API; Crow et al., 2005). In-situ observations of soil moisture from the OzNet hydrological monitoring network (Smith et al., 2012) and Australian national cosmic ray soil moisture monitoring facility (CosmOz; Hawdon et al., 2014) are used to validate the modelled and remotely sensed soil moisture datasets.

The verification shows that the NWP soil moisture analyses have greater skill and smaller biases than the KBDI, MSDI and API analyses. This is despite the NWP system having a coarse horizontal resolution and not using observed precipitation. The average temporal correlations between observed CosmOz and modelled soil moisture are 0.81, 0.63, 0.76 and 0.73 for NWP, KBDI, MSDI and API. Verification also shows that the remotely sensed Advanced Scatterometer soil wetness product is of good quality. This study suggests that analyses of soil moisture can be greatly improved by using physically based land surface models, remote sensing measurements and data assimilation.

Keywords: *Soil moisture, verification, wild fire, ASCAT, KBDI*

Revisiting the King's Cross Underground disaster with implications for modelling wildfire eruption

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Abstract: In 1987 a fire engulfed the King's Cross Underground station complex, killing 31 people and seriously injuring more than 60 others. The extreme fire behaviour witnessed in this disaster was at odds with the fairly benign beginnings of the fire halfway down a wooden escalator trench. The first responders actually described the fire as like a 'small campfire' or 'cardboard box on fire'. The subsequent rapid development of the fire was unexpected, and at the time, unexplainable. In the following years, intensive investigation into this disaster identified a distinct physical mechanism that drove the extreme and rapid development of the fire: the 'trench effect'. The trench effect arises as a consequence of the geometry of the escalator trench and involves the flames and hot plume attaching to the bottom of the escalator trench. As part of the King's Cross fire investigation, detailed Computational Fluid Dynamic (CFD) analyses of the fire, which included the escalator configuration as well as the ticket hall, where most of the fatalities occurred, were performed. In the intervening years, CFD methods and implementation software have progressed significantly and so it is of interest to reconsider the scenario of the King's Cross fire in light of these new developments. It is also of interest to consider a number of similar scenarios that were not considered in the original CFD analyses. In this paper we use the ANSYS CFX package to provide a detailed numerical analysis of the heat-induced flows that arise in a number of scenarios related to the King's Cross fire. These include reanalysis of the original situation, in which the escalator trench is inclined at 30°, as well as cases with lower angles of inclination.

Simulation of the flows within the escalator trenches displayed marked differences in the flow characteristics depending on the inclination of the escalator trench. For the 10° and 20° tunnel inclinations the hot plume emanating from the modelled fire source separated from the floor of the elevator trench and advected up the tunnel in a distinctly turbulent manner. The separated and turbulent flow that manifested at lower tunnel inclinations was decidedly different to the simulated flow for the 30° case. For the 30° case the flow attached to the floor of the escalator trench and developed a distinctly laminar structure, which is consistent with findings of previous investigations into the King's Cross fire. Moreover the 30° case gave rise to flows that were both faster moving: 7 ms^{-1} as opposed to 2 ms^{-1} for the 20° case, as well as hotter: 430°C as opposed to 350°C for the 20° case.

These results provide the first numerical verification of the existence of a threshold angle of inclination γ^* that demarcates the separated, turbulent flow regime from the attached, laminar flow regime. As far as the authors are aware, the existence of this threshold angle of inclination has previously only been established in experimental work. Moreover, the numerical simulations presented indicate that $\gamma^* \in (20^\circ, 30^\circ)$, which is consistent with the value of $\gamma^* \approx 24^\circ$-$26^\circ$ determined from experiments.

The results presented have clear implications for the behaviour of wildfires burning in steep and confined terrain elements such as canyons and gullies. These implications are discussed.

Keywords: *Eruptive fire, trench effect, fire hazard, slope, flame attachment*

EXTENDED ABSTRACT ONLY

Models for Lightning-Caused Bushfire Ignition

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Abstract: The two most popular bushfire ignition modelling approaches are logistic regression and point process models. Logistic regression models cut up the landscape into grid cells and use covariates such as precipitation, temperature, topography, vegetation and fuel moisture codes to calculate the probability of an ignition occurring in a grid cell in a day. Point process models operate on a continuous landscape with point ignitions occurring according to a probability intensity function that is dependent on covariates. These intensity functions give the average number of ignitions in space and time and can also be used to calculate the probability of ignition on a given day in a given spatial region.

In their basic form, both of these modelling approaches have an underlying assumption of conditional independence. That is, given the value of the covariates, each ignition occurs independently of the others. In the case of lightning-caused bushfire this assumption is poor, as we would expect to see clustering in both time and space, as a single storm front will account for multiple ignitions.

The auto-logistic regression model is an extension of the logistic regression model that allows for the sort of dependence outlined above. This is achieved by the inclusion of a neighbour covariate, which takes a value equal to the number of neighbouring cells with an ignition. These models have been applied in the ecology literature to model the spread over time of a colony of plants where offspring are more likely to appear closer to their parents. In lightning ignition modelling, the neighbouring covariate doesn't have a natural physical interpretation and may not produce realistic ignition patterns.

The point process models currently seen in the literature are mostly Poisson process models with intensity functions dependent on the covariates. In their most basic form these models do not consider explicit dependence between the points. A paper by Turner (Point patterns of forest fire locations, Environmental and Ecological Statistics, June 2009, Vol. 16, Issue 2, pp 197-223) looks at a pairwise interaction process, but after some exploratory work decides to drop the interaction term and relies only on a spatial trend term. Turner concludes that his choice of trend term may be dominating the interaction term and that future work is required. Furthermore he is fitting a single model to all bushfire ignitions rather than ignitions from a single cause, which could further obscure any dependence between the points.

We propose to look at a cluster-type point process model for lightning-caused ignition. These processes explicitly model storm fronts, with strikes of lightning and rain cells clustering around them. Each lightning strike has a chance of causing an ignition based on the value of the covariates at the point of contact. In this way we hope to build a model that reflects the physical process and provides more accurate probability estimates.

Keywords: *Point processes, logistic regression, bushfire ignition, lightning*

Modelling overland flow on burned hillslopes using the KINEROS2 model

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Abstract: A process-based study was conducted to investigate soil infiltration and overland flow dynamics in response to post-fire soil-surface characteristics on a dry burned hillslope one year following wildfire. The study consists of analysing data from paired rainfall-runoff plots, field and laboratory measurements, and plot-scale simulations of overland flow using the KINEROS2 rainfall-runoff model.

Post-fire soil-surface characteristics and rainfall data were collected from paired rainfall-runoff plots located in dry eucalyptus forest, southeast Australia, severely burned by wildfire in January 2013.

Field and laboratory measurements were undertaken on six separate occasions during the study period and confirmed the existence of strong hydrophobicity within 4 cm soil depth, restricting vertical infiltration and increasing the rate of runoff, although with a declining trend with time since fire. The strength of hydrophobicity steadily weakened from depth 4 cm downward, becoming non-repellent below 8 cm.

Event-based simulations of soil infiltration and surface runoff were implemented using the KINEROS2 model for fourteen rainfall events. Spatial factors representing post-fire soil-surface conditions were calibrated with highly acceptable model efficiencies for the majority of the events. Simulated hydrographs were validated against observed data from runoff plots. The key properties impacting dynamics of simulated hydrographs were identified as soil hydraulic conductivity (K_{sat}), net capillary drive (G) and surface roughness respectively. The existence and breakage of fire-induced water repellency was simulated by appointing variable values for effective hydraulic conductivity.

Parameterized values of soil saturated hydraulic conductivity (K_{sat}) showed that the existence and breakage of fire-induced water repellency during the first year following fire did not follow seasonal oscillations of natural water repellency. The calibrated effective hydraulic conductivity was in the range of 2-4 mm/h during the first winter following fire, reflecting strong water repellency. Fire-induced water repellency broke down during the early autumn next year and soil hydraulic conductivity increased suddenly to (K_{sat}>10 m/h). A constant value of 2 mm was parametrized with the factor of 0.1 for the net capillary drive (G) parameter. The capillary depression could be result of large contact angle (>90°) between liquid-solid interface in water repellent soil.

Hydraulic roughness was represented by Manning's n coefficients and simulated hydrographs with higher roughness values obtained lower errors in peak and mean values. The theoretical primary roughness factor that only included bed size particles (0.085 $sm^{-1/3}$) was re-calibrated by the factor of seven after calibration (0.64 $sm^{-1/3}$). Similar trend of higher values for Manning's n was also reported by Chen et al. (2013) who used Kineros2 for modelling rainfall-runoff in fire affected watersheds.

Dynamics of simulated hydrographs were found less sensitive to variations of the second group of soil hydraulic properties (porosity, pore index and initial water content), <5% variations in model efficiencies and error indicators.

The soil infiltration model in KINEROS2 was well-adjusted to fire-induced hydrophobic soil by adapting infiltration concepts and domains to measurements and observation of post-fire soil-surface conditions in the initial model setup and parametrization (ME > 50% and R2 > 0.5). The model successfully simulated dominant factors in controlling vertical preferential water movement and their trend change during post-fire recovery period.

***Keywords**:* *Soil water repellency, overland flow, modelling, KINEROS2, infiltration*

WRF-Fire simulation of pyro-convection under the influence of low-level jet wind profiles

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Abstract: Blowup wildland fire behaviour is characterised by a sudden increase in the fire intensity or forward rate of spread that precludes direct control. It is often accompanied by extreme pyro-convection and can pose a serious risk to firefighters. Blowups are difficult to predict due to our limited understanding of their environmental thresholds and the underlying driving physical processes. Low-level jets, a fairly common feature of the atmospheric boundary layer, have previously been observed at a number of blowups. However, there is currently no well-tested causal theory to explain this apparent connection between low-level jets and blowup fire behaviour.

In this study, a two-way coupled atmosphere-fire model is used to conduct a series of idealised simulations that examine the sensitivity of modelled pyro-convective plume dynamics to variations in the low-level jet height and wind shear above the jet. The Weather Research and Forecast (WRF) numerical weather prediction model is used here in a large-eddy simulation configuration, and coupled to the WRF-Fire wildland fire physics module. Sensible and latent heat fluxes are calculated in WRF-Fire and can directly modify the potential temperature and water vapour mixing ratio in WRF, allowing the modelled fire to modify the local atmospheric dynamics. This dynamic feedback allows WRF and WRF-Fire to directly model the development of a pyro-convective plume under the influence of a low-level jet.

The model simulations show only a limited sensitivity of the pyro-convective plume dynamics to the presence of a low-level jet and the variation in jet properties. In particular, the level of tilting and total vertical development of the plume, in addition to the resolved turbulent kinetic energy within the core of the plume, display some differences due to variations in the wind shear above the jet. It seems likely that the fire intensity is too high to allow for more pronounced variations in the plume properties, and future work will focus on fuel types with a lower fuel mass per unit area.

Keywords: *Coupled atmosphere-fire modelling, large eddy simulation, pyro-convection, low-level jet*

Modelling water quality risk in wildfire-prone catchments

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Abstract: Risk to water quality in forested water supply catchments from fine suspended sediment after wildfire is an important concern for water supply safety. Fire can cover parts or all of these large catchments and burn severity is often heterogeneous. The probability of spatial and temporal overlap of fire disturbance and rainfall events, and the susceptibility of hillslopes to severe erosion determine the risk to water quality. Previous research found that post-fire debris flows have erosion rates up to three orders of magnitude higher than background rates. A model was developed to calculate recurrence intervals of high magnitude sediment delivery from debris flows to a reservoir in a large catchment (>100 km²) accounting for heterogeneous burn conditions. The system to be modelled was represented by the relationship between the stochastic drivers of rainfall and wildfire ignition, deterministic processes of wildfire spread, overland flow, debris flow initiation and sediment delivery, and their properties (Figure 1). Properties were either variable in time, or fixed.

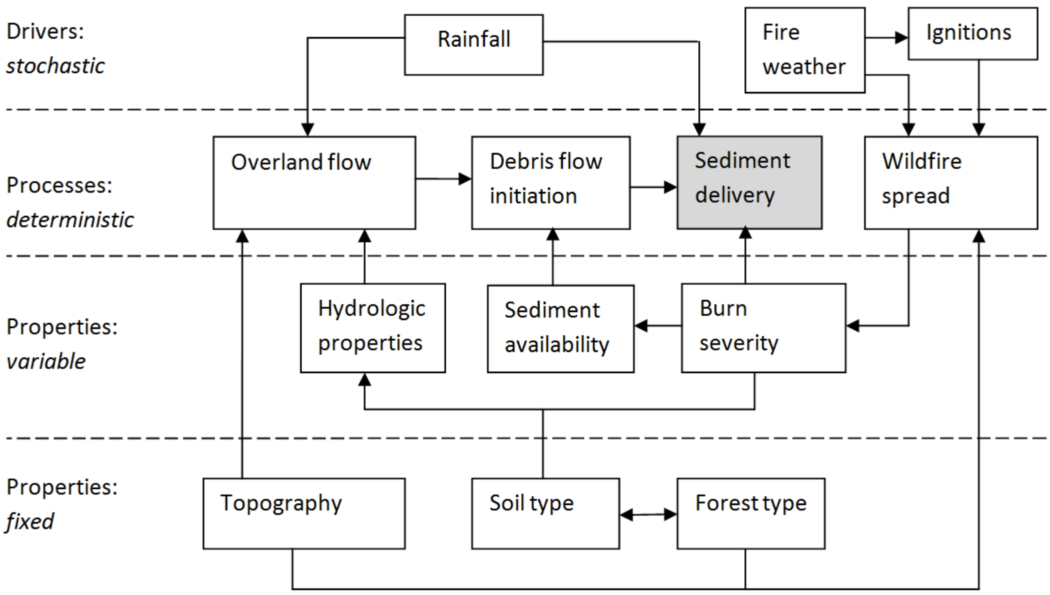

Figure 1. Conceptualization of the system to be modelled.

The exceedance of critical values of peak stream power during rainfall events and the mass of non-cohesive material on the soil surface are assumed to be the drivers of debris flow initiation in headwaters. Debris flow volume was calculated with an empirical model, and the mass of fines was calculated using simple, expert-based assumptions. In a Monte-Carlo simulation, wildfire was modelled with a fire spread model using historic data on weather and ignition probabilities for a forested catchment in central Victoria, Australia. Multiple high intensity storms covering the study catchment were simulated using Intensity-Frequency-Duration relationships, and stream power calculated with a runoff model for hillslopes. A sensitivity analysis showed that output is most sensitive to variables related to the texture of the source material, debris flow volume estimation, and the proportion of fine sediment transported to the reservoir. SE Australia lacks long term debris flow observation data that could be used to validate the model directly. However, as a measure of indirect validation, denudation rates of 3.3 – 19.3 mm ka^{-1} were estimated that compared well to other studies in the region. From the results it was extrapolated that critical sediment concentrations in the studied reservoir could be exceeded in intervals of 27 – 167 years. This is the first study to couple fire spread simulation with risk assessment for water quality in large catchments.

Keywords: *Wildfire, water quality, runoff, erosion, Monte-Carlo simulation*

Fire spread prediction using a lagged weather forecast ensemble

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Abstract: From October to early December 2014 the Bureau of Meteorology conducted a pilot trial of a Rapid Update Cycle (RUC) numerical weather model. The model was run at a horizontal resolution of approximately 1.5 km, with hourly updates to the forecast, and was nested within the operational ACCESS suite of weather models. At this resolution, convection can be resolved without parameterization and the influence of topography on near surface conditions should be better captured. As part of this trial the model data was made available to the NSW Rural Fire Service in order to gauge how useful it would be in an operational setting.

We present a set of three case studies of wildfires that occurred during the RUC trial period. In each case a short overview of the fire is presented, and the broad synoptic scale weather pattern outlined. The 0000UTC RUC model run and the morning official Australian Digital Forecast Database (ADFD) nearest grid cells were compared with observations at a nearby Automatic Weather Station (AWS) location as a check on the broad scale performance of the model. The gridded weather at the fire ignition point was then compared with the gridded weather at the AWS site to assess any local variation in expected conditions, e.g. wind change timing. The RUC guidance and ADFD guidance were then used as input to the Phoenix fire spread model, with an examination of the relative performance of each model in predicting the resulting fire spread. For each case, a proof of concept lagged ensemble 'probability burnt' prediction map was produced using five consecutive (unweighted) RUC forecasts. RUC model runs were initiated hourly on the morning of each case study from 0700 local time (2000UTC on the previous day). All times are given below as UTC.

One issue that we encountered with attempting to construct a lagged ensemble type fire spread product was that the intermediate RUC model runs (i.e. those falling between the major six hourly updates) had quite short forecast time domains, and an overlapping period of a few hours only was available. This was considered sufficient to assess the initial phase of fire spread, however, and comparisons with the actual burn extent generally become more difficult on longer time scales as active suppression becomes more of a factor.

The selection of cases to examine was based on a combination of an interesting weather situation, a sufficiently large fire run, and the availability of aircraft linescan data at appropriate times to verify the actual fire spread. We also wanted to ensure that we examined at least one case in predominately grass fuels and one case in predominately forest fuels. None of the cases selected occurred under extreme weather conditions, as little extreme weather occurred during the RUC trial period, and uncertainty around the applicability of the fire behaviour models that underpin Phoenix in extreme conditions would make comparisons with the actual fire spread maps less certain.

We also present a short discussion on the sensitivity of the Phoenix model to fuel state, ignition pattern and the weather forecast, and consider the relative magnitudes of these sensitivities with reference to one of the case study fires, showing that sensitivity to the weather forecasts is comparable to the other inputs.

Keywords: *Ensemble modelling, fire behaviour, Phoenix*

Modelling Australia's Fire Seasonality

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Abstract: There are now enough years of high quality MODerate-resolution Imaging Spectroradiometer (MODIS) hotspot data to attempt a review Australia's fire seasons. MODIS is carried on both the Aqua and Terra spacecraft. Standard algorithms assess the spectral signature of each pixel and the pixel's neighbourhood to tag some as indicating fire. The databases of these are now readily available for analysis.

Hotspots are point objects with some positional uncertainty due to viewing angle, terrain and orbital instability. They are fully attributed with data about collection time and assessed intensity. Aggregation of these for the purposes of identifying patterns is not straightforward.

Australia's fire industry still largely relies on fire-season maps produced decades ago, long before modern remote sensing technology. Changes in land use, social structures and even climate can be expected to have potentially altered the seasonality pattern.

A seasonality pattern derived from hotspot data was produced on the following basis. Firstly, month was the temporal unit for aggregation. Secondly, all fire hotspots were used, including both wildfire and higher intensity fuel reduction burns. While this produces issues, it is suitable for a range of key applications. Thirdly, aggregation was done by means of a 1° grid. Finally, all hotspots from July 2002 to June 2013 were included.

Spatial software was used to produce, for each grid cell, a "wind rose" type diagram, with twelve spokes radiating out from a central core. The length of each spoke was proportional to the relative frequency of hotspots in that grid-cell, with months arranged like on a clock-face with January being month one.

It was found that to a large degree there were extensive, coherent groups of these roses, referred to as zones. In all 29 zones have been identified. Many have a clear unimodal distribution, while some are clearly bimodal. Six were classified more by a lack of a clear modality, in contrast to their neighbouring zones. These were termed "aseasonal".

The results were also used to produce a national hotspot frequency map. This identified some areas where the existing climatology may be insufficient to have confidence of a stable zonation. Dynamically extending the climatology may resolve this in future years.

It was found that the seasonality is very different from that current in use. This may be due to the conflation of deliberate and wildfire hotspots. It is not currently practical to separate all wildfire hotspots, but those due to major wildfires will be identified as part of on-going research.

Keywords: *Satellite hotspot, MODIS, fire season*

Assessing mitigation of the risk from extreme wildfires using MODIS hotspot data

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Abstract: A taxing question in wildfire risk management concerns the effectiveness of fuel reduction burning on mitigating the risk to Australia's communities from extreme wildfires. Extreme wildfires account for the majority of wildfire damage over recent years. In part the uncertainty arises from how questions are framed, in part from the lack of effective datasets to conduct definitive analyses. The development of a climatology of satellite-derived fire hotspots over the last thirteen years has permitted new approaches to the problem that yields answers that may provide valid insights into improving community safety.

The complexity of the problem necessitated focusing on a study domain. The effectiveness of fuel reduction arises from the inter-annual accumulation of leaf litter in eucalyptus dominated forests. The forests of mainland southeast Australia were selected to meet that criterion in a well understood setting.

Within the domain, included hotspots for each fire year were separated, aggregated and used to generate a 2km radius buffer area. This was designed to minimise issues associated with hotspot positional errors and to, in some sense, account for associated milder fire areas that would not trigger the hotspot algorithm. Small scale or low intensity fuel reduction burns are missed by this approach, but they are unlikely to be effective against an extreme wildfire.

If intensive fuel reduction were effective, then there would be an expectation of burnt areas in preceding years affecting, in a measurable way, the extent of an extreme wildfire. To do this, a subset of the buffered area was generated for hotspots associated with extreme wildfires. These were identified based on the expected spatio-temporal clustering of their hotspots and on-going research into these events.

Two hypotheses are explored. Firstly, as is often claimed, fuel reduction burning may be effective. Overlaps of specific sets of hotspots were analysed with respect to this. If this is not the case, this may be due to the small proportion of the domain burning each year, making overlaps unlikely. Secondly, if fuel reduction burning is not effective, this may be due to remoteness and ruggedness. The distributions of extreme wildfires and other fire were compared with respect to these environmental parameters.

By examining the four preceding years it was found that some extreme wildfires were not affected despite appreciable overlap with preceding fuel reduction activity. The main proportion of an extreme wildfire that was recently burnt is estimated at 19%, including the downwind edge. In terms of distance in from the edge of a forested area, it was found that fuel reduction occurred mainly towards the edge, while extreme wildfires were relatively much more frequent in the interior. Further, extreme wildfires present greater operational challenges in rugged landscapes. It was found that fuel reduction is more frequent in flat landscapes, while extreme wildfire is most common on rugged landscapes.

The implications of these patterns for mitigation of the impacts of extreme wildfires are discussed. Statistically, most extreme wildfires are unlikely to encounter previously burnt areas, but that this does not imply that the latter prevents the former. Where they do overlap there is little indication of an interaction. Mitigation of the risks arising from extreme wildfires through fuel management, ignition prevention or response arrangements, must take account of the nature of these fires.

Keywords: *Extreme wildfires, hotspots, hazard reduction, ruggedness, remoteness*

Integration of Remote Sensing Data with Bushfire Prediction Models

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Abstract: The ability to predict the spread of a bushfire is important for operational management during bushfire events as well as risk assessment in vulnerable regions. Models for the rate of spread of a bushfire typically require a number of input parameters to operate, including topographic information, meteorological conditions and information on fuel conditions and variability. The predictive ability of a bushfire spread model is limited by the accuracy of these input parameters. Accurate national topographic information exists and detailed meteorological information is readily forecast. However, fuel condition information is often specific to a particular fire behaviour model for a particular vegetation type, such as forest or grassland, and generally requires detailed surveys of disparate sources to prepare suitable spatially explicit maps. This preparation can be both time-consuming and cost-prohibitive. Furthermore, these fuel parameters often require a pre-processing step before they can be used in a predictive model.

We demonstrate an approach to determining vegetation and fuel classification from remote sensing data such that the data can be directly integrated with a computational bushfire perimeter propagation model. We use freely available Landsat 8 spectral data for the input remotely sensed data set. The fuel classification uses an unsupervised K-Means algorithm allowing forest, grassland, and water regions to be classified. Two extensions to the method are also trialled for potential improvement to results; the addition of a topography data set as an additional input to the spectral data sets, and a principal component analysis run prior to the K-Means classification.

The bushfire perimeter propagation model uses the CSIRO Spark framework for predicting the spread of fires across the landscape and is already integrated with the open-source OpenCV image analysis tool-kit. The K-Means algorithm is also implemented in OpenCV such that the data can be processed within the same framework. We demonstrate the applicability of the approach to a bushfire prone region in South East Australia. Our system can be used for any region within Australia and potentially worldwide, allowing up-to-date fuel classification and input data to be automatically generated and used in predictive models.

Using these methods, it was determined that, out of all the spectral band combinations, using the coastal aerosol, green, and SWIR 1 produced the best classifications. The addition of topography information did not appear to improve the method, and neither did the principal component analysis on its own. However, using the first component of the principal component analysis in combination with an input band containing the local variance of this component gave a slight increase in the calculated accuracy.

There is the potential for fuel information to be similarly generated from the spectral data, as well as full colour images of the terrain. Input data layers produced using this process would all share the same spatial characteristics, removing the need for any pre-processing such as cleaning, re-projection or alignments steps. Furthermore, the layers can be generated immediately from the most up-to-date data sets available, ensuring currency in the modelling process.

Keywords: *Remote sensing, satellite imagery, bushfire modelling, k-means, unsupervised classification*

INVITED PAPER

EXTENDED ABSTRACT ONLY

CFD techniques for the simulation of experimental prescribed fires

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Abstract: The study of wildland fires can benefit greatly from the use of computational models. This is true owing to the significant complexity and the wide range of scales over which the phenomena driving wildland fires occur. Additionally, it is difficult and expensive to capture this complexity through experimentation, as full-scale wildland fires cannot be simulated in the field with consistency, reliability, or replication. To augment field and lab-based studies, detailed physics-based models, in particular, have gained increasing attention in the community in recent years. These models use a computational fluid dynamics (CFD) approach, solving governing equations of mass, momentum, and energy in 3 dimensions. The driving phenomena relevant to fire behaviour are either directly resolved or require approximation, depending largely on whether they occur at sub-grid scale. Such an approach has the potential for great flexibility, as it aims to limit empiricism, but requires rigorous testing and thoughtful implementation.

As part of a project aimed at understanding both the behaviour and impact of prescribed fires in the Pinelands National Reserve (PNR) of New Jersey, USA, one such model – the Wildland Urban Interface Fire Dynamics Simulator (WFDS) – is being tested. Measurements conducted on experimental prescribed fires have provided a relatively unique data set. This includes a combination of point and stand-scale remote measurements of both fire behaviour and pre- and post-fire fuel structure. Such data allows for a detailed assessment of model predictions of variables such as spread rates and fuel consumption, when implemented at the field scale.

In the presented work, we focus on the specification of wind and fuel structure within the model, and the role this plays in model prediction of fire behaviour. In particular, LiDAR-based techniques for generating the spatial variation of canopy bulk density (CBD) are considered. Comparisons are made between a previously validated technique for obtaining CBD values on a rectangular grid (10m x 10m x 1m), and a novel technique for refining the data based on the identification of canopy polygons (0.5m x 0.5m x 1m) (Figure 1).

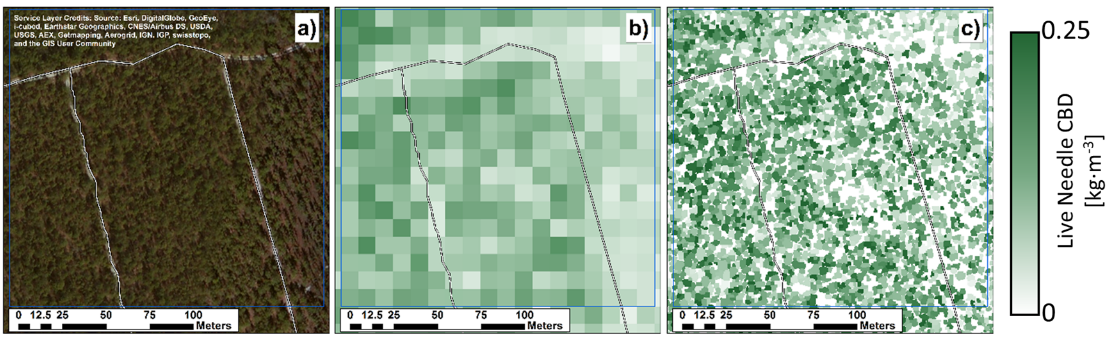

Figure 1. Computational domain (outlined in blue) showing the canopy vegetation as a) satellite imagery, and horizontal slices of b) CBD from the grid method (z = 5-6 m AGL) vs. c) CBD from the polygon method (z = 5-6 m AGL).

Using the polygon method, vegetation was only present in 60% of the volume predicted by the grid method, but the mean CBD value increased by 64%. The influence of greater CBD with increased void spaces in the canopy is predicted to influence model outcomes such as the shaping of the flow field by the canopy and the absorption of radiation from the fire front. An ongoing assessment of the sensitivity of model predictions to the detail of such inputs, and the related uncertainty, is presented and can shed light on the current state of model performance. It will also guide the extent and type of measurements required by future experimental campaigns for the continued testing and use of physics-based models of wildland fire.

Keywords: *Canopy bulk Density (CBD), Computational Fluid Dynamics (CFD), fire spread, wildland fire, wind*

Measurement of topographic controls on the moisture content of surface fuels in south east Australian forests

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Abstract: Prediction of fuel moisture content (FMC) is important for estimating the rate of spread of wildfires, the ignition probability of firebrands, and for the efficient scheduling of prescribed fire. The moisture content of fine surface fuels varies dramatically at a range of spatial scales; at large scales (10's to 100's km) due to variation in meteorological variables (eg. temperature, relative humidity, precipitation), and at smaller scales (100's of metres) in steep topography due to factors that include differences in radiation due to aspect and slope, differences in precipitation, temperature and relative humidity due to elevation, and differences in soil moisture due to hillslope drainage position. Forest structure and canopy shading responses to these topographic influences adds further to the spatial variability in surface fuel moisture. Finally, it is likely that the interactions between these topographic influences, vegetation response and fuel moisture content will vary across climatic gradients, potentially creating a high level of complexity in the relationship between topography and fuel moisture. As a result of this complexity there have been few attempts to model FMC at smaller spatial scales that could assist fire managers in prediction and planning. In this study we aim to "untangle" these factors, and in particular answer the following questions i) How does fuel moisture vary with aspect? ii) How does fuel moisture vary with hillslope drainage position? iii) How do these topographic variables interact with vegetation structure to result in net FMC effects, and iv) How do these topographic and vegetation interactions change along a climatic gradient? To achieve the project aims, a new method was developed and validated to enable the monitoring of FMC over seasonal timescales. Microclimate stations were established in southeast Australian forests to monitor surface fine fuel moisture at 15-minute intervals using these newly developed instrumented litter packs, in addition to temperature and relative humidity measurements inside the litter pack, and measurement of precipitation and energy inputs above and below the forest canopy. Stations were established to monitor FMC and microclimate throughout a fire season across a gradient of aspect, drainage position, forest structure, and climate in order to address the research objectives. Preliminary conclusions from three months of data collection are that; 1) aspect effects on FMC are mostly due to secondary effects on canopy cover and shading, rather than the direct effect of aspect on incoming above-canopy radiation, 2) drainage position influences FMC due to the secondary effects on canopy cover and shading as well as the direct effect of drainage area on soil moisture, and, 3) as a result, both aspect and drainage position effects on FMC are strong when they result in significant change in canopy cover, and weak when they don't, resulting in highly variable topographic effects across a climatic gradient. These results based on an unprecedented field measurement campaign provide a major step forward towards the larger goal of constructing high spatial resolution models of FMC for implementation in complex landscapes.

Keywords: *Fuel moisture, bushfire, radiation, aspect, spatial variability, downscaling*

A fire regime risk management tool

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Abstract: Wildfires can cause significant damage to people, property and the environment. For example, the 2009 Black Saturday Fires resulted in the loss of 173 lives and over 2000 houses. These fires affected large areas of natural forest with a high value to society, in particular as catchments that provide Melbourne with drinking water and the habitat of threatened biodiversity. While these fires were the most destructive in human terms, the quantification of the existing and future risk posed from wildfire to multiple assets requires consideration of the total fire regime over a multi-decadal scale (Penman *et al.* 2014) and not just single events.

Fire regimes are the spatial expression of area burned over multiple years which includes consideration of fire frequency, intensity, heterogeneity and seasonality (Gill 1975; Whelan 1995). Fire management agencies seek to alter the fire regime to reduce risk to all assets however no actions universally reduce risk to all asset types. For example, fuel treatments are commonly used to reduce risk to people and property, but this can be to the detriment of environmental assets (Penman *et al.* 2011a). The challenge is therefore to develop management strategies that simultaneously satisfy the gamut of management objectives (Driscoll *et al.* 2010).

Here we present a new fire regime tool which builds on the PHOENIX RapidFire Fire Behaviour Simulator, hereafter PHOENIX. PHOENIX simulates fire behaviour based on empirically derived models for a range of environments based on fuel loads, topography and weather. The fire regime tool provides a novel simulation approach to quantify the risk to houses, ecological assets, water and carbon posed by natural and anthropogenic fire regimes. In doing so, the model allows for comparison of risk to assets over a range of realistic fuel management strategies across a landscape, as well as basic suppression responses.

Keywords: *Risk management, fire management, trade-off, Bayesian Networks, assets*

Effects of post-fire vegetation regrowth on wind fields over complex terrain

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Abstract: The spread of bushfire is highly sensitive to wind speed and direction. Consequently, strong variation of wind fields over areas of complex terrain, with multi-scale changes in topography and surface roughness, significantly complicates the prediction of bushfire behaviour. In the current suite of operational fire modelling schemes, mesoscale variations in wind fields are often over-simplified, thereby reducing the accuracy of fire behaviour modelling in areas of potentially volatile or dangerous fire behaviour. To address this issue, emerging fire modelling frameworks are using ensemble-based approaches to accommodate for the inherent uncertainties in the factors influencing fire behaviour. To account for the effects of wind variability within ensemble approaches it is necessary to recast wind field information in probabilistic terms.

As part of an investigation into a probabilistic representation of wind field information, the mountainous region west of Canberra is used as a case study. In particular, analysis is focussed on Flea Creek Valley within the Brindabella Ranges. The valley runs in a north-south direction, approximately perpendicular to the dominant west-north-westerly (WNW) prevailing wind direction. Flea Creek Valley, and much of the surrounding region, was heavily burnt during the 2003 Canberra bushfires but the region has since experienced no major fire activity. In 2007 and 2014, wind data were collected across a 3-4km east-west transect of Flea Creek Valley.

To statistically characterise wind fields across complex terrain, the directional response of surface winds to changes in prevailing winds is considered as a toroidal, or bivariate circular, probability distribution. To construct these distributions, wind direction measured on the ridge top (indicative of the prevailing winds) is plotted against the concurrent wind direction measured within the landscape. Discrete observed directional response distributions are taken as noisy realisations of continuous underlying distributions of wind direction response. These continuous distributions can be estimated using a number of mathematical techniques including cubic or thin plate smoothing splines. Both the observed discrete and estimated continuous distributions highlight the modal nature of wind direction response across the landscape. Understanding the impacts of variables such as surface roughness on this directional response is an important step towards spatially extending a statistical characterisation of wind fields across complex terrain.

To discern any changes in the probabilistic response caused by changes in surface roughness due to vegetation regrowth, a number of mathematical and statistical comparison techniques are available. In this paper, techniques from astronomy, biometrics and statistics are employed to investigate the effects of seven years of post-fire vegetation regrowth on the directional response of surface winds across Flea Creek Valley.

The findings of this study suggest that the choice of statistical test as well as smoothing technique can have a significant impact on the results. Despite this, there is also evidence that the wind response across Flea Creek Valley may have been significantly altered by regrowth in some areas, but in other areas no significant difference is found. There are important implications here for wind and fire modelling, and it is clear that there is much more work to be done to better understand the impacts of physical variables on the probabilistic characterisation of wind fields.

Keywords: *Wind modelling, vegetation regrowth, complex terrain, extended Kolmogorov-Smirnov test, non-parametric surface comparison*

Dynamic development of the 2013 Aberfeldy fire

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Abstract: The 2013 Aberfeldy fire, in eastern Victoria, exhibited unexpectedly rapid fire spread after its ignition on 17 January. In the first 16 hours after ignition at around 11:30am, the fire spread approximately 30 kilometres towards the southeast and burned 20,000 hectares. Much of this rapid fire spread occurred at night. Also of significance was that the fire burnt in complex topography, with slopes greater than 20°, and that in a number of instances the fire exhibited lateral spread; that is, spread in a direction almost perpendicular to the prevailing wind direction. In this paper we consider the development of the 2013 Aberfeldy fire in light of a number of recent insights into the dynamic behaviour of fires burning in rugged terrain under strong winds. In particular, we draw on findings that initially related to the 2003 Canberra fires to explain the occurrence of the lateral spread. More recent numerical and experimental work will also be discussed in this context.

The observed development of the fire is also considered in the context of the traditional fire spread modelling approach, whereby the fire is assumed to propagate at a quasi-steady rate of spread modulated by the combined effects of wind and terrain. In particular, vector fields representing the expected rate and direction of fire spread are derived using traditional methods and are applied across the fire affected landscape. Infrared linescans, showing the development of the fire at several junctures in time, exhibit fire propagation patterns that are difficult to reconcile with the rate of spread vector fields at several key locations. Specifically, the development of the fire into narrow fingers propagating laterally across the tops of slopes in the immediate lee of a ridge line do not match with the predictions derived from traditional quasi-steady fire propagation models.

This pattern of fire spread does however match quite well with that shown to occur when fires are affected by vorticity-driven lateral spread (VLS). The VLS phenomenon arises due to a three-way interaction between strong winds, steep terrain and a significant fire in the landscape. Analysis of the Aberfeldy fire showed that the observed spread adhered to VLS occurrence thresholds established through consideration of other notable fires, and through numerical modelling and experimental analysis. The strong pyroconvection and pattern of smoke observed in association with lateral spread events in the Aberfeldy fire were also consistent with that observed in other confirmed VLS events.

The findings of this case study indicate that there were readily identifiable dynamic processes that drove the development of the Aberfeldy fire. These processes were essentially the same as those that drove the development of the 2003 Canberra fires and a number of significant fires in the ensuing years. The findings further suggest that research into the dynamic drivers of extreme bushfires, which now spans about 10 years, can offer significant improvements in the way such fires are modelled operationally. Some suggestions about how these improvements could be implemented within the working environment of a Fire Behaviour Analyst are offered.

Keywords: *Dynamic fire spread, extreme fire behaviour, vorticity-driven lateral spread, atypical lateral spread, fire-environment interactions*

Pyrogenic vorticity from windward and lee slope fires

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Abstract: Research into dynamic bushfire behaviour conducted over the last few years has shown that bushfires burning on lee-facing slopes can exhibit atypical forms of propagation under extreme weather conditions. For instance, recent numerical simulations have indicated that pyrogenic vorticity (the curl of the velocity field) is a key driver of rapid lateral fire spread - as a consequence, this type of fire propagation is being referred to as Vorticity-driven Lateral Spread (VLS). The VLS phenomenon has also been reproduced in laboratory-scale experiments, some of which show clear vortex structures. The presence of vorticity in the experiments and simulations suggests that additional insights into the physical processes may be drawn from direct examination of the fluid dynamical equation governing vorticity. We neglect Coriolis effects and divergence but do not make the Boussinesq approximation, giving the governing vorticity equation:

$$\frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega} \cdot \nabla)\mathbf{u} + \frac{1}{\rho^2}\nabla\rho \times \nabla p + \nabla \times \mathbf{F},$$

where $\mathbf{u}$ is the velocity field, $\boldsymbol{\omega} = \nabla \times \mathbf{u}$ is the vorticity, ρ is the density, p is the pressure and $\nabla \times \mathbf{F}$ represents eddy viscosity and body forces.

In this paper we provide a rudimentary theoretical analysis of the vorticity equation for the separate situations of fires burning on leeward and windward sides of a triangular ridge under the influence of a strong cross-wind and assumed separation of the flow in the lee of the ridge. We consider the behaviour of the right and left flanks of the fire with some simplifying assumptions about the effects of the fire on the local wind flows.

The analyses indicate that on the leeward slope the fire should produce pyrogenic vorticity in the vertical direction due to tilting of ambient lateral vorticity (due to the separated boundary layer) by the plume of the fire. As vertical vorticity is produced it is enhanced through stretching by the accelerating buoyant updraft. Longitudinal vorticity is generated in the downwind direction by tilting of the vertical vorticity in addition to the presence of baroclinic torques caused by pyrogenic differences in density of the flow.

The generation of pyrogenic vorticity over a fire on a lee slope arises due to the fact that separation of the flow in the lee of the ridge creates a sheet of vorticity at some height above the lee slope. This region of ambient vorticity occurs at a height where the pyrogenic velocity gradients are large enough to drive interactions that result in tilting of the ambient vorticity. For the windward fire case, the ambient vorticity only occurs close to the surface where the pyrogenic velocity gradients required to tilt the ambient vorticity are negligible. So while some longitudinal vorticity can arise through baroclinic forcing, the case of a windward fire is far less likely to produce the strong vertical vorticity required to drive the VLS phenomena. The same conclusions will also hold for fires burning on flat ground.

While these analyses should be considered as preliminary and approximate, they do provide some useful insights into the dynamics of the VLS phenomenon. For instance they provide a physical explanation of why the VLS phenomenon occurs exclusively in connection with steep, lee-facing slopes, or with lee slopes that possess features such as sharp bluffs, which act to promote flow separation. Moreover they demonstrate the importance of the various driving factors, namely tilting of ambient lateral vorticity, stretching of vertical vorticity by Lagrangian acceleration of the buoyant plume and baroclinic forcing arising due to the effect of the heat of the fire on the density of the flow.

Keywords: *Pyrogenic vorticity, extreme fire behaviour, VLS, atypical lateral spread, fire-environment interactions*

A rate of spread index for fires in spinifex fuels

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Abstract: Fires in spinifex occur throughout arid and semi-arid parts of Australia and in some cases can affect large tracts of the landscape with associated environmental impacts. In response to this environmental challenge an empirical model for the prediction of fire spread rate in spinifex fuels has recently been developed, based on a number of experimental burns conducted in Western Australia.

In other research related to fires in grasslands, a simple rate of spread index for quasi-equilibrium fire spread was developed and, despite its simplicity, was shown to provide practically identical output to current operational grassland fire spread prediction models. This simple rate of spread index for grasslands conceptualises the rate of fire spread as wind speed divided by fuel moisture content, where fuel moisture content is estimated using a fuel moisture index (FMI). Such a conceptualisation embodies the notion that fires will spread faster in windier conditions and in fuels that are drier. The rate of spread index, as it applied to grassfires, also incorporates a term that accounts for an intensity-dependent indraft that counters the prevailing winds at the fire line. As such, the rate of spread index can be viewed as a two parameter model for quasi-equilibrium fire spread.

In this paper we investigated the performance of the rate spread index when applied to the discrete spinifex fuels of arid and semi-arid Australia. The performance of the rate spread index was evaluated through the use of empirical data relating to fires in spinifex and through comparison with the existing spinifex fire spread model.

The results indicated that the rate of spread index, as it was applied to grassfires, was only able to account for 68% of the variation in the observed rates of spread. Multiplication of the rate of spread index by fuel cover improved it's predictive ability to 73%, but this was still not as good as the existing spinifex model, which could account for 83% of the variation in the data. The main reason for this relatively poor performance of the rate of spread index was found to be due to the fact that the FMI did a poor job of estimating the moisture contents of spinifex fuels. As such, we concluded that application of the FMI should be restricted to more temperate fuel types, for which it has been shown to work quite well.

An alternate form of the rate of spread index, using actual fuel moisture content rather than the FMI, was considered and found to produce much more accurate predictions. Indeed, when multiplied by fuel cover, this alternate rate of spread index was able to account for 85% of the variation in the observed rates of spread, thereby slightly outperforming the existing models for spinifex. The final version of the rate of spread index can be expressed as a function of fuel cover c, 2m wind speed U and profile fuel moisture content m:

$$S(U, m, c) = 37c\frac{\max(1, U)}{m},$$

with corresponding rates of spread well predicted by the model

$$R^*(U, m, c) = 1.5S(U, m, c) + 600.$$

These results have implications for the parsimony of fire behaviour models and demonstrate how conceptual and pedagogical simplifications can be incorporated into fire spread models with no practical loss in model performance. The results are also relevant to the possible unification of fire spread models across different fuel types.

Keywords: *Fire spread, spinifex, wildfire, fire behaviour modelling*

WRF-Fire Simulation of Lateral Fire Spread in the Bendora Fire on 18 January 2003

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Abstract: On the afternoon of 18 January 2003, a number of separate fires located to the west of Canberra, Australia, began major runs under extreme fire weather conditions, and impacted upon the city. These events were well documented by a range of instruments, including a multispectral line-scanning instrument attached to an aircraft. Analysis of the data collected revealed that a number of the fires had exhibited atypical lateral fire spread, in a direction transverse to the background wind, on steep leeward slopes. These lateral fire spread events often contributed considerably to the size and impact of the fire.

In one particular instance, a fire burning to the west of Bendora Dam (35° 28' S, 148° 50 E), which had been burning for the previous ten days subject to control efforts, breached control lines and rapidly developed into a large conflagration. The Bendora fire then ran into the edge of urban areas, where it combined with other fires that had escalated significantly on that day. The fact that the Bendora fire developed so rapidly, from a relatively small breach of the control line, attests to the abrupt transitions that bushfires can exhibit under extreme weather conditions.

In this study, the WRF numerical weather prediction model was coupled to the WRF-Fire wildland fire physics module at high resolution and used to simulate the early development of the Bendora fire on 18 January. The modelled fire spread was compared to the multispectral line-scan data with the fire to atmosphere coupling enabled and disabled. With the coupling enabled, the fire advanced around 1 km further laterally to the south, and this lateral fire spread occurred predominantly in the lee of a ridge. The lateral fire spread was partly driven by pyrogenic vorticity that formed in the lee of the ridge due to the interaction between the opposing pyrogenic and background winds. Additionally, differences between the modelled and actual fire spread on the windward side of ridges suggest that more careful consideration of the combined effects of wind and slope on the rate of spread is required in future versions of WRF-Fire.

A large number of near-surface vortices, with a large component of vertical vorticity, were identified over the leeward slopes and downwind of the fire when the fire to atmosphere coupling was enabled. Additionally, a region of high turbulent kinetic energy extending to the southeast of the fire supports the notion that the fire was carried across the Bendora Reservoir by mid to long-range spotting. As there is no spotting model in WRF and WRF-Fire, the fire was unable to cross the Bendora Reservoir in the numerical simulations, as was observed in the multispectral line-scan data.

The results demonstrate that WRF and WRF-Fire can model atypical lateral fire spread across steep leeward slopes in more realistic terrain than has previously been considered. It may therefore be possible to investigate other known atypical lateral spread events, such as the 2003 Broken Cart fire in Canberra, the 2009 Jesusita fire in Santa Barbara and the 2013 Wambelong fire near Coonabarabran, using this or a similar model configuration. However, we caution that these results were obtained using a single coupled atmosphere-fire model for a highly idealised configuration, and further work is required to replicate this fire behaviour in other coupled models.

Keywords: *Coupled atmosphere-fire modelling, WRF-Fire, fire whirls, atypical lateral fire spread, VLS*

Pyroconvective interaction of two merged fire lines: curvature effects and dynamic fire spread

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Abstract: The interaction of one fire with another can substantially alter the behaviour of the individual fires. This may occur, for example, during the coalescence of spot fires or when separate fire fronts merge. The resulting fire-fire interactions may lead to unexpected, and in some cases extreme, fire behaviour. One manifestation of this behaviour is a change in the rates of spread of the individual fires. Viegas et al. (2012) studied this effect analytically and experimentally in the case of the intersection of two line fires meeting at an acute angle, and have reported on the so-called 'jump fire' phenomenon whereby initially the fire front in the vicinity of the intersection of the two fires advances very rapidly. They interpreted this as a rotation of the lines of fire, however it may also be interpreted in terms of the curvature of the merged fire front. Indeed, Sharples et al. (2013) were able to qualitatively reproduce the 'jump fire' behaviour using a simple numerical model of frontal evolution in which the rate of spread in the normal direction is dependent on the curvature of the fire line. Such curvature dependent flows occur elsewhere in nature, for example in the growth of crystals and in gas-phase flame propagation, and have been studied extensively (Sethian, 1985). In the context of wildfire, possible mechanisms for such an effect include atmosphere-fire interactions and geometric effects relating to the radiative and convective transfer of energy. The inclusion of curvature dependence may be a tractable way to incorporate the effects of these complex phenomena into models of fire spread that do not currently accommodate them. To determine the extent to which this curvature effect is captured by a coupled atmosphere-fire model (WRF-Fire) we perform numerical experiments and analyse the relationship between the rate of spread and the curvature of the modelled front. This study focuses on geometric configurations of fires similar to those considered by Viegas et al. (2012).

The coupled atmosphere-fire simulations produced patterns of fire propagation that were qualitatively similar to those reported by Viegas et al. (2012). This is despite a significant difference in the spatial scales of the two studies: the experiments of Viegas et al. (2012) considered fire lines a few metres in length, while those considered here are about one kilometre long. The main feature of the coupled simulations was the formation of a strong convective updraft between the two fire lines near their point of intersection, which caused that part of the merged fire to advance more rapidly. Comparisons with simulations in which the two fire lines were allowed to burn independently indicated that pyroconvective coupling between the two fire lines increased the overall rate of advance of the intersection point by a factor of about 7-10. As such, the simulations suggest that a fire spreading under similar scenarios will propagate with a considerable dynamic element.

Local fire-line curvature was calculated and compared with instantaneous rates of spread to test the hypothesis that the rapid advance of the point of intersection can be thought of as a curvature effect. This comparative analysis did not find that large negative curvature is associated with higher rates of spread; in fact the highest rates of spread in the simulations were consistently associated with parts of the fire line with local curvature very close to zero. However, the analysis presented here does not rule out the existence of such a curvature effect in some mean sense.

Keywords: *Dynamic fire spread, curvature, coupled fire-atmosphere modelling, fire line merging*

Bushfire modelling with coupled atmospheric and fire propagation models

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Abstract: Two-way coupled atmosphere-fire simulation models describe the land surface fire and the atmospheric air motions above it simultaneously. The coupling of a land surface fire and the atmosphere is an important feature of a fire spread model, as without it the atmosphere does not feel the effects of the fire and can not react to it. Coupling the fire and atmospheric models can improve the realism of the fire simulation by creating a non-linear feedback loop between the models. The coupling is achieved by the exchange of physical information between the models and can be done in multiple ways. The fire model might send sensible heat and moisture fluxes to the atmospheric model, and the atmospheric model might send the low level wind, temperature and humidity back to the fire model, for example.

Because of the large spatial and temporal extents of major Australian bushfires, it is not possible to simulate them using very fine model grid resolution. Instead, one is forced to use larger grid resolution of the order of tens to hundreds of metres. This excludes the use of first principles reaction-diffusion models which take the explicit chemistry of combustion into account. Practically solvable coupled fire spread models typically use empirical fire front speed formulas that give the rate of spread as a function of the near surface meteorological variables, fuel loading and land surface slope, and use a front tracking model to simulate the advance of the fire front.

In this conference we describe a coupled numerical atmosphere-bushfire propagation model. The model runs as a submodel inside the ACCESS model, whose atmospheric solver part is the UK Met Office Unified Model. Our fire spread model uses the level set method to describe the moving fire front:

$$\frac{\partial F}{\partial t} = -S\,|\nabla F| \tag{1}$$

for the level set function $F(x, y, t)$. The front speed S is based on the empirical McArthur formula which depends on meteorological conditions at the surface. Alternatively, the model can use the Rothermel formula.

Full coupling with the atmospheric model requires an additional model that produces the sensible heat and moisture fluxes from burning fuel behind the advancing fire front. The model we use treats the burning as an exponential decay with a decay time constant τ. Because our grid spacing is usually of the order of 100 metres, the fire front takes many model time steps to cross a grid cell. Each grid cell must therefore be made to ignite and burn gradually as the fire front moves over it. This is achieved by solving a subgrid scale differential equation for the burning fraction of surface fuel loading $w(x, y, t)$ for each grid cell:

$$\frac{dw}{dt} + \frac{w}{\tau} = \frac{w_0}{A_0}\frac{dA}{dt}. \tag{2}$$

In this equation $w_0(x, y)$ is the initial fuel loading, A_0 is the total area of a grid cell and $A(t)$ is the currently burning area of the grid cell, which is estimated from the level set function using linear interpolation. The subgrid scale burning model produces smoothly evolving sensible heat and moisture fluxes that are added to the surface heat and moisture fluxes of the ACCESS Model to achieve bidirectional coupling between the fire and atmospheric models.

This coupled atmosphere-fire propagation model allows us to simulate the large bushfires that occurred during Black Saturday in 2009. Our goal is to understand how large bushfires affect the lower atmosphere and on the other hand how various atmospheric effects affect the fire propagation.

Keywords: *Coupled fire-atmosphere modelling, ACCESS model, level set method*

Approaches to simulation of prescribed burns in forests of southern Australia

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Abstract: The simulation of wildfires has received significant worldwide attention, and a number of useful models have been developed to predict fire propagation and the risk of damage to infrastructure. In contrast, few models have been developed for low intensity prescribed burns, which are used extensively by land managers in southern Australia for fuel and ecosystem management. Such burns require careful control to reduce unintended environmental, economic and social impacts. Particular issues of concern to communities are smoke exposure and the risk of burns escaping their prescribed boundaries.

We considered the problem of forecasting the behaviour and outcomes of a prescribed burn scheduled to be undertaken in the next 7 days, given a burn boundary, a weather forecast, the intended burn date and a burn prescription. We looked for models capable of predicting the total amount of fuel consumed, the rate of fuel consumption (which can be used to derive smoke emission rates), the spatial pattern of burnt and unburnt areas, and fire behaviour parameters such as average fire intensity.

Prescribed burn simulation presents a number of challenges. In particular, the burn prescription often specifies that fire should only be applied to a fraction of the land area within the burn boundary; in Victoria these target fractions can be as low as 30%. As fuel loads are spatially variable, the amount of fuel consumed can only be estimated if we can predict the spatial pattern of burnt areas within the boundary.

Several modelling approaches were considered including direct simulation of fire propagation, simplified simulation of typical burning strategies, and generic non-spatial methods using average fuel loads. Each approach was evaluated in terms of the level of input required, numerical stability, and potential value for predicting burn outcomes. Model results were also evaluated against observations at an experimental site burnt in March 2012 (Henderson Creek, Otway Ranges, Victoria). Ground surveys and satellite data were used to accurately determine the spatial pattern of fire and the level of canopy scorch at this site. Measurements were also made of pre- and post-burn fuel loads, allowing total fuel consumption to be estimated.

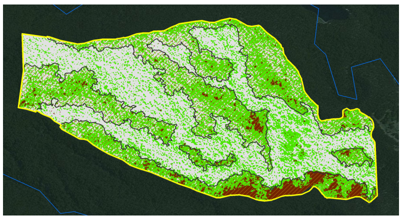

Fig. 1: Observations: Ground survey of burnt area (black line), overlaid on a burn severity assessment derived from RapidEye 5m satellite imagery (grey=unburnt, green=surface burnt, brown=surface burnt and canopy scorched).

We found that using a burning strategy, plus McArthur's Leaflet 80 to predict fire intensity, results in good agreement with observations with only moderate input data requirements. In contrast, fire propagation methods require a detailed ignition pattern as input, which is typically not available before a burn is conducted. Generic methods were found to be useful for providing a first approximation to the total fuel consumption, but did not allow prediction of fire behaviour parameters or the spatio-temporal pattern of fire.

This study has shown that prediction of prescribed burn outcomes may be achievable with inputs typically available several days before the burn, by using a burn strategy simulator. With further development and verification, this type of model may assist land managers in achieving safe and effective prescribed burns.

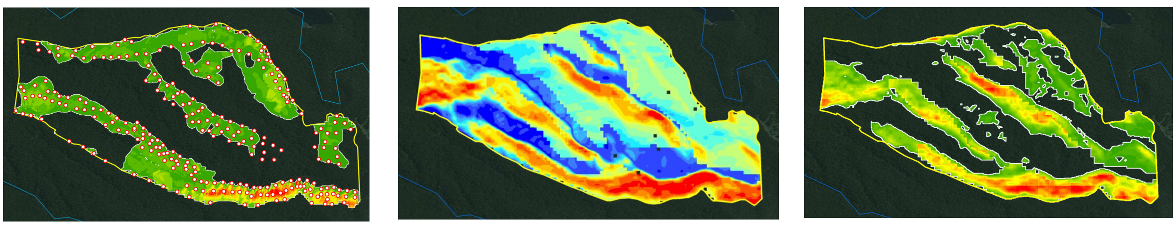

Fig. 2: Model predictions: Left: Full fire simulation using PHOENIX RapidFire with a modified extinction threshold (ignition points marked, colors indicate fireline intensity). Middle: Predicted fuel moisture (Matthews 2010) at the start of the burn (red=dry, blue=wet). Right: Leaflet 80 burn simulation making use of the fuel moisture prediction, burning from dry areas to wet areas until the target area coverage is achieved, without requiring an ignition pattern.

Keywords: *Fire simulation, fuel moisture, prescribed burning, smoke emissions*

Modelling dynamic bushfire spread: perspectives from the theory of curvature flow

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Abstract: It has long been thought that fires are a purely advective phenomenon, but new insights indicate that advection alone is insufficient to adequately account for certain important effects. In this paper we investigate different bushfire scenarios and their relation with newly emerging mathematical results concerning the evolution of curves and surfaces by curvature-dependent speeds. For many fire dynamic effects, even though they arise due to highly complex interactions between fire and atmosphere, it seems that the inclusion of higher-order curvature terms can effectively emulate such behaviours. In previous work, the authors introduced a new cur-vature flow based mathematical model for a fire front, with a perspective toward the modelling of bushfires. The model predicts how the fire front moves by describing the evolution of an isosurface by its mean curvature and a forcing term, consistent with the advective phenomenon. Experimental data and past recorded events of fires have indicated that in certain situations fire fronts with initially finitely many non-smooth points will become smooth. This smoothing effect is captured well by our model. However, in more general settings the smoothness of the evolving isosurface is highly dependent on the smoothness of the initial surface. In real fires the shape and smoothness of the fire front depends on a multitude of factors including the atmospheric conditions, terrain, geographic placement and the type of fuel and its homogeneity. In particular, often the iso-surface of the ignition temperature will not correspond to a smooth surface in the mathematical model. In this paper we consider models that could allow for the propagation of such nonsmooth surfaces. We conclude that a model more complex than our initial mean curvature based model is required for more general applicability. Some analytical results that we have in mind arise from a curvature flow based on a normal evolution with speed given by a homogeneous, symmetric function of the curvatures of the surface. The persistence of non-uniformly convex regions or flat sides, singular parts or ridges of infinite curvature, in the initial surface has been analytically proved and will correspond to some interesting behaviour of nonsmooth initial isosurfaces.

Keywords: *Curvature flow, partial differential equation, free boundary problem, fire front*

Development of spatial models for bushfire occurrence in South-Eastern Australia

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Abstract: Australia is one of the most flammable continents in the world. The southeastern region of the continent, where the population is densely settled, is susceptible to low frequency and high intensity bushfires that can threaten human lives and cause extensive loss of properties. This paper describes the development and validation of spatial models for bushfire occurrence in South-Eastern Australia, especially in New South Wales, Victoria and the Australian Capital Territory.

The active fire database from the Moderate Resolution Imaging Spectroradiometer (MODIS) is used as original data source of fire activity over the 11-year period 2003-2013. Those active fire detections are grouped into burning events using the Fire Spread Reconstruction approach (FSR) algorithm based on the spatial and temporal proximity between fire detections. Fire occurrence point is defined as the ignition point of each identified event. Univariate and multiple logistic regression models are investigated for the comprehensive understanding of determinants contributing to the spatial distribution of bushfires. The probability of bushfire occurrence in South-Eastern Australia is also studied for the prediction of future fire occurrence.

Bushfires in the study area are significantly influenced by both environmental and anthropogenic variables. The mean annual precipitation positively influences the fire incidence, because the semi-arid regions lack the fuels necessary for a fire to start, while the coastal regions with abundant rain provide ample fuels for fire ignition. This finding is inconsistent with that at a small landscape scale. Fire probabilities are different regarding various land cover types. Forests are most likely to burn because they are covered by heavy fuel loads. Savannas are equivalently fire-prone because they are fundamentally easy to ignite. Permanent wetlands are also susceptible to fire possibly due to the influence of climate change and urban expansion. Shrublands are less fire-prone because of the low-level shrub canopy cover. Fires are also found to distribute in areas near the zero meso-scale elevation residual contour, which is consistent with the previous finding. Anthropogenic variables also show predictive power because of the influence of human activities on fire occurrence.

The final model for the probability of bushfire occurrence include mean annual precipitation, MODIS land cover, distance to zero meso-scale elevation residual contour, distance to secondary road and distance to railway. The bushfire probability map was generated accordingly. From the information provided by the quantitative statistics and the bushfire probability map, bushfires in the study area mostly likely to occur in coastal and mountainous areas close to various types of infrastructure and zero meso-scale elevation residual contours, as well as on forests, savannas and permanent wetlands, while they rarely occurred inland. It is concluded that the proposed model provides practical guidance for fire management actions in South-Eastern Australia.

Keywords: *Bushfire occurrence, spatial pattern, MODIS*

EXTENDED ABSTRACT ONLY

Unified Plant Growth Model (UPGM) development: challenges and application from a component-based and simulation modeling framework perspective

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Abstract: The Unified Plant Growth Model (UPGM) has been developed to: 1) combine various capabilities, (i.e., serve as a "system integrator") for different Environmental Policy Integrated Climate (EPIC) model-based plant growth components into a single plant growth model; and 2) deliver improved sub-models for phenology, seedling emergence, and canopy height derived from the Phenology Modular Modeling System (PhenologyMMS) V2.0. Multiple versions of UPGM exist including: 1) a modular FORTRAN-based component integrated using the Object Modeling System 3 (OMS3) environmental modeling framework into the Java-based AgroEcoSystem-Watershed (AgES-W) model; and 2) a comprehensive simulation modeling framework with UPGM technology as the focal point of a comprehensive FORTRAN-based plant growth model. The purpose of this research study is fourfold:

1. Illustrate the challenges and difficulties involved in linking the FORTRAN-based UPGM modular component with the Java-based AgES-W model. The linkage involves the following primary steps:

- Creation of a variable list that describes UPGM component input and output. This is needed for determining what information the AgES-W model is expected to send to and retrieve from UPGM.
- Modifying the UPGM FORTRAN component to build an "interface" so that OMS3 can pre-process the component. Among other things, this requires addition of OMS3 annotations (e.g., In, Out) to tell OMS3 whether a variable functions as input, output, or both.
- Relocation of UPGM component output variables that were local in subroutines to global in common blocks. Although counterintuitive for component-based modeling, this was done so that OMS3 could easily read the UPGM output variables and pass them back to AgES-W.
- Development of two wrapper utility programs to facilitate AgES-W/UPGM integration. The first program initializes static crop parameters, the second controls temporal processes which require daily input (i.e., climate data) for various calculations and produce daily output which is stored in common block variables. OMS3 is used to generate an interface for each of the wrapper programs and also a dynamic (on-the-fly) OMS3 component for calling the compiled UPGM FORTRAN code.

2. Describe capabilities of and enhancements to the UPGM simulation modeling framework. The framework is currently comprised of a graphical user interface (GUI), science model, databases, a state-of-the-art model output visualization tool, and the newly developed Model Optimization, Uncertainty, and SEnsitivity Analysis (MOUSE) open-source, Java-based toolbox of calibration and sensitivity/uncertainty analysis components.

3. Present a calibration/evaluation application of the UPGM simulation modeling framework to a multi-year irrigated maize (*Zea mays* L.) study from northeast Colorado, USA. Model evaluation statistics for canopy height, grain yield, final above ground biomass, and harvest index were reasonable with UPGM responding well to water deficit conditions, thereby improving UPGM robustness for more diverse (semi-arid) environments.

4. Use the GLUE and Bayesian model uncertainty analysis approaches contained in MOUSE to assess and quantify uncertainty in UPGM simulation modeling framework crop yield predictions for the Colorado, USA study.

Future research will continue work to identify existing enhancements from other EPIC-based plant growth components and integrate them within both the UPGM component (incorporated into AgES-W) and the UPGM simulation modeling framework.

Keywords: *UPGM, component-based modeling, Object Modeling System, crop growth modeling, model evaluation*

Describing variations in microclimate on hill country and its effect on pasture growth in APSIM simulations

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Abstract: Computer models are commonly used to support agricultural and environmental research. The Agricultural Production Systems Simulator (APSIM) is one example of such tools and it is increasingly being used to simulate pastoral farming systems in New Zealand. Pastoral farms occur on a wide range of landscapes, typically with intensive dairying and finishing systems in flat areas and more extensive systems where the terrain is steep. Agriculture in hill country is a major land-use worldwide and represents about 75% of the land area farmed in New Zealand. The hill country terrain can be very complex and difficult to represent in simulation models. Variations in slope and aspect have a significant impact on the local microclimate which, alongside differences in soil characteristics, can significantly alter plant growth and animal grazing behavior. Topography has a large direct effect on wind speed and solar radiation which induce variations in temperature and, subsequently, on the water balance. To produce reliable simulations, it is crucial to use the best data or to account for the microclimatic variations when describing such conditions.

Gathering appropriate values for the environmental parameters can be a challenge for remote sites and even more so for areas with complex topography. The use of data from a nearby weather station or interpolations from regional data is common practice, but, typically, weather stations are specifically located where the surroundings would not produce any significant interference on its measurements. For simulations of hilly terrain this data is likely to be inappropriate and adjustments to the weather parameters are recommended when actual measurements are not available. There are several parameters that may be adjusted, so an issue is to determine which are most influential and need to be corrected.

This work presents an approach for adjusting the incident solar radiation according to topography for use in APSIM simulations. The procedure is extended to include variations in temperature based on the fact that temperature can be related to incident radiation and wind speed. APSIM requires weather data on a daily basis and it is assumed here that the data initially provided represent the average parameters of a nearby flat surface. A module developed using the procedure being presented can then be used to adjust these values during the simulation according to the slope and aspect of the surface being simulated. The potential effects of variations in the microclimate on pasture growth and N leaching were investigated for a sheep farming enterprise in New Zealand. The analyses examined the extent of the effect of slope or aspect separately and the errors arising when the variations are ignored. Sensitivity analysis of the model was also used to identify the most relevant parameters.

Using the approach proposed here, we show that it is possible to describe the effect of topography on weather for a variety of conditions (e.g. in Figure 1). APSIM was able to simulate well the observed patterns of pasture growth in hill country farms. The sensitivity analysis revealed that model outputs were more sensitive to physiographic parameters (soil depth, slope, etc.) than model parameter, which suggests the approach can be used for a wide range of environments.

Keywords: *Farm systems model, plant growth, slope, aspect*

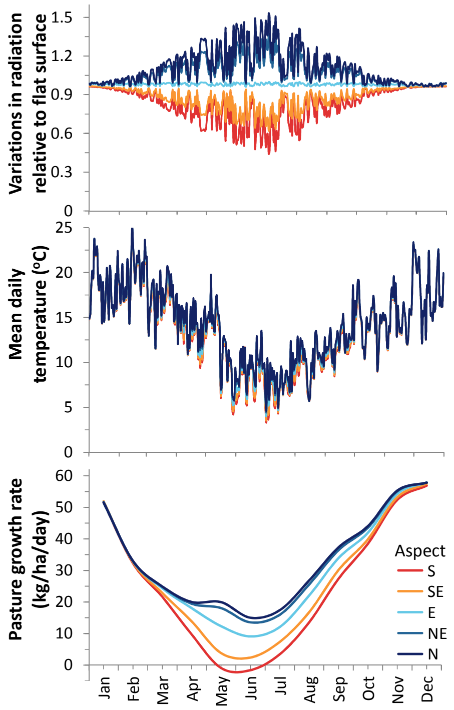

Figure 1. Variations in solar radiation, mean temperature and pasture growth for a 15° slope at different aspects simulated for Ballantrae, NZ (40.3° south)

Using APSIM, C# and R to Create and Analyse Large Datasets

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Abstract: With the advent of cheap cluster computing, advanced models and improved analytical techniques, scientists are able to explore larger problem spaces than ever before. However, with this power comes added complexity. Large factorial simulations need to be designed and created then the output – which can be many hundreds of gigabytes or more – needs to be analysed and presented in a meaningful way. This paper details one such scenario using the Agricultural Production Systems Simulator (APSIM) (Holzworth et al, 2014). Almost 60 000 simulations were created using five base simulations that generated approximately 100GB of output data.

This output data was loaded into R using a new package designed for loading, testing, manipulating and exporting both input and output APSIM formatted data. This paper explores the mechanics of large scale APSIM simulations including how to leverage the APSIM User Interface (UI) to quickly build a starting point simulation, using the XML libraries in the .NET framework (C# in this case) to easily duplicate, replace and modify structures in the base simulation to create a large factorial and finally looks at methods to analyse large output data sets.

The techniques demonstrated here are scalable; while 60 000 simulations were generated for this project, the same method could be applied to a grid analysis with millions of simulations. Similarly, the processing in R will work with any size data set so long as the computer used has enough memory. Even the language used for generating the simulations can be changed. C# is used here but any language with a robust XML interpreter could be used.

In order to keep the analysis run time down and simplify factorial combination generation, the top level factor (crop type) was used as a divider to split up the output into individual batches that were then processed in R.

APSIM writes a single output file for each simulation. As such, large factorial simulations can produce millions of individual files that need to be processed. To assist with this, an R package has been created and is available on CRAN (under the package name 'APSIM') that automates the loading of multiple APSIM output files into a single R data frame or data table (Dowle, et al., 2014). This package is able to handle single output and factorial simulations as well as import constants as separate columns. Additionally, extra utilities have been added that simplify the process of creating meteorological data files for simulation input.

R has many ways of doing the same thing, some of which are more efficient than others. A number of processes for reading and parsing data were evaluated and the most efficient methods were incorporated into the APSIM package. This evaluation has applications beyond APSIM as they are methods that anyone importing large quantities of data into R will be able to implement.

The package assumes that any data sets loaded will fit into system memory. As simulations become more complex this assumption will become less valid and new approaches will need to be taken such as the use of databases to store data that is not being actively worked on. There are R packages already in existence that do this and the APSIM package will be expanded over time to utilise these options.

Optimisations used include minimising file access, binding files after reading all of them, using dedicated data reading packages and applying techniques that reduce the amount of memory management required. The optimised data reader was able to import and bind APSIM output data at speeds in excess of 11MB/s for 5MB data files.

Keywords: *APSIM, R, programming, XML, grid*

Modelling Mixed Farming Enterprises using AusFarm

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Abstract: Australian agriculture faces challenges to improve the efficiency and profitability in the face of changing weather, regulatory and economic conditions. As farmers adapt to changing conditions and attempt to reduce risk, it is necessary to assess the mix and composition of their farm enterprises (e.g. cropping and livestock). Whole farm models are a useful tool that can be used in this decision making process.

The AusFarm software package has been designed to model biophysical systems and allow modelling of mixed crop and livestock farming systems. Cropping rotations, pasture mix, variability of soil types and integration of stock into these systems can be modelled successfully with AusFarm. Once a base simulation model has been constructed and tested, it is possible to modify management activities, cropping and stock parameters to examine how the production and natural resource management indicators are affected.

AusFarm has been used in a recent national, Commonwealth funded project to assess risks associated with strategic changes to farming enterprises in the southern wheat-sheep zone (Western Australia, South Australia, Victoria). A feature of this project has been the development of a decision support tool called Farm4Prophet. It is designed to examine questions such as; what would be the effect of decreasing the area used for cropping, or increasing the area sown to pasture, and increasing the size of the sheep flock? During development of this system several different mixed farming systems were modelled, and a range of scenarios were tested. To model these systems it was necessary to describe crop rotations, animal flock structures and management activities using AusFarm Management scripts. On-farm data were used to validate the baseline simulation designs.

This paper will describe the methodology used to model these farming systems and present the results.

Keywords: *Mixed farming, AusFarm, simulation, decision support, Farm4Prophet*

APSIM Next Generation: The final frontier?

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Abstract: For twenty four years, the Agricultural Production Systems sIMulator (APSIM) has grown from a farming systems framework used by a small number of people, into a large collection of models used by many thousands of modellers internationally. The software consists of many hundreds of thousands of lines of code in 6 different programming languages. The models are connected to each other using a 'common modelling protocol'. This infrastructure has successfully integrated a diverse range of models but isn't capable of easily meeting the challenges outlined above. For these reasons, the APSIM Initiative has begun developing a next generation of APSIM (dubbed APSIM Next Gen) that is written from scratch and designed to 'run anywhere'.

The new framework incorporates the best of the APSIM 7.7 framework with an improved supporting framework. C# was chosen as the programming language and together with MONO, the models and user interface run on Windows, LINUX and OSX. The Plant Modelling Framework (a generic collection of plant building blocks) was ported from the existing APSIM to bring a rapid development pathway for plant models. The user interface paradigm has been kept the same as the existing APSIM version, but completely rewritten to support new application domains and the newer Plant Modelling Framework. The ability to describe experiments has been added which can also be used for rapidly building factorials of simulations. The ability to write C# and VB.NET scripts to control farm and paddock management has been retained. Finally, all simulation outputs are written to an SQLite database to make it easier and quicker to query, filter and graph outputs.

The software engineering process has also been significantly improved. We have adopted GitHub to host the APSIM Next Gen. repository and have built a workflow around it involving feature branches, pull requests for peer-review of code and science reviews for major tasks. We have improved the testing regime and are building validation data sets for all models. These datasets are re-generated every time there is a change to APSIM and regression statistics are compared with previously accepted values. This improves the likelihood of detecting unexpected changes to model performance when a developer commits new changes. We have also enhanced the way we document all models by auto-generating all documentation from the validation tests and from using reflection to examine comments in the source code. The result is a nicely formatted PDF that describes a model and presents its validation, with regression statistics, graphically.

This paper explores each of the design decisions outlined above and discusses why the decision was made to 'start from scratch'.

***Keywords**: APSIM, agricultural modelling, model*

Agricultural systems modelling and software: current status and future prospects

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Abstract: In 2003, the European Journal of Agronomy published a special issue on "Modelling Cropping Systems". They explored the various approaches taken, the processes of model parameterisation and testing, model application, and software development issues. Now it is time to update this synopsis. In the past decade, much has changed in the cropping systems modelling domain. Global food shortages and in particular climate change has driven a marked change in the science context which, in turn, has driven change in many of the leading cropping and agricultural models.

The domain of research has also broadened beyond cropping system models to frameworks that can simulate pasture and grazing systems, agro-ecology and forest systems, the expression of genes on various crop processes and the impact of pests and diseases on crop production. Driven by this need for new science capability and cross discipline integration, the frameworks have had to evolve to support these new capabilities. This has been done in the face of dramatic change in the software development industry; mobile computing, social networking and cloud based computing are now everyday technologies.

All of the major agricultural modelling frameworks (DSSAT, APSIM, CropSyst, EPIC and STICS) have evolved in some way to address the changing problem domain but there has not been a significant and sustained focus on the software platforms of these models. There are many modellers and scientists worldwide investing in new science capabilities but only a few software engineers are thinking about the software platforms on which these models will run.

There are many challenges in improving the software systems underlying the major agricultural modelling frameworks. They are built using a range of programming languages (FORTRAN being the dominant). The code bases are typically old, closed source, with large code bases that hinder reuse and swapping. Software testing is often done in an *ad hoc* way. In addition, intellectual property issues often hinder reuse, although this is slowly being resolved.

There is a renewed willingness for modellers to work together to span disciplines (ICASA in the late 1990s, SEAMLESS, APSIM Initiative, MACSUR: a large European initiative and AgMIP). Each of these teams combine researchers across disciplines to generate new ideas, tools and methodologies. Given this increased willingness to collaborate, is it time to examine the software modelling systems we use with a view to better enable cross comparison of approaches and sharing of algorithms among existing frameworks? Some activities that need further efforts include; a) examination and extension of existing approaches to writing framework independent algorithms; b) exploration of using meta-languages (e.g. XMILE) to writing models; c) creating guidelines for documenting algorithms; d) focussing on the testing of algorithms; e) continued development of publicly available datasets.

These efforts would a) allow more cross comparison at a finer level of granularity; b) provide better transparency of alternative approaches and c) lead to more openness amongst agricultural modellers, leading to better sharing ethics (open access and open source). Open, transparent and free software processes, models and tools have promoted more open collaborations in the agricultural modelling community. The field of ICT is moving rapidly. Our modelling capability needs to evolve to meet these changing demands.

***Keywords**:* *Agricultural modelling, model, software, model reuse*

Big data technologies for agricultural systems research

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Abstract: Agro-environmental science traditionally has found ways of dealing with large sets of data, e.g. from earth observation or in-situ sensors, and using them efficiently for scientific model studies, mostly staying within the same discipline. Recently the focus of the agro-environmental science community has turned to data sharing with improved discoverability, data homogenisation, and opening up of datasets and providing them freely on the Internet as part of movements of open access and open data. Big data has emerged (and too some extent hyped as a new trend) to provide unlimited capabilities in data analysis for revolutionary new insights. Big data is defined as encompassing the use of techniques to capture, process, analyse and visualize potentially large datasets in a reasonable timeframe, while incorporating both structured and unstructured data and covering several disciplines and domains. It is timely to investigate easy-to-use methods for cross-disciplinary data use, as most data has been kept in silos of individual scientific disciplines. The computational resources have massively increased over the past decades, according to Moore's Law, with improved availability and accessibility of storage and computational resources in the cloud. These developments of more (open) data and higher connectedness in principle support larger, faster and more complex data-intensive processing and analysis across disciplines.

One of the required steps is currently being taken in the SemaGrow EU-funded research project that builds and tests an infrastructure for querying and discovering distributed heterogeneous large datasets in an efficient, scalable and real-time responsive way. A requirement of the infrastructure is that it is flexible and robust enough to handle data in any schema and from different disciplines and make them accessible through a unifying (SPARQL) end-point on the Internet. The infrastructure is piloted through a demonstration use case that handles heterogeneous datasets from climate and crop studies. Selected large spatiotemporal datasets (from CMIP5) are being made available according to the RDF (Resource Description Framework, in triples) standard. These data are being linked using the AGROVOC controlled vocabulary and other ontologies, using NLP (Natural Language Processing) and semantic reasoning technology to process and enrich the available metadata. To evaluate the usefulness of the applied technologies against an existing reference, a demonstrator application replicating the functionality from an existing application has been built based on the SemaGrow infrastructure. The application provides metadata search capabilities to discover datasets and allow access to the data itself in different formats, for example as NetCDF. The demonstrator application has subsequently been reviewed by a panel of testers, i.e. representatives scientists who could in the future use such technologies.

A conclusion is that transparent and unified access to RDF datasets for the purposes of agricultural systems research/modelling is not yet trivial and technologies seem not mature enough. To date, RDF datasets and semantic technologies deal mostly with bibliographic data and text documents, however handling scientific multi-dimensional datasets efficiently in triple stores is different from bibliographic data and text documents. Even though this can be operationalized as was done in the demonstrator, a couple of research challenges remain which provide serious obstacles. First, there are still many difficulties in ontology matching between CF-Conventions, the ICASA variable list and AgroVoc. Second, spatial projections and temporal scales consistently are not handled consistently. Third, while there are high expectations about "magical" semantic (and linguistic) query processing, the focus turns out to be more on "technical" query processing (distributed querying; i.e. deciding which part of the RDF dataset to apply which part of the query to). Fourth, and most important to the domain, meta-data of data sources are very often not self-explanatory with often a lack of clear and simple descriptions that can be matched to ontology terms. The data sources need a fair amount of expert interpretation. On the positive side, a web-based access, discovery and extraction method that brings together large amounts of data from different disciplines in one (big data) repository was evaluated as a very promising step for increasing the efficiency of science and scientific integration.

Keywords: *Big data, modelling, analytics, semantic technologies, thesauri, ontologies*

A framework for uncertainty evaluation of agricultural computer simulation models with a focus on allocation of uncertainty to model components

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Abstract: We propose a framework for Uncertainty Evaluation, UE, to explore how the components of a crop model contribute to overall model output uncertainty. We develop a state-space structure to classify the types of uncertainty introduced by each model component. The state-space structure, $r = f(\boldsymbol{Z}_t, \boldsymbol{\theta}, \boldsymbol{E}_t, \boldsymbol{C}_t, \varepsilon)$, predicts the real world $\boldsymbol{r}$ as a function $\boldsymbol{f}$ of state variables $\boldsymbol{Z}_t$, input parameters $\boldsymbol{\theta}$, calibration and environmental data $\boldsymbol{C}_t$ and $\boldsymbol{E}_t$ and noise $\boldsymbol{\varepsilon}$.

Bio-physical agricultural models, colloquially crop models, are simplified mathematical representations of physiological and physical processes. Such deterministic models are made up of many components that together simulate real-world agricultural systems. Although the models are deterministic, there are many possible sources of uncertainty; incorrect specification of the governing equations, incorrect input parameters, bias, scaling, aggregation, and inherent stochasticity in data.

Our UE framework has seven steps to provide guidelines for the identification and utilisation of the uncertainty inherent in different aspects of crop models. We illustrate the UE framework using the SIRIUS model as a case study for simulating spring-wheat development. In this paper we combine the three aspects; different types of uncertainty, use of state space structure to describe a time-step model; and a framework for UE. This allows us to explicitly describe and allocate each type of uncertainty within a state-space structure and then curate available information *prior* to diagnosing principal sources of uncertainty and setting or adjusting analysis objectives in the light of actions. It consists of seven steps that sequentially: 1. Describe, validate and verify the model, 2. Clearly identify and compartmentalise model components, 3. Curate available information, 4. Identify principal sources on uncertainty in model components, 5. State the objectives of the evaluation, 6. Generate simulation data and 7. Analyse the simulation data. Our framework can link qualitative UE to quantitative analysis by classifying some classical and modern techniques for generating and analysing data from crop models. The UE framework is illustrated via a case study for simulating spring-wheat development with the SIRIUS model.

Keywords: *Uncertainty, computer simulation model, state-space model*

Automated satellite-based estimation of crop water requirement for irrigated horticultural industries in northern Victoria

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Abstract: The horticultural industry in Victoria is currently experiencing significant structural pressures due to a range of issues, including water constraints through the introduction of Sustainable Diversion Limits (SDL's), access to productive land and infrastructure, climate change and competition with overseas imports. Bio-economic models such as the Victorian Water Policy Model enable policy makers to explore scenarios which aim to optimize agricultural productivity and the trade-offs between various agricultural industries and regions under a series of water availability and physical constraints. However, the current data-sets which populate these models such as land-use, irrigation demand and production estimates are often sparse and not frequently updated. This paper discusses the design and implementation of an automated process to provide enhanced estimates of irrigated water use across the horticultural industries of northern Victoria. The service derives regional crop coefficient relationships for the horticultural industries using SEBAL-METRIC estimates of Evapotranspiration, Penman-Monteith estimates of potential evaporation and calculated Normalized Difference Vegetation Index (NDVI) from the Landsat-8 satellite. Application of the crop coefficient relationships provides estimates of crop evapotranspiration rates and irrigation water use over time. Automated reports for each horticultural industry within the water-trading-zones of the northern Victoria irrigation districts provide information on the distribution of crop coefficient curves, irrigation area, estimated evapotranspiration and water application. This information is critical for water resource management and to support physically-based biophysical models. It is anticipated that over time the service will also provide information on land-use transition and the adaptation of irrigation practices to changes in water availability.

Keywords: *Irrigation, Landsat-8, crop water requirement, NDVI, horticulture*

An evaluation of POAMA and APSIM based soil water outlooks for winter wheat

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Abstract: Water is a limiting resource in most Australian ecosystems; including most broad-acre cropping zones. In dryland farming, soil water and rainfall are the key water supplies but Australia has a highly variable climate. This presents challenges to farmers who must make a wide range of decisions that are partly weather dependent and hence subject to uncertainties associated with climate variability. Weather and climate forecasting can assist by providing information that reduces (but doesn't eliminate) climatic uncertainty at a range of different timescales. Seasonal rainfall and temperature outlooks are now firmly established among the services offered by the Bureau of Meteorology (Bureau). This paper examines the performance of seasonal outlooks of soil water storage in the context of wheat cropping (autumn planting, late spring harvest). Soil water information could complement the rainfall outlooks, making the water resource "outlook" for dryland farming more complete.

Ensemble soil water "outlooks" were constructed based on weather ensembles simulated by the Predictive Ocean-Atmosphere Model for Australia (POAMA), combined with the Agricultural Production Simulator (APSIM) at twenty sites across south-eastern Australia. POAMA provides 33 ensemble members and there is a 33 year hindcast data set that was used for this work. The overall modelling flow for the outlooks was:

1. Downscaling of POAMA daily weather series (rainfall, min/max temp, humidity, radiation) ensemble members from the ~250km grid scale to a local weather station was undertaken using quantile-quantile (Q-Q) correction of the statistical distribution (incl. no. of rainy days) based on 33 year hindcast and 33 year observation record at twenty Bureau climate stations (SILO data drill product). Q-Q Corrections were independent of the forecast period (the relevant year was omitted when developing the correction);
2. Soil water ensembles were then simulated by running APSIM using the previous 5 years observed weather (to establish initial conditions for the forecast) and then each of the 33 9 month hindcast ensemble members; and
3. Soil water ensembles were summarized using various percentiles and placed in climatological context using a soil water climatology constructed using APSIM and the 33 year observation record at the relevant site.
4. The soil water ensembles were then evaluated against a "truth" run of APSIM (based on observed weather) for their ability for forecast dry (lower tercile) conditions.

Step 4 calculates the area under the Receiver Operating Characteristic (ROC) curve to provide a measure of how well the model predicts the occurrence of dry (lower tercile) conditions balanced by the occurrence of false positives (false predictions of dry conditions) (Figure 1). Values >50% are better than random guessing. Figure 1 shows how performance varies with lead time and month of the year. Outlooks generally have useful forecast skill (ROC>55%) for lead times of up to two-three months, except late spring. This is in line with current useful lead times for rainfall outlooks. Outlooks perform better through summer and autumn when vegetation cover and hence water use is low, which possibly leads to longer soil water storage memory benefiting the forecasts at that time.

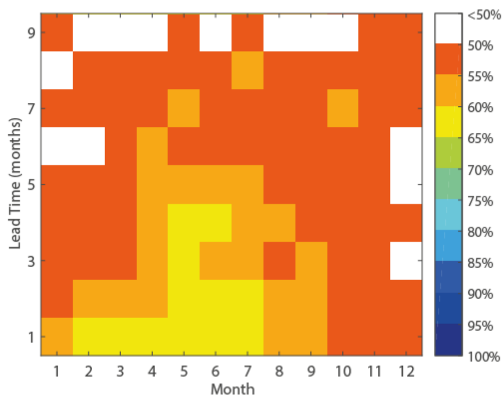

Figure 1. Plant Available Soil Water outlook performance for prediction of dry (1st tercile) conditions averaged over 20 stations in south-eastern Australia. Area under ROC curve for the lowest tercile. All entries for a particular column represent outlooks forecasting the conditions at the end of that month from a start point between 1 and 9 months earlier.

Keywords: *Soil moisture, Seasonal forecast, POAMA, APSIM*

Decoupling Energy and Natural Resource Use from Economic Growth: An Agent-Based Modelling Approach

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Abstract: The current economic crisis draws renewed attention to the underlying mechanisms of the market economy and its increasing effects on the environment (MDG's, 2008). One area of particular concern is the focus on economic growth, induced by the monetary system, which requires an ever increasing use of natural resources. Daly (2011) pointed out that the interest rates associated with the stock of debt forces society to create a continuously increasing income flow, resulting on the accumulation of more and more debt to finance the economic growth ultimately and reduce the availability of natural resources. However, the impact on the environment is not factored in to the cycle of interest, debt, growth, thus creating the so-known negative externalities. This disjunction between the economic and natural resource systems may be preventing sustainable development (ICSU, ISSC, 2015).

Despite the fact that decoupling economic growth from natural resource consumption is at the heart of initiatives such as the Green Economy Initiative of UNEP, conceptual frameworks for achieving it are still in their infancy and, therefore, further models are required (UNEP, 2011). Based on this, we construct a conceptual agent-based model (ABM), implemented in NetLogo (Wilensky, 1999), in order to determine whether there is a built in bias in the economic system towards unsustainable outcomes related with energy consumption and resource use. We also wished to examine which combination of variables may lead to more sustainable use of natural resources. Our monetary model simulates a basic credit economy, consisting of three agents: bank, firms, and households. We model the access to a resource by the industry, which consumes energy through a resource exploitation process. We include households which consume the resources made available by the industry. Finally, the bank settles payments and extends loans with interest to the industry and households. The economic activity is modelled through a financial market, which includes both a goods market (i.e. money spent by households on assets delivered by the industry) and a debt market (i.e. credit delivered by the bank for the industry and households).

Our ABM model is designed to be as simple as possible while capturing the desired dynamics. It rests on a set of macroeconomic functions. In particular, we use Steve Keen's 'vault' model of a Wicksellian pure credit economy (2009, 2010a) and also his cyclical model of the macro-economy (2010b, 2011a,b) as a basis, which was able to reproduce the real macroeconomic trends that occurred between 1970 and 2010. We replicate these models by adding additional environmental variables (e.g. energy consumption), necessary to obtain more information from the environmental pillar of sustainability.

Our model shows how credit, created by the bank, is brought into the economy endogenously at the demand of the market. Due to this, our simulations show positive short-run trends in economic indicators. However, in the long-run this gives way to economic collapse, as long as the driving forces of productivity and population growth exist. As Keen (2010) argues, this occurs because the money that funds economic growth does not enter according to private profit-seeking, but rather for speculative goals. As a consequence, economic growth has negative effects on the other two pillars of sustainability (i.e. social and environmental), creating a decoupling process between the growth curve of debt and energy production, and the decline curve of total resources available in the system. In our model, more sustainable outcomes are obtained when the curves of total debt and resource availability are parallel over time. This could be achieved, for example, by reducing resource consumption or in a system that would not rely on an increasing stock of debt for industrial growth, but rather on expanding money supply only when deflationary pressures reveal a need for more money.

Keywords: *Agent-based model (ABM), debt monetary system, sustainable development, economic and environmental decoupling, natural resources*

Spatiotemporal agent-based modelling to analyze sustainability issues at the landscape level – The grazing herbivores metaphor

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Abstract: This model aims at simulating herbivores grazing in a rangeland landscape. The first aim is to find a balance between the herbivores and the vegetation dynamics guaranteeing sustainability: maintain a healthy animal population and a green landscape. Two opposite processes threaten this equilibrium: overgrazing, leading to desertification, reversible; under-grazing leading to shrub invasion, irreversible. Both processes may ultimately lead to the population extinction by starving and pasture invasion by shrubs. The model implementation with the NetLogo simulation platform (Wilensky, 1999) comprises two types of agents: "Patches" standing for land plots; "Turtles" standing for herbivores. Patches are characterized by their color: shades of green for grass, red for shrubs. Herbivores are characterized by attributes like birth date, age, previous location, destination, pathway, travelled distance, ingested feed, body weight, calving dates. During simulation each turtle iterates the following: find a destination, move, graze, gain and lose weight, age and, possibly, reproduce or die. Simulations have been made to check variants of the system's structure and behaviors based on a reference landscape comprising 1,225 patches (1 ha each) and 1,225 turtles standing for cattle (1 head/ha). Simulation assessment criteria are the herbage biomass, herbivore population size, individual body weights, birth and mortality rates, land-use patterns and landscape fragmentation obtained after a 5-year time period. The following issues have been explored by simulation experiments:

- Heterogeneity of landscape at initialization: starting with patches uniformly green or with different greens in a relatively narrow range makes almost no difference. However, with higher heterogeneity the system's performances decrease in terms of population size, pasture area and shrub extension. Homogenous landscapes become more heterogeneous and conversely. Whatever their initial state, all landscapes converge eventually towards the same heterogeneity degree.
- Heterogeneity of spatial distribution of animals at initialization: starting with all turtles located on the same patch leads to a quick resource depletion radiating in concentric circles around the origin with huge mortality. The remnants colonize a few peripheral patches where they stabilize at a very low level, abandoning the rest of landscape to shrub invasion.
- Graze as much as you can or preserve resource? The best strategy for all turtles proved to be: if grass on the current patch is above a certain height, then keep on grazing, otherwise move to another patch.
- Type of animal walks: directed walks (e.g. individuals move to patches with maximum herbage) tend to create excessive local density much higher than non-directed (random) walks, inducing overgrazing, high herbivores mortality and bushy patch extension.
- Length of elementary moves: among random walks, short moves (local foraging) are most likely to lead to animal wealth and herbage preservation than long ones. "Levy walks", alternating both moves, lead to intermediate results. Landscapes resulting from short walks are less heterogeneous. However, long moves, fostering quick animal distribution in space, are better to reduce local excessive densities and resource depletion. Introducing two breeds of herbivores endowed with different walks in the same ecosystem confirmed this conclusion: the short walk population takes over the long-distance one which may go to extinction because of over-mortality due to weight losses caused by excess displacements.

These findings are in accordance with both herbivores behaviour as well as cattle farmers' grazing management rules. If the emphasis has been put here on animal movement, which proved to be crucial in shaping the whole ecosystem, the model allows also one to explore issues linked to ecosystem complexity (adding other trophic levels), percolation (dissemination of products through space) and resilience (assessment of disturbances through time and space on animals and land). How far this "herbage-herbivores" model, basically featuring the interaction between immobile and mobile agents (i.e. patches and turtles), can be used as a metaphor to represent other kinds of systems will be discussed.

Keywords: *Agent-based modelling, landscape simulation, grazing ecosystem*

Making the most of secure water: a framework to aid decision making

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Abstract: Decision-making on agricultural land-use in Tasmania is a very complex process that involves consideration of opportunities generated from the expansion of irrigation to meet agricultural water demands and mitigate climatic risks to crop yields. Tasmania Irrigation (a State Government owned company) is interested in attracting farmer investment to new water schemes. Tasmanian farmers are concerned about production choices that might maximize investment returns when buying into irrigation schemes. In this context of increased water security and changing crop values, farmers and other decision makers need a framework to guide investment decisions.

Geo-spatial Agent-Based modelling (ABM) has potential for representing the dynamic processes in decision-making and agricultural systems. It allows for a flexible use of tools and modelling techniques particularly in relation to geospatial modelling. Agent Analyst is a free and open source extension recently developed by ESRIArcGIS to be implemented as a new model-tool type of ABM to analyze the spatial relationships of agents. It has the potential to create agents[1] from GIS layers and execute the agent behavior rules with display of the result of the simulation within the ArcGIS environment. Advances in Agent Analyst allow creating, editing, and running Repast models from within the ArcGIS 10 Geoprocessing framework. As a result, Agent Analyst is a useful tool for analyzing the decision making process and simulating actions of farmers and measuring the resulting system behaviors and outcomes.

This paper covers the development of an agent based model using Agent Analyst software to study the consequences of changes in patterns of both land use and water use over time in the Dorset region of Northern Tasmania. Dorset has been a region undergoing significant change from commodity based production to higher value added production with access to guaranteed water and opportunities to consider new and alternative crops. Agent Analyst offers a way of taking into account decision-making on agricultural land use at different levels by taking advantages of ABM within ArcGIS modelling environment. The paper illustrates the types of information that can be generated in order to support farmers' decision with respect to irrigation expansion.

[1] Agents could be farmers, buildings, land parcels, stakeholders.

Keywords: *Agricultural land-use , geo-spatial agent-based modelling, agent analyst, irrigation*

Toward a new approach for plant modelling

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Abstract: Understanding the processes governing plant growth and response of the latter at different stress (water, heat or drought, ...) are fundamental in order to improve and better adapt plant in their fluctuating environment (mainly rice, sorghum, sugar cane and oil palm in our case).

Modeling and simulation of such plant complex models allow testing, in silico, different assumptions about the processes controlling plant growth. There are already many models of plants that all have their strengths and weaknesses. These include, for example: STICS, GreenLab, APSIM, DSSAT, Sunflo, SarraH, EcoMeristem, ... In these models, behaviors, or reactions, were activated, typically by functions (or equations) with thresholds which allow trigger behavior with greater or lesser intensity levels. For example: destruction of a sheet, carbonaceous material reallocation, etc.

Now it appears (according to knowledge given by ecophysiological expert) that in natural systems, this analogy is not always true. Indeed, these systems, a plant for example, are constantly in a steady state while trying to reach their final goal that is growing on order to produce. Due to these facts, one can realize that there are always adjustments between the different organs of the plant. Unfortunately, the above conventional approaches used so far does not allow to take into account this fact, let alone implement them.

Also, the objective of this work is to try to fill this gap in our plant models. To do so, we should focus on the elementary bricks (or organs) within a plant: leaves, between node axis, tiller, etc. and describe individual behavior and interactions. Naturally enough, one can imagine that the multi-agent systems, from distributed artificial intelligence, are a good candidate to represent these phenomena.

To do this, we decomposed the plant into six agents: culm, root, leaf, internode, panicle, and peduncle. Then the plant is seen as a society of such agents. The *culm* agent's behavior is to stand the other agents defined below. The first culm is called *mainstem* and the others one are called *tiller*. The *root* agent's behavior is to catch assimilation and water into the ground. The *root* agents is seens as a single bulk compartment and is no more sophisticated. The *leaf* agent's behavior is to growth up to predefined length and then to start the senescence process that, at the end, destroy the leaf. It intercepts the light coming locally from the sun so that it produces assimilation. The *internode* agent's behavior is to start elongation and store starch in its tank. The *panicle* agent's behavior is almost the same than the internode one. The *peduncle* agent's behavior is to create spikelets and then filling grains (according to a potential sterility) in the case of rice for example.

At the society level, the agent plant's behavior is to maintain the plant state. These states can be (in the biological order): morphogenesis, elongation, panicule initiation, flowering, end filling, and finally maturity. These state are managed by an oriented finite state automaton. The transition between two states at a given state t is a function that combined the state a $t-1$, the thermal time, the plastochron, and the stock.

Moreover, the organ topology is represented by a network of acquaintances between them. There are different levels of networks according to the different levels of topology. As we have to manage at least two types of environments (network, physical), we decided to use the "mind-body" approach. An agent is decomposed in one conative system (the mind) and this conative system has multiple physical representation in the multiple environments. It means that one body is plugged in one environment (network or physical). It embeds captors to catch information from the environment and actuators to act on the environment. As an example, the *leaf* agent has a body in the environment that produces the air temperature, the radiance, and the evaporative demand; and a body in a graph that links the leaf with its internode.

All this model will be implemented within the TurtleKit platform: `www.madkit.net/turtlekit`. TurtleKit is able to use the multiple environments approach and provide GPGPU acceleration in order to manage environmental data.

Keywords: *Plant modelling, Multi-agents system, environment, GPU*

Macroscopic Analysis of Agent-based Models using Equation-free Methods

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Abstract: Agent-based models (ABMs) have been extensively used to study the behaviour in a number of disciplines including social and biological sciences. The ability of this framework to produce complex dynamics from relatively simple rule sets has made them popular in simulations of behavioural phenomena in systems where a mathematical description may be unavailable. Currently the analysis of ABMs is through observation of simulation results, possibly averaged over multiple runs, and may also include parameter sweeps indicating dependencies in the system. However there is a distinct lack of systematic analysis tools for ABMs in general. The non-linear and often stochastic nature of ABMs make understanding the emergent (macroscopic) behaviour from simulations at the agent (microscopic) level difficult. The development of equation-free methods (EFM) provide a platform to utilise well established mathematical techniques to systematically analyse the behaviour of ABMs. Specifically EFMs enable parameter path following through numerical continuation of the non-linear systems. Equation-free continuation can efficiently follow solution branches of the system, providing rich mathematical analysis of the emergent behaviour directly from the agent-level simulation. The solution branches describe the parameter dependencies in the system as well as stability and bifurcations in the system. The solution branches can provide a mathematical understanding of changes in emergent behaviour in different parameter regimes such as tipping points, transients and path dependence. Such a deep mathematical understanding of the macroscopic behaviour of ABMs is difficult, if even possible, through direct simulation alone. Existing tools, which may require third party programs for statistical tests, cannot perform this type of analysis.

Despite their suitability for investigating non-linear systems such as ABMs, EFM have previously only been applied to a few specific examples. The primary reasons for restricted use are; 1) the need to tune EFM parameters to specific problems and 2) the lack of an available framework. For each investigation, choices have to be made for algorithmic parameters, such as: the number of micro-simulations carried out at each parameter point; the time window for each micro-simulation and the size of the steps in parameter space. These parameters have been chosen largely by trial-and-error and often a large number of micro-simulations are needed. As a result the EFM are limited to users with knowledge of the underlying mathematics and require a significant over-head in algorithmic parameter determination.

Here we develop a generic framework for the analysis of ABMs using EFM that does not require any knowledge of the mathematics involved. Our generic framework is highly robust and allows any ABM user to efficiently perform macroscopic analysis on their model of interest. Additionally, our framework includes a systematic method for the automatic tuning of algorithmic parameters for EFM to a specific ABM.

We demonstrate our method with application to several ABM models revealing parameter dependence, bifurcation and stability analysis of these complex systems. In each case we examine the dynamics of the model and describe the transient behaviour in different parameter regimes. We illustrate the robustness of our algorithm using well studied benchmark problems, before application to a number of open-source ABMs. These examples highlight the complex dynamics in simple models and demonstrate the use of EFM by uncovering parameter regimes for changes in emergent dynamics. One important application is to an ABM of the development of the bio-waste industry in the UK under different policies. By understanding the emergent behaviour of this real-world ABM, we can inform stakeholders of the impact of different policies to decision making at the national level.

The support of the UK Engineering and Physical Sciences Research Council for programme grant EP/H021779/1 (Evolution and Resilience of Industrial Ecosystems (ERIE)) is gratefully acknowledged.

Keywords: *Macroscopic analysis, emergent behaviour, agent-based models, equation-free methods, bifurcation analysis*

RF-MAS: Including inter-annual variability in the Cost Benefit Analysis of an investment in irrigation

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Abstract: The RF_MAS (Rural Futures Multi-Agent Simulation model) has been developed to investigate 'what if' questions on land use and economic and environmental variables. So far, all of the pastoral farming systems represented in the RF_MAS, have been modelled using average annual pasture dry matter yields (DMY). In many regions of New Zealand (NZ) irrigation is increasingly been considered as an option for increasing on-farm production, profitability and resilience by increasing pasture growth in the summer months, and importantly reducing inter-annual variability. The capital investment in irrigation and associated operating costs exposes the farmer to higher financial risk. To date most analysis of the benefits of irrigation has been limited to an average rainfall year. To investigate the cost-benefits of irrigation when individual growing years are considered the functionality of RF-MAS was expanded to include inter-annual climatic variability.

The Ruataniwha Plain, in the Central Hawkes Bay, NZ, which has a temperate climate with predictable summer dry months was used as a case study to explore the cost-benefits of irrigation. Pasture growth was simulated using the Agricultural Production SIMulator APSIM for 20 different years. The impact of the annual variation in pasture growth and the response to irrigation water on associated profit was calculated using the RF-MAS model, which consists of three layers: (i) spatial datasets of farms and land resources within the region, (ii) a set of production budgets and environmental impacts, and (iii) farmer-agents and their social, economic and demographic characteristics.

Results:

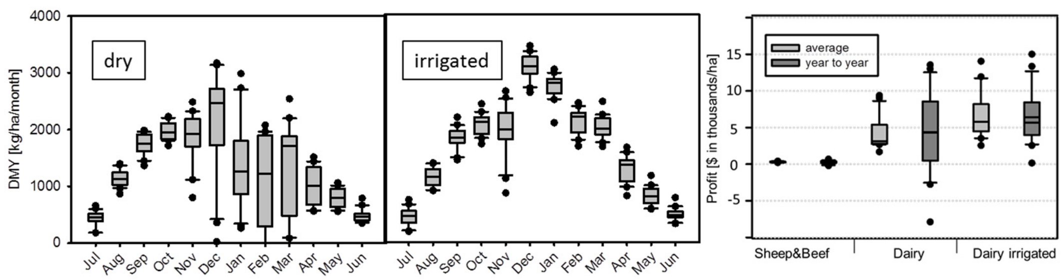

Figure 1. Pasture Dry Matter Yields (DMY) for dryland and under irrigation simulated by APSIM for 20 years, and associated profit for 20 years as obtained by the RF-MAS model for various farm enterprises.

Average annual pasture growth simulated by APSIM was 15 t/ha on the elite soils and 13 t/ha on the less versatile soils, increasing to 20 and 18 t/ha under irrigation, respectively. Year to year variability decreased under irrigation, with a coefficient of variation (CV) decreasing from 16% under dryland to 5% under irrigation. Profit, calculated by the RF_MAS model for dairy farming enterprises increased with irrigation, and including year to year variability increases the variation in average profit over the 20 years. In 11 out of 20 years the profit under irrigation was greater than under dryland.

Keywords: *Multi agent simulation modelling, inter-annual variation, irrigation, farming*

Spatially explicit individual-based modelling of insect-plant interactions: effects of level of detail in Queensland fruit fly models

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Abstract: A form of agent-based modelling known as individual-based modelling has been used widely to simulate hypothesised mechanisms underlying processes in the real world, especially in the field of behavioural ecology. To apply this approach to insect-plant interactions the Queensland fruit fly (Qfly), *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae), a major native insect pest of horticulture in Australia, will be examined. Due to restriction on use of some chemicals, currently there is no suitable management system for control of Qfly. However, better Qfly management can be potentially advanced by targeted behavioural, physiological and ecological research on this species. Many control options depend on behavioural fundamentals of Qfly such as foraging and movement patterns (e.g. trapping control technique), and the use of resources like protein and food sources (e.g. bait spray control technique).

In the present study, two 3-dimensional individual-based models with different levels of detail have been developed to simulate Qfly behaviour and movement patterns on host plants, one with NetLogo, and the other with L-studio. Both provide a dynamic platform for simulating insect movement decisions underlying searching and feeding behaviour. The spatial unit in the NetLogo model is based on 'vegetation cubes', while the Lindenmayer System (L-System) formalism-based approach underlying L-studio allows the model to have more detailed plant architecture, with individual leaves and stem segments. Both models predict that Qflies spend more time in the mid to upper canopy, which shows a good agreement with published literature. The overall objective is to test whether it is possible to predict fruit fly movement and distribution based on hypothesized behaviour and also assess whether such a model can provide insights that may have been missed in past experimental studies, investigate what level of detail is best used for addressing different types of questions from entomologists, and to show the advantages and disadvantages of both models.

Our study suggests that, the NetLogo model can be better used to investigate scientific questions like insect spatial population distribution on plant canopies and how different tree architectures affect their behaviour, while the L-system model is better to use to look at how foliage density and foliage position affect fruit flies behaviour and to simulate landscape scales such as orchards including multiple trees. Using the model with the right level of detail to inform, develop and test research allows new insights into insect-plant interactions and can inform experiments carried out in the field that have application in better pest management.

Keywords: *Agent-based model, computational model, computer simulation, behavioural ecology, insect-plant interactions*

Integrating biophysical and whole-farm economic modelling of agricultural climate change mitigation

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Abstract: Agriculture is the source of 16 percent of Australia's greenhouse gas (GHG) emissions. Research has shown that changes in agricultural practices can increase carbon sequestration in soils and/or vegetation and reduce GHG emissions. Given worldwide commitments to reduce GHG emissions, there is a need to better understand the potential for Australian agriculture to contribute to GHG mitigation. GHG abatement practices will only be adopted if profitable to farmers. Without strong evidence for increased profitability, there is no incentive for farmers to move away from their current practices. Therefore, it is necessary to incorporate economics in any assessment of the potential for Australian farms to contribute to GHG mitigation.

We performed an integrated modelling exercise to predict the GHG mitigation potential and whole-farm economic implications of different mitigation practices that can be implemented on Australian grain farms. This exercise was undertaken in two stages. In the first stage, a range of potential management practices that could provide GHG abatement were identified; these involved adding extra organic matter to the soil or altering nitrogen fertiliser use. The Agricultural Production Systems sIMulator (APSIM) was used to estimate the effects of abatement practices on productivity, soil carbon sequestration, nitrous oxide emissions and net GHG emissions over time. In the second stage, we develop an economic model that predicts annual revenues at a paddock scale, as well as whole-farm costs and benefits. Taking a whole-farm approach ensures that the full costs of different practices, such as investment in new capital equipment, is included.

We present results for a 6,000 hectare dryland cropping farm in the north-central wheatbelt of Western Australia. This area is representative of the typical Mediterranean climate found in some of Australia's major grain growing regions. We predict that stubble retention and other organic matter additions increase soil carbon, which is important for greenhouse gas emissions reductions. Productivity gains are possible under some of the GHG abatement practices, i.e. GHG abatement and productivity gains can be achieved simultaneously. Increasing nitrogen fertiliser application or replacing volunteer, weedy pastures with improved, legume pastures are predicted to increase earnings and operating profits. However, when accounting for interest and tax, there was no economic advantage or disadvantage of adopting any of the GHG abatement practices. While gross margins per hectare are positive in almost every season, the whole-farm annual profits were negative for 30-40 percent of years.

This study demonstrates the benefits of comprehensive economic analyses to accompany any biophysical analyses of the GHG mitigation potential of the Australian agricultural industry, and outlines a framework in which economic and biophysical analyses can be combined.

Keywords: *Greenhouse gas, nitrous oxide, carbon sequestration, grain production, gross margins*

Systemic adaptations to climate change in Western Australian mixed farm systems

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Abstract: Australia's primary industries have historically operated in a highly variable climate. This has posed significant challenges to production, requiring sound and responsive risk management practices. Climate change has, and will, introduce even greater challenges. This means that there is a clear need to continue to assess the opportunities for farmers to improve how they respond to climate variability and changes. We built representative mixed farm systems (using AusFarm) across climate gradients to investigate likely effect of climate change and variability and systemic adaptations to explore system's resilience, to enhance productivity under climate variability, and change by 2030. We used AusFarm to build mixed farm systems. Model inputs were derived by consulting with producers and models performance was validated against survey data.

For a climate gradient of 335-215 mm rainfall (Apr-Oct) in Western Australia, we evaluated long term average effectiveness of changes in planting date, fertilizer application rate, crop and stubble grazing, and stocking rates (SR) for 2002-2012 as baseline. To assess the impact of climate change, we used two high-emissions CMIP3 scenarios (A1FI and A2) with high and medium sensitivity and six global climate models projected climate for 2030. In 2030 and in a relatively medium rainfall region (MR) of the climate gradient, wheat, barley, canola production changed by +6%, +2%, and -2% on average while meat and wool production increased by 1% and 2%. In 2030, and in lower rainfall (LR) end of gradient, wheat, barley, canola, and lupine production changed by -8%, -2%, -11% and -16% while meat and wool production changed by -2% and -4%. In 2030, GHG emissions changed by -10% for LR and -5% for MR under current management.

In addition to systemic combination of options described above, we evaluated a range of climate adaptation packages, which were determined in collaboration with stakeholders. These adaptation packages designed specifically for each region to reduce negative impact and risk of climate change and benefit from likely opportunities. Alteration of the crop-livestock balance is an adaptation that can compensate negative impact of climate change by reduction in business risk. These were evaluated through a package with elements of optimizing area proportions of cropping and pasture either by changing the relative areas of existing crop & pasture sequences or the relative length of crop & pasture phases, optimizing stocking rate, and adjustments in livestock joining and sale dates. We designed low-variability to high-intensity mixed farming as adaptation packages optimised for different risk and return management approaches. Overall, financially optimal systemic adaptations were projected to offset negative impact of climate change on production and profitability of whole farm system in 2030 at majority of sites. This would require for practice and land use change to cope with changes in climate.

Keywords: *Modelling, complex agro-ecosystems, Western Australia, APSIM, GRAZPLAN*

Modelling the impact of climate variability and irrigation on winter canola yield and yield gap in Southwest China

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Abstract: Southwest China (SWC) is one of the major canola production areas in China. Due to frequent seasonal drought during the canola growing season, irrigation plays a vital role in improving canola yields. However, the impact of irrigation and climate variations on canola yield and the yield gap (the difference between potential and rainfed yield) has not been properly addressed. Existing experimental data are limited and are not sufficient to answer these questions. A modelling study is therefore warranted to extend the experimental findings.

In this study, we used a modeling approach to quantify the yield potential and the yield gap of canola crop, how they are affected by inter-annual climate variability, and how much water is required for irrigation to close the yield gap in southwest China. The APSIM−Canola model was firstly calibrated and validated against experimental data at Yuxi site in SWC from 1981 to 1989. The model was then used to simulate the canola yield under irrigation and rainfed conditions from 1961 to 2010. The simulation results were used to explore the impact of different irrigation scenarios on canola yield.

From 1961 to 2010, minimum temperature increased by 0.5°C per decade ($p < 0.01$) during the canola growing season, whereas daily global radiation decreased by 0.3 MJ m^{-2} per decade ($p < 0.01$). Growing season precipitation ranged from 44.3 to 310.9 mm with a non-significant decreasing trend. The warming and dimming trend from 1961 to 2010 was estimated to reduce the potential yield at the rate of 151 kg ha^{-1} per decade ($p < 0.01$), mainly due to reduced radiation and length of growing period.

Simulation results with a single hybrid cultivar showed that the potential canola yield under fully irrigation (3452kg ha^{-1}) is about three times the rainfed yield (1215 kg ha^{-1}). Improved irrigation increases yield and water productivity, particularly in dry seasons. To achieve ~80% of the potential yield, an average amount of 330.1 mm, 302.9 mm, and 265.2 mm irrigation water, were required for canola in wet, medium, and dry seasons, respectively. Longer season canola cultivars may help to mitigate the negative impact of further climate warming in the future.

Keywords: *Potential yield, rainfed potential, crop water productivity, water management, APSIM-Canola*

Potential of increasing yield while mitigating climate change in Australian wheat systems: a simulation study

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Abstract: Sustainable management of agroecosystems is required in order to produce more food to feed the growing global population with less environmental costs. The management strategies have to be developed based on local soil and climatic conditions and for specific stakeholders' interests. In this study, we developed a framework to analyse optimal nitrogen (N) requirement for targeting different levels of crop yield and/or climate change mitigation. The Agricultural Production Systems sIMulator (APSIM) was applied at near-uniformly distributed multiple sites to simulate wheat yield in response to N applications, with the aggregated results tested against the national-level data in Australia. The calibrated model was applied to identify the optimal N management for different targets. Thereafter, correlation analysis was performed to quantify the relationships between N demand, yield and climate change mitigation potential (CCMP) and soil and climate variables. The CCMP was defined as the net soil carbon (C) change minus nitrous oxide (N_2O) emissions in CO_2 equivalents (Mg CO_2-eq ha^{-1} yr^{-1}).

At the national scale, the aggregated modelling results could well predict the average wheat yield and soil C change under the current N fertilizer input level. Simulation results with different N application rates indicated that wheat yield could be considerably increased by up to 70% (from 1.8 to 3.0 Mg ha^{-1}) by increasing N fertilizer input comparing to the current practice. To achieve 90% of the maximum yield, an average N input of 110 kg ha^{-1} yr^{-1} was required across the wheat growing regions, which was ~80 kg ha^{-1} yr^{-1} higher than the current N fertilizer application rates. If we targeted the maximum CCMP per unit area and per unit yield, the simulation results also showed a requirement of increased N input compared to the current level, which could result in a wheat yield level similar to or higher than 90% of the maximum yield. Importantly, such increased N input also led to a substantial decrease in net GHG emissions as compared to the current N management.

The crop N demand, yield increase and climate change mitigation potential correlated strongly with site-specific precipitation, temperature, soil water holding capacity, and antecedent soil carbon content. Across the study area, the N demand, yield and CCMP varied widely under all four targets (maintaining current crop production, targeting the 90% of the maximum crop production, targeting the minimum net emissions, targeting the minimum net emissions per unit production). In general, rainfall had significant positive effect on simulated N demand and yield, and the degree of the effect varied across targets. The plant available water capacity (PAWC) also had significant positive effect on N demand and yield. However, rainfall had negative effect on CCMP. Compared with rainfall, the effects of temperature on N demand and yield were relatively neutral. Soil organic C content had significant positive effect on yield. For CCMP, soil organic C content had a negative effect. The effects of time period on N demand, yield and CCMP were negligible under current N management

The results highlight the opportunity with well-managed intensification to simultaneously increase crop production and mitigate climate change by reducing net GHG emissions in Australian wheat systems. The same opportunity may be present in other low-input dryland cropping systems. The 'win-win' N management recommendations should and can be specified according to local climate and soil conditions by considering the target crop yield and/or climate change mitigation objectives.

Keywords: *Agricultural intensification, carbon sequestration, food security, greenhouse gas emissions, nitrogen management*

EXTENDED ABSTRACT ONLY

Modelling productivity and water use efficiency of alternative cropping systems in the North China Plain

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Abstract: Winter wheat – summer maize double cropping rotation (WMWM) is the dominant cropping system in the North China Plain (NCP); one of the most important grain production areas in China. While its productivity has consistently increased, its sustainability has increasingly been questioned due to excessive groundwater consumption for irrigation, which is leading to rapid groundwater depletion. Alternative cropping systems that have a lower water use have gained increasing attention especially in recent years.

This paper uses farming systems modelling (APSIM) to assess the performances of five alternative cropping systems under long-term climate variability from 1961 to 2012. They include continuous winter wheat (Wt), continuous summer maize (Mz), continuous spring maize (SMz), continuous winter wheat – summer maize double rotation (WMWM-four crops in two years) and winter wheat – summer maize – spring maize rotation (WMsM - three crops in two years). Crop productivity and water use efficiency were evaluated at four representative sites (Anyang, Jinan, Luancheng and Beijing) across the NCP between 1961 and 2012. The results were analysed to determine which system had a lower water use whilst maintaining productivity.

Preliminary results showed that the WMsM system could achieve similar total yield to the WMWM system, but use significantly less irrigation water. Total productivity over two years was in the order of WMsM ≈ WMWM > Wt > SMz > Mz. To achieve the same yield, WMWM system needed 10, 13, 6 and 23% more irrigation water than WMsM system in Anyang, Jinan, Luancheng and Beijing, respectively.

Under rainfed conditions, the simulated highest total crop yield (in two years) was from WMsM cropping system. At Anyang, Jinan, Luancheng and Beijing sites, yields of WMsM system were 5, 3, 13 and 8% higher than that of WMWM system, respectively. Without irrigation, yield of cropping systems (total over two years) were in the order of WMsM > WMWM > SMz > Mz > Wt. Among the four sites, average annual rainfall amount were: Jinan (620mm) > Anyang (553mm) ≈ Luancheng (551mm) > Beijing (540mm). Water use efficiency (WUE_{ET}) of Wt system was the lowest of the five systems at four sites. At Jinan, WUE_{ET} of WMsM and WMWM were the highest, and the former was higher than the latter. At Anyang and Luancheng, WUE_{ET} of WMsM was the highest, and no significantly difference from that of Mz system. At Beijing, WUE_{ET} of SMz and WMsM were the highest two among five systems. In addition, WUE_{ET} of Mz was higher than that of WMWM. Under future conditions of likely reduced water supply due to groundwater depletion, the total yield and WUE of WMsM system was higher than the WMWM system, WMsM can be a suitable alternative cropping system to the current double cropping rotation (WMWM).

Keywords: *Cropping system, grain yield, water use efficiency, ground water, modelling*

Evaluating wheat water footprints in the North China Plain

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Abstract: The increase of grain production in the North China Plain is mainly dependent on the irrigation. Many years of high intensity and over irrigation has caused a rapid decline in groundwater level and severe degradation of ecosystems. The sustainability of agriculture is becoming a major concern for the region. The objective of this study is to estimate crop evapotranspiration (i.e. water consumption) and quantify the water footprint (blue and green water) of wheat over the last decade. A model based on crop coefficients and remotely sensed vegetation data was developed to estimate crop evapotranspiration. The simulation results were consistent with that of ETWatch and the observed evapotranspiration from Luancheng station. Evapotranspiration of winter wheat was in excess of 400 mm in the piedmont region of Taihang Mountains and the irrigation region of Henan-Shandong along Yellow River. Evapotranspiration of winter wheat was less than 350 mm in the middle plains and less than 200 mm in coastal areas due to lower planted areas in those regions with salinized soils. Our analysis shows that the blue water footprint of winter wheat was more than its green water footprint, and the proportion of blue water to the total water footprint varied from 58~ 62% in different parts of the NCP. The wheat used more ground and surface water than rainfall. In the piedmont region of Taihang Mountains, total net groundwater consumption during 2000 – 2010 was about 26.3 km^3 and groundwater table declined 9.4 m. In contrast, there was a significant decline in the area plant to winter wheat and irrigation water consumption in the northern Hebei Plain over the past 14 years. The reduction in irrigation has slowed the downward trend in regional groundwater levels. In order to reduce the consumption of blue water resources, we suggest developing water- saving agricultural system. Efforts should be made to increase the use efficiency of rainwater, wastewater and brackish water in order to reduce the use of groundwater and optimize crop productivity.

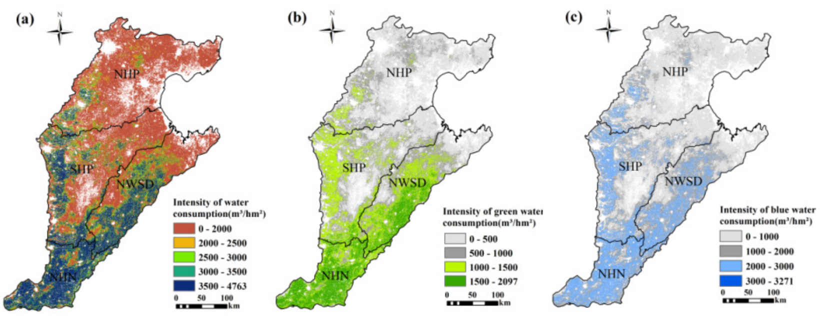

Figure 1. Distribution of water consumption intensity of winter wheat in the NCP from 2000 to 2013.

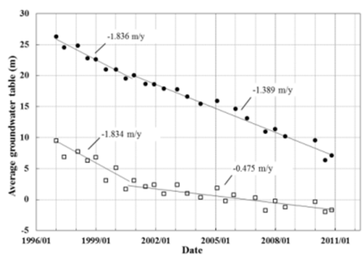

Figure 2. Change of averaged GWD in the north (blank squares) and the south (solid dots) parts of the plain.

Keywords: *Water footprint, groundwater depletion, North China Plain*

Quantifying key sources of variability in cover crop reduction of N leaching

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Abstract: The effectiveness of cover crops in mitigating nitrogen (N) leaching is highly variable. The reasons for this variability are unclear and difficult to isolate from field experimentation only. A modelling experiment to represent a cover crop (forage-wheat) and spring crop (silage-maize) sequence, using 30 years of historical weather data input from Lincoln, Canterbury (New Zealand), was set up to quantify key sources of this variability in cover crop effectiveness. A locally calibrated biophysical model (APSIM) was used to simulate the effects of crop management (four sowing dates for cover crops from mid-March to mid-June) and two soil water holding capacity (WHC) rates on the effectiveness of N leaching mitigation. Crop management determined the average effectiveness of cover crops, with consistently lower effectiveness at later sowing dates. The soil WHC effect was less prominent on cover crop effectiveness. Within any sowing date by soil WHC combination, the variability in cover crop effectiveness was mostly driven by the stochastic effects of weather on plant growth and soil N processes. These results can inform impact assessments about the contribution of management and environmental factors that control the effectiveness of cover crops to mitigate N leaching.

Keywords: *APSIM, cover crops, nitrogen leaching, water quality*

Will modifying soil water holding capacity increase the resilience of southern Australian crop-livestock farms to climate change?

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Abstract: Southern Australia is expected to face a warmer and drier climate in the near future that will affect dryland crop-livestock farming enterprises. As soil provides a buffer to store water between rainfall events, a suggested climate adaptation option is to reduce subsoil constraints (physical or chemical) to increase the soil plant available water capacity (PAWC). The considerable costs to modify the subsoil raises a question of how much PAWC needs to be increased and how often the increased PAWC would be advantageous. This research examines the effect of increasing PAWC from 40 to 120 mm in 20 mm increments on wheat and pasture production along a climate transect from 385 to 219 mm mean growing season rainfall during the historic climate and in two potential climate projections for 2030: moderate warming with little changes in rainfall, and more severe warming with declining rainfall.

Biophysical simulation models of integrated crop-livestock systems were constructed by linking APSIM (V7.7) to GRAZPLAN using the AusFarm environment (V1.4.12).

Locations and projected future climates with lower rainfall gained the least from an increased PAWC. Not only was this evidenced by reduced pasture and wheat yields but also in the frequency of years when there was a benefit. In lower rainfall conditions a larger PAWC increased wheat yield by at least 10% in only 60% of years, compared to 95% of years in higher rainfall conditions. A larger PAWC was of no benefit in very dry conditions.

Overall, productivity gains diminished not only as rainfall increased, but also as PAWC increased. Pasture production showed little benefit of PAWC above 60 mm presumably due to shallower roots or rainfall more closely matched to water demand; while average wheat yield in a PAWC of 80 mm was over 90% of that in a PAWC of 120 mm.

Wheat yield was reduced by water stress experienced during the growth cycle with the seasonal distribution of rainfall affecting the severity and timing of water stress and yield components of grain number and grain size. However, wheat grown in soils with higher PAWC had less water stress even under the same rainfall conditions. This was due in part to greater availability of water because of reduced water loss from deep drainage and increased soil water storage between rotations.

Modifying PAWC will not counteract an extreme drying trend. In some years there will be little benefit of modifying the subsoil because the rainfall is extremely low or its distribution is matched to crop and pasture requirements. In years when rainfall is high a larger PAWC will be of benefit as the increased buffering capacity of the soil will assist with carryover of water from a wet run of days to a dry period. Modifying the subsoil raises complex questions of nutrition, engineering and farm management economics. However, simulation modelling using a transect from wetter and drier sites in both current and future climates contributes to discussion on management of climate risk in the coming decades and effective adaptation options for future climates.

Keywords: *Wheat yield, pasture production, mixed farm system, adaptation, soil modification*

Predictions of nitrogen leaching from a well-drained soil under dryland and irrigated dairy farming using APSIM and OVERSEER

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Abstract: As urine patches from grazing livestock are the single largest source of leached N, biophysical models that incorporate the effect of N leaching from urine patches are required to assess the impact of changes in farm management on N leaching. The objective of this study was to compare predictions of N leaching from a dairy farm as made by two contrasting tools; APSIM (Agricultural Production Systems Simulator) and the OVERSEER Nutrient Budget Model. Typically, these models are used for different purposes, require different input data, and produce outputs that are not readily comparable. APSIM is a process-based model that works on a fine scale and daily time-step whereas OVERSEER calculates N leaching on a monthly time-step and reports annual averages of N leaching for relatively large areas. As OVERSEER has been calibrated for New Zealand's farming systems and uses inputs that are readily accessible by farmers, it is the favoured tool for assessing compliance of dairy farms to proposed new regulations. However, APSIM is increasingly being used to analyse existing and proposed farming scenarios in greater detail.

The dairy system modelled in this study is located on a well-drained Manawatu silt loam soil at Massey No. 1 Dairy Farm, Palmerston North, New Zealand. Dryland and irrigated scenarios were defined to cover a range of possible management options. Results from simulations over 25 years using APSIM were analysed to obtain long-term estimates of N leaching to compare with OVERSEER predictions. Although the model inputs were set such that both models were under similar weather and management conditions, there were differences between the models regarding the effect of irrigation on N leaching (Table 1). These differences were attributed to a) differences in how the two models describe irrigation and its effect on drainage, b) uncertainties in the calculations of urinary N load, and c) differences in simulations of other components of the N cycle. Our modelling exercise revealed those N transformation processes that behave similarly from those that differ between the two models, highlighting potential knowledge gaps. The exercise also highlighted the difficulties of comparing models, and great care should be taken when comparing outputs from different sources.

Table 1. Annual N balance (kg/ha) and drainage (mm) estimates for Block 4, Massey University No.1 Dairy Farm. [1]Rainfall + irrigation.
[2]Net transfer (kg N/ha) = [(supplements produced + supplements imported + transfer to block) – (removed as supplement + transfer from block)].
[3]N in milk.

Item	Block 4 – Dryland		Block 4 – Irrigated	
	OVERSEER	APSIM	OVERSEER	APSIM
Inputs (kg N/ha)	193	181	240	184
Fertiliser	69	69	69	69
Rain[1]/fixation	110	131	143	167
Net transfer[2]	14	-18	28	-52
Outputs (kg N/ha)	131	124	173	137
Product[3]	66	66	84	84
Volatilisation	40	11	51	10
Denitrification	3	15	4	16
Leaching	*22*	*32*	*34*	*32*
Soil changes (kg N/ha)				
Organic pool	62	58	65	37
Drainage (mm)	351	338	420	368
Pasture yield (t DM/ha)	12.1	9.6	14.8	13.2

Keywords: *Dairy farming, irrigation, Nitrogen leaching losses, APSIM, OVERSEER*

Improvement of maize phenology simulation under climate change in China's Corn Belt

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Abstract: Crop phenology affects the partitioning of assimilates to different plant organs and determines the appropriate time of agronomic management. Any uncertainty in simulation of phenological development will subsequently lead to uncertainty in simulated crop yield. Therefore, accurate simulation of crop phenology is of importance to crop yield simulation and climate change impact assessment. Maize is one of the most important food crops over the world, and has the largest sown area in China. Some previous studies have used a single crop growth model to assess the impact of past and future climate change on maize production. However, different maize crop models vary in their response functions of phenology to both temperature and photoperiod, particularly at temperatures above the optimum. How such different handling of response functions between the models transfers to differences in simulated maize phenology under current and future climate conditions has been rarely addressed.

This study investigated the uncertainty in simulated maize phenology using six widely used models (SIMCOY, MAIS, Beta, WOFOST, CERES and APSIM). Significant differences exist between the models in the cardinal temperatures of the temperature responses used to simulate maize phenology. The models were firstly calibrated and validated using long-term observational data at 10 sites across China's Corn Belt. The validated models were then used to simulate maize phenology changes in response to climate change. Future climate change scenarios were obtained from Beijing Climate Center (BCC) derived from regional climate model RegCM4 at a resolution of 0.5°×0.5° in China with two emission scenarios, RCP4.5 representing relatively low emission scenario and RCP8.5 representing relatively high emission scenario. To explore the uncertainties in simulated maize phenology under future climate change, the six maize phenology models were run for baseline 1980s (1970-1999) and projected future climate in 2030s (2020-2049) and 2080s (2070-2099) under both RCP4.5 and RCP8.5 scenarios.

As a result of different temperature response functions and cardinal temperatures, different development rates were simulated by different models at any given temperature but very similar development rate at around 20°C. When temperature changed between base temperature and optimal temperature, all the models simulated an increasing developmental rate with temperature, though the absolute rates were different. The evaluation of the six models showed that all the models could reach acceptable precision (NRMSE < 8%) for simulation of phenology under current climate. The uncertainty between models in simulated maize silking date, determined by the coefficient of fluctuation, increased from 3.2% under the baseline to 6.3% under RCP4.5 and 7.4% under RCP8.5 in 2030s, and to 8.9% under RCP4.5 and 14.5% under RCP8.5 in 2080s. The uncertainty for the simulated maturity date increased from 4.2% under the baseline to 7.0% under RCP4.5 and 7.7% under RCP8.5 in 2030s and 10.2% under RCP4.5 and 16.7% under RCP8.5 in 2080s. The uncertainty in predicted phenology is largest for summer maize in North China Plain, smaller for spring maize in northeast and southwest China. Different models disagree most in response to temperatures beyond the optimum temperature, which is a key area for model improvement.

Keywords: *Maize phenology, simulation, photoperiod, temperature sensitivity, climate warming*

Potential impact of increased heat tolerance of grain formation on maize yield under future warming

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Abstract: Variety has been a dominant factor in crop production to achieve high yield. Efforts to identify suitable crop varieties to increase yield under future climate conditions remains essential for sustainable agriculture development and food security.

Previous studies have evaluated the impact of varietal changes on crop productivity under global warming, mostly in terms of varietal improvement that changed growing duration, growth characteristics and disease resistance. Potential impact of varietal improvement to increase the tolerance of grain formation to extreme temperatures has been rarely studied, particularly in the North China Plain (NCP).

The objective of this study is to assess the likely impacts of future climate change scenarios on maize productivity in North China Plain (NCP), and evaluate the potential impact of using 'new' varieties with increased tolerance of grain number formation to high temperatures in response to climate warming.

The 'new' maize variety, derived from existing variety *Xundan29* in the APSIM model package, has a higher tolerance of pollen viability to high temperature. That is its grain number development has a higher maximum temperature threshold of 40°C as compared to *Xundan29* (38°C).

The process-based crop model APSIM, coupled with outputs of a regional climate model RegCM4, was used to simulate the impact of climate warming on maize yield in the periods of 2020-2045 based on RCP4.5 and RCP8.5 at Yuanyang, Yongnian and Shijiazhuang in the NCP.

Results show that the reduction in maize yield caused by climate warming (without considering the contribution of variety adaptation) increased from northern to southern sites, by 12% on average, taking 1980–2005 as the baseline period. Introduction of a variety with increased tolerance of grain number formation to high temperature could be one of the effective adaptation strategies to offset the negative impact of climate change. It could lead to an average yield increase of 1-9% as compared to no adaptation, depending on sites and climate scenarios.

Keywords: *Climate change, adaptation, maize yield, heat tolerant variety*

Quantifying the effects of management practices on crop production and water use efficiency under a changing climatic background

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Abstract: The North China Plain (NCP) is one of the most important grain production regions in China. Winter wheat and summer maize form the annual double cropping system, which consumes large amount of groundwater for irrigation. The rapid decrease in groundwater table is threatening the sustainable agricultural development in the region. Further increase in grain production will require improved management practices to increase water use efficiency (WUE) in agriculture. This study combined simulation modelling and observational data from a field experiment lasting for three decades (from 1980s to present) to quantify the effects of weather and management on yield and WUE of winter wheat, the crop requires most of the irrigation.

The yield change of winter wheat over the last three decades was divided into three time periods: the 1980s, the 1990s, and from 2000-present. Wheat grain yield during the 1980s was relatively stable, but continuously increased during the 1990s by 193 kg/ha/yr ($P<0.01$). In the last decade, wheat yield was maintained at relatively higher level, but with much larger inter-annual variation. The WUE of winter wheat during the past three decades was also improved with an annual average increase of 0.014 kg m^{-3} (Figure 1), due to the increase in grain production. This increase was largely associated with the improvement in crop harvest index (which was related to cultivar renewing), increase in chemical fertilizer use and subsequent improvement in soil fertility.

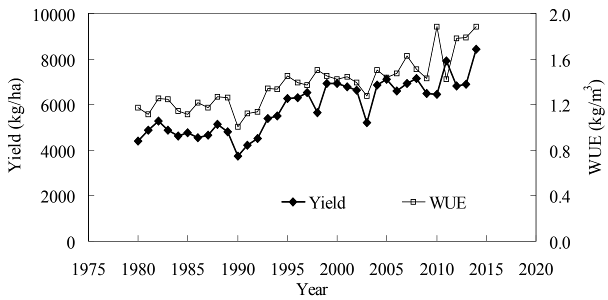

Figure 1. The Changes in yield and water use efficiency (WUE) of winter wheat during the past three decades at Luancheng in the North China Plain.

The CERES-Wheat model was validated against the experimental data and used to investigate the effects of weather and management practices on grain yield. Seven scenarios were simulated with and without improvements in management. The simulation results showed that the seasonal yield variation caused by weather factors was around -39% to 20%, indicating the great effects of inter-annual climate variability. Correlation analysis of observed wheat grain yield with weather variables showed that sunshine hours and diurnal temperature difference (DTR) were positively, and relative humidity (RH) was negatively related to grain yield of winter wheat. There has been a declining trend in both DTR and sunshine hours since 1980, negatively affecting winter wheat yield potential.

Yield improvement by cultivars was around 24.7% during 1990s and 52.0% during the recent 12 seasons as compared to yield during 1980s. Yield improvement by increase in soil fertility and chemical fertilizer input was 7.4% and 6.8% during the two periods, respectively.

In addition, the impact of four irrigation strategies (critical stage irrigation, minimum irrigation, rainfed and full irrigation) on wheat yield and WUE were simulated. The results indicated that critical stage irrigation could significantly reduce irrigation water use, with less impact on wheat yield, leading significant increase in WUE. With new cultivars and improved management practices it is possible to maintain or further increase grain production without significant increase in water use.

Keywords: *Winter wheat, grain yield, water use efficiency (WUE), management, weather*

Modelling nitrogen uptake by sugarcane crops to inform synchrony of N supply from controlled release fertiliser

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Abstract: Sugarcane is a dominant cropping system in the tropics and sub-tropics of Australia. High nitrogen (N) input to support sugarcane productivity has, however, been associated with low N use efficiency due to N losses. Controlled release fertilisers (CRF) have gained interest for their potential to reduce N losses through better synchronisation of N release with crop N demand.

There is almost no experimental data on N release from CRF specific to conditions experienced in sugarcane soils and the limited data on N uptake patterns typically come from short-term experiments under specific conditions. So, a systematic analysis of N uptake patterns, as a function of soil, crop and management factors as well as considering the effect of seasonal climate variability, is needed in order to inform the required synchrony.

As a first step, this paper presents an analysis of N uptake patterns of sugarcane crops in response to varying seasonal climate conditions by extending field observation data using APSIM modelling. The objectives of the analysis were to characterise the seasonal variability in N uptake patterns and to explore what this may mean for the design of CRF release patterns for Australian sugarcane systems.

The analysis was based on past simulations by Keating et al. (1999) of a number of experimental datasets on sugarcane growth and yield. Ten datasets containing both biomass and biomass N measurements for plant or ratoon crops from one growing season were selected. The datasets came from five different locations to capture the key climatic differences within the Australian sugarcane growing region. Selected single year datasets and simulations from Keating et al. (1999) were extrapolated using historical climate data (1958-2013) and scenario modelling. Management rules were used to mimic actual management in the one year trials, but defined in more general terms to allow extrapolation to 55 additional seasons. Above-ground biomass and biomass N accumulation were simulated to characterise the system's productivity and N accumulation in response to seasonal climate variability. In addition, total N uptake, which includes N accumulated in below-ground roots, was predicted. The simulated N uptake patterns were then compared with a three-stage, conceptual release pattern commonly attributed to polymer coated fertilisers.

Preliminary results show that large variations were found in observed (experimental) above-ground biomass and biomass N accumulation. Both, however, showed some consistency during the early growing period across sites although patterns for plant and ratoon crops were different. The APSIM simulated time-course of above-ground biomass either using original management from the experimental trial or general rule-based management, agreed well with the observations across all the selected datasets conducted under high N and water input conditions. During the early growing stages of sugarcane, simulated N accumulation in above-ground biomass also closely followed the measurements, providing support for the extrapolation to other seasons through simulation. For each dataset there was considerable variability in predicted total N uptake across the 56 seasons. During the early stages of growth (100 - 150 days after planting or ratooning), however, the simulated variation in above-ground biomass, N accumulation and total N uptake were quite small and as a consequence the simulated N uptake pattern was quite well defined and relatively insensitive to seasonal climatic differences. In terms of CRF design, these simulation results provide an early indication of the required release patterns, the length of a potential delay in release and subsequent release rate, if N from CRF is targeted at the rapid N uptake stage and early N requirements can be met from other sources (initial soil N, N in planting mix or N mineralisation).

The simulation based systems approach enabled the quantification of N uptake patterns of sugar systems in response to soil, crop and management factors as well as seasonal climate variability. The simulated variability in uptake patterns and responses to seasonal climate were caused by a combination of factors including crop class (plant or ratoon), crop age, genotype as well as management (e.g. planting and ratooning date). Further research will systematically explore the effects of these factors on N uptake patterns.

Keywords: *Sugarcane, nitrogen uptake pattern, controlled release fertiliser, APSIM*

Using statistical and process-based crop models to predict maize yield responses to climate change

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Abstract: Crop models are widely used to simulate crop yield for impact assessments, but few studies have focused on the likely difference in projections from statistical and process-based crop models. Both types of models have strengths and weaknesses. Statistical models are simple and require less input data, but may not be extended to different conditions. Process-based models build on physiological principles, which make them more extendable. However, they need extensive input data on cultivar, management, and soil conditions. Inaccuracy in input data together with imperfect process understanding may lead to increased uncertainty in crop simulation results.

In this study, we evaluated the likely impact of future climate change on maize crop yield in Northeast China using the process-based model APSIM and a statistical model that was developed based on historical record of maize yield in response to past climate change from 1992 to 2009. Both models were driven by the outputs from a Regional Climate Model (RegCM3) to simulate the impact of climate warming on maize yield at the Zhuanghe site. The crop data from 1992 to 2009 in Zhuanghe agro-meteorological station was also used to calibrate and evaluate the crop models.

Observed phenology and yield data for a single late-maturing cultivar were used to parameterize the APSIM model. The parameterized APSIM model could explain more than 70% of the variations in phenological stages and 80% of the variation in observed grain yield against all the observed data.

For the statistical model, the long time sequence of observed crop yield was decomposed into trend yield (contribution of improvements in agricultural technology and/or investment) and meteorological yield (impact of climatic fluctuation). The trend yield (7.5 t/ha) was derived by fitting a polynomial model against historical yield data. The meteorological yield was estimated using a multiple regression method, with the residual yield (between the observed yield and the trend yield) and meteorological factors during 10-day periods over the maize growing season (April–September) from 1992-2009. The statistical model explained more than and 80% of the variation in observed grain yield.

The simulation results with future climate scenarios showed that APSIM model predicted average yield reduction of 14% with range of -60%~22%, while the statistical model predicted a reduction of 11% with range of -42%~13% during 2021－2050, relative to 1971－2000. Overall, maize yield during 2021-2050 was simulated to decrease by 13% on average, relative to 1971－2000.

The projected yield range from APSIM model was much larger than that from the statistical model, which might be a result due to that process-based crop model could capture complex non-linear yield responses to the changing climate factors, compared to the statistical model.

Keywords: *Climate change, Statistical model, Process-based models, Maize yield*

Spatially discrete linear optimization of manure transports with a focus on supply for biomass power plants in agriculture

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Abstract: High-intensity livestock farming on a regional level often faces the problem of surplus animal manure with respect to legal application limits to cropland. Manure is both a valuable fertilizer and a valuable fuel for biomass power plants. However, it triggers logistic challenges if the local manure nutrient amount is beyond the local fertilization demand of crops, and/or beyond the legal threshold for the application of animal manure nutrients and/or beyond the biomass demand of local biomass power plants.

We present a linear optimization approach which identifies optimal manure transports (at lowest transport effort given as the product of distance and mass, km*tonnes) between individual spatial units within a defined region. The optimization takes place within the constraints of (a) meeting both crop nutrient demands and manure application limits, (b) providing energy crops and manure for local capacities of biomass power plants, and (c) costs for transportation. Costs for artificial fertilizers can, but do not have to, be integrated to show how much of the manure transports are economically feasible in competition to artificial fertilizers. For this study, the model optimizes manure use and transport in a region with 1047 spatial units and a total of 2.6 Mega hectares of agricultural land in northwest Germany. Each spatial unit comprises 25 livestock categories with up to three manure categories each, 13 crop categories (two of which can be used as energy crops), and a capacity of producing energy in biomass power plants. As an example on what might be analyzed with the model we present the results of a scenario analysis on a specific feeding strategy for biomass power plants (60% renewable raw materials and 40% manure as supported by the 2012 version of the German Renewable Energy Act). Both the costs for mineral fertilizers and for transportation of manure were included into this analysis. For example, the results show (a) what kind of manure and how much of it needs to be transported how far, (b) where the manure predominantly originates from and where it goes to, (c) how much and what kind of manure and how much energy crop is used for energy production, (d) how much of the transports are economically feasible. In the scenario's results, liquid manure largely remained in the spatial unit where it originated from while solid manure was transported over larger distances. 76 % of the biogas produced in the region was generated from maize silage and 24 % was generated from manure, with solid manure serving as main manure input. Only 25 % of the nitrogen demand of the crops in the region was covered by manure. For the remaining 75 % it proved cheaper to use artificial fertilizers at the given price than transporting manure over larger distances.

The model framework allows for a sensitivity analysis across varying assumptions and constraints regarding the complex regional nutrient balance between intensive livestock farming and arable farming with special focus on energy production from biomass (both manure and maize). To enable realistic analyses in the future according to future legal aspects, the model shall be expanded to include nutrient use and transports of biogas digestates.

Keywords: *Linear optimization, spatial modelling, agricultural nutrient balance, supply/demand, bioenergy*

Model-based explorations to assess climate risk to summer crop production and its effects on wheat yield in the central wheatbelt of Western Australia

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Abstract: Traditionally, summer crops are not grown in the farming systems of central Western Australia (WA) as summer rainfall is infrequent in this Mediterranean-type climate, and crops may not survive or yield poorly. However, summer rainfall has increased in the past few decades, and there have been some interests in growing crops over summer for grain or livestock production. Before integrating them into the farming system, it is important to understand the risk and potential benefit of summer cropping. Agricultural system models such as APSIM can quantify such production possibilities and risks via simulation analyses.

In this study, APSIM and long-term (1955–2014) weather data were used to investigate the biomass and grain yield of millet (*Panicum milliaceum)* and cowpea (*Vigna unguiculata*) and the potential effects of growing these crops on the yield of the following winter wheat crops near Northam in central wheatbelt of WA, where an average of 21% of the 421 mm annual rainfall (1955–2014) fell in the summer period (November-April). The APSIM model, which has been evaluated extensively against field measurements in various other studies, was tested again to gain further confidence in using it for these investigations, by using data from a one-year summer crop (fallow, millet or cowpea)-winter wheat cropping system experiment.

The model predicted biomass of summer crops and yield of following winter wheat well. The observed biomass was 0.22 t ha^{-1} for millet and 0.31 t ha^{-1} for cowpea, and the corresponding simulated values were 0.24 and 0.32 t ha^{-1}, respectively. Long-term simulations showed that summer millet produced 0.85 t $ha^{-1}$of biomass and 0.07 t ha^{-1} of grain yield on average. In 20% of seasons, when it rained, millet produced 1.33–2.00 t ha^{-1} of biomass, with 0.14–0.36 t ha^{-1} of grain yield. On average, cowpea produced 0.96 t ha^{-1} of biomass and 0.20 t ha^{-1} of grain. In 20% of seasons cowpea produced 1.55–2.89 t ha^{-1} of biomass and 0.40–0.83 t ha^{-1} of yield. Summer millet crops slightly reduced winter wheat yields (3–4%). By comparison wheat yield grown after summer cowpea was increased by 9–16%, as cowpea increased the reserves of soil mineral nitrogen.

The simulation results suggest that summer cowpea cropping could add value to the farming system and replace summer fallows, however the system needs further evaluation. This analysis also illustrates the power of modelling approach in exploring and understanding plant physiology in cropping systems.

Keywords: *APSIM, millet, cowpea, wheat, water balance*

Understanding, managing and forecasting *Pea seed-borne mosaic virus* in field pea

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Abstract: *Pea seed-borne mosaic virus* (PSbMV) is a non-persistently aphid-borne virus which is seed-borne in field pea (*Pisum sativum*). Most Australian field pea seed stocks are infected with it and it causes a serious disease in field pea crops and other important grain legumes in Western Australia (WA) and around the world. Sowing infected seed produces infected plants that act as a primary inoculum source for secondary spread by aphid vectors throughout the growing season. In field experiments in WA involving sowing seed lots with different levels of infection, sowing 6% infected seed caused up to 25% losses in yields. Losses and seed quality damage were accentuated when crops became infected at high levels prior to podding. In WA, the disease PSbMV causes is second in importance only to pea black spot disease caused by *Mycosphaerella pinodes*. However, its importance is often underestimated due to difficulties in recognising its foliage symptoms. This study is to attain a better understanding of the epidemiology of PSbMV under WA conditions with the ultimate purpose of developing a forecasting model and DSS to provide a more effective IDM regime to growers tailored to suit their particular circumstances. For validation of the model, large square 'validation blocks' of field pea were set up annually between 2010 and 2014 across 5 different sites in the Avon and Esperance regions of the WA grainbelt (2–3 sites per year). The 'validation blocks' were located at Muresk (2010–2011), York (2012), Bolgart (2013–2014), Wittenoom Hills (2010- 2012) and Grass Patch (2010–2014). Two cultivars were used, Kaspa and Twilight. Data from the different years and sites represents a wide variety of climatic scenarios, including ones ranging from dry to very wet starts to the growing season. All sites were sown between the 26 May and 22 June depending on rainfall and seed availability. Sites were visited weekly to change aphid traps and every 2 weeks to collect leaf samples. Yellow sticky traps were used in all years to monitor aphid build-up and flights. In 2014, pan traps were set-up to collect intact aphids which are easier to identify to species level. Leaf samples collected in the field were tested for PSbMV by ELISA in the laboratory. Levels of seed transmission in samples of sown or harvested seed were established by growing out representative seed samples and testing the seedlings for PSbMV by ELISA. As an example of collected data; in March to June 2015, Bolgart received approximately 180 mm whilst Wittenoom Hills received 68 mm at the same time in 2011. Aphid build-up in pastures in earlier sown crops and weeds was higher at Bolgart due to this earlier rain. This then led to earlier aphid arrival in field pea blocks and peak aphid flight numbers being high, thus resulting in earlier spread and higher final incidence of PSbMV and therefore higher yield losses. The low pre growing season rainfall in Wittenoom Hills resulted in low levels of plant biomass and therefore delayed aphid arrival and lower aphid numbers earlier in the season. This resulted in minimal spread of PSbMV and low final incidence. Being able to forecast the 'higher virus' year allows a grower to take action before and during sowing to minimise losses. Alternatively, being able to forecast the 'lower virus' year allows the grower to appropriately avoid using resources to control PSbMV. Currently, the template for the forecasting model has been built and is being calibrated using historical data and data from the last 3 years of 'validation blocks'. The model will then be validated using data from the first 3 years of the 'validation blocks' as well as various other data collected from field pea crops over the past 3 years.

Keywords: *Epidemiology, forecasting model, management*

A new model to investigate whether regional crop rotation strategies can protect crops from fungal pathogens

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Abstract: Plant pathogenic fungi cause severe damage, widespread losses, and are challenging to manage. Control strategies rely on fungicides, deep tillage of the crop residues, use of resistant cultivars, and crop management (specific sowing period, crop rotations). Farmers must yearly allocate fields to different crops and choose among these crop management options. Far from being obvious, these decisions are critical because they modify farm productivity and profitability in the short and long run. We built a new model specifically to address the issues described above. The first version of the model describes the population dynamics of a fungal pathogen over a large agronomic region comprising a number of fields in which both susceptible and neutral (non-susceptible) crops are grown. We compared different rates of rotations to see what rotation strategies were optimal in maximising non-infected susceptible crop area and minimising infected crop area. Then we adapted the model to investigate the case where three different crops can be used in the landscape, one non-susceptible crop, one susceptible host crop with low resistance and one susceptible host crop with high resistance. Our results showed that for a wide majority of cases, the configuration where we rotated infested fields into neutral fields at a faster rate than we rotated neutral fields back into susceptible crop gave better yield overall by reducing fungal incidence.

Keywords: *Durability, resistance breakdown, crop rotation*

A new evaluation system to estimate the impact of Coal Seam Gas activity on economic returns of agriculture

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Abstract: There is an ever growing demand for energy worldwide and the demand for gas alone is predicted to double between 2010 and 2035. This demand together with concurrent advances in drilling technologies caused the production of unconventional natural gas such as shale gas and coal seam gas (CSG), which is in the focus of this paper, to grow rapidly in the last decades. With the gas bearing coal seams extending across vast areas within their respective basins and with CSG production having to follow these seams through a network of production wells, pipelines and access roads, CSG activity affects large areas and therefore interferes with existing land uses predominantly agriculture. For the eastern Australian Surat Basin and the southern Bowen Basin alone there are projected active well numbers in excess of 15,000 to 20,000 between the years 2020 and 2030. The spatial overlap of CSG with agricultural land use on a large scale has raised concerns about the impact of CSG on farmland, food security, water resources and the socio-economic environment within the affected regions and beyond. This paper presents a newly developed GIS based model which provides order of magnitude figures of the impact of CSG activity on the economic returns of current agricultural land uses in a given region over the time of CSG production and beyond. The model is capable to account for a variation in a variety of parameters including the number of local impacts caused by repeated work-overs of CSG wells, differences in soil types and associated varying responses of soil productivity, varying length of the CSG production phase and more. The model is flexible in that it can be transferred and applied to other regions. Based on a literature research and given that CSG is an industry that started operating at larger scales relatively recently, we claim that the presented model is the first of its kind to provide these important agro-economic indicators for a mining operation at this large scale.

Keywords: *Coal Seam Gas, CSG, economic impact, agriculture, mining*

Statistical ensemble models to forecast the Australian macadamia crop

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Abstract: Australian production of macadamia nuts has generally been increasing over time. This underlying trend, however, features considerable year-to-year variability – for example, the 2011 crop was 28,500 tonnes nut-in-shell, *vs.* 44,000 tonnes in 2014. This degree of variability is generally attributed to climatic influences, particularly around the key phenology phases of flowering, pollination, nut-set and nut-drop. Of late, some management effects have also tended to become equally important to climatic variation. Accurate crop forecasts for the Australian macadamia industry are required each year, in order to facilitate planning, handling, processing and marketing.

A range of statistical and other forecasting methods have been used in agricultural systems. These forecasts have shown quite mixed results. Where the independent variables represent the underlying agronomic processes (or are proxies for these), the forecasts should be reasonably accurate. However some projects have produced quite disappointing results, as the forecasting process is well-known to be fraught with problems. One major issue here concerns the 'changing nature' of the macadamia industry as the orchards age, resulting in recent and current yields being lower than those that have been achieved in past years.

In this study, two levels of crop predictions were produced for the Australian macadamia industry for each of the six separate production regions. Firstly, the overall longer-term forecast was based on tree census data from growers in the Australian Macadamia Society (AMS), scaled up to include non-AMS orchards. Expected yields were based on historical data provided by the growers, with a nonlinear regression model incorporating the interacting effects of tree age, variety, year, region and tree spacing. Orchard decline amongst older trees, which has recently become more apparent, was also incorporated into the yield model. Long-term forecasts were made out to about 10 years, after which the effects of (unknown) future plantings, tree removals and rejuvenation of orchards begin to have a major impact.

The second level of crop prediction was an annual climate-based adjustment of these overall long-term estimates, taking into account the expected effects of the previous year's climate on production. The dominant climatic variables were observed temperature, rainfall and solar radiation, and modelled water stress. Based on the proven forecasting success of boosted regression trees and 'random forests' statistical methods, the average forecast from an ensemble of general linear regression models was adopted (rather than using a single best-fit model). Exploratory multivariate analyses and nearest-neighbour methods were also used to investigate the annual patterns in the data. In parallel, AMS each year conducts an annual survey of about 20 key industry growers and consultants. Their replies were integrated into a 'growers forecast' for each year, and this is also taken into account when the AMS releases its annual crop forecast.

Overall, the success rate from this 15-year project has been less than desirable. This is attributed to a number of reasons, including incomplete base-data, macadamia varietal differences and their interactions with climate, and variable management approaches within the industry. Out of the fourteen years of forecasting, the targeted ±10% maximum error rate was only achieved in seven years for the climate forecasts, and six for the growers forecasts. The first seven years of the project generally saw a period of 'good crops', and here the absolute error rates averaged 8.2% for the climate forecasts and 11.6% for the growers forecasts. The next four years had notably poor crops due to low prices which lead to less-intensive management, and all forecasts were too high. The climate-adjusted forecast models had optimistically assumed 'about the same production patterns as before', but these yields were clearly not being achieved. Following a return to more normal prices, the forecasts for the more recent years have shown average absolute error rates of 8.6% for the climate models and 6.8% for the growers forecasts. These are within the targeted ±10%, and compare quite well with other crop forecasting applications.

Keywords: *Regression, yield, tree-crop*

Modelling the rhythms of mango: Understanding growth patterns of *Mangifera indica* shoots

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Abstract: With a goal of intensifying mango (*Mangifera indica* L.) production in Australia, a better understanding of the patterns of mango growth is needed to fully understand canopy functionality. Growth of mango is cyclic with periods of active growth followed by periods of inactivity throughout the year. Vegetative growth occurs between one and four times a year as short bursts (flushes) with dormant periods in between. The reproductive growth cycle occurs simultaneously, starting with floral induction, inflorescence growth, flowering, fruiting and finishing with mature fruit abscission. Vegetative and reproductive development in mango is governed by interaction of plant physiology in response to environmental factors. For example, cool temperatures in the subtropics are an important stimulant for floral induction, while in the tropics where temperatures are not as cool the age of the last vegetative flush has an important bearing on its ability to flower. We use a computational model to integrate and test a variety of hypotheses about the underlying system.

A compartment-based carbon allocation model was used to simulate distribution of photosynthate produced in leaves to carbon sinks such as growing flush tips and leaves. Existing component respiration is accounted for based on our current hypotheses of tree physiology. This was combined with a structural model of developing flush architecture described using the Lindenmayer-system formalism. The resulting functional structural model provides visualisations of growth, as well as output of system parameters and resulting structural variables.

Data for parameterizing the models were collected for five varieties of mango, grown near Mareeba, Queensland. Four pest and disease free vegetative growth units (flushes) arising from axillary buds behind previously flowering or pruned terminals growing on the periphery of the canopy were selected to study. Data taken on these flushes included leaf and internode number, length and width. Changes in these parameters were recorded daily for 38 days during the summer flushing period.

The model integrates daily temperature data, using thermal time principles that define allowable growth in a day based on the time above the base temperature (12ºC) below which the tree will not grow. Varietal parameters such as maximum potential leaf size, leaf growth duration, phyllochron, and flush size are derived from the experimental data.

An empirical model (without carbon allocation mechanisms) was used to visualize the growth patterns of the different varieties. This forms a basis for comparison to the outputs of the mechanistic model in a sensitivity analysis of the underlying hypotheses and associated parameters, allowing us to gain a better understanding of the factors underlying mango flush development and how it differs by variety.

In the future, individual flush models will be combined with mango fruit development models to produce whole tree models, allowing the use of more detailed light models to drive photosynthesis. This will be followed by explorations of how canopy architecture and light environment affect flowering and fruit set and therefore yield.

Keywords: *Mango, rhythmic growth, degree day, carbon allocation model, FSPM, L-systems*

Covariance analysis of sugarcane variety experiments (Saccharum spp.) in contrasting environments

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Abstract: This contribution presents the results of a covariance analysis of experiments with sugarcane varieties (Saccharum spp.) in contrasting environments on a Vertisol soil type, both under normal soil conditions and in flooding conditions. The varieties of the used sugarcane were commercial varieties of the cuban sugarcane breeding program, C87-51, C1051-72, C120-78, C8612, C86-456 and C90-469.

Plant cane and first ratoon cane, both at 12 months of age, were evaluated in a Randomized Complete Block Design (RCBD) with five replications. The first ratoon cane corresponds to a plant in its second season. It is formed during the first harvest of a plant, when the lower part of the plant is left uncut, such that ratoons can grow from the buds. First ratoon cane provides a faster maturing but delivers a less amount of yield.

The dependent variable was the cane yield measured in tonnes (metric tons) per hectare ($\mathrm{tcane \cdot ha^{-1}}$). As a covariate variable of the model the millable stalk number plot was chosen. The two variables were evaluated at the age of 12 months.

The results demonstrate the usefulness of a covariance analysis in the presence of a quantitative variable, which affects the experimental units or plots. In particular, adjusted average values of agricultural performance and a correct ordering of the merit of these variables could be obtained. Thereby, a bias in the results is avoided, which might occur if the variety experiments are evaluated in contrasting environments.

The covariance analysis minimizes the variability among experimental units by adjusting their values to a common value of the covariate. The use of the covariate reduced the mean square error in the analysis and increased the reliability of the experimental results. If the millable stalk number per plot were not measured, then the variation of the cane yield in dependence on the impact of the specific crop-plot combinations could not be determined and would be included in the error term (mean square error). The use of a covariate reduced the mean square error in the analysis and increased the significance of the experimental results in plant cane and in the first ratoon cycle.

Under the effects of water excesses in the soil a marked reduction of the cane yield could be detected for all varieties. Thereby, the varieties C1051-73, C87-51 and C120-78 were affected most, and the other group integrated by C90-469, C86-12 and C86-456 in a significantly smaller proportion. This evidences that the latter group of varieties counts with a morphophysiology and biochemical mechanisms that make them adapt better to flooded soils.

No marked difference between the first and second sugarcane cutting could be detected, except a decrease in the cane yield when the number of cuttings is increased. Therefore, similar results were obtained for the plant cane and in the first ratoon cycle, with only slight differences in the magnitudes.

Keywords: *Covariance analysis, sugarcane, flooding, contrasting environments*

Predicting Pasture Nitrogen Content using ANN Models and Thermal Images

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Abstract: This study explored the possibility of estimating nitrogen content in a pasture grass using thermal images and artificial neural networks (ANN), based on the premise that plant herbage with a higher N content would be absorbing more light energy for active photosynthesis, therefore emitting excess energy as heat. This is the first reported study to use thermal infrared images and ANN to estimate pasture nitrogen content under different conditions of nitrogen (N) fertiliser. The research was conducted in a controlled-climate environment to isolate the effect of a key environmental parameter, available soil N, on pasture grass herbage temperatures. The project was the first step towards developing a smart fertiliser spreader to manage N applications based on plant temperature.

A small glasshouse pot experiment was conducted to determine the degree of the correlations between leaf N content and the surface temperatures of perennial ryegrass (*Lolium perenne*) herbage. Using a thermal imaging camera, periodic measurements of the herbage surface temperatures were made in conjunction with herbage cuts and analysis of grass dry matter for % N content. At the same time, other environmental factors, such as air temperature and humidity, were also measured.

As data constituted the core of the study, the database should be flexible, accessible and simple, for both data entry and data analysis. Subsequently, an ANN model was developed to predict N content based on herbage temperatures and the other factors measured. The final ANN model was developed based on three input variables: plant temperature, number of days after planting, and number of days after the last nitrogen application, with an error margin of ± 0.93 and ± 0.87 %N for the training and validation data, respectively. Comparing actual and predicted data showed that the ANN model could be fitted to pasture nitrogen content and accounted for around 84% and 92% of the variance in the training and validation data, respectively. The outcome of this study will aid the development of technology for estimating nitrogen content of perennial ryegrass (*Lolium perenne*) under field conditions which was seen as critical in the design of an advanced fertiliser spreader to manage nitrogen application on farms.

Keywords: *Modelling, pasture, thermal images, nitrogen, artificial neural networks*

Agricultural Productivity Assessment and Farming Systems Modelling to Identify Costs and Opportunities from Coal Seam Gas in the Surat Basin

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Abstract: While there are promising contributions from the coal seam gas (CSG) industry to the Australian energy sector and economy, concerns have been raised relating to its threats to agricultural productivity. Despite criticism, CSG could provide additional income to farmers which could be used in farm improvement. This research seeks to identify areas where a potential synergy exists between agriculture and CSG development by studying the financial implications and opportunities of CSG operations on farm enterprises within petroleum leases in the Queensland part of the Surat Basin, which is a geological basin in eastern Australia.

Hypothetical case studies were investigated where farm intensification is viable given an adequate increased investment assumed to come from CSG payments. Whole-farm simulation modelling was used to explore the financial impacts and opportunities of CSG for some chosen case study areas. Different scenarios were simulated to investigate current practice, current practice but with CSG impacts and payments, and a situation where CSG payments were used to improve the farm resource base.

While a majority (77%) of the areas undergoing CSG development were devoted to grazing, the remaining areas were deemed controversial given their high productive capacity as determined by the biophysical environment characterised by the slope, plant available water, climate and soil. 9% of these CSG tenements have are highly productive cropping areas, such as Cecil Plains and Dalby (Chinchilla).

The APSIM farming systems model was used to simulate virtual farm management scenarios for the eastern Darling Downs involving dryland (wheat-sorghum) and irrigated (maize-cotton-wheat) rotations over a 30-year period of CSG development. Calculated gross margins were used to capture the impact of CSG development on farm income and therefore the impact on Net Present Value (NPV) over the 30 year period of CSG development on these hypothetical farms. The effect of climate variability on economic indicators was captured through the use of multiple climate sequences in financial analyses. The study investigated the relative values of various compensation payment strategies versus the impact of CSG operations on agricultural productivity. Adverse impacts of CSG infrastructure on machinery efficiency were considered, as were scenarios where CSG payments used in a strategic investment to improve machinery efficiency. The study considered permanent or persistent losses of production after CSG infrastructure withdrawal.

Initial results suggest that the financial cost of the CSG footprint in selected cropping areas is relatively small compared with income received from the CSG payments, even if some areas are compromised or permanently damaged. Therefore, the study corroborates with previous related studies that other, often intangible, effects of CSG operation (i.e. future risk and uncertainty, stress, health, landscape) have more impact on farmers and farm operations and so should be factored into compensation calculations. The most important impact of CSG may not be on the productivity of farms as an enterprise, but its effect on business legacy. The uncertainty of future resources such as soil quality and water, is a factor not included in the study but may have substantial impact and thus be targeted for future research.

Keywords: *Farm intensification, Agricultural Production Systems Simulator (APSIM), compensation*

Does adding a spatial component to a herbicide resistance population model improve understanding and predictions of the build-up of herbicide resistance over time?

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Abstract: Weeds are patchy, and these patches can be dynamic. A model of weed population dynamics and herbicide resistance evolution that includes a spatial component can allow for more realistic modelling of important spatial heterogeneity. Local variability in genetic mutations and frequencies and density/yield interactions, and the stochastic nature of genetic drift and migration can be included. This can lead to new insights and understanding and an increase in grower and researcher confidence in model predictions.

One useful way to increase the transparency, accuracy and usefulness of an herbicide resistance model is through increasing the realism whereby biological processes are represented in the model. To model plant interactions occurring uniformly across a whole field of weeds is unrealistic; biological interactions and dispersal are typically local scale, likely causing the patches of weeds that occur in fields. The aim here was therefore to include a spatial component in an existing model by dividing a single homogeneous population into many individual sub-populations in areas defined as `sections'. This allowed us to incorporate both natural and anthropogenic pollen and seed spread within and between sections into the new SOMER model (Spatially Orientated Model of Evolutionary Resistance).

This new spatial model was developed by dividing a single homogenous population into many smaller sub-populations. These sub-populations were spread to cover the central area (1.1664 ha) of a larger homogeneous field. Pollen and seed spread between sub-populations (and pollen from further afield) was added each year to simulate realistic conditions. This new SOMER model was then compared with an identically parameterized non-spatial model of a single homogeneous population of the same size (1.1664 ha).

The spatial model has already provided new insights. For example, earlier non-spatial models predict that the number of resistant weeds in a field typically increases by a constant factor each year, at least until densities become high. However preliminary results from this spatial model indicate that resistance builds up more slowly when spatial factors are accounted for, due the need for the resistance genes to spread through the population. Additional studies evaluating the importance of pollen dispersal and the movement of seed by machinery are currently being examined.

Keywords: *Herbicide resistance, spatial modelling, SOMER, agriculture*

Extending "SafeGauge for Nutrients" to rainfed dairy systems in Victoria, Australia

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Abstract: As agricultural systems continue to intensify, there is a need for farmers and farm advisors to understand how soil, climate and management interactively affect nitrogen losses at the paddock scale through the various pathways. This is particularly the case in dairy systems because of the complexity of nitrogen inputs including fertilisers, dairy effluent and grazing which are all managed on a paddock basis.

Computer-based decision support tools have been in use to build farm advisors' capacity to identify high risk nutrient loss environmental conditions and management practices specific to a particular paddock or farm. SafeGauge for Nutrients uses site specific soil and rainfall information in combination with user-entered management practices (including inputs of nutrients) to assess the risk of off-site nutrient movement to surface water (by runoff) and groundwater (by drainage), as well as the atmosphere (by denitrification). SafeGauge is currently configured for use in the sugarcane cropping systems of Queensland, Australia.

In this paper, we present the design of a nitrogen loss decision support tool for high rainfall dairy systems based on SafeGauge for Nutrients. Users define the paddock being simulated through a range of inputs including: paddock position in the landscape (slope, depth to groundwater, distance to watercourse and area of the paddock), soil type, animal management (number of cows per paddock, grazing rule, grain/forage fed per cow) and paddock management (fertiliser/manure/effluent usage), a subjective estimate of actual dry matter yield for the previous rotation, and target dry matter yield for the current rotation. Information on management practices in combination with a pasture-nitrogen response function and animal nitrogen conversion efficiency are used to estimate pasture nitrogen demand for a grazing rotation and nitrogen contribution to the paddock by urine/dung. Surplus nitrogen for the day in the grazing paddock is determined from pasture nitrogen demand, nitrogen from urine/dung, fertiliser/effluent/manure nitrogen, nitrogen fixation to soil and nitrogen losses on the previous day. Finally the tool predicts the daily risks of nitrogen loss via the various pathways using daily average runoff, deep drainage and soil moisture (obtained by running a biophysical model for 50 years for various soil types and climatic zones) in wet, average and dry years. Percentage water filled pore space derived from daily soil moisture values determines the atmospheric losses via denitrification. The risks are then modified to account for differences in slope and paddock position in the landscape. The tool provides a visual representation of the risk in all three pathways as well as a summary report on nitrogen input/output balance for the current and last grazing periods of the selected grazing paddock. Results are comparable to the available field measured data and modelled outputs from biophysical models.

Keywords: *Decision Support System (DSS), water quality, denitrification, N loss pathways*

Transformation of the BeefSpecs fat calculator: Addressing eating quality and production efficiency with on-farm decision making

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Abstract: The BeefSpecs fat calculator is a decision support tool conceived to assist beef producers with their decision making to achieve better compliance with domestic and international market specifications. BeefSpecs combines data obtained from beef cattle growth-path studies and the extensive body of knowledge contained in animal growth and body composition models with easy to record on-farm measurements to make real-time predictions of body composition. To facilitate producer acceptance and uptake, BeefSpecs makes explicit use of practical end-user knowledge, captured by the simple user interface, by translating it for incorporation into the underpinning research models and returning the outputs in producer language that is easily locatable on the interface. The current version of BeefSpecs (version 1) has three functional forms:

- The primary interface acts as an educational tool to demonstrate the relationship(s) between management decisions and the performance of animal groups,
- The second interface is designed to facilitate animal management on-farm by assisting drafting decisions for creating sub-groups based on predicted performance, and
- The final interface optimises feeding and marketing decisions to increase profitability in both feedlots and pasture finishing systems.

The BeefSpecs calculator currently addresses consumer concerns surrounding portion size and levels of subcutaneous fat deposition by focusing on hot standard carcass weight (HSCW; kg) and carcass P8 rump fat depth (P8 fat; mm) specifications. However, other carcass attributes influence consumer perceptions of meat quality and production efficiency. Intramuscular fat content, or marbling, has been shown to have positive effects on consumer eating experiences while not receiving the negative perceptions associated with high levels of subcutaneous fat. Carcass yield, as described by lean meat yield, is associated with increased efficiency at the abattoir and remainder of the beef supply chain. These efficiency improvements are reflected in higher premiums reported by the National Livestock Reporting Scheme for higher muscled, higher yielding animals. These attributes have also been combined with other production variables to create a prediction of overall meat quality in a system known as the Meat Standards Australia index, or MSA index.

The evolution of BeefSpecs to improve compliance and the viability of beef production needs to mirror the continued evolution of market specifications to address changing consumer demands. Currently, the Meat Animal Research Centre (MARC) model underlying BeefSpecs predicts composition of empty body weight using a description of animal type and growth rate (kg/day). Current BeefSpecs inputs and the MARC model are built upon by partitioning lean and fat in the empty body into carcass and non-carcass components with fat being further partitioned into carcass fat depots allowing carcass lean and intramuscular fat to be used to predict marble score. An additional input, muscle score, is used to scale components of the MARC model to make predictions of carcass fatness and lean meat yield. In order to combine the predictions of marble score and lean meat yield with rib fat and HSCW predictions to make a prediction of eating quality using the MSA index, a prediction of ossification score was developed using current BeefSpecs inputs. These enhancements are all designed to improve the utility of all three interface versions of BeefSpecs, with muscle score being the only additional input required. These enhancements also boost the compatibility BeefSpecs has with the national carcass feedback mechanism, Livestock Data Link (LDL), which will allow the impacts that management decisions have on a wider range of carcass traits to be explored with greater emphasis on consumer requirements.

Keywords: *Decision Support Systems (DSS), beef cattle, model development, market specifications*

Modelling the Dynamics of Vernalization: The Role of Conceptualization in Model Formulation

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Abstract: For a plant to flower, its development must switch from the vegetative to the flowering state in order to make the seeds for the next generation. For cereals and the model plant Arabidopsis, the switching occurs in response to a cold event, signalling to the plant that it is winter with spring and summer soon to follow. Much is understood about the nature of this switching process genetically in terms of how the expression of the FLOWERING LOCUS C (FLC) gene, orchestrating the vegetative development, is repressed. Only recently has a mechanism been proposed that explains how the cold initiates the repression process that switches OFF the expression of Arabidopsis FLC. This paper will discuss how the mathematics of rubber elasticity has been *the conceptualization step* in the formulation of a model for this proposed mechanism for the initiation, in response to a cold event, of the genetics steps that initiate the repression. In part, the goal is to use the modelling of the switching of a plant from its vegetative to its flowering phase as an illustration of the pivotal role played by *the conceptualization step* in model formulation.

The successful implementation of the conceptualization process in modelling and simulating real-world processes hinges on two separate matters:
The need is required not only for
(i) direct involvement, experience and familiarity with and understanding of different successful real-world (industrial) modelling endeavours,
but also for
(ii) a complete and comprehensive understanding of the workings of the particular real-world system being studied along with the motivation for and the essence of the questions to be answered.

The importance of (i) is the need for modelers to gain experience by being directly involved with the solving of real-world problems, such as industrial mathematics study group meetings and related endeavours. That of (ii) relates to the need to have a close and productive collaboration with the originators of the real-world problem that results in a win-win relationship with them.

For example, the modeler must be certain that in the conceptualization step, the outcome must not only capture the essence of the actions responsible for the observed phenomenon, it must not be inconsistent with other features, particularly those related to actions resulting from the observed phenomenon. It is also important, for a model to be truly useful, that it not only captures the observed phenomenon or event but also makes predictions of events not yet observed, which could subsequently be used to test the validity of the model. It is only with such validation that the accuracy/success of the conceptualization step be truthfully measured.

Keywords: *Vernalization, conceptualization, polymer elasticity*

High throughput root phenotyping for cereal plants using spatial distribution in polar coordinate system

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Abstract: With the growth of the global population, the demand for better living standards and the accelerating use of grain for biofuel production, the pressures on global grain supplies are becoming immensely high. To satisfy the growing, worldwide demand for grain, it is necessary to improve the productivity of existing farmland. This is a very challenging task in the face of global environmental change. Plant breeders need to focus on traits with the greatest potential to increase yield. In this paper, we focus on the phenotyping of cereal plant roots as roots are the hidden parts of plants and are the principal organ of plants for the absorption of water and the uptake of nutrients from soil. It is well known that the root system architecture is determined by environmental factors, particularly soil conditions as well as plant's genetic makeup. This is typically called the genotype by environment (GxE) interaction. Clearly, the phenotype of a genotype is environmentally dependent. Various studies have been conducted on the effects of abiotic stresses on plant growth and adaptation, including the phenotype-genotype mapping, which has been applied to the problems from finding genes association to plant breeding. Currently, it is popular to identify the genetic factors controlling root system architecture by measuring root growth angles and there are evidences that the maximum root angles of primary roots are associated with shallow-rooted and deep-rooted cereal crops.

However, there are few factors affect the results of root growth angles. The growth angle of a primary root is not a constant and the maximum growth angle may not the best trait to model the root system architecture. Instead, we propose to use spatial distribution to represent the root system architecture. In order to reduce the manual involvement to save the cost and to achieve the high-throughput and accurate root phenotyping, we develop an automated image processing software solution. In this paper, we will describe the image processing solution including automatic segmentation, non-root removal, automatic detection of top root sources, the computation of the spatial distribution of roots as well as automatic counting of root tips and the measurement of total root length.

Keywords: *Root phenotyping, spatial distribution, root growth angle, cereal plants, high throughput*

Gaussian Mixture Models for Image-based Cereal Plant Canopy Analysis

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Abstract: In this paper, we report our results of applying Gaussian Mixture Models (GMM) to the analysis of the canopy of cereal plants grown in competitive environments, such as large bins. We will particularly focus on the segmentation problem, i.e. separating the plant regions from the other image regions, such as soil, water pipes, and bin walls. We will show that GMMs, which require few training images, provide a flexible and efficient tool for high throughput segmentation at various growth stages and even in the presence of complex background. We discuss various implementation issues and provide results on a large scale experiment, where cereal plants of different genotypes are grown in large bins and subject to two different treatments (well watered and under drought stress).

Keywords: *Plant phenotyping, canopy coverage, plant growth analysis*

Growth Measurement of Arabidopsis in 2.5D from a High Throughput Phenotyping Platform

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Abstract: The last few years have seen an increasing interest in the development of high throughput phenotyping platforms (HTP) that allow the automated measurement of plant growth and structure. These platforms have utilised various imaging technologies, including fluorescence imaging, thermal imaging, and visible imaging. Since plants are structurally complex and inherently three-dimensional (3D), 3D imaging and reconstruction approaches have distinct advantages over 2D imaging when it comes to quantifying structural information (such as leaf angle distribution, leaf area etc.).

High throughput phenotyping platforms, when combined with 3D image analysis, enable researchers to investigate complex functional traits related to plant structure, including responses to external and internal signals or perturbations. Moreover, image-based reconstruction techniques are able to produce complex structural models of both large and small individual plants, which retain colour information and are topologically coherent.

In this paper, we present a computational workflow for analysing the growth of *Arabidopsis thaliana* rosettes over time using stereo reconstruction. Stereo reconstruction for plant phenotyping generally includes data collection and point cloud generation. In our approach, we not only use stereo image pairs to generate point clouds of the plants but also reconstruct mesh surfaces for further analysis.

By applying a semi-global matching algorithm, 2.5D point clouds of *Arabidopsis* growing in trays with multiple plants were generated. Point clouds were then filtered and segmented in order to isolate single plants using clustering methods. A variety of surface reconstruction methods were then used to generate meshes from the point clouds. These meshes were analysed to quantify the plant dimensions and surface area in three dimensions. The segmentation was stable over time and was used to generate a time series for the growth of the individual plants over time.

The advantages of such a stereo reconstruction system are: i) the system is able to construct realistic point clouds and meshes of the scene, ii) the processing pipeline is computationally efficient, iii) it allows stereo reconstruction and segmentation of individual plants in trays of 20 plants each for high throughput analysis. The overall approach proved useful in quantifying morphometric parameters in 3D for a set of *Arabidopsis* accessions and relating plant structure to plant function.

Keywords: *Stereoscopic reconstruction, 3D mesh, Arabidopsis, plant phenotyping, semi-global matching, point-cloud filtering*

A model of oxygen and nitrogen biogeochemical response to hydrodynamic regimes in the Yarra River estuary

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Abstract: Nitrogen biogeochemical response to alternative hydrodynamic regimes in estuaries that experience frequent anoxia has major implications for coastal water quality due to the significance of denitrification as a loss pathway for bioavailable nitrogen. The efficiency of nitrogen removal and storage in estuaries is dependent on a range of hydrodynamic and biogeochemical processes, in particular, the position of the salt wedge and effect of associated regions of anoxia. The purpose of this study was to demonstrate how rapidly shifting oxygen concentrations in the periodically anoxic Yarra River estuary, Australia, drive dynamic shifts in nitrogen cycles driving nitrogen assimilation efficiency of the estuary. Unravelling the complexity of the process response of nitrogen cycles in estuaries has been difficult to undertake empirically, so a numerical modelling approach is presented here to quantitatively predict variability in nitrogen assimilation, and demonstrate use as a tool to support optimal estuarine management.

A coupled 3D finite volume hydrodynamic-biogeochemical model of the estuary was developed to simulate flow, transport, mixing and biogeochemical reactions of oxygen and nitrogen, and used to quantify nitrogen cycling processes under alternative hydrodynamic regimes that occurred over a period of 12 months. The model was forced by boundary conditions that included meteorological data, inflow from two river sources and a tidally driven water level at the downstream boundary. Simulated concentrations of organic nitrogen, ammonium and nitrate were compared to measured data from field observations to evaluate model fit. Model output of both concentrations and process rates of mineralisation, nitrification, denitrification and sediment fluxes were analysed in relation to upstream nutrient loads under changing hydrodynamic regimes.

The model simulated observed patterns of both seasonal and spatial variation of inorganic and organic nitrogen in the estuary. A system-level validation comparing the deviation from mixing line for both ammonia and nitrate against oxygen concentrations also paralleled patterns in observed data. Simulated patterns of oxygen and nitrogen varied significantly over the simulated period both temporally and spatially. Tidal forcing balanced by changes in upstream flow volumes drove patterns of response in oxygen and nitrogen concentrations that varied across the model domain on both episodic and seasonal time-scales. Patterns of net nitrogen flux closely matched patterns of oxygen concentration. On a temporal scale, periods of low flow led to depleted oxygen concentrations, increase in sediment ammonium flux and reduction in rates of denitrification. During the dry summer season, episodic high flow events reversed this pattern over periods of 2-7 days. It was identified that low flows generally lead to an average positive net nitrogen flux across the estuary, whereas increased flows tend to switch the system towards a net negative nitrogen flux.

This application has demonstrated that utility of the model to unravelling the complex biogeochemical pathways that determine oxygen and nitrogen response to hydrodynamic regimes in a highly dynamic salt wedge estuary. Of particular interest to estuarine management is the pattern that emerged at the system-scale, whereby the volume of flow required to switch the net nitrogen budget of the estuary from positive (nitrogen source) to negative (nitrogen sink) was linked to the antecedent conditions that vary seasonally.

Keywords: *Estuary eutrophication, nitrogen cycling, coupled hydrodynamic-biogeochemical model, anoxia, hypoxia*

Thermal change and heat budget in shallow and small, urban lakes

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Abstract: A comparison is made of three urban, constructed, shallow (<1 m) lakes located at the University of Waikato campus in Hamilton, New Zealand. These three lakes (Chapel, Oranga, and Knighton) have had persistent problems of high turbidity, seasonal macrophyte growths and phytoplankton blooms. Restoration measures have included fish removal, sediment removal and alum dosing but these improvements appear to be largely temporary, and the poor aesthetic qualities of these lakes are still a concern. Historical (2001/02), unpublished, temperature measurements at the air, surface and bottom of all three lakes during the year were obtained. The data showed the water temperature has smaller fluctuations than the air temperature. Chapel Lake is the deepest (maximum depth 1.8 m) and has more stable temperatures than the other two lakes. The minimum temperature in all lakes in their temperate climate (latitude 39°) was always > 6 °C. The number of hours where the surface temperature was less than the bottom, expressed as a percentage, was used to determine stability of all three lakes. The result was that Oranga Lake was the most unstable, and Chapel Lake was the most stable. In spring and summer, all lakes were comparatively stable but in autumn and winter the lakes mixed more frequently. The temperature profiles of Knighton and Oranga lakes were measured every minute during the period 8–16 June, 2014, and 16–29 June, respectively, with the use of thermistor chains (see Figure 1). Our results showed that temperature profiles of shallow lakes, particularly in the top 200mm could be quite dynamic compared to deep lakes.

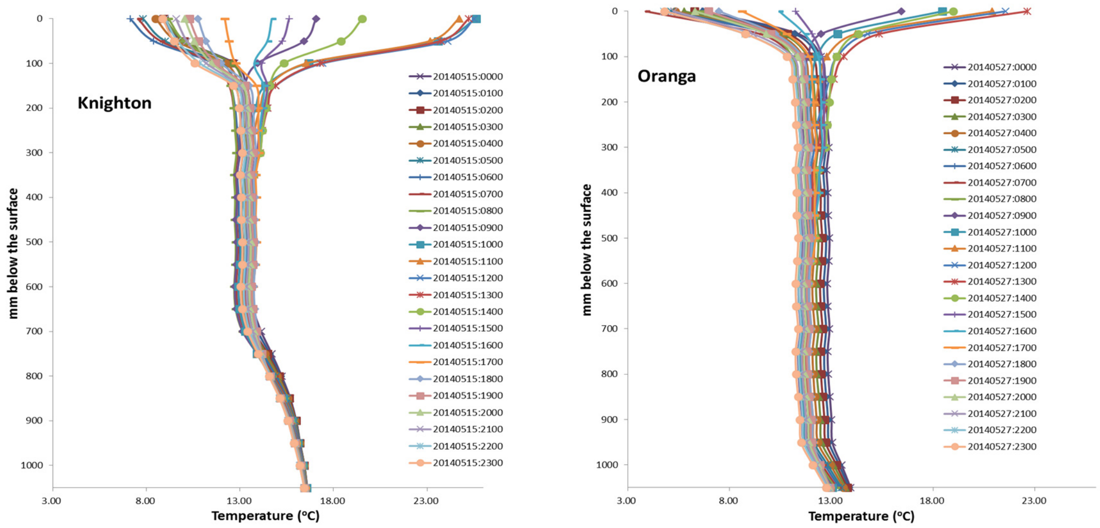

Figure 1. Temperature profiles of Knighton lake on June 15th and Oranga lake on June 27th, respectively, measured every minute during the day, and presented hourly.

A heat balance was used to calculate the hourly heat flux of Knighton and Oranga lakes and the results were compared with experimental results. Meteorological data for the nearby Ruakura site (< 1 km away) were obtained from *CliFlo*, the National Climate Database. Short- and long-wave radiation, latent heat, sensible heat and sediment heat were taken into account in the calculations, with heat from inflows, outflows and precipitation being neglected. Physical lake metrics were also computed for all three lakes and compared. This study on thermal changes and heat balances complements studies of nutrient inputs to the lake from stormwater and groundwater inflows.

Keywords: *Urban lakes, thermal change, heat budget, thermistor chains, temperature profiles*

Modelling the Effects of Cracking of Lake Sediments During Drying on Acid Generation and Acid Transport to the Water Column Upon Rewetting

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Abstract: An extreme "millennium" drought from 2007 to 2010 resulted in the lowest River Murray levels (1.75 m decline from average) in over 90 years of records at the end of the river system in South Australia. This resulted in low inflows of water to Lake Alexandrina and Lake Albert and exposed large areas of soils on the lake margins to drying. This drying caused the sediments to shrink and crack with the formation of large columnar blocks of soil.

Sediment physical properties were measured on samples taken from the lake at different locations (Cook et al., 2011) and used to develop a HYDRUS2D/3D model to determine the oxygen penetration into cylindrical peds (soil blocks) with varying radii (0.05, 0.1, 0.15 m), depth of cracks (0.1, 0.2, 0.5 m) and water table depth (WTD) (0.1, 0.2, 0.5, 1.0 m). The peds were assumed to be initially saturated and lost water due to drainage (to the water table) and evaporation (potential 4 mm day^{-1}), from both the top and sides of the ped. Oxygen (O_2) penetrated the peds due to gas advection (as water was lost), and diffusion, and was lost due to oxygen consumption by organic matter (98% of the sink strength) and pyrite (2%). This drying and oxygenation process was modelled for 1000 days and the O_2 concentrations recorded. O_2 penetrated to the center of the ped at the sediment surface, but the radial penetration decreased with depth (Figure 1) and the concentration varied little after the first day due to near balance between diffusion and consumption.

Pyrite oxidation and hence the formation of acidity in the peds was modelled using a first-order chain reaction based on oxygen concentration. This resulting in a slow increase in Fe^{2+} concentration with time (Figure 2). Various scenarios were tested to describe rewetting and hence transport of acidity to the lake; a rising water table with seepage from the crack and surface, inundation of the surface and crack, and water flow into the ped from the crack and seepage at the surface. These were compared to simulations of the sediment without cracks as a control, with two rewetting scenarios: rewetting due to watertable rise, and surface inundation. The mass of acidity generated from oxidation of pyrite was most sensitive to increasing ped radius, and then linearly with time. Acid generation within the peds was greater than in sediment without cracks. The scenario where the water table rose from below resulted in the most acidity transported from the soil to the lake water, while the scenario where both the surface of the ped and crack were instantaneous inundated resulted in the least acidity transported to the lake water. These results have implications for how lake rewetting is allowed to occur.

Keywords: *Acid flux, acid sulfate soils, pyrite oxidation, solute transport, water quality*

Modelling surface-ground water interactions in reflooded acid sulfate soil landscapes in the Lower River Murray following the Millennium Drought

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Abstract: There has been increasing recognition of the importance of surface-groundwater interactions in river systems. However, there has been limited research or modelling of the geochemical changes that can occur in adjoining floodplain groundwater systems in response to changing surface water levels. An extreme "Millennium" Drought from 2007 to 2010 resulted in the lowest River Murray levels (1.75 m decline from average) in over 90 years of records at the end of the river system in South Australia. Due to the low river level and inability to apply irrigation, groundwater depth on the adjacent agricultural flood plain also declined substantially (1–1.5 m) and the alluvial clay subsoils dried and cracked. Acid Sulfate Soils with sulfidic material (pH>4, predominantly in the form of pyrite, FeS_2) in these subsoils oxidised to form sulfuric material (pH<4) over an estimated 3,300 hectares on 13 floodplains. Once river and groundwater levels returned to normal post-drought (2011 onwards), and irrigation recommenced, the acidity in the soils was mobilised to drainage channels (see Fig. 1 inset photo). The return of drainage water with low pH (3–5) and high dissolved metal content (10–100 mg/L) to a river reach with major drinking water offtakes has posed significant risks and management challenges for government agencies. An ability to model the surface-ground water interactions would be beneficial to enable management strategies to be developed for future droughts. Droughts are predicted to increase in frequency under climate change and a "systems type" approach is required to evaluate impacts and optimal management responses. We developed an integrated 2-dimensional (Hydrus-2D) surface-groundwater model along a transverse transect from the river, along the floodplain, to the adjacent highland. The river level was implemented as a variable head boundary condition and the regional highland groundwater as a constant head. Performance of the model was assessed using groundwater level data obtained from piezometers and soil and groundwater chemical profiles on the floodplain. Results from the modelling of the river-floodplain hydrological processes were consistent with field measurements during the drying phase. Figure 1 illustrates how the declining river levels led to lowering groundwater levels (Day 600–1600) which exposed pyrite in the floodplain, the oxidation of which caused soil acidification. Implementation of two soil layers and the dual permeability functionality in Hydrus improved the ability of the model to represent post-drought groundwater levels over a 7 year simulation (Fig. 1). A future drought management scenario demonstrated how river level stabilisation and some irrigation could have greatly lessened the severity of the acidification.

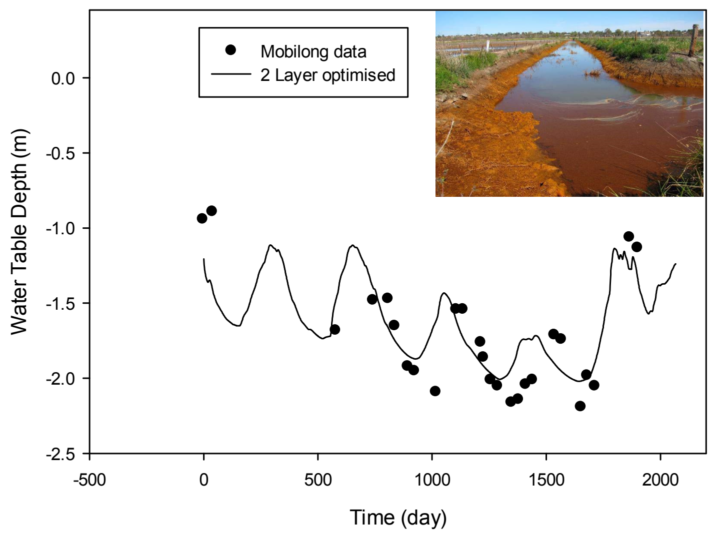

Figure 1. Calibrated model (-) versus measured (•) groundwater levels over a 7 year simulation and (inset) photo of an acidic (pH 4) drainage channel in the Lower Murray agricultural study area showing the presence of the orange-brown iron-oxyhydroxy sulfate mineral schwertmannite.

Keywords: *Acid sulfate soils, drought, pyrite oxidation, surface-ground water interactions, floodplains*

Predicting critical thresholds of aquaculture waste loading to coastal sediment

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Abstract: The use of cages in the ocean to support finfish aquaculture is increasing as an important food supply industry. However, local environmental impacts directly below and around cages can include the degradation of water and sediment quality. In particular, high rates of organic matter deposition to the sea floor beneath the cage, primarily from the deposition of faeces and uneaten food, drives dissolved oxygen consumption and hydrogen sulfide production, ultimately leaving the sediment environment uninhabitable for benthic macrofauna.

The aim of this study was to develop and apply a vertically-resolved sediment biogeochemical model (Figure 1) to simulate the response of marine sediment to organic matter loading from fish cages. After an initial spin-up period, the model simulations assume aquaculture operations for a five year period, followed by seven years of recovery. The model is run within a Monte Carlo framework to assess sensitivity to key parameters. A series of simulations were then undertaken to define how changes in the extent of loading impact upon sediment chemical concentration profiles and sediment-water fluxes of variables such as oxygen, nutrients and sulfide. We then defined threshold-loading rates, based on sulfide accumulation in the surficial sediment, that correspond to a low, medium or large impact to sediment quality.

The recovery time for sediment experiencing five years of fish-waste input is then computed, with an associated range of uncertainty. Recovery time is defined as the time taken from the end of aquaculture operations to the time when oxygen in the surficial sediment recovers to 85% of its base concentration. For each rate of loading, we categorize whether the top 5 cm of sediment would recover in less than 1 year, between 1 and 5 years, or >5 years.

The results of the analysis may be interpreted by managers and operators to assess the likelihood of sediment condition, and the potential for recovery once farming has ceased, for a range of stocking densities. Further the model approach may be applied in conjunction with hydrodynamic model assessments of waste dispersion and deposition to assess the potential footprint of cage installations.

Keywords: *Sediment biogeochemical model, early diagenesis, coastal sediment quality, fish cages, environmental impact thresholds*

A hydrodynamic-ecological model for Lake Rerewhakaaitu

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Abstract: Lake Rerewhakaaitu is a shallow (average depth 7m, maximum depth: 15m) lake in the Rotorua region and is unique amongst the 12 Rotorua Lakes in that its catchment is the only one dominated by dairy farming as the main type of land use. At present, Lake Rerewhakaaitu is an attractive and popular lake with fairly good water quality, although over recent years the lake has shown signs of declining, water quality and biodiversity. It is essential that water quality in the lake is maintained or improved in order to retain the intrinsic, cultural and economic benefits the lake provides to the region. A computer modelling tool is required by lake managers to simulate current lake conditions and assess the potential impact of changes such as land use and/or inflows, and farm management practices. The purpose of this study was to implement, calibrate and validate the coupled hydrodynamic-ecological model, DYRESM-CAEDYM, to Lake Rerewhakaaitu.

The one-dimensional (1D) hydrodynamic model DYRESM (Dynamic Reservoir Simulation Model) was coupled with the aquatic ecological model CAEDYM (Computational Aquatic Ecosystem Dynamics Model). DYRESM is a process-based model with a Lagrangian layer scheme that is used to predict the vertical distribution of temperature, salinity and density in lakes. Inputs to DYRESM are lake morphology, daily meteorological data, daily inflow temperature and volume and daily outflow volume. The CAEDYM model incorporates the major biogeochemical processes influencing water quality: primary production, secondary production, nutrient and metal cycling, oxygen dynamics and movement of sediment. The inputs to the CAEDYM model are nutrient inputs and the outputs are the oxygen distribution in the water column, nutrient distribution in the water column (N, C, P, Si), phytoplankton/zooplankton, algae, and more.

Lake bathymetric data were obtained for April 2011. Meteorological data was obtained for the Rotorua Airport climate station about 20km away from the lake. There are two stream inputs to the lake: Mangakino Stream and Awaroa Stream. Surface inflows were available for the Mangakino Stream and/or filled using rated flows in the permanently gauged Ngongotaha stream. Flows from the Awaroa stream were obtained from a regression equation relating Awaroa Stream flows to the Mangakino stream flows. Daily nutrient concentrations (NO_3-N, NH_4-N, PO_4-P) for the Mangakino Stream were derived by interpolation between monthly samples. Suspended solid concentrations for the Mangakino Stream were obtained by using a regression equation relating flow rate and suspended solid concentrations. Labile organic nitrogen and phosphorus concentrations were calculated using monthly stream nutrient measurements and were evenly divided into dissolved and particulate fractions. For the Awaroa stream, an average daily concentration of nutrients and suspended solids were used. A further 7% of the catchment was assumed to drain directly into the lake. Lake surface outflows were assumed to be zero.

To calibrate the DYRESM-CAEDYM model, data from 2005–2010 was used and to validate the model, data from 2010–2015 were used. Parameters chosen were in the range given in the literature. Simulated concentrations of temperature, dissolved oxygen (DO), total nitrogen (TN), NO_3-N, NH_4-N, total phosphorus, PO_4-P and chlorophyll *a*, at various depths were compared to measured data from observations to evaluate model fit with model error represented by a series of model performance statistics. The calibrated coupled model may be used to predict water quality in Lake Rerewhakaaitu, and ultimately, as a tool to test various management change scenarios.

Keywords: *Lake, modelling, hydrodynamic-ecological model, DYRESM, CAEDYM*

A Fading Memory Model for Indoor Evacuation - Preliminary Results

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Abstract: Observations of a process in an environment happen over time and their validity can be ephemeral. Thus, knowledge of the environment may quickly become out of date, which matters especially in safety-critical applications. For example, emergency situations happen after sudden changes to the environment and are continuing to change the environment, while people are trying to evacuate based on their outdated spatial knowledge. This means, the value of time-stamped spatial knowledge fades over time. While historical spatial knowledge can be an accurate mapping of the historical environment, the validity of this knowledge in a changed or changing environment should be considered when used for decision making in the current environment.

This paper combines spatial knowledge and the time when the knowledge has been acquired in investigating whether fading memory is beneficial in dynamic environments. Fading memory devalues spatial knowledge with time, trusting more recent explorations more than other ones. The hypothesis of this paper is that fading memory is beneficial for agents decision making in a dynamic environment. The models of fading memory, and route planning based on the age of knowledge have been implemented and tested for indoor evacuation scenarios through agent-based simulation with Repast Simphony. Experiments suggest that this model is potentially a better representation of the dynamic environment in terms of providing evacuation guidance, which also has implications for all kinds of spatial analysis.

Although the test shows that in most cases decision making has benefited from fading memory, there is still some cases where applying fading memory deteriorates the results, which throws up fundamental ethical questions: A service devaluing information that actually still is true may come up with suboptimal (evaluation) information. The reason for this is not the imperfection of fading memory per se, but the simplicity of heuristics applied in the experiments when exemplifying fading memory for testing purpose. In the experiments of this paper, the correctness of the heuristics corresponds to its coincidence with the mechanism of how fire spreads, which is beyond the task in this paper. A sophisticate design of heuristic rules when applying fading memory should improve the performance, and in an ideal situation, guarantee in all cases that applying fading memory leads to better results.

Keywords: *Spatial knowledge, dynamic environment, evacuation, routing, agent-based simulation*

On the Use of Local and Global Search Paradigms for Computer-Aided Diagnosis of Breast Cancer

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Abstract: Cancer is one of the most dangerous diseases around the world and the most common cancer among women is breast cancer. Although not all the cancer types are curable upon diagnosis, breast cancer can be cured if it is diagnosed early. The most reliable way of diagnosing breast cancer is mammographic screening which can diagnose the disease 1.5 to 4 years before it is clinically diagnosed. Double Reading is the important diagnostic process in which two experts/radiologists should read the same mammogram image to make an accurate diagnosis. But this process is not a cost-effective approach for early detection of breast cancer. Computer-Aided Diagnosis (CAD) can act as the second expert and therefore one expert would be enough for breast cancer diagnosis. In this study, we use the data extracted from low-resolution as well as high resolution mammography images. The attributes extracted from mammographic images are imported into Support Vector Machine (SVM) to classify the patients. An important point about the attributes is that sometimes there may be some irrelevant or even noisy attributes that have negative effect on the classification accuracy. Therefore, the main objective of this study is to apply local and global search paradigms in order to find the best subset of attributes to construct the most accurate CAD system that can effectively distinguish between benign and healthy patients. Artificial Bee Colony (ABC) is a population-based swarm intelligence algorithm with good global exploration ability, and Simulated Annealing (SA) is a robust local-search algorithm. Thus, we utilize a hybrid global and local search algorithm (named ABCSA) to simultaneously benefit from the advantages of both ABC and SA. In this approach, ABC is firstly performed for the global exploration in the search space. Then, SA is utilized to search locally in the vicinity of the best solution found via ABC, in order to improve the quality of the final solution. Obtained simulation results over four different mammographic datasets show that the proposed algorithm outperforms the existing metaheuristic feature selection approaches in terms of minimizing the number of features, while maximizing the detection accuracy.

Keywords: *Early detection of breast cancer, mammographic data, Support Vector Machine (SVM), feature selection, Artificial Bee Colony (ABC), Simulated Annealing (SA)*

A Review of Computational Models of Mammalian Cell Cycle

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Abstract: Cell cycle, which comprises an ordered sequence of phases (G1, S, G2, and M) that leads to growth and division of a cell, is an essential part of life and its malfunction may cause formation of tumors and cancer. Therefore, study of cell cycle system has been the topic of many computational modelling research studies. In this paper, a thorough review of all modelling methods for mammalian cell cycle and corresponding models are presented. Due to its high complexity, mammalian cell cycle system has been less modelled than other organisms, such as yeast. Majority of models have investigated various parts of mammalian cell cycle, with few covering the whole system including all the phases. There are four main modelling types (discrete, deterministic continuous, stochastic continuous, and hybrid) that enable researchers to explore and understand system properties, such as dynamics of key regulators, oscillation behaviors, feedback loops, etc. Discrete models provide an abstract view of the system where different nodes interact with each other based on discrete logic. On the other hand, continuous models usually utilize Ordinary Differential Equations (ODEs) to incorporate continuous dynamics of the system elements (*i.e.,* protein concentrations). The effect of noise in biological systems has been modelled through stochastic models. Hybrid models combine aforementioned modelling methods to overcome limitations of individual methods. The paper covers all the above methods highlighting their strengths and weaknesses and presents some open questions as promising future prospects for modelling cell cycle.

Keywords: *Mammalian cell cycle, computational modelling approaches, Ordinary Differential Equations (ODEs)*

System Modelling of Mammalian Cell Cycle Regulation Using Multi-Level Hybrid Petri Nets

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Abstract: An important process in the growth of any biological organism is its ability to proliferate, a tightly controlled process in which a cell divides into two daughter cells. This happens within a dynamic environment, where a cell responds to various internal and external signals through a well-ordered sequence of events called cell cycle. Underlying these events are a complex and elegantly orchestrated web of interactions that function as an integrated system with various sub-systems that specialize in various tasks. The important task is the response of cell cycle machinery to proliferative signals in order to initiate a process which eventually leads to production of two daughter cells. Malfunction of cell cycle system causes diseases, such as cancer.

This study proposes a novel systems approach to modelling mammalian cell cycle to gain insights into how it coordinates such an intricate system of interactions in a robust and timely manner. It involves identification of the most essential controllers of mammalian cell cycle (as primary elements) and regulators of these controllers (as secondary elements) at different levels of abstraction to develop a minimal yet comprehensive model. In this paper, a Multi-Level Hybrid Petri Net (MLHPN), a graphical Petri Net-based modelling method, is proposed to model the mammalian cell cycle regulation system. Intuitive nature of MLHPN makes it possible to represent biological properties and processes with different time scales through a combination of continuous and discrete paradigms at different levels of abstraction. The goal is to gain a deep understanding of the mechanism of mammalian cell cycle regulation in the presence of growth factors.

Keywords: *Computational systems biology, mammalian cell cycle regulation, Petri Nets (PNs), hybrid modelling*

Computational techniques in mathematical modelling of biological switches

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Abstract: Mathematical models of biological switches have been proposed as a means to study the mechanism of decision making in biological systems. These conceptual models are abstract representations of the key components involved in the crucial cell fate decision underlying the biological system. In this paper, the methods of phase plane analysis and bifurcation analysis are explored and demonstrated using an example from the literature, namely the synthetic genetic circuit proposed by Gardner et al. (2000) which involved two negative loops (from two mutually inhibiting genes). Figure 1 shows a schematic diagram of the synthetic genetic circuit constructed by Gardner et al. (2000). Particularly, a saddle-node bifurcation is used as a signal response curve to capture the bistability of the system. The notion of bistability is obscure to most novice researchers or biologists because it is difficult to understand the existence of two stable steady states and how to flip from one stable steady state to another and vice versa. Thus, the main purpose of this paper is to unlock the computational techniques (bifurcation analysis implemented in a software tool called XPPAUT) in mathematical modelling of bistability through a simple example from Gardner et al. (2000). In addition, time course simulations are provided to illustrate: 1) the notion of bistability where the existence of two stable steady states and we demonstrated that for two different initial conditions one of the genes is 'ON' and the other gene is 'OFF'; 2) hysteresis behaviour where the saddle-node bifurcation points as two critical points in which to turn 'ON' one gene happens at a larger parameter value than to turn 'OFF' this gene (at a lower parameter value). The hysteresis behaviour is important for irreversible decision made by cell to commit to turn 'ON'. In conclusion, the understanding of the computational techniques in modelling biological switch is important for elucidating genetic switch that has potential for gene therapy and can provide explanation for experimental findings of bistable systems.

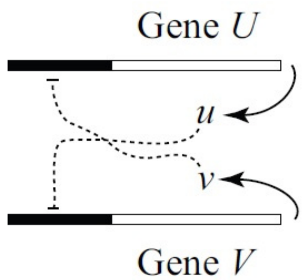

Figure 1. The construction of a genetic toggle switch by Gardner et al. (2000), who used bacterial plasmids to engineer this circuit in a living cell. Here the two genes, U, V produce products *u*, *v*, respectively, each of which inhibits the opposite gene's activity. (Black areas represent the promoter region of the genes.) Copyright © 2013 Society for Industrial and Applied Mathematics. Reprinted with permission. All rights reserved.

Keywords: *Biological switch, mathematical model, saddle-node bifurcation, bistability*

Big Data Analytics for Biosecurity: Monitoring Large Area for Salad Leaf Disease Prevention

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Abstract: In this paper a novel application of salad leaf disease detection has been developed using a combination of big data analytics and on field multi-dimensional sensing. Biosecurity plays a key role in sustaining the Australian economic growth. Intelligent data analytics can track the massive volume of big data and its influencing resources to represent new biosecurity related knowledge. Detection and early intervention of salad leaf related disease is a challenging problem for the salad-growing farmers with severe economic consequences. Sudden change in environmental condition, extreme weather condition, such as hail storm, high wind, very low temperature with humid condition or severe solar radiation can cause a series of scenarios, which can cause different diseases in salad leaves. In this study we focus upon developing methodologies to detect the presence of a particular disease or pest infestation damage of salad leaf through machine learning based analysis of spectral profiles recorded by a Spectroradiometer in the in-situ field environment. The motivation behind this study was to demonstrate a proof of concept of the effectiveness of the hyperspectral sensing of salad leaf physiology to create ground truth data along with the climatic data (temperature, rainfall, humidity, wind speed etc.), in accordance with the very high resolution remote sensing data integration for rapid plant disease hot-spot prediction. A total of 1050 spectral samples were collected through three different experiments from the baby salad leaves, disease affected salad leaves, and soil samples from the surroundings. Seven groups of data were categorized from the whole set for the machine learning based classification exercise. In the machine learning based analytics phase, multiple significant feature extraction and cross-validated multi-classification performances were evaluated against the ground truth vector generated during the field experiments. The group averages of the seven classes, namely, a) leaf with disease (350 samples), b) spinach leaf (100 samples), c) spinach leaf on white reference surface (100 samples), d) soil dry (100 samples), e) rocket leaf (100 samples), f) soil wet (200 samples), g) rocket leaf on white reference surface (100 samples). One spectral sample represents reflectance digital number (DN) on a spectral range of 2151 different wavelengths (nm). For the analytical stage, 2151 different spectral wavelengths were treated as different features. Visual inspection proves that there are expected high level of overlapping among the data groups, so feature selection and data preprocessing would be essential to remove all highly correlated spectral point to maximize the linear separation and classification accuracies. A process including Linear Discriminant Analysis (LDA), Adaptive neuro-Fuzzy Inference System (ANFIS), Multi-Layer Perceptron (MLP), and Radial basis Function network (RBFN), an ensemble supervised method that exploits the class labels of the samples to identify feature projections that potentially maximise class discrimination was employed. The identified significant features were used to classify the disease affected salad leaves or area of the farm with healthy plantation, the soil, and the healthy salad leaves or areas with potential abnormalities which requires some attention and monitoring. A conventional 10-fold cross-validation was performed using the 50% holdout to have a better estimation of the classifier performance. Best result shows that from this particular data set up to 88% prediction accuracy is achievable with 85% specificity and 80% sensitivity. Based on the modelling done using ground truth data and various remote sensing observations during a specified time period, we have developed a cloud computing based intelligent big data analysis platform (http://iekbaseanalytics.csiro.au/big-data-analytics/hot-spots-monitoring) to predict farm hot spots with high probability of potential biosecurity threats and early monitoring system aiming to save the farm from significant economic damage. Success from this study would be used to validate the current predictions of disease or pest likelihood on the farm and improve the model through adaptive learning accordingly.

Keywords: *Machine learning, big data analytics, salad leaf disease prevention*

Agricultural Decision Support Using Heterogeneous Remote Sensing Guided Machine Learning

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Abstract: This paper proposes and investigates a novel approach of using data-driven machine learning technique to overcome the drawbacks of conventional water balance modelling approaches due to the fact that the spatial and temporal resolution are limited as well as relying highly on condition-specified field experiments as a control group. The proposed approach integrates various independent data sources of meteorological information as a knowledge base, and then conducts a two-stage analysis of the data.

Heterogeneous spatio-temporal database including ‘Australian Water Availability Project (AWAP) database’, ‘Australian Digital Elevation data (ADED), and ‘NASA MODIS and LANDSAT Vegetation Index (NDVI) data’, and ‘Pléiades commercial satellite data (NDVI)’ were processed and integrated. An irrigated farming area (covering 5km X 5km) in Tasmania described by S 42°36 Latitude and E 147°29 Longitude, where weekly data from the period Jan 2013 – Dec 2014 (total 320 weeks) were studied.

In this paper, a novel knowledge integration and machine learning analysis based water usage recommendation system has been investigated and proposed based on the CSIRO Sensor CLOUD. The ultimate challenge in environmental forecasting and decision support systems is to overcome the uncertainty associated with the data quality, to cross validate the knowledge automatically, and to make the decision making process more efficient. Here, we have also proposed and developed an ANDROID mobile phone based recommendation framework to represent the dynamic water availability for any farming area in Australia. The irrigation water usage indicator was calculated for the whole duration of the research experiment. Historically there were only two possible water management decisions that one farmer could take on a given day - buy extra water for crop irrigation, or there was enough water in soil that they did not need to. Positive results from the CLOUD based water balance calculation system indicated enough water in the soil (represented by Class 1 or ‘1’ values) whereas negative results indicated the necessity of buying water (represented by Class 2 or ‘2’ values). An ensemble machine-learning framework combining Sugano type Adaptive Neuro Fuzzy Inference System (ANFIS), Elman (ENN), Cascade Feed Forward (CFFNN), and Function fitting neural networks (FFNN) were trained with combined training inputs of VI and ADED demographic data against the AWAP based water balance estimations as training targets. Based on the spatial distribution of the training performance, corresponding models were selected to estimate water balance at various spatial locations purely based on VI and ADED inputs, where no AWAP data were available.

The resulting combination may be used as a linear classifier or, more commonly, for dimensionality reduction before later classification. Classification performance was encouraging with 92.3% overall accuracy with 93% sensitivity and 94% specificity. Finally the model was applied to formulate a high-resolution (50cm) water availability map for the whole area on a weekly temporal scale, which could potentially provide accurate irrigation management support over a very large area (size of any spatial area, reference to CSIRO’s web system i-EKBase (http://iekbaseanalytics.csiro.au/)) at an amazing spatial resolution of 50cm.

The first stage of this project consists of the implementation of a computing cloud based central server and an Android client-end application which delivers the analytical results to the users, as a proof of concept demo. The findings in the paper indicate that given sufficient data, the same data-driven approach can be adapted for estimating area wise irrigation water usage on a high-resolution surface and efficient planning with high accuracy.

Keywords: *Heterogeneous remote sensing, water balance, machine learning*

Estimation of Leaf Wetness Duration Using Adaptive Neuro-Fuzzy Inference Systems

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Abstract: The estimation of leaf surface wetness has received considerable attention in recent years from a diverse group of scientists. Leaf wetness is widely accepted as one of the most important input variables for modelling many biophysical processes such as the development and spread of fungal and bacterial diseases. Various types of sensors have been developed for measuring leaf surface wetness. The rapid development and varied nature of these sensors have contributed to a lack of standardisation and the lack of a single accepted protocol for the use of sensors. An alternative to the use of sensors is the simulation or modelling of leaf surface wetness (Huber & Gillespie, 1992; Weiss, 1990). Simulation enables surface wetness to be estimated from historical, forecast weather data, or both, rather than from monitoring and measurement using in-field leaf wetness sensors.

The objective of this work was to develop and evaluate Adaptive Neuro-Fuzzy Inference Systems (ANFIS) as an approach to modelling Leaf Wetness Duration (LWD). This paper reports on a comparative analysis of ANFIS with Classification and Regression Tree/Stepwise Linear Discriminant (CART), Number of Hours Relative Humidity Greater than 90% (NHRH>90%), Fuzzy Logic System (FLS) model, Penman-Monteith (P-M) model, and the Surface Wetness Energy Balance (SWEB) model. The experimental results in this study shows that the overall mean absolute error of ANFIS model was lower than all other models. It was also shown that ANFIS model resulted in higher estimation accuracy over FLS in all five stations.

Keywords: *Leaf wetness duration, fuzzy logic, adaptive neuro-fuzzy inference system, CART*

Diagnostic study on early detection of lung cancer using neural network

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Abstract: Treatment of any disease has a greater chance of success if detected early. One of the most important leading cause of death in both men and women is lung cancer. Lung cancer like other cancers is the uncontrolled growth of abnormal cells that start off in one or both lungs. Usually in the cells that line the air passages. The abnormal cells do not develop into healthy lung tissue, they divide rapidly and form tumors. Early detection of cancer highly increases the chances for longer living and reduces mortality rate from this deadly disease, because treatment depend on the histological type of cancer, the stage (degree of spread), and the patient's performance status which means if it detects at initial stage effects in curing the disease effectively. Lung cancer is a disease that is frequently misdiagnosed. In this study, we briefly examine the potential use of classification based data mining classifiers namely Support Vector Machines (SVM), Artificial Neural Network (ANN), Self Organizing Map (SOM) and Evolving Self Organizing Map (ESOM) are applied to healthcare data and comparison is made with respect to accuracy, sensitivity, and specificity. The main aim of this research is to get a better knowledge of lung cancer early detection models and propose an early detection model for correct diagnosis of the disease which will help the doctor in saving the patient's life. With diagnosis of lung cancer we can answer complex what if queries which traditional decision support system cannot. By using all of generic symptoms such as sex, age, pain (in shoulder, chest, arm), shortness of breath we can predict the likelihood of patients getting a disease.

Keywords: *Support vector machines, artificial neural network, self organizing map, evolving self organizing map, lung cancer*

EXTENDED ABSTRACT ONLY

Hydrologic Simulation through Dynamically Evolving Models – A Data Assimilation Approach

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Abstract: It is well recognised that a single model can rarely represent a catchment's streamflow response adequately. This may be due to deficiencies in the model and/or its "optimal" parameterisation or due to changes in the catchment dynamics which may be unbeknown to the modeller (herein referred to as catchment non stationarity). Typically a single model parameterisation is adopted and assumed to be adequate outside the period of calibration/validation. A modelling framework that can adequately represent catchment processes now and in the future is therefore in need.

We have developed a novel method for accommodating catchment non stationarity that allows model parameterisations to evolve in time through a Data Assimilation (DA) framework. DA has traditionally been used for estimating stationary parameter distributions; here we investigated its potential for estimating time varying model parameters. This was undertaken using Joint State – Parameter estimation with the Ensemble Kalman Filter (EnKF) and the Probability Distributed Model (PDM), a lumped conceptual hydrologic model. It was found that careful consideration of the artificial parameter evolution model (which is used to generate background or prior parameter ensembles at each time step) is critical in this context. A range of traditional artificial parameter evolution techniques were initially considered. These were the Standard Kernel Smoother, Kernel Smoother with Location Shrinkage and the Homoscedastic Kernel Smoother. All were found to be problematic when parameters exhibit temporal variability. Two new approaches, 1) The Multi-Layer Method and 2) The Locally Linear Method, were developed which rely on a more meaningful description of parameter evolution to improve the prior parameter distribution. Both were found to outperform the traditional parameter evolution models in a number of synthetic case studies (greater than 30% and 50% increase in the Nash Sutcliffe Efficiency from the Locally Linear method and Multi-Layer method respectively compared to the Standard Kernel Smoother). The DA framework was also applied to the Wights and Salmon paired catchments in Western Australia. Both catchments were initially forested, but after 3 years, the Wights catchment was fully cleared whilst Salmon remained unchanged. A stationary set of model parameters for each catchment was determined by calibrating over the initial 3 year period using the Shuffled Complex Evolution (SCE-UA) algorithm. Streamflow observations were then assimilated into the EnKF framework with the Locally Linear method as the parameter evolution model, due to the minimal apriori knowledge required for this method (so called LL Dual EnKF). Parameter and state updating was undertaken for a total of 12 years, with the SCE-UA parameters used to initialise the EnKF. Parameter trajectories for the Salmon catchment were relatively stationary, with no significant changes over the 12 year period. Conversely, parameters for the Wights catchment experienced considerable change, consistent with increased runoff due to deforestation. Streamflow prediction using the time varying parameter approach was also significantly improved compared to when the initial stationary parameters were assumed to apply (see Figure 1). The proposed methodology provides a general framework for establishing dynamically evolving models that will be particularly useful for rapidly changing catchments.

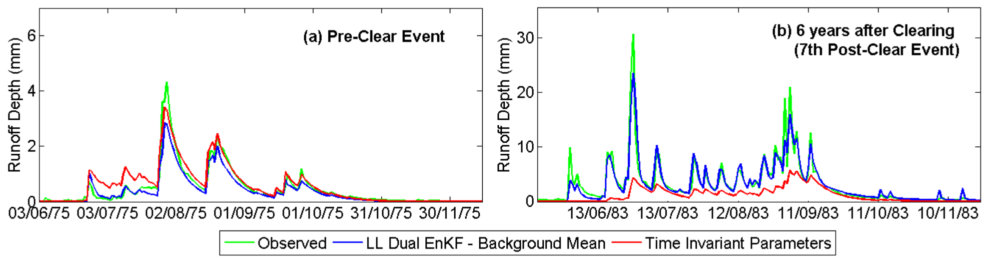

Figure 1. Streamflow hydrographs for the Wights (treated) catchment a) Prior to Clearing and b) 6 years after clearing.

Keywords: *Non-stationarity, time varying parameters, data assimilation, catchment modelling*

Stepwise symbolic regression compared to a probabilistic bivariate test for step-change detection

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Abstract: The idea of stepwise symbolic regression (SSD) using genetic programming was introduced at MODSIM 2013 and illustrated with climate data. SSD cleanly separates signals into linearly combined symbolic modal functions (the “explained” components) and a residual (the “unexplained”). The idea of examining the residuals for signatures of slowly developing processes, for example sea level change, was demonstrated.

SSD can be used for exploration of multivariate series, and modal functions can be composed of smooth as well as non-differentiable functions – for example IF-THEN-ELSE, and hence has potential for change-point detection in either univariate or multivariate time series.

Climate change is inherently a multivariate problem suite, and regime shifts (for example the Pacific Decadal Oscillation) may show as change points in either univariate or multivariate time series. Jones in 2012, proposed that periodic step-like regime shifts occur in the recent climate record. He used a bivariate test to examine possible shifts in SE Australian regional climate records. A working hypothesis is proposed, that climate change can be usefully modelled as a series of step shifts which comprise a large component of recent change. This is further hypothesized to be more observable at finer scale and so this and related work looks at global and then hemispheric and then zonal data sets and, to date, has shown that the working hypothesis holds.

A major feature of interest in recent temperature records, certainly in the context of risk, is the trend and the changes of trend. Both debate and climate risk are often framed in a context of an expectation that climate changes, especially anthropogenic ones, are expected to reflect smooth change. It is of interest to be able to identify times of regime shifts in composite records such as mean annual temperature records, as these may indicate increased near term risk.

The Maronna bivariate test used assumes no trend or change of trend and at most a single step shift. Testing has shown its ability to locate a time of shift is not sensitive to trend when even small shifts are present although its imputed significance could be. A probabilistic bivariate test (*PBV*), which builds on the Maronna test, incorporates some decision rules, and can be applied to data which contains zero to many shifts, is the subject of another paper submitted to this conference.

This gives the opportunity to compare PBV to the very general framework of SSD. Two different SSD modal function types and selection procedures were tested. One, *SSDstep* with early termination at each iteration, although quite general, is shown to produce similar results to the bivariate test. The second, *SSDtrend*, with delayed termination at each iteration, specifically models a break as a piecewise regression with two unrelated linear segments. It shows different behavior, especially during the early records, but converges on the *SSDstep* and the bivariate test after the 1960s where all methods showed good consensus on timing of shifts. This is consistent with regime shifts in temperature records being augmented by anthropogenic heat retention.

This paper will demonstrate the potential use of non-differentiable SSD modal functions in explorations of data sets which may be imprinted by regime shifts, and contrast the results with the PBV test which is under development.

Keywords: *Symbolic regression, stepwise symbolic decomposition, Maronna bivariate, regime shift*

Pilot study on an online transition course in mathematics

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Abstract: This report documents the experience generated by a pilot study of an online mathematics course offered to last and second last year high school students. The course counted with 109 participants from Chile, Colombia and Ecuador. The goal of the course is to support students in secondary education in learning mathematics with the help of a virtual platform, enabling them to continue with higher studies. As a main activity of the pilot study, the project team in Chile realized the online course during seven workshops, where the students working in a computer laboratory were observed and supervised.

A main conclusion is that the generation of working knowledge on how to manage the learning process using an online platform is a learning issue by its own, with implications that should not be underestimated. Even though most students are familiar with social network applications, there is no ability transfer when it comes to deal with productivity tools. One reason is the dependence of abilities on the used device. Dealing with smartphones is different to using desktop computers. For example, some workshop participants did not manage to scroll down the screen in order to find an exit button to confirm that a task has been completed and can be send to evaluation. Another example is that some do not manage the login procedure for the simple reason that they did not remember the password. They are not used to deal with passwords since usually smartphone applications do not request them. The implication for the overall project was that the session supervisors needed to track technical details including the login procedure.

One interesting observation made was that most of the course used to quit their work immediately after the break time bell. This behavior falsifies the supposition that individual and self-organized work might overcome the usual classroom conditioning that aims to minimize the time spend in classroom.

The adaption to a more autonomous working style, where the students work self-guided within the virtual environment took in average two sessions. Towards the end of the course, the students turned out to be motivated and in their majority interested in online learning, recognizing the complementary support to traditional classroom teaching.

Keywords: *Distance education, STEM, transition course, math education*

Reactive Documents for Modelling and Simulation

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Abstract: Traditionally we find ourselves using static documents for reporting on analysis of modelling and experimental data. However, static documents constrain the author to defined formats for presenting information and explaining concepts. An author's thinking must be condensed using text, charts, diagrams and images representing selected snapshots or narrow slices through large datasets. Such formats limit the ability of the author to effectively communicate the subtleties of their insights with the reader. Access to large datasets must be referenced in an external source.

Reactive documents employ dynamic, interactive elements and visualisations within the document to explore data sets and models. This allows the reader to play with the author's assumptions and analyses, and see the consequences. By providing direct access to interactive data visualisations the reader is able to explore and verify the author's claims.

The primary motivation for incorporating reactive documents into analysis reports is to improve the communication of concepts and ideas, and to increase the trust the reader places in the claims made by the author. Reactive documents enable and encourage active reading by providing the reader with an 'environment to think in'. The author can guide the reader through a cogent analysis of the data, where the reader can further explore the data for themselves and test the author's claims. Traditional reporting approaches require lengthy appendices or reference external data sources to provide the reader with such access to the data.

In order to evaluate the effectiveness of reactive documents custom data visualisations were developed for two separate analysis tasks; a study into the mobility of a convoy limited by sensor coverage, and a study exploring the performance of Time Management within constructive High Level Architecture (HLA) simulations. These were developed utilising standards-based, client-side web technologies, namely HTML5, CSS, and JavaScript. The use of web technologies allows the documents to be read by a wide audience. Numerous development resources are available with a significant influx in web-based data visualisations and associated libraries over recent years.

Our initial work into implementing reactive documents has yielded several insights. Firstly, the use of visualisation for reporting can often be more constrained than for initial analysis work, where an analyst is likely to require a much more flexible environment within which to explore the data. Secondly, interactive data visualisation does not inherently avoid introducing author biases, as every visualisation is designed with a particular view of the data in mind. Thirdly, custom visualisations require careful design, particularly where interactivity is concerned. Even carefully designed interactions may not be obvious, and it may be useful to provide textual help to direct the reader. Fourthly, existing business processes may make this approach difficult to adopt. The use of static documentation for reporting is entrenched in such processes, both internal to the organisation and for external publications. Finally, reactive documents require a new design language. There is currently a lack of authoring tools targeting reactive documents where the integrated and interactive nature of the document requires a new way of thinking about how the document's message is delivered.

This initial work has generated enough interest and it has been determined there is enough potential to warrant further exploration of this approach. It has been demonstrated that reactive document techniques can be an effective tool to improve communication of concepts and results.

Keywords: *Reactive documents, analysis, visualisation, web technologies*

A simulation system with educational applications that may be used on smart phones

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Abstract: We have been researching simulation systems that may be easily used by non-specialists. Our purpose is to measure the spread and acceptance of using simulation in order to facilitate the spread of simulation usage throughout the world. For instance, if a student in the liberal arts can easily make use of a system simulation related to queues in the supermarket, then his interest in simulation will grow stronger, and this will prove useful.

To this point, most simulation systems have been targeted to specialists. While the CAD mechanism has rendered them somewhat easier to understand in recent years, to grasp the world view and their principles of language is no simple matter, and the general public has been largely shut out of their use.

In order to create a simulation system that even amateurs can understand and use easily, we have researched and developed SIMUS (SIMUlation system using Smartphone). SIMUS creates models on smartphones (or tablets); it is a simulation system that can easily construct and display simulation models that are comprehensible even to non-specialists. Moreover, the system also supports output from Excel, since most university students today have mastered that program. Given that the system is capable of exploiting Excel's graphing and numerical processing functions, we are certain that the program will increase students' interest in simulation, and lead them to use the system.

The simulation procedure for this system is as Fig.1 : A solid line part is the one built this time in this figure, and a dotted line part is the part which will be built in the future.

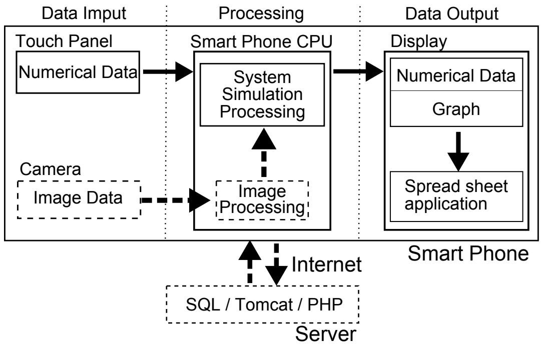

Fig. 1 SIMUS system diagram

It is easier to implement this system than a former similar simulation system. And, after inputting, we will get the result of information on Excel, like "Trace Simulation worksheet" which SIMEX has realized.

In the future we hope to achieve a simulation system in conjunction with spreadsheet that will take advantage of input application developments using smart phones. Even when programs (applications) are run independently, they will be able to share data through a network and run unified simulations. In other words, it is a network-type, object-oriented simulation system.

In this paper we describe the concepts of SIMUSS, its method of model building, its simulations, and the results. Finally, after using SIMUSS to carry out a simple queue simulation, we verify and report on its functionality and performance.

Keywords: *Smartphone, Android OS, simulation education, queuing system*

A Stacked-RuleSet Methodology for Provenance Management

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Abstract: According to the W3C, provenance is "information about entities, activities, and people involved in producing a piece of data or thing, which can be used to form assessments about its quality, reliability or trustworthiness". For modelling and simulation results to be accepted as a key part of decision-making processes, this isn't enough - the assumptions, data, and modelling processes need to be available and repeatable. Finally, the system needs to be useable and accessible. Correct data management practices need reliable tools with simple human interactions.

Here, we consider the tooling and design choices for a provenance information management architecture supporting NeCTAR virtual laboratories. Each such lab that wishes to manage provenance in the larger sense generates provenance reports by incorporating one of a number of toolkits we provide into its systems. This toolkit is used to generate reports which are sent to a single, central repository established for all the labs to use. Reports are logged with the lab identifier and any job identifier the lab allocates for lab/repository linking. Such reports rapidly become complex graphs with challenging validation, all of which is performed seamlessly by the tools to minimise the need to understand provenance which would be required to implement the methodology.

To ensure that each lab achieves the provenance standard it aims for, it is necessary to validate many layers - from the validity of the provenance report, such as ensuring each activity in the process ends after it starts, to the actual availability and integrity of the datasets - in a tailorable manner. The tools' validation ensures, at a minimum, that reports adhere to the W3C's PROV data model. Our stacked-rulesets approach allows any architecture user such as a lab to specify additional validation criteria. Reports on the status of validation are returned to the lab process for logging, and can be used during software design to ensure that valid reports are generated; however in operation, errors in providence reporting are not flagged to the user, but are stored alongside the report.

With the repository guaranteeing to provide access to validated, standardised, reports for each job run by each lab, sophisticated provenance data mining may take place to establish the required trustworthiness. Further, it enables holistic investigation into the scope of lab activities to assess coverage in experimentation and explore variation between operations. This approach minimises the inconvenience of data management to the user; while maximising the potential for a process to be truly repeatable.

The various provenance reporting toolkits, the repository system and the validation rulesets form a collection of Provenance Management System (PROMS) tools which can be used for systems other than the virtual laboratories. We conclude this paper by mentioning some in-development usage scenarios.

Keywords: *Provenance, virtual laboratories, reporting systems*

Complex licence requirements for the Bioregional Assessments Programme managed by provenance

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Abstract: The Bioregional Assessment Programme (BAP), is a large, multidisciplinary program of work, assessing the impacts of coal and coal seam gas on water resources. It must provide persistent and well managed access to both products (documents such as reports) and the datasets that support development of the products. To fulfil this requirement we have built a project repository that stores documents and datasets, and gives access to them via persistent URIs.

A requirement of the BAP is to make its datasets and products available at the conclusion of the programme. This raises the issue of how to determine data and metadata access based on a datasets' licence conditions. What makes this issue complex for the BAP is that both the licence of a particular dataset and the licences of its ancestors bear on dataset access rights and use.

In addition to designing the BAP project repository, the authors have implemented the presentation of provenance information that describes the lineage of datasets in accordance with the World Wide Web Consortium's PROV data model and standard. This lineage, presented as a graph, is used to lend transparency and some measure of reproducibility to the datasets by revealing their development history. It can be used to find the ancestor datasets for a dataset of interest and hence those ancestors' licences. Thus, along with a dataset of interest's own licence, all of the factors determining dataset access rights and use can be determined automatically.

In this paper we present our licence management methodology. We detail our licence data model which builds on Creative Commons by using a different rights association mechanism that is reliant on dataset ownership metadata stored elsewhere, and provenance graphs for licences derived from other licences. It then associates properties the Creative Commons model sees as licence properties, with other non-licence objects such as organisations, which are managed elsewhere, in other systems that we also briefly introduce. We describe our RESTful licence web service tool used to manage licence objects and how it delivers them using Linked Data principles via a version of Epimorphics' Linked Data API. We then describe how the BAP's project repository associates datasets with licences and how its provenance graph is leveraged to calculate the appropriate access rights for a dataset, based on the dataset's and its ancestors' licences.

Keywords: *Licence, attribution, rights, datasets, provenance, Linked Data*

Creating provenance super graphs using pingbacks

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Abstract: In computer science, provenance information is about a digital object's generation and, like 'provenance' in the art world, is recorded to answer such questions as "who produced what, when?" or "what data was used to make this product?". It is critical for scientific data's transparency of production.

If provenance information is recorded for work done to a dataset, questions such as "which datasets were derived from this dataset?" can be answered. This illustrates the concept of 'forward provenance'. Organisations that supply datasets can benefit from receiving forward provenance information from external agents that use their datasets in many ways. One great benefit in the science community is to determine impact from the publication of a dataset – a key issue for government funded research institutions. Another benefit could be that if errors in a dataset are discovered, a dataset publisher could notify users of that dataset.

A key enabler of effective provenance information sharing is the W3C's PROV Data Model recommendation (http://www.w3.org/TR/prov-dm/) which specifies structure for provenance information representation. PROV is generic, high-level and derived from many precursor provenance information systems such as Proof Markup Language (PML) (https://en.wikipedia.org/wiki/Provenance_Markup_Language) and the Open Provenance Model (OPM) (http://openprovenance.org/). Adherence to PROV ensures provenance information can be understood, at least at some level, by heterogeneous producers and consumers of it. The PROV Ontology (PROV-O) (http://www.w3.org/TR/prov-o/) provides a formalisation of the PROV data model that can be used to record provenance information according to the Web Ontology Language (OWL) (https://en.wikipedia.org/wiki/Web_Ontology_Language) which is thus compatible with the Semantic Web. Provenance information structured according to PROV-O takes the form of RDF graphs which can be stored in graph or other databases or serialised as RDF documents.

Provenance data model standards such as PROV do not directly address mechanisms for provenance discovery and access. PROV-AQ ("Access & Query") is a W3C technical note (http://www.w3.org/TR/prov-aq/) that specifies how to use standard Internet protocols to obtain information about the provenance of resources on the Web. One part of PROV-AQ specifies mechanisms for provenance 'pingbacks' which can be used to inform parties about use of their data thus communicating forward provenance with data originators. PROV-AQ provides a high-level specification for the process of sending pingbacks and also pingback message content guidelines. It does not describe how or when a pingback generator or receiver would generate, process or use pingback information.

In this presentation, we detail our extensions to the PROMS Server (https://wiki.csiro.au/display/proms) that enable provenance pingbacks within and between organisations. We demonstrate adherence to both PROV-AQ, the well-known data description vocabulary DCAT (http://www.w3.org/TR/vocab-dcat/) and formalisms specified in the Data Provider Node Ontology (DPN-O) (http://purl.org/dpn) which provides a generalised architecture for data and data service description.

Specifically, we describe how our extensions to the PROMS Server allow it to:

1. Determine when and for which things pingbacks should be sent;
2. Implement a user-selectable set of strategies that use different approaches to determine reception endpoints for pingback messages;
3. Implement several user-selectable pingback message content options.

Finally, we will discuss how a network of PROMS Servers with these pingback extensions, by allowing the creation of 'super graphs' which are linked provenance graphs within and across organisations, may benefit Australian scientific agencies. We will present our first steps in establishing such a network, including PROMS Server installations using pingbacks across 3 agencies and initiatives.

Keywords: *Provenance, pingback, PROMS Server, PROV*

PROV and Real Things

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Abstract: The PROV data model is becoming accepted as a flexible and robust tool for formalizing information relating to the production of documents and datasets. Provenance stores based on the PROV-O implementation are appearing in support of scientific data workflows. However, the scope of PROV does not have to be limited to digital or information assets. For example, specimens typically undergo complex preparation sequences prior to actual observations and measurements, and it is important to record this to ensure reproducibility and to enable assessment of the reliability of data produced. PROV provides a flexible solution, allowing a comprehensive trace of predecessor entities and transformations at any level of detail. In this paper we demonstrate the use of PROV for describing specimens managed for scientific observations. Two examples are considered: a geological sample which undergoes a typical preparation process for measurements of the concentration of a particular chemical substance, and the collection, taxonomic classification and eventual publication of an insect specimen. We briefly compare PROV with related work.

Keywords: *Provenance, PROV, sampling, specimen*

Capturing Data Provenance With A User-Driven Feedback Approach

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Abstract: Various portals have been developed to provide an easy way to discover and access public research data sets from various organizations. Data sets are made available with descriptive metadata based on common (e.g., OGC, CUAHSI, FGDC, INSPIRE, ISO, Dublin Core) or proprietary standards to facilitate better understanding and use of the data sets. Provenance descriptions may be included as part of the metadata and are specified from a data provider's perspective. These can include, for example, different entities and activities involved in a data creation flow, such as sensing platforms, personnel, and data calculation and transformation processes. Moving beyond the provider-centric descriptions, data provenance may be complemented with forward provenance records supplied by data consumers. The records may be gathered via a user-driven feedback approach. The feedback information from data consumers gives valuable insights into application and assessment of published data sets. This might include descriptions about a scientific analysis in which the data sets were used, the corrected version of an actual data set or any discovered issues and suggestions concerning the quality of the published data sets. Data providers might then use this information to handle erroneous data and improve existing metadata, their data collection and processing methods. Contributors can use the feedback channel to share their scientific analyses. Data consumers can learn more about data sets based on other people's experiences, and potentially save time by avoiding the need for interpreting or cleaning data sets. The goals of the study are to capture feedback from data users on published research data sets, link this to actual data sets, and finally support search and discovery of research data using feedback information. This paper reports preliminary results addressing the goals. We provide a summary of current practices on gathering feedback from end-users on research data portals, and discuss their relevance and limitations. Examples from the Earth Science domain on how commentaries from data users might be useful in practice are also included. Then, we present a data model representing key aspects of user feedback. We propose a system architecture to gather and manage feedback from end-users. We describe how the core PROV model may be used to represent the provenance of user feedback information. Technical solutions for linking feedback to existing data portals are also specified.

Keywords: *User feedback, Provenance, Open research data, Linked data, RESTful web service*

Implementing an organisation-wide approach to provenance management for Geoscience Australia

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Abstract: Geoscience Australia (GA) is Australia's federal government custodian of national geographic and geological data. It is a science organisation that produces a diverse set of scientific information products such as reports, regular datasets, forecasts and papers. It aims to ensure scientific product quality and transparency according to its *Science Principles*. To do this, GA has embarked on a whole-of-organisation assessment of its product' provenance. Following from that and over the next few years, GA intends to build the systems and skills necessary to capture, manage and use provenance information for many of its products in best-practice and standardised ways.

In this presentation we describe the work undertaken to produce a *Provenance information implementation plan* which is part of GA's product provenance assessment. The work needed to confirm that a consistent approach to the capture and use of provenance information across GA is possible and sensible and, if so, provide GA with a workplan with sufficient detail to guide the first phases of systems and procedures implementation. This work built on a previous provenance scoping study commissioned by GA that recommended it engage with its leadership to articulate the motivation(s) for investment in the area of provenance and the use of a particular provenance information interchange standard, the World Wide Web Consortium's PROV.

This work started with a workshop at GA in November, 2014, open to interested staff in order to understand the similarities in provenance situations and needs across several GA project groups. Significant interest in and the need for managing provenance information within GA was seen clearly as was the potential benefit in applying a systematic and coordinated approach to dealing with it across the organisation. Following the workshop, interviews were conducted with a range of process owners and IT staff who are likely to be stakeholders in a potential future provenance management regime. From the interview questions, we were able to not only identity the specific requirements of provenance information, but also to identify and map into PROV the workflows used to generate several key, very different, products. This showed that describing a heterogeneous set of GA's product generation processes using the single provenance data model previously recommended for use was possible.

After interviews, a framework was developed to 'provenance enable' any GA product by modelling its generation processes and determining the work required to extend them in order to create and transmit provenance information to enterprise provenance architecture. Templates for subsystem components' evaluation regarding their ability to interact with the enterprise provenance architecture were created and descriptions of a small set of enterprise provenance tools and methods that GA might implement were also provided. The tools chosen were either well known publicly available metadata and storage tools or specific provenance management tools from some of the authors' previous work.

Finally, a detailed project plan was created so GA might have an estimate of specific costings and timings associated with initially some pathfinder products' and then latterly all products' provenance enablement.

Keywords: *Provenance, PROV, Geoscience Australia, organisation-wide approach*

Identifying actors: a first step in effectively communicating provenance

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Abstract: Decision makers are increasingly requiring not only scientific information as evidence for their decisions, but also transparency with respect to the data, processes and decisions that were used to generate this information. There are challenges in not only recording and representing the provenance of this information, but also in communicating the provenance information. This paper uses the Bioregional Assessment Programme (www.bioregionalassessments.gov.au) as a case study to discuss the issues in communicating provenance information. The actors (the people, roles and systems that interact with the provenance information) are identified as a first step in effectively communicating provenance information.

The programme provides scientific information for decision makers, industry and the community to use when considering coal seam gas and coal mining developments and their potential impacts on water resources. A significant effort in data management and process reporting has allowed a suite of integrated products (both documents and an information platform) to present both scientific results and also the research data used to generate results. Cross-links to the data are reported using in-text data citations with persistent uniform resource identifiers (URIs) that are resolved to online publication of metadata and (where possible) the data itself. While complete provenance has not yet been formally represented, stored or used consistently across the programme, future products are expected to report formalised provenance, and current products need to anticipate this future reporting for consistency.

To communicate provenance information well it is necessary to consider the following actors and their requirements:

- researchers in the programme, who need to record, report, re-use and communicate the provenance information
- industry, who need to understand, re-use and potentially re-purpose the provenance information, so that they can undertake similar bioregional assessments on different systems
- decision makers, who need to understand, check and compare the provenance information with that provided by proponents of developments
- stakeholders with an interest in the potential developments and their impacts (e.g. environmentalists, landholders, concerned public), who need to understand the provenance information in order to judge the credibility and usefulness of the scientific information for their local needs.

For effective communication, the language used to describe and categorise the provenance information needs to be understood by this diverse range of actors. The provenance information must be integrated into the rest of the scientific information presented, to ensure that actors understand the context as well as the linkages to content, data and metadata. Finally, the different actors might want to consume the information in multiple ways, each of which pose different communication challenges: human-readable text, machine-readable text, static visualisations, or searchable and traversable dynamic user interfaces. If multiple formats are provided, the system would need to store information in a way that makes it possible to easily translate between these different formats.

Once the actors and their requirements are fully understood, the programme needs to move from an environment where only minimum provenance information is stored and communicated, to one where complete provenance is stored, formally represented and actively communicated. This is a substantial change in work practice and a social process must be put in place to facilitate this change, so that researchers can effectively record and communicate provenance information that is useful and relevant for these actors.

Keywords: *Provenance, data management, transparency, reproducible science, communication, actors*

Feature and attribute level provenance for spatial data supply chain using semantic web technologies

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Abstract: Spatial data supply chains (SDSC) for next generation spatial infrastructures require extensive investigation to address several contemporary issues and challenges that are hampering the innovation and use of spatial information across different industry sectors. SDSCs consist of multiple value chains. Each value chain has heterogeneous geo-processes, methods, models and workflows that combine to generate, modify and consume spatial data.

The integration and processing of multiple datasets gives rise to questions about trust, quality, and fitness for purpose, currency and data authoritativeness. This is because multiple datasets originate from heterogeneous sources, and different geo processes have been executed to reach the final product. Users have different data requirements and therefore knowing how data is collected and at what level of accuracy, provides knowledge about what it can be used for leading to increased user confidence.

With the advent of semantic web technologies, new methods for exploring and understanding the provenance of spatial data have become possible. However, there are few models that address spatial data provenance and none that adequately cater for spatial information management and the dissemination of data to users. A comprehensive provenance model for the spatial domain in Australia and New Zealand is an industry imperative to establish trust, fit for purpose and quality. Understanding provenance is crucial to capturing information about spatial features such as who/what/when/how/why it has been generated. This information is needed to support well informed and reliable evidence-based decision making.

This research is addressing spatial data provenance issues using semantic web technologies to resolve the gaps in our understanding of data provenance when disseminating spatial products. Two generic models from the World Wide Web Consortium (W3C) and the Open Provenance Group are available for general data on the Web. However, both models do not satisfy geospatial needs. The Open Geospatial Consortium (OGC) has investigated the W3C PROV model for spatial datasets. Issues identified are the need for provenance to be captured at various levels including at the spatial feature and attribute levels, for time series data sets, for representation and in presentation interfaces and elements, and for different levels of provenance.

In this research we are focusing on a specific example, namely capturing provenance at feature and attribute level from capture through process such as edge matching to dissemination. It is very important that structural steps of each geo process model and in most of the cases groups of geo processes in a complex analysis data model including overlay, proximity and table analysis should be captured. In this paper we suggest a feature and attribute level provenance and develop an ontology model for an edge matching geo process. We chose feature and attribute level provenance because it has geometric and non-geometric attributes derived from different techniques and originated from multiple features and sources. In order to allow a user to determine the suitability of a dataset for their purposes, provenance information at the single feature level including its history and several other attributes are required. Four phases of edge matching process ontologies have been developed and relationships between classes and sub classes have been defined with object and data properties.

This model named as GeoPROV captures information of the geo process "generate edge matching feature links" and workflow history. This geo process examines features such as segments of a road network acquired by different people using possibly different techniques with the result that the features don't always align. Information about the data sources and how adjacent features are matched and linked to form new dataset is stored. This is an incremental process and at each stage all provenance information is captured. The history of each function and changes that occurs are recorded. Information captured according to ISO 19139 geographic information metadata specifications is stored as an RDF file, and SPARQL queries are used to search the RDF provenance store. Having access to real-time provenance information supports data access and end-user confidence in data products.

Keywords: *Spatial data supply chain, data provenance, modelling, ontologies, semantic web technologies*

Standard Provenance Reporting and Scientific Software Management in Virtual Laboratories

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Abstract: The Virtual Hazards Impact & Risk Laboratory (VHIRL) is a scientific workflow portal that provides researchers with access to a cloud computing environment for natural hazards eResearch tools. It allows researchers to construct experiments with data from a variety of sources and execute cloud computing processes for rapid and remote simulation and analysis. The service currently includes tools for the simulation of three major hazards affecting the Asia-Pacific region: earthquakes, tsunamis and tropical cyclones.

For scientific results, the establishment of provenance is key to reproducibility and trust. Thus the need for any virtual laboratory to provide provenance information for the tasks it manages is obvious, but the appropriate way to report and manage provenance information is not always so straightforward.

Many virtual laboratories and workflow systems provide bespoke provenance management with a focus on internal system use. This has clear benefits for reproducibility within the system, but it limits the interoperability of systems. For VHIRL, a provenance solution was required that was as interoperable with other, external, provenance systems as possible.

A related common issue facing workflow tools and virtual laboratories is the need to manage software code. With this comes well-known issues associated with code sharing: licensing, source code management, version management and dependency resolution. There are a wide selection of commonly used tools to help solve these problems, for example Git and Subversion.

A key goal of VHIRL was to externalise as much information management as was reasonable. VHIRL is a virtual laboratory: it is not designed to be a data store, software repository, or records management system. A solution was required that could hand off the management of provenance records and code to external services, with links between them, other data services and VHIRL jobs where appropriate.

Scientific software can be quite complicated and systems for managing dependencies and source vary from system to system. In order to provide the least friction for authors of software, we designed a system called the Scientific Software Solution Centre (SSSC) to manage solutions to scientific problems and deliver the solution templates, code and dependencies that enable them for use in VHIRL and other Virtual Laboratories and applications.

We discuss our integration of the PROMS provenance toolkit into VHIRL in order to generate standardised provenance reports according to the W3C's PROV ontology. We describe the collection of provenance information through the VHIRL service and the submission of that information to an external provenance system. We also present the SSSC design as an example of how to meet the disparate requirements of managing scientific codes and solutions while dealing with publishing, discovery, licensing and versioning. We show how the SSSC assists in provenance report generation.

Keywords: *Provenance, software deployment, software management, virtual laboratories*

Metadata in Research Data Australia and the Open Provenance Model: A Proposed Mapping

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Abstract: Research Data Australia (RDA) is a flagship data discovery service provided by Australian National Data Service (ANDS). RDA consists of two major components: a collection registry component that harvests metadata from a range of data providers and a data discovery component that makes metadata visible and searchable over the web. Metadata maintained at RDA are encoded according to the RIF-CS (Registry Interchange Format - Collections and Services) schema. RIF-CS is based on an international standard information model ISO2146:2010 that contains descriptive and administrative metadata for collections and related services, parties (people and organisations) and activities, and also supports the expression of relationships between those entities.

In the past, metadata ingested to the RDA registry have had a focus on metadata describing data collections once created, and less on the data provenance describing how a data collection came to be. As data provenance has been gaining increasing importance in areas such as data intensive research and policy making, more and more data providers intend to capture and publish data provenance information in order to enhance data's trustfulness and reproducibility. ANDS partners are at different maturity stages in implementing systems to capture, represent and publish data provenance information. In terms of provenance representation, some data providers may conform to the W3C recommended provenance data model (PROV-DM), some may use a discipline specific data model which may or may not conform to a community endorsed standard, and others may use just free text.

This paper compares the RIF-CS data model with PROV-DM and suggests a mapping between RIF-CS schema and the W3C recommended provenance ontology (PROV-O). The paper also discusses how one might go about linking provenance to RIF-CS records. This work will help to derive PROV data from contextual rich RIF-CS records and thus promote awareness and adoption of data provenance by ANDS partners.

Keywords: *Provenance, metadata, RIF-CS, PROV-O, Research Data Australia (RDA)*

A Distributed Session Initiation Protocol Solution for Mobile Ad Hoc Networks Using Elliptic Curve Cryptography

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Abstract: Mobile devices (e.g. iPhones and iPads) are on the top of technology pyramid now days. Mobile Ad hoc Networks (MANETs) is one of the hot and challenging topics in the field of computer and telecommunication research. What make MANETs distinctive are the specifications (i.e. infrastructure-less and self-configuring) that provide an autonomous way to connect mobile devices. One of the current and most challenging areas is the implementation of Voice over IP (VoIP) services over MANETs. Such implementation requires a well-structured solution considering all factors, such as voice protocol, routing protocol and security mechanism, to form a solid solution for such implementation. In this paper, we extend our previous solutions published in 2013 and 2014 of adapting the widely used Session Initiation Protocol (SIP) (a signaling protocol used to establish, manage and tear a VoIP session) over MANETs by enhancing the solution with a security suite using the Elliptic Curve Cryptography (ECC). Our proposed solution provides an enhanced security mechanism for such implementation with relatively low cost on the network to form the underlying model of adapting SIP service over MANETs. The proposed solution is simulated under different conditions and scenarios using various metrics and compared with our previous works from 2013 and 2014.

Keywords: *Mobile Ad hoc Networks (MANETs), Session Initiation Protocol (SIP), Voice over IP (VoIP), ECC*

Speedup Techniques for Molecular Dynamics Simulations of the Interaction of Acoustic Waves and Nanomaterials

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Abstract: Nanomaterials are seen to have great potential for use in the area of sound absorption. However, direct inspection of the interactions between acoustic waves and nanomaterials is not feasible due to the short time and length-scales involved. Molecular dynamics simulations can assist in improving understanding of the mechanisms involved in this process, but they have limitations that must be overcome to make their use viable.

The primary limitation is that molecular dynamics is computationally expensive, making the time-scales over which results can be obtained very short. This, in turn, makes the acoustic frequencies that can be examined extremely high. In the current work, the use of a simplified force field, multiple time-stepping, and an analytical description of the sound source producing the acoustic waves are investigated as methods to improve the speed of a model that simulates acoustic wave and nanomaterial interactions, as speedup directly translates into increased feasibility of longer time-scales (lower acoustic frequencies) and larger domains. The speedup and accuracy of these techniques are determined through benchmarking against existing computational results for the interaction of a carbon nanotube with a 2.57 GHz acoustic wave propagating through argon gas.

Significant speedup is obtained using these techniques: replacing the oscillating atomistic wall in the benchmark case with the analytical oscillating wall produces a speedup factor of 1.3; using the simpler Dreiding force field for the carbon nanotube instead of the benchmark case's REBO potential results in a speedup factor of 3.6; and exchanging the Velocity Verlet time integrator in the benchmark case with an rRESPA multiple time-step integrator along with using the Dreiding force field leads to a speedup factor of approximately 39. Combining all of these techniques further increases the speedup, resulting in a speedup factor of approximately 50 compared with the benchmark. The error introduced into the numerical results is no greater than 6%, suggesting these speedup techniques are appropriate for molecular dynamics simulations of acoustic wave and nanomaterial interactions.

Keywords: *Molecular dynamics, nanomaterials, acoustics*

Modeling Neural Networks and Curvelet Thresholding for Denoising Gaussian noise

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Abstract: Modeling facilitates simulating the behavior of a system for a variety of initial conditions, excitations and systems configurations. The quality and the degree of the approximation of the models are determined and validated against experimental measurements. Neural networks are very sophisticated modeling techniques capable of modeling extremely complex functions employed in statistics, cognitive psychology and artificial intelligence. Especially, neural network model that emulates the central nervous system is a part of theoretical as well as computational neuroscience. Since, graphs are the abstract representation of the neural networks, graph analysis has been used in the study of neural networks, anatomical and functional connectivity. This approach has given rise to a new representation of neural networks, called Graph neural network, which encompasses both Biological neural networks and Artificial neural networks. In machine learning and cognitive science, a class of artificial neural networks is a family of statistical learning algorithms inspired by biological neural networks (the central nervous systems of animals, in particular, the brain) and they are used to estimate or approximate functions that depend on a large number of unknown inputs. Particularly, in the area of signal processing, the prime goal of the neural networks is to obtain a good approximation for some input/output mapping, by enhancing the performance of captured signals. Consequently, improving quality of noisy signals/images through noise reduction has become an active area of research. In such noise reduction problems, the graph neural networks can be used quite effectively by suitably designing it to train with input sequences; which are assumed to be a composition of the desired signal plus an additive Random/Gaussian noise.

Until recently, wavelets had been widely used in signal processing. However, wavelets suffer from the limitations of orientation selectivity and as a result, they fail to represent changing geometric features of the signal along edges effectively. Curvelet transform, on the contrary, exhibits good reconstruction of the edge data as it incorporates a directional component to the conventional wavelet transform and therefore can be robustly used in analysis of higher dimensional signals.

In this paper, the endeavour is to employ graph neural networks in combination with the curvelet transform for the enhancement of the corrupted signal and device a unified signal denoising technique using appropriate thresholding function. The experimental results show that the proposed model produces better results in terms of signal to noise ratio and computed mean square error - the most commonly used measures to determine performance factor/quality of the captured signal.

Keywords: *Graph neural networks, curvelet transform, thresholding function, signal denoising*

Using Workspace to automate workflow processes for modelling and simulation in engineering

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Abstract: Workspace provides a framework that allows researchers to focus on their science, to develop robust and sustainable software and to accelerate software development timeframes with a faster path to market for their commercialisation. The requirements of scientific application development such as visualisation, distributed computing, testing, integration and provenance reporting are all provided. Researchers and developers can easily develop new capabilities or expose existing libraries through C, C++, Python or JavaScript via inbuilt facilities, or "callout" to other software packages such as R. The Workspace framework makes it straightforward to mix and match existing and new capabilities within an easy to use graphical drag and drop environment, without the burden of having to design and implement the glue to make the components work together. Workflows are built and modified using an intuitive flow chart like graphical interface. They can then be executed directly within the workflow editor environment (typically as part of research or development), batch executed using the command line, or can have customised user interfaces attached (which is typical when creating fully compiled software products for distribution to other users). Workspace is built upon Qt and makes use of Qt Designer for development of application graphical user interfaces which can be connected to the Workspace workflows. Workspace is able to provide significant interoperability between otherwise independently developed and incompatible software components or operations. This is particularly useful in collaborative development between different disciplines or teams. For modelling research, the ability to connect pre- and post-processing components with pre-existing research simulation software and to package this as distributable software products represents an opportunity to commercialise pre-existing research without the need to re-develop the modelling software.

Several Workspace use cases for enhancing, supporting and commercialising engineering modelling and simulation are presented. These include:

1. Simple workflows for the full automation of operations typically performed by a user interacting with one or more pieces of software, such as pre- or post-processing operations.
2. Customised visualisation of large complex data stored, for example in NetCDF files.
3. Integration of third party libraries with inbuilt file reading and visualisation, for example in geometry construction from point clouds from laser scanned data.
4. Simple distributable software products, which can be provided to users, collaborators or customers. These would usually have a customised graphical user interface (GUI) and components for input, computation and then visualisation. An example is GrainScan.
5. Fully featured simulation packages. In this use case, the challenge is to take an existing engineering simulation package (often written in-house for research purposes using text input files for option selection and with analysis usually by collections of third party software) and to package it with a fully featured graphical user interface and embedded visualisation capability to produce a standalone software product that is easy to use. An example for simulation of particle motion in a grinding mill will be presented.
6. Multi-disciplinary research and development, which involves multiple different teams with different skill bases, software development capabilities and background modelling and analysis technologies. An example of the development of a process for automated markerless human motion capture is given which involves image analysis, optimisation and CFD modelling disciplines.

For each usage case, the nature and value of the opportunity is described and examples are discussed that demonstrate both the way that they are built and how they can be used. The benefits and challenges of using Workspace to support more efficient development of modelling and simulation platforms will be discussed.

Keywords: *Workspace, workflow, software platform, Qt*

An Investigation into the Modelling Challenges for Overland Flow Path Mapping and the Analysis of Practical Solutions

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Abstract: The lengthy computation time and very high computing capacity required to simulate high resolution catchment-wide stormwater models are significant challenges in developing overland flow path maps. Current practise tends to sub-divide a catchment into many sub-catchments, each with own stormwater pipe network in order to reduce the computing capacity, however this method tends to promote further complications due to cross-flows and backwater effects, particularly in flat catchments. An alternative approach is to remove the stormwater network and to estimate its impact through loss parameters. The first approach resolves the computing capacity limitations; however, the required modelling time remains an issue. In addition, full implementation of this approach requires an estimation of sheet flows and tailwater conditions at the boundary of each sub-catchment which can be very difficult to implement in relatively flat catchments. The second approach resolves both boundary condition and run time issues. This investigation involved a case study to examine the feasibility as well as the pros and cons of both approaches. Currumbin Creek, located in the southern part of the Gold Coast, was selected as a case study. First a coupled 1D-2D model of the catchment was developed to establish the most accurate overland flow path. Then two sets of overland flow paths were developed using the two abovementioned approximate approaches. Their results were compared with the results of the whole of catchment model to establish the better approach. The study shows that the second approach provides better results. It is important to note that the accuracy of the second approach depends on assigning an appropriate loss parameter to account for drainage capacity of the stormwater networks. In this study, various conceptual hydrological models were proposed to assess loss parameter estimation by finding a relationship between the volume of water conveyed by the stormwater pipe network and the input rainfall hyetograph. The study contributes to the body of knowledge by providing further insight into overland flow path modelling and mapping.

Keywords: *Overland flow path, flood modelling, hydrology, rainfall hyetograph, stormwater modelling*

Team Oriented Execution Models for Multi-Agent Simulation of Air Combat

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Abstract: Multi-agent simulation is often used to study complex socio-technical systems especially in fields such as operations research. Constructive simulation of air to air combat is used to undertake operational analysis to support fighter acquisition and tactics development. Computational simulation engines typically undertake two key functions. They determine the execution order of various simulation components and they facilitate the exchange of data between these components. In the air combat domain these components are used to represent multiple fighter aircraft and intelligent agent models of fighter pilot decision making.

In addition to representing physical systems such as aircraft, sensors, weapons, avionics and mission systems, modelling of future air combat operations places additional requirements on the design of these systems. These include the ability to implement different types of simulation components including cognitive systems such as aircrew, multi-level aggregation of combat aircraft into teams and forces and the representation of multi-modal environments to facilitate the interaction between the various entities in the modelled world.

Existing approaches to constructive air combat simulation have largely focused on the sub-component model (such as platforms, sensors and weapons) as a first order simulation design construct. As the complexity of scenarios have evolved over time, this type of approach has had limitations in being able to represent more complex aggregated simulation components such as teams and has left important environmental interactions implicitly modelled.

To address these evolving requirements, high level and detailed design (using UML modelling) was conducted to generate an architecture for simulation model execution. Central to the proposed architecture are a number of first order design constructs for modelling modern air combat scenarios.

Components represent computational models of aircraft sub-systems including platform dynamics, sensors, weapons, mission systems and counter-measures. **Entities** represent the aggregation of sub-component models into simulation entities such as fighter aircraft. **Teams** represent the aggregation of multiple fighter aircraft into teams such as flights and into subsequent more complex teams such as forces. The team model allows for the arbitrary nesting of sub-teams to represent complex organisational structures. Team is the basic building block around which scenarios are developed and executed. **Agents** represent tactical decision making both at the individual level (for example a fighter pilot) and at the team level (for example a pair or 4-ship of fighter aircraft). **Environments** represent the physical, electromagnetic and tactical environments and to provide an explicit mechanism for entities to interact with each other.

A prototype was developed to evaluate the quality of the design and to test the interaction between the five constructs in an air combat scenario. The prototype highlighted several advantages. The aggregation of fighters into teams raises the level of abstraction for the analyst, allowing for more detailed analysis of the results. Another advantage is that due to the modularity of the design, the architecture promotes extensibility. Clear definition of simulation components also improves the explainability of proposed designs.

The results presented in the paper fall into three categories. First, an object model and associated scenario execution algorithm is presented that demonstrates how arbitrarily nested and environmentally situated multi-agent teams can be executed. Second, the paper demonstrates how the theoretical model can be adapted for implementation within a constructive simulation. Third, the paper demonstrates the algorithm execution through a multi-agent air combat example. Finally the paper demonstrates how these results are broadly applicable for multi-agent simulations beyond the military domain.

Keywords: *Multi-agent simulation, execution model, teams, agents, air combat*

Simulation of Crack Generation on a Concrete Wall

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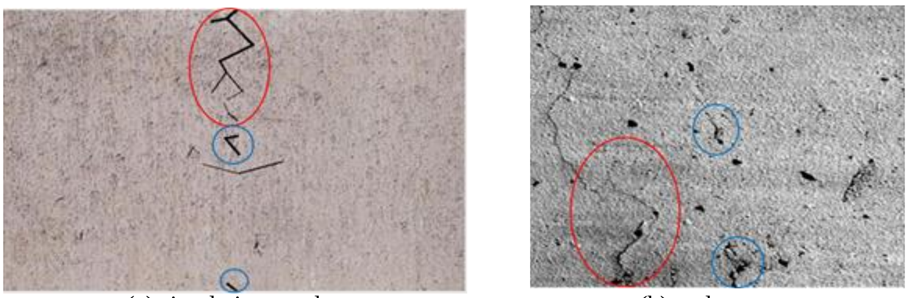
Abstract: One of the applications using computer graphics is landscape simulation, which evaluates the scenery changed by constructing new buildings. The scenery is built with models generated by computer graphics modelling software or image based modelling techniques. The models generated by computer graphics modelling software is beautiful without stains or cracks on the building walls so that some sceneries are built by mapping real images of real buildings onto the walls of the buildings in order to improve the reality. However, even if real images are mapped onto the building walls, the scenery remains the same unless the images change as time passes. Many researchers have been trying to represent stains or cracks on the surfaces of objects built in a virtual space.

Cracks on buildings or roads affect the landscape simulation very much so that this paper considers how cracks are generated and how to represent them. A crack is generated by fatigue of materials that construct objects such as buildings or roads in a virtual space, and also the heat at the vertex of a crack affects the process of crack generation. In order to represent cracks on building walls, it is necessary to simulate the process of crack generation, and there are many methods for the simulation. The simplest method is the Mass-Spring model that has some vertices having masses, which are located at several points on the target material, and are connected with springs. FEM (Finite Element Method) is also generally used in the simulation, which divides the target material into finite small elements and calculates the stress in the material. These physically based simulations can generate detailed crack patterns; however, it takes a lot of time for the simulation so that some patterns are generated using leaf venation or Voronoi diagram. In addition, some patterns can be generated by NPR (Non-Photorealistic Rendering).

Previous works generated many kinds of crack patterns; however, those were generated on free surfaces on an object and stresses caused by the surrounding materials were not considered. In fact, a concrete wall that constructs a building is surrounded by reinforcing bars, and the crack is generated by the stress due to the reinforcing bars in addition to the gravity. Previous researches also did not consider the change of crack width. The crack can be elongated as time elapses; however, the width did not change even if time passed. Therefore, this paper proposes a simulation method of crack generated on a reinforced-concrete wall with physically based simulation, which method changes the width of crack as time passes. In this paper, we adopt RBSM (Rigid Body Spring Model) for the simulation, which can calculate the inner stress faster than FEM and generate more precise patterns than Mass-Spring model. In addition, we use Delaunay triangulation to generate a variety of crack patterns with small number of elements, and change the crack width by referring to the experimental results of crack on a reinforced-concrete wall.

As the result of the simulation, we have succeeded in generating crack patterns on a reinforced-concrete wall, where the crack grew with the width change as time passed. Figure 1 shows the result of the simulation and a real concreate wall. By comparing them, we can see that some parts surrounded by circles are similar.



(a) simulation result (b) real concrete

Figure 1. Comparison between a simulation result and a real concrete.

Keywords: *Physically based simulation, crack generation, RBSM, Delaunay triangulation*

Bi-criteria Scheduling on Parallel Machines Under Fuzzy Processing Time

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Abstract: Job scheduling is concerned with the optimal allocation of scare resources with objective of optimising one or several criteria. Job scheduling has been a fruitful area of research for many decades in which scheduling resolve both allocation of machines and order of processing. If the jobs are scheduled properly, not only the time is saved but also efficiency of system is increased. The parallel machine scheduling problem is widely studied optimization problem in which every machine has same work function and a job can be processed by any of available machines. Optimising dual performance measures on parallel machines in fuzzy environment is fairly an open area of research. In real life situations, the processing times of jobs are not always exact due to incomplete knowledge or an uncertain environment which implies the existence of various external sources and types of uncertainty. Fuzzy set theory can be used to handle uncertainty inherent in actual scheduling problems.

This paper pertains to a bi-criteria scheduling on parallel machines in fuzzy environment which optimizes the weighted flow time and total tardiness simultaneously. The fuzziness, vagueness or uncertainty in processing time of jobs is represented by triangular fuzzy membership function. The objective of the paper is to find the optimal sequence of jobs processing on parallel machines so as to minimize the secondary criterion of weighted flow time without violating the primary criterion of total tardiness. The bi-objective problem with total tardiness and weighted flow time as primary and secondary criteria respectively, for any number of parallel machines is NP-hard. A numerical illustration is carried out to the test efficiency of the proposed algorithm.

Keywords: *Fuzzy processing time, total tardiness, weighted flow time, due date, weighted job*

Network Analysis of Fuzzy Bi-serial and Parallel Servers with a Multistage Flow Shop Model

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Abstract: Queuing theory is the one of the classical mathematical tool for study waiting lines or queues. In queuing theory a mathematical model is constructed to find various queue characteristics like average waiting time, mean queue length and number of the customers etc. Infact, waiting for service in queues has become an integral part of our daily life. Queues are often undesirable as they cost time, money and resources. Generally, queues come into play when the service resources are not sufficient to satisfy the demand. Most of the queuing optimization problems are static in nature in which the system characteristics are constant with respect to time or deterministic. In real life situations, one has to move from descriptive where all parameters are given to the prescriptive or normative where parameter changes with time and may be uncertain or vague in nature. In present scenario, it is difficult to find an exact distribution of arrival, service rate for the queuing applications. To express these rates mostly the linguistic expressions such as 'service is fast', 'service is slow' or 'service speed is moderate' are used. Therefore, it is more realistic to say the service rate, arrival rate etc are more possiblistic rather than probabilistic. Under these circumstances the fuzzy queuing models are more realistic approach than classical queuing theory model.

From many decades, job scheduling has been a constructive area of research for deciding the order in which the jobs are to be processed. Proper scheduling of jobs not only save time but also increase the efficiency of the system. Flow shop scheduling models are effective tools for the optimal allocation of scare resources with objective of optimizing one or several criterions.

In this paper a linkage between network of queues consisting of bi-serial and parallel servers linked to a common serve (phase I) with a multistage flow shop scheduling model (Phase II) is considered to deal with real world fuzzy network problem. Fuzzy sets are used to model uncertain arrival and service rates. The objective considered is average waiting time, mean queue length and total completion time. The triangular fuzzy membership function, α-cut approach and various fuzzy arithmetic operations are considered to estimate the uncertainty associated with input parameters. As problem related to completion time is NP-hard, a heuristic algorithm is developed to find the solution with maximum grades for objective. The developed algorithm is tested with numerical computation. The results of proposed model is useful and significant for system designers and practitioners.

The model finds its applications in manufacturing or assembling line process in which units processed through a series of stations, each performing a given task. Practical situation can be observed in a registration process (vehicle registration) where the registrants have to visit a series of desks (advisor, department chairperson, cashier, etc.), or in a clinical physical test procedure where the patients have to pass through a series of stages (lab tests, electrocardiogram, chest X-ray etc.).

Keywords: *Bi-serial servers, parallel servers, fuzzy arrival rate, service rate, mean queue length*

The Effectiveness of using CFD modelling in optimising the cooling of a low power compute server

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Abstract: Power consumption of devices is a significant environmental impact for personal computing and innovative sustainable devices are needed to address this issue. Any device needs to address the power drawn for the operation of the boards and their cooling which can be up to a third of the power used for such a server. A device designed to address this issue is a new low power personal super computer (compute server). This server uses many low power CPUs on the same board, packed into a tight space and generating a significant amount of heat that needs to be safely dissipated. Many of these servers can also be daisy chained together to increase computing capacity when needed. This heat generation requires significant cooling and considerable power savings can be made to the system if traditional fan cooling in the server case is not used. A device case therefore needed to be designed that allowed effective passive cooling of the components. Other design considerations were size, cost effectiveness and safety in a stackable distinctive case that became a challenging engineering design problem.

It is time consuming and expensive to optimise designs through prototyping and physically testing. Modelling can be a cost effective, sustainable and faster alternative. Computational Fluid Dynamics (CFD) has already been used in the aerospace industry to maximise understanding of physical phenomena, minimise physical testing and prototyping and improve the overall design of products. However such industries are large and have capacity to invest in such analysis tools. There is less understanding of the capability, effectiveness and capacity for use of modelling in smaller, niche or quick turn around projects.

CFD allowed the position and size of the case ventilation openings to be optimised; minimized manufacturing costs and desk real estate; determined the efficacy of dissipating the heat via a heat sink for the highest chip temperature; and allowed a client driven design approach. These factors were inter-related so the effectiveness of each solution and determination of optimal combinations of case characteristics was not straightforward. The initial design was changed significantly as a result of the modelling and considerable time and cost saved as a result of using CFD rather than prototyping and testing.

Using CFD modeling for a smaller engineering design problem can be very beneficial but issues arise. If undertaken by an experienced analyst it can significantly reduce product development time, increase understanding of the physical situation, improve innovation and give confidence in the product performance. Lack of understanding of the tool by the client can however lead to distrust in results and endless alterations to the design that are time consuming and resource expensive. Business size only affects the scale and number of engineering design problems CFD can be beneficial for, with little distinction in their complexity. The justification for small businesses using numerical tools in a systematic way to allow increased understanding with each design problem becomes more difficult as putting engineering analysis into the product development process requires investment in time, people and resources.

Keywords: *Computational Fluid Dynamics (CFD), compute server, optimization, prototyping, natural ventilation*

An Algorithm for the Automatic Detection of Abnormal Mitotic Figure towards the Automated Diagnosis of Melanoma

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Abstract: Histopathology is a recognised technique for the detection of melanoma, and is often referred to as the 'Gold Standard' for the detection of this disease. However, its results can sometimes be rendered inconclusive, hence demanding the need for further, more advanced, forms of testing to be conducted (e.g., FISH testing and comparative genomic hybridisation (CGH)). In order to support pathologists with the detection of melanoma, an algorithm has been proposed for the detection of abnormal mitotic figure; a feature of melanoma that is a key indicator of malignancy. It is anticipated that this work can contribute towards research and development in the area of automated histopathological detection of melanoma. The proposed algorithm is described here as a flow diagram. It is currently undergoing further improvement, and it will then be implemented in computer code and tested.

Keywords: *Histopathology, automated abnormal mitotic figure detection, algorithm, computerised, image processing*

Mobile data acquisition technology evolution in hydrogeochemical applications

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Abstract: Reliable collection of scientific data is always an essential part of any research and is particularly important in man-in-the-middle data acquisition scenarios. CSIRO Discovering Australia's Mineral Resources Program in the Mineral Resources is conducting a regional study to define distal footprints of covered ore systems in the Capricorn region – an underexplored area of known mineral potential that lies between Pilbara and Yilgarn Cratons in Western Australia, two of the most significant mineral economic regions in the world. Field sampling campaigns over the past few years have yielded thousands of water and vegetation samples. The field sampling process has evolved from hand written notes in an arbitrary format to gridded logbooks, and later was standardised into a set of procedures and guidelines. This was the very first step that yielded a form to capture observations and measurements along with associated sample and site metadata.

In 2014 a growing need in automated data integration resulted in an extensive technology review with an aim to automate the field data acquisition process with further integration with data systems via the Spatial Information Services Stack (SISS). Two separate implementations of mobile data acquisition app were considered as potential candidates: (i) a purpose-built prototype application developed for capturing hydrogeochemistry and vegetation sample data, and (ii) a hydrogeochemistry data acquisition module for the Federated Archaeological Information Management System (FAIMS). FAIMS is a framework for mobile field data acquisition, developed at the University of New South Wales for archaeological field data collection. The benefit of the FAIMS solution was in its flexibility to adapt to different kinds of samples, integration with GPS, and the ability to associate photographs taken with the device embedded camera with captured data. FAIMS also allowed networked collaboration within a field team using mobile applications as asynchronous rich clients. The network infrastructure supported by a FAIMS Server, although optional, can be installed in a field vehicle to provide data synchronisation, backup and transfer. The two different data acquisition applications were trialled in the field in a comparison study. The field trial was conducted in various conditions by different teams for over a year, which provided an unbiased user feedback critical for further improvement. User interface and user experience aspects were given a particular attention in the comparison study and a computer science expert observed field teams during the use of the app. The ergonomics of the app has proven to be of paramount importance in gaining user acceptance. This extends from general fit with the standard operating procedures to self-descriptive and intuitive user interface features that are well aligned with these procedures. All these factors ultimately contributed to the implementation of a Collect-As-You-Go approach, removing the necessity of manual data transfer between logbooks, spreadsheets, and, eventually, data storage and data analytics platforms. Following a number of sampling campaigns with multiple teams involved, we tested both solutions and results clearly outlined the winner. Whereas the mobile data acquisition approach proved to work, the first prototype application failed to get the user acceptance due to poor user experience and eventually most teams reverted to the use of logbooks. On the other hand, the FAIMS solution trialled in other campaigns outperformed its rival and most teams fully migrated to its use instead of logbooks within the first few days.

In the Australian outback, technological issues such as an absence of network connectivity and a stable power supply, combined with harsh conditions (e.g. dust, heat, sun glare, etc.) may challenge the use of tablet-based applications. Thus, a thoughtful approach to the selection of a suitable hardware platform is critically important for each environment. The recent sampling campaign with the full FAIMS kit mounted in the field vehicle proved to be a reliable solution, improved quality of collected data by reducing the amount of manual data entry and automated data verification, and improved the overall efficiency of teams. In the next stage, we plan to continue work on automated seamless integration of the FAIMS framework with the SISS platform.

Acknowledgments: We would like to thank Shawn Ross from Macquarie University, Sydney, Australia, for his advice and contribution in the development of water, soil, and rock modules for the FAIMS framework.

Keywords: *Mobile data acquisition, data collection, FAIMS*

A New version of Autonomous Ocean Energy Recovery System for Oceanic Applications

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Abstract: Over 70% of the earth's surface is covered by water and there is abundant energy in the sea. Imagine if people could make full use of the energy resources under the ocean, how profoundly it would change people's lives for the better. The energy that this research is concentrated on is from the surface wave motion, which is totally eco-friendly and to some extent 'endless'.

Ocean wave motion energy can be collected and transformed to useful energy by ocean wave energy conversion devices (OWECDs). Sea condition is complicated and wave force and motion are diverse in direction. However, most OWECs are designed to collect wave movement in a single-degree of freedom (DOF) and research has not considered various sea states.

In this research project, based on the study of the existing ocean energy recovery system research outcomes, a research-prototype of an autonomous multi-DOF OWEC device is presented, which is capable of collecting multi-DOF movement of ocean-waves independently. The concept and feasibility will be proved and the performance and efficiency under different sea states will be investigated. Different types of OWECs will be compared. The specific oceanic device (test-bed) has been optimized, simulated and manufactured.

In this research, the Finite Element Analysis (FEA) method was adopted. The process involved modelling the prototype using the CAD Inventor software, analyzing and simulating the interaction between ocean wave and the prototype using the ANSYS software and calculating the mechanical efficiency and output by using the software Abaqus.

Keywords: *Wave energy, ocean, conversion devices, autonomous, energy recovery*

Negotiation Protocol Comparison for Task Allocation in Highly Dynamic Environments

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Abstract: A robust negotiation protocol is required for a multi-agent simulation involving two adversarial teams in a highly dynamic and hostile environment. In this environment agent failure is possible due to a number of circumstances such as running out of fuel or being destroyed by other agents.

This paper compares three existing negotiation protocols: the Contract Net Protocol (Smith, 1980), the Distributed Contract Net Protocol (Cano and Carbo, 2006), the Extended Contract Net Protocol (Aknine et al., 2004) and two protocols developed by the authors (termed herein the `Simple' and `Hybrid' protocols). The objective of this paper is to determine which protocol is best suited to our application in terms of scalability, robustness against agent failure, communication overhead, and response time.

To evaluate these negotiation protocols an experiment was conducted, involving three different test cases, which varied the availability of agents at different stages of the negotiation process. In these test cases a team of software agents (the `blue team') were tasked with destroying a number of stationary targets (the `red team').

The experimental results showed that the Contract Net Protocol (CNP) was suitable for low risk environments due to its low communication overhead, while the Distributed Contract Net Protocol (DCNP) was more suitable for high-risk environments due to its greater robustness against agent failure. However, this robustness was achieved at the expense of greatly increased communication. An alternate approach that showed promising results was to use a Hybrid protocol that switched between CNP and DCNP depending on the environment. Additional work is required to develop the Hybrid protocol further.

Keywords: *Negotiation protocols, task allocation, multi-agent systems, resource management*

Uncovering Industrial Control Systems Vulnerabilities by Examining SCADA Virtual Packages and Their Communication Protocols

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Abstract: Supervisory Control and Data Acquisition (SCADA) is the centralized computer system that controls and monitors the Industrial Control Systems (ICS) that are connected to it. SCADA is used in various industries and the military, and it is essential to many critical infrastructures. However, in most nations SCADA was introduced a few decades ago, as one of their security measures. With rapid technology advancement over the decades, this out-dated security measure could never be on par with the security risks that SCADA systems are facing. It is necessary to investigate the potential vulnerabilities on the structural level and mitigate them. Focusing on the software vulnerabilities, this paper aims to investigate the potential security issues that could cause malfunction of SCADA systems that control critical infrastructures, including electricity, water, gas, traffic, military, and others which causes impact to the survival of a nation. With various SCADA packages available in the market, Citect SCADA from Schneider Electric Corporation has been selected for this research due to their popularity in Australian industry. Several versions of the Citect SCADA are being used in the investigation due to the fact previous versions are still widely used in industry at the time of writing. This paper investigates the structure and functionality of the SCADA packages to uncover their vulnerabilities and proposes recommended countermeasures.

Keywords: *SCADA, cyber security, critical infrastructure*

A Quadrotor UAV Navigational Command and Control Aid: A Landing Pad Detection and Localisation System

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Abstract: Research and development of quadrotor UAV robots is a fast-growing area. There is currently a high R&D focus by many companies on UAVs for delivery purposes, swarm applications, farming applications, search and rescue missions, environmental studies and other advanced applications. GPS is a navigational system that can be used to guide a UAV toward a target destination. However, as GPS navigation is prone to local errors, there is a vital need for another sensor to assist with short-range navigation and finding the target landing position. In this case, the quadrotor's on-board camera could act as a useful, optical, sensor to collect real-time data about a destination area and the location of a landing pad. In this research work, successful landing pad detection was accomplished by employing the most ideal of a number of classifiers, which were trained using OpenCV. Two different types of classifier training were performed: these were Haar and LBP (Local binary patterns) training. Theory was also derived to localise the UAV within the earth-fixed coordinate system, based upon its position with respect to the landing pad within the captured image. This article briefly discusses the principles, procedures and results for landing pad detection, as well as image analysis, UAV localisation and command generation.

Keywords: *UAV, localisation, image processing, OpenCV, landing pad detection*

Modelling and Simulation of the Autonomous Underwater Vehicle (AUV) Robot

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Abstract: Autonomous underwater vehicles (AUV) have been used widely in the oceanic applications for many purposes, such as maritime fishery study, the installation of underwater pipelines in the oil and gas industry as well as to support offshore engineering, and mine hunting and defence applications.

Projects in the development, manufacturing and testing of AUVs are complex, requiring a large investment of time, money and effort. Therefore, the simulation of the AUVs has been identified as being cost effective and time saving, as simulation is a vital step in understanding the behaviour and operation of the system before its actual deployment in the field.

A number of subsystems must be considered for building a successful AUV simulator, these are the Inertial Navigation System (INS), Machine Vision, Sonar, Communication (underwater and on surface), and the Simultaneous Localization and Mapping (SLAM) module systems. This paper discusses the methods and the outcomes of the feasibility study of the AUV simulator under investigation.

Keywords: *Autonomous Underwater Vehicle (AUV), simulator, simultaneous localization and mapping, SLAM, robotics*

CFD Modelling and Real-time testing of the Wave Surface Glider (WSG) Robot

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Abstract: This paper consists of two main parts. First part describes a new method for investigating the dynamic behaviour of a Wave Surface Glider (WSG) robot with the help of CFD analysis.

The second part focuses on the real-time testing of this platform and comparing the results obtained from the trial. WSG test-bed, designed and manufactured by the University of Adelaide, is categorised as a new marine vehicle which is fully dependant on sustainable energy of ocean waves and the sun.

Abundant energy of ocean waves is converted to propulsion, which allows this vehicle to roam freely in the ocean and gather useful oceanic data. Solar panels installed on the vehicle's surface, supplies the electricity for electronic components of this vehicle such as sensors (e.g. temperature sensor, servo, GPS, compass and etc.).

This paper discusses the computational fluid analysis approach that is employed to extract the contributing propulsive forces generated by the robot and relate this force to characteristics of regular waves and sea states in the ocean. Then, the robot has been taken for a real-time test and the results have been reported.

***Keywords*:** *Wave Surface Glider, robot, marine vehicle, dynamic model, fluid dynamic analysis*

Design and Simulation of New Versions of Tube Launched UAV

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Abstract: Currently, Unmanned Aerial Vehicles (UAVs) are widely used on exploring and monitoring the oceans. Such as a Tube Launched UAV (TLUAV), that may tightly pack into a water-resistant narrow tube and can be conveyed via an Autonomous Underwater Vehicle (AUV). After the TIUAV launched on the sea-surface, with having onboard automated, command, control, and navigation systems, it can easily reach to the high cruising-radius. There are several fully developed TLUAVs, such as 'MAVERIC' designed by Prioria Robotics Company, enlisting in a number of applications including with the United States Army. With the development of a large-scaled economically viable TLUAVs, they can support the exploration of the ocean resources, search and rescue missions, operational recognizance and surveillance missions, and so on.

The goal of this research was to compare the performance between different types of Tube launched UAV under different sea states with diverse wind directions, and further more to optimize a new version, which may achieve better performance. There are two new versions have been developed in this project, which are the unfurling-methods of structure of the flexible UAV wings. One version was inspired from the bat wings and umbrella's pulley system respectively, and the idea of the other version comes from the process of the birds' wings during takeoff procedure. The wings of both models can be opened automatically after the UAV launched from the tube-launcher by its control system, and can be locked and fixed when the wings are fully unfurled.

For the monitoring purpose, due to the advantages of low speed of the TLUAV and its stability on air, it can carry several small sensors including with a small real-time video camera, to be able to monitor a pre-specified part of the surface ocean. In this case, the unmanned air-robot is designed to perform with the cruise speed of 10 m/s. In addition, the new models designed and investigated within this research are compared versus the existing TLUAV models under different wind velocities and based on the sea states 0, 1 and 2, as well as various wind directions including with windward and crosswind conditions. Furthermore, in this research study, a comparison of the lift-force, drag-force and side-force of the TLUAV model by using the computational fluid dynamic (CFD) method is investigated. Moreover, the results were compared with the popular models including with the MAVERIC model and other civilian versions to show the differences and improvements.

Keywords: *UAV, tube launched, sea state ,CFD*

The Keyword Aggregator web service — a tool and methodology for managing digital objects' keywords

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Abstract: The need to tag digital objects in various repositories such as datasets or scientific papers to allow for thematic classification is a well-known problem. In some cases a free tagging approach is used where contributors can add any keywords they desire while in other cases, selection from a controlled vocabulary is mandated.

To enable repository managers to allow both free tagging and the use of controlled vocabularies, we have created the Keyword Aggregator (KWA) system, which consists of the following components:

- A web service that:
  - provides fast search access to vocabulary content;
  - stores multiple, controlled, vocabularies of terms;
  - permits the addition of new keywords.
- An example widget that makes use of the web service and can be embedded in a web page.
- Use of a relational database that captures keyword use statistics.
- A management methodology that:
  - allows particular vocabularies to be selected for use on a per-widget instance basis;
  - allows vocabulary updating through storage in versioned repositories;
  - stores vocabularies with vocabulary-level metadata enabling vocabulary discovery;
  - permits one vocabulary to link to a single term in another vocabulary (allows a 'vocabulary-of-vocabularies').

Formal vocabulary representation systems such as the Simple Knowledge Organization System (SKOS) (Miles and Bechhofer, 2009) have been endorsed by the World Wide Web Consortium (W3C) where complex term relationships need to be represented. Keywords and whole-of-vocabulary metadata in KWA are stored as SKOS graphs in a graph database. Identification and, where necessary, creation or conversion of an initial set of science keyword vocabularies in SKOS has also been part of the work.

Although the focus of KWA is on the creation of a flexible keyword aggregation, management and search system for science keywords, vocabularies of any kind could, in principle, be handled by this system.

We describe our Keyword Aggregator system, which is aimed at lowering the effort required to provide digital object controlled vocabulary and folksonomy term tagging functionality to repository users. We present usage scenarios relating to CSIRO's Data Access Portal (DAP) and the MODSIM2015 paper system, key design goals, implementation details, current progress and future work.

Keywords: *Aggregation, keyword, vocabulary, RDF, SKOS*

PID Service – an advanced persistent identifier management service for the Semantic Web

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Abstract: Persistent identifiers are an integral part of the Semantic Web and Linked Data applications: they enable the stable identification of digital objects and may be used as a top-level application programming interface (API) to bind multiple representations of digital objects into a single, coherent, data model. In addition to these technical tasks, persistent identifiers and their management are of prime concern for the governance of Domain Name System (DNS)-based domains containing output from multiple parties that need to ensure identifier uniqueness as their first order of operation.

Our contribution to solutions for the technical and governance challenges posed by identity management is the PID Service – a persistent identity service – which is a web service offering advanced persistent identifier management with features not found in proxy servers and other web redirection products. The PID Service is able to store and implement large numbers of complex Uniform Resource Indicator (URI) redirection rules and handle related sets of rules according to rule hierarchies. This, combined with a web-based graphical user interface and database rule storage, allows users of the PID Service to far more easily manage large numbers of complex rules within a domain avoiding rule collision and specialised partial URI delegation. The Application Programming Interface allows programmatic access to all features of the service that, in turn, provides boundless integration possibilities with other applications and services. These possibilities include, but are not limited to, applications such as automatic data harvesting and digital entity identification.

The PID Service is being used for a number of operational Semantic Web and Linked Data applications including the 'environment' portion of the Australian Commonwealth Government's data.gov.au project operating at environment.data.gov.au. There the PID Service handles the identifiers for a range of Linked Data products including the large and complex national Australian Hydrological Geospatial Fabric. In addition to handling current products within the domain, the design of the PID Service is such that it will be able to cope with large increases in number of persistent identifiers, which is important given the rising popularity of open government data and the use of services such as environment.data.gov.au. The PID Service has also formed part of the key service infrastructure in the Spatial Identifier Reference Framework (SIRF) (Atkinson et al., 2013) – a scalable linked data infrastructure that aims to improve the supply of open, spatially enabled and linked information. SIRF provides means to reliably cross-reference identifiers for the real-world locations and encodes spatial relationships between features (i.e. containment and adjacency). This framework of spatial identifiers is used to link together information (e.g., socio-economic statistics) about locations, stored in multiple distributed systems.

In this paper we outline the motivation for the PID Service including the limitations of other proxy and redirect technologies. We provide an overview of the system design and describe both its technical functionalities and use cases. Finally, we describe the aforementioned installation of the PID Service at environment.data.gov.au and discuss how it impacts domain governance.

Keywords: *Persistent identifier, Uniform Resource Identifier (URI), redirection service, web proxy, Semantic Web*

EXTENDED ABSTRACT ONLY

A review of the eReefs project: its goals, products and place within the Australian interoperable data project landscape

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Abstract: The original vision of the eReefs project was for an integrated system of data, models, visualisation, reporting and decision support tools that span the Great Barrier Reef. The system would allow a step change in the quality and timeliness of reef data used regulatory, planning and management decisions.

In this presentation we review the progression of eReef's development, particularly aspects relating to whole project/system delivery. We compare previously published (including in previous MODSIM conferences) statements about eReef's expected products and the expected challenges and the actual products delivered in 2015/2016 and the actual challenges faced. We discuss shifts in emphasis away from delivering "integrated" systems and "model ensembles", which featured heavily in early presentations, to delivering conceptual and standards frameworks that allow open-ended data and service integration. Some portion of this we attribute to technology changes with the emergence of Linked Data being very important. Other portions we attribute to changing stakeholder institution interests.

We also place eReefs within the context of national Australian data integration and interoperability initiatives, such as the National Environmental Information Infrastructure, the Bioregional Assessments project, the Integrated Marine Observing System, OzNome, *et cetera*. As with eReefs' changing internal goals, its place amongst these other initiatives has changed since project inception. We tease out what has changed and why.

The main phase of the eReefs project concludes in 2016 and this presentation concludes by asking "what's next for the eReefs partners, tools and methods?" Planning for project end and follow-on operations has taken place recently and a frank assessment of the outcomes from this will be given.

Keywords: *eReefs, Great Barrier Reef, information platform, interoperability, Australian data projects*

Performance characteristics of Source calibration service

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Abstract: Using optimisers to calibrate hydrological models is a computationally intensive process. Most optimisation algorithms run on desktop machines, with some running on Linux clusters and a couple that run on cloud infrastructure (e.g. cloudPEST). Complex hydrological models require a relatively powerful machine and calibration runtimes vary from an hour or less, to days and sometimes weeks. Increasingly, organisations are looking to outsource provision and management of computationally intensive infrastructures. While virtualisation technology can provide similar performance to high end desktops, there are opportunities to harness parallelisation and reduce calibration times, by hosting the modelling software on the cloud infrastructure and exposing its functionality through web services. This paper investigates the practicality and performance of implementing a calibration wrapper to the eWater Source river modelling package. The Source calibration service allows user to calibrate models, where the modelling software, eWater Source, is running on the cloud and not on end user's premises.

The aim of this analysis was to compare the performance characteristics of a simple GR4J model for the Legerwood catchment using eWater Source running as desktop software versus running as a Source calibration service on the cloud. Shuffle Complex Evolution was used as the parameter optimisation algorithm for the GR4J model parameters.

The eWater Source product running as desktop software took around 4 minutes to calibrate the model whereas the Source calibration service took around 73 minutes to do the same calibration with similar results. The difference in run times can be attributed either to: 1) the chatty nature of communication between the machines running the eWater Source and the optimization algorithm; and/or 2) time inefficient implementation of SCEoptim routine from the hydromad package; and/or 3) performance bottle necks in Source's external interface which exposes eWater Source modelling capability through command prompt. Given the long simulation runtimes, the current Source calibration service fails to meet expectations of hydrological model builders for improved performance. For software implementers, we would recommend careful attention to the software architecture and performance characteristics of proposed cloud-based software implementations early in development. In this case, we anticipate future improvements to the infrastructure, or renewed effort improving the implementation would lead to a faster implementation.

Keywords: *Web services, hydrological model calibration*

Tools for enabling rapid deployment of water and energy consumption and supply data services

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Abstract: Improving data consistency and facilitating opportunities for cross-domain urban research is important to understanding patterns of urban development and modelling urban growth for a sustainable future. Researchers and policy analysts are confronted with a number of technical challenges when comparing data in the water and energy industries both within and across these sectors. These include variability in data formats, spatio-temporal granularity, access methods and differing semantic definitions. These hinder attempts to access, analyse, interpret, compare and combine the respective water and energy datasets. The AURIN Lens 6/2 project has developed the Water and Energy Consumption and Supply (WESC) data protocol for encoding WESC datasets and tools for consolidated access via standardised geospatial web services. In addition, a number of data agreements across Australian utilities and peak body organisations have developed in order to establish a thematic data hub, called the WESC data hub. The WESC data hub currently hosts relevant datasets and uses the WESC data protocol to provide access to them via the AURIN data portal. In developing the WESC data hub, a number of tools and techniques have been developed to streamline and automate the data extract-transform-load and web service deployment process for each data provider as well as set up continuous testing frameworks to provide quality assurance and performance monitoring of the WESC data hub. In this paper, we will present the technical challenges in delivering the WESC data hub across multiple datasets and data providers, as well as the tools and methodologies used to rapidly deliver data services and its testing framework - namely, Docker, Linux virtual containers, Python and TeamCity. Previously, such deployments required considerable expertise in systems administration, configuration management, and web application development, were time-consuming and not easily repeatable. However, the tools and techniques presented in this paper provides a generic pattern for rapidly developing and deploying standardised geospatial web services and is thus applicable more broadly for other domains and data. The methodology used provides software infrastructure resilience as the data services can be re-deployed easily using Docker. Continuous build and testing tools, such as TeamCity, provide quality assurance as data services are deployed and re-deployed to ensure data integrity as well as performance monitoring which allows the systems to be fine-tuned and made more efficient.

Keywords: *Data services, web services, geospatial data, Deployment technologies, Docker*

Mathematical techniques to aid the Australian Army in selecting new defence vehicles

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Abstract: When the Australian Army requires new land combat vehicles to replace their legacy fleet, it is not simply a matter of swapping each old vehicle with a new one. Many competing factors play a role in determining which and how many vehicles to purchase. Our work forms part of the Australian Army's large Land 400 project, which seeks to find the best solution to this problem. In this paper we examine two situations requiring vehicles. In each situation we determine both the optimal number of vehicles and how best to use the vehicles. These two situations are the Area Search vignette and the Cavalry Screen vignette. In the Area Search vignette, vehicles are tasked with finding a specific target (for example, a bridge or an enemy troop) in a large area. The aim is to find this target in the shortest time possible, while minimising the number of vehicles used in the search. We consider three different search patterns called *Random, Zigzag* and *Spiral*. There are several parameters in this vignette including the size of the search grid, the number of search vehicles, the initial positions of the vehicles, the initial position of the target, and whether the target is stationary or moving. We conduct a comprehensive set of simulations in which we vary a subset of these parameters to determine the effectiveness of a given search pattern with a given number of vehicles. The effectiveness is measured by the number of time steps taken to find the target.

In the Cavalry Screen vignette, an object (for example a battalion or a building) is screened by a number of vehicles. The vehicles in the screen provide surveillance and gather information on any approaching enemy troops that may pass through the screen, while remaining undetected themselves. The aim is to find the best placement within the screen of a specified number of screening vehicles. We measure the effectiveness of a particular vehicle placement pattern by the proportion of enemy vehicle paths (from a pre-specified collection) that have a probability of detection of 0.5 or greater when passing through the screen. We use simulation to evaluate the effectiveness of three different vehicle placement patterns (*Random, Evenly Spaced* and *Zigzag*) for varying numbers of screening vehicles. To find an optimal placement of vehicles within the screen we use a probabilistic search technique called Cross-Entropy Optimisation, which generates many different vehicle placements by using a probability distribution P. At each iteration of the Cross-Entropy Optimisation method we use a selection of elite solutions to update P and thus converge to an optimal vehicle placement pattern.

We develop a simulation of each vignette, which can be used to explore how different vehicle numbers and vehicle abilities affect the outcome. Our recommendations to the Defence Science and Technology Group (DST Group) will assist them in deciding on the numbers and types of new vehicles to purchase.

The research described in this paper arose as part of the 2014 Mathematics Clinic at the University of South Australia (UniSA). The Mathematics Clinic is a year-long team-based sponsored research project undertaken by final-year mathematics undergraduates. The Mathematics Clinic offers a rigorous research experience in tackling real-world mathematics problems sourced from industry and with support from academic advisors. The Defence Science and Technology Group was the sponsor for the 2014 Mathematics Clinic project.

Keywords: *Simulation, cross-entropy optimisation, defence, undergraduate research*

Constraint-Based Heuristics for Amphibious Embarkation Planning

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Abstract: An important problem when planning an amphibious operation (the transportation and landing from the sea by army units) is how to optimally pack items onto a ship's deck. The items are typically dominated by vehicles, and the deck is usually a vehicle deck. This *amphibious embarkation planning problem* can be represented as a *packing problem*.

The packing problem is concerned with placing a set of items (rectangles), of varying length, width and mass, onto a ship deck (a larger two-dimensional rectangular space). An item can be positioned on the deck if it is entirely contained within the deck space and does not overlap with any other packed item. Each item can only be positioned according to its given orientation, and therefore, no rotation is permitted.

In addition the following constraints can be imposed:

1. **Priority ordering**: Items are positioned on the deck in order of priority. This can be considered in situations where items need to be unloaded in a particular order.
2. **Mass distribution**: Ensures that the centre of mass of all packed items is within a given distance to the centre of the deck.
3. **Mass threshold**: Loading constraints may preclude heavy items from being packed on the deck.
4. **Obstacles**: Accounts for the presence of inherent natural barriers and/or obstacles on the deck, around which an item can be placed without overlapping.

The objective of the packing problem is to minimise the total unused space on the deck. To obtain solutions, two constraint programming based heuristics have been developed:

1. **Aggregation**: This heuristic merges identical items from a priority list before they are packed. Aggregation can take place along an item's width or length axis, and the aggregation routine can be called multiple times. The heuristic loops through the priority list, making comparisons between the characteristics of adjacent items. When two adjacent items have the same dimensions and mass, they are aggregated into a single item. Aggregating items may help to improve the speed and efficiency of search, as reducing the number of items to be packed can significantly reduce the size of the search space.
2. **Sequential packing**: This heuristic uses a series of warm-start solutions with position restrictions placed on items that have already been packed. Utilising the sequential packing heuristic can prove beneficial in cases where only local moves of items need to be considered. When there are only a few items to be packed they can be feasibly placed in almost random locations. It is important, therefore, to ensure that the items can move around to more optimal locations. This is accomplished by giving a generous movement allowance early on in the sequence and then slowly limiting that allowance as the sequence progresses and the density of packed items increases.

The heuristics have been implemented in a Java-based software package called the Constraint Optimisation Packing Tool (COmPacT). The heuristics are underpinned by the constraint programming solver from the *IBM ILOG CPLEX Optimization Studio*. COmPacT was written to facilitate concept exploration and to compare various modelling and algorithmic approaches to the amphibious embarkation planning problem.

We outline the application of the constraint-based heuristics to a variety of test problems. The computational results of different implementations of the heuristics are also compared.

Keywords: *Constraint programming, embarkation planning, heuristics, packing problem*

Is the Contested Urban Networked Littoral Environment a Step too far for Agent-Based-Modelling?

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Abstract: The broad Defence problem addressed by our current work is, *how do we handle the expansion of our modelling requirements to deal with violent conflict in contested urban environments (CUE)?* Guidance regarding the relevance of the CUE from the upper echelons of Defence with Chief of Army endorsement, can be found in the Modernisation and Strategic Planning Division Staff's Future Land Warfare Report (FLWR) (MSPD-Staff, 2014), and in Kilcullen's (2014) *"The Australian Army in the Urban Networked Littoral"*. Both echo a similar message that future military operations are most likely to be held in highly networked littoral CUE, where the degree of complexity of such environments is far beyond that of conventional force-on-force engagement.

With regard to the operating environment FLWR (MSPD-Staff, 2014) indicates that the environment for future operations has five meta-trends; *crowded*, *connected*, lethal, collective, constrained. The term '*crowded*' encompasses a range of factors that interplay to create complex human, informational and urban physical terrain, including urbanisation, rural to urban migration, population growth, resource scarcity and environmental and regional political instability. The term '*connected*' refers to the flattening effect of the interconnected global economic, social and communications systems. It is Kilcullen's (2014) *seminal* observation, that the central novel feature is the highly *networked* nature of the urban world, which encompasses complex flow systems of trade, people, idea-systems, information with competition for not only territory, consisting of the natural land and built environs, but the built environment services such as, water, electricity, transportation, communication and the like. The competition does not, however, stop there; it is also a competition for idea-systems in what some have called the *"battle for ideas"* (Clarke, 2004). Many interrelated factors contribute toward population movements toward littoral mega-cities, upon whose physical terrain, exist turbulent seas of complex flowing dynamic topologies which we term the *human-terrain*.

This discussion paper attempts to start an exploration of the issues involved in studying violent conflict in the *uncertain complex CUE*. A small multi-disciplinary-team has been formed within LD and JOAD with an initial focus on the Knowledge Representation (KR) of littoral urban environments for highly networked actors within an Agent Based Model (ABM) and other simulations. We suggest, based on previous work of Johnson and Ivancevic (2013; 2015), two psychological constructs which may well be applicable to ABM for either beauty of KR or computational efficiency.

The current work is being conducted as a horizon survey within the frame of unbounded systems thinking (UST) due to Mitroff and Linstone (1993). With regard to world views, in addition to the traditional perspective of science/technology, the *Technical T* perspective, two other perspectives are taken into account in deciding what action to take next. They are the *Organisational O* perspective of the social-entity and the *Personal P* perspective of the self/individuation. It is a challenging approach in which everything is connected to everything and none of the sciences or professions involved in a study is considered fundamental.

Against this frame the sociological stance is considered at some length and seven basic aspects of sociological theory are introduced (Macionis and Gerber, 2010); *culture*, *society*, *socialisation*, *social interaction* in everyday life, *groups and organisations*, *sexuality and society* and finally *deviance*. We recommend that in highly networked urban environment that the sociology discipline be considered for modelling social-interactions, including emotions and language, within and between various social-groups for studies of future military operations within CUE. Finally, some difficult questions, from a UST point of view, are raised for using ABMs with respect to making progress towards defence outcomes.

Keywords: *Agent-based-model, contested urban environment, unbounded systems thinking*

Bobbing up and down like this: weather data as a predictor of patrol boat hull strain measurements

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Abstract: Driving a boat in high seas causes hull strain. Hull strain can cause fatigue and costly damage. The Royal Australian Navy (RAN) has a fleet of 14 Armidale Class Patrol Boats (ACPBs) – 57 meter, aluminium hulled patrol boats. The primary role of the ACPB fleet is border and fisheries protection on Australia's northern approaches. The ACPBs have suffered structural damage as a result of prolonged high operational demands.

In this paper, we investigate the feasibility of using weather data to predict hull strain measurements in patrol boats. The weather data is sourced from the Bureau of Meteorology and contains the values of various wave attributes (e.g. wave height and period) across the world's oceans. The weather data is combined with Global Positioning System location data to develop a weather experience profile for a given ship. The reference strain data used in this study is a derived measure, "*slams* per hour", and was generated by the Defence Science and Technology Organisation's Maritime Division for the purposes of a separate study. The measure is based on sensors placed on board ACPB *HMAS Glenelg*. This study required the use of interpolation, linear regression and big data techniques such as machine learning to investigate the interrelation of the data sets.

Current methods of detecting ACPB hull damage require a ship to stay in port for several days while engineers manually investigate indicators of fatigue. During these maintenance periods, the ship and crew are unavailable to engage in operations and this results in reduced fleet capability. The approach discussed in this paper would allow maintenance inefficiencies to be reduced as a ship would potentially only require manual inspection when its weather experience profile indicates necessity.

The ACPB fleet has an approximate whole of life cost of $1 billion; finding efficiencies in the maintenance cycle has the potential to save the RAN millions of dollars.

Keywords: *Mathematical modelling, data science, defence, Navy, weather, hull fatigue*

A Stochastic Scheduling Approach for Maintaining Capability Interdependencies and Defence Program Investment

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Abstract: Defence decision-makers are faced with the problem of scheduling and allocating funds to sustain identified capability priorities. Subsequently, an integrated Defence Capability Plan (DCP) is then prepared based on these capability development directions. The DCP is a living document influenced by a range of domestic and international factors. It contains projects and sub-projects which have a large number of interdependencies between their milestones. Any change to the DCP or a desire to find potential savings in the early years of the planning horizon brings about a rescheduling requirement. This may be viewed as a complex, multi-criteria decision problem that is amenable to balance of investment mathematical approaches directed at maintaining and observing capability interdependencies.

We first assume all inputs in the model are static and unchanging then formulate it as a mixed-integer linear program. Our mathematical programming approach is designed and implemented as a scheduling tool using public software to allow the required calculations to be completely automated.

We then provide management or decision makers flexibility in the optimal decisions by accommodating uncertainty of inputs (if for example at entry to the DCP a *funding band* might be provided until the project work is initiated or the project enters the Forward Estimates period of the 10 years budget plan) using Monte Carlo simulation together with optimisation. The uncertainty factor can be represented with probability distribution functions (such as Normal, Triangular, etc.) so that a simulation can be run for each trial schedule, then the output of the simulation are applied in the static model and optimal scheduling data computed. By repeating this process over a number of trials we can estimate the mean and variance of key forecast statistics. Instead of obtaining single-point estimates from the optimisation model, we can now obtain a distribution of the decision variables and hence, a range of optimal values for each decision variable. This provides a form of risk analysis in support of decision making.

Finally, a typical analysis and numerical experiment are demonstrated with general guidelines to consider when using the scheduler tool. The analysis using this mathematical optimisation approach with Monte Carlo simulation can be used to present the least disruptive reschedule for various budget levels and a precision level to make decisions about the budget saving.

Keywords: *Project scheduling, mathematical programming, Monte-Carlo simulation, decision support tool, Defence capability plan*

Algorithmic complexity of two defence budget problems

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Abstract: A fundamental challenge in the development of defence capability is to decide on a collection of projects that represent the best value within a given budget constraint. A complicating factor in doing this is taking account of the inter-relationships between projects when assessing value. We investigate two such models. The first assigns value based on subsets of projects that come together to provide effects, the second assigns value through the intermediary of scenarios. In terms of recognized combinatorial optimization problems the first is a form of the Set Union Knapsack problem while the second appears to be a new problem we call the Budget Scenario problem. We analyse the known results about the algorithmic complexity of these problems by showing their relationships with existing problems and known approximation and inapproximability results. We also provide new approximation results for both problems. The main results of this paper are summarised as follows.

When prospective projects mature into operational capabilities they typically come together in subsets to provide joint effects. Thus capabilities that work together and depend upon eachother provide extra value than that provided by each capability in isolation. It seems natural then to balance the cost of a collection of projects against the value provided by the subsets in the collection. This problem is a form of the Set Union Knapsack Problem which generalises a number of well known combinatorial problems in two broad classes. The Knapsack, Subset-Sum and Partition problems have a *polynomial time approximation scheme PTAS* (see Garey and Johnson (1979) and Vazirani (2003)). That is for any given $\epsilon > 0$ there is an algorithms that approximates Knapsack to within $1 - \epsilon$ of the optimal with a run time that bounded by a polynomial of the input size. Further it has a *fully polynomial time approximation scheme FPTAS* with an approximation algorithm with run time bounded by a polynomial of both the input size and $1/\epsilon$. On the other hand Quadratic Knapsack, Weighted Clique, maximum Edge Weighted Clique, and Densest k-Subgraph does not admit a PTAS assuming that random 3-SAT formulas are hard to refute Feige (2002), or if NP does not have randomized algorithms that run in sub-exponential time Knot (2004). On the positive side there is an approximation algorithms for DkS that is within the ratio $O(n^{1/4+\epsilon})$ of the optimal and runs in time $n^{O(1/\epsilon)}$ Bhaskara et al. (2010). We show that the The Set Union Knapsack Problem with subsets of size at most m has an approximation algorithm with run time of at most $O(\frac{n^{m+2}}{\epsilon})$ with an approximation ratio of at least $\frac{m!(1-\epsilon)}{n^{m-1}}$.

In the Budget Scenario problem a list of initiatives is provided each with an anticipated cost. Each initiative is scored against a number of scenarios with a value indicating how useful the initiative is against that scenario. For a collection of initiatives the total value is calculated by summing the best value obtained by any initiative for that scenario in the collection. This initiative can be thought of as the best tool in the toolbox (collection) for the particular job (scenario), while the total value reflects the ability of the toolbox (initiative collection) to address any single job (scenario). The Budget Scenario problem is shown to generalise the established problems of Budgeted Maximum Coverage, Maximum Coverage, Weighted Set Cover and Set Cover. In Khuller, Moss and Naor (1999) an approximation algorithm for Budgeted Maximum Coverage is presented and shown to provide an approximation factor of $(1 - \frac{1}{e})$ of the optimal solution. On the other hand all of the problems in Figure 2 are NP-hard. Also Khuller, Moss and Naor (1999) and Feige (1996) show that if Maximum Coverage, respectively Set Cover is approximable within a factor of $(1-\epsilon)\log n$ for any $\epsilon > 0$ then $NP \subseteq DTIME(n^{loglogn})$. It follows that the same must be true of Budget Scenario, Budgeted Maximum Coverage, and Weighted Set Cover. We prove that for any given $\epsilon > 0$ the Budget Scenario Problem $G(X, Y)$ has a polynomial approximation algorithm that achieves a factor of $(1 - \frac{1}{e} - \epsilon)$ of the optimal solution.

Keywords: *Set union knapsack, budgeted maximum coverage, approximation, inapproximation*

Optimisation Model for Defence Investment Planning – A Goal Programming Approach

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Abstract: Defence investment planning involves selecting a portfolio to invest in order to address a mix of strategic objectives. In Defence applications, the portfolio may be called the project list, the program, the system of systems, or the enterprise. The selection of a Defence investment portfolio is a complicated decision-making problem in which several (conflicting) objectives must be achieved simultaneously and many issues such as project interdependencies, resource and system constraints must be considered.

Mathematical formulation of the portfolio selection problem is usually described with a multiple-objective decision making problem (MODM). Traditionally, multiple objectives are converted into a single objective optimisation problem by the weighting method and the ε-constraint method. The weighting method transforms a set of objectives into a single objective by multiplying each objective with a user-supplied weight. On the other hand, the ε-constraint method selects one objective as primary and the others as secondary. The primary objective is used as the optimisation objective function, while the secondary objectives are assigned acceptable minimum or maximum values and are treated as problem constraints. However, if careful considerations were not given while assigning the weight for the weighting method and the acceptable objective levels for the ε-constraint method, a feasible solution that satisfies all the constraints may not exist, especially when the conflicting objectives are considered.

This paper aims to explore the possibility of using a Goal Programming (GP) approach to overcoming the above difficulties in the Defence portfolio selection problem. In formulating a GP, all the objectives are assigned target levels and a relative priority on achieving those levels. GP treats those targets as goals to aspire for and not as rigid constraints. It then attempts to find an optimal solution that minimise the non-achievements of the corresponding goals.

A small example is presented to illustrate the approach of applying GP to the selection of a Defence investment portfolio. A GP model for portfolio optimisation across a multiple year planning horizon is proposed. The model takes account of objectives for achieving the optimal portfolio values and keeping the project portfolio cost "as close as possible" to the allocated budget. It also respects the project interdependencies, mandated projects and other system constraints. The optimisation model can be solved efficiently using the Solver function within Microsoft Excel 2013. The input data are based on a real case of selecting a Command, Control, Communication, Computer, and Intelligence (C4I) investment portfolio.

The computational results have shown that:

(1) The proposed GP model can provide the optimal C4I portfolio results which reflect the preference of the Decision Maker and respect the project interdependencies and other constraints;

(2) In comparison with the single-objective linear programming result, the GP results can generate a better C4I portfolio value, but also allocate the project funds more close to the available budget; and

(3) While the method is primarily illustrated by a one-year planning example, the proposed multiple-year extension of the GP model has also demonstrated the feasibility of the GP model for the portfolio selection for a multiple-year planning horizon.

Further extensions of the Goal Programming portfolio selection model may include the integration with other methodologies such as Analytical Hierarchy Process and the "value –focused thinking". Those extensions would allow the GP model to be adapted to address a variety of Defence decision-making problems such as Force Design and Defence capability acquisition.

Keywords: *Goal programming, portfolio selection, multi-objective decision making*

An Overview of Analytic Wargaming in the U.S. Department of Defense

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Abstract: There are still many “wargames” being conducted in the U.S. Department of Defense (DoD) that are little more than BOGGSATs (bunch of guys and gals sitting around a table). Deputy Secretary of Defense Bob Work highlighted this in a recent (9 February 2015) DoD memo “Wargaming and Innovation” where he stated: “To … avoid operational and technological surprise, and make the best use of limited resources, we need to reinvigorate, institutionalize, and systematize wargaming across the department.”

Wargaming is often defined as “a warfare model or simulation in which the flow of events shapes and is shaped by decisions made by a human player or players.” We differentiate analytic wargaming from other wargaming purposes (e.g., training or educational wargames) as such: “Analytic wargames are designed to collect and analyze information from wargame play, and these results either feed directly into a decision, or are used to develop other analytic products (Appleget and Cameron, 2015).”

Wargames are often combined with other analytic tools, such as computer-based combat models and simulations (M&S). Outputs of analytic wargames can serve as the operational foundation for computer-based combat simulation analysis. Analyses of Alternatives and Campaign Analysis are often completed using both wargaming and computer-based combat M&S.

We offer a sample of best and worst practices, using the basic framework for wargame creation as a guide:

Problem definition:

- Worst Practice: Accepting the sponsor’s initial objective and issues without clarification or scoping.
- Best Practice: Develop a continual dialogue with the sponsor and negotiate the appropriate scope of work so both parties agree what will be delivered and on what time line.

Design:

- Worst Practice: Designing a game without an analysis plan
- Best Practice: Create a Data Collection and Management Plan (DCMP) that decomposes the sponsor’s objective and issues into the information that the wargame will be required to obtain from its players.

Development:

- Worst Practice: Conducting a game without ever play-testing it
- Best Practice: Get a quick and dirty game design completed, play it and find where it doesn’t work.

Conduct:

- Worst Practice: Failing to plan for contingencies (the game will go exactly as planned)
- Best Practice: Developing injects and vignettes as needed to ensure the DCMP is completed.

Analysis:

- Worst Practice: Relying solely on the players’ memories to provide the basis for the analysis.
- Best Practice: Creating a detailed DCMP and contingency data collection methods to gather the information from the players required for the analytic products.

Keywords: *Wargaming, Campaign Analysis, Analysis of Alternatives, simulation, Defense*

The use of human-in-the-loop and constructive simulation to support operations research into MH-60R tactics development

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Abstract: Joint and Operations Analysis Division (JOAD) of Defence Science and Technology Group (DST Group) is currently tasked by the Royal Australian Navy (RAN) to provide operations research (OR) support to tactics development for the MH-60R 'Romeo' maritime combat helicopter in the Australian context. This is part of the Romeo acquisition and introduction into service process, as it is integrated into Australia's force-in-being.

JOAD employs a number of OR techniques of varying fidelity to support tactics development, with the selection of methods depending on the nature and complexity of the requirement. One of the approaches employed extensively is the complementary use of human-in-the-loop (HIL) and constructive simulation. Several studies have been conducted using this approach to examine and compare the effectiveness of various Romeo tactics over a range of operational environments and requirements.

Accurate elicitation of tacit operator knowledge is known to be a difficult problem. The DST Group-developed Synthetic Human-in-the-loop Air 7000/9000 Research Program (SHARP) provides a framework in which to expose operators to an interactive real-time simulated mission. SHARP provides an immersive environment in which the operator can explore various tactical employment options in real time. Information can be captured describing critical decision points and the operators' decision-making processes during the mission. This information then forms a baseline for first modelling, then simulating, operator and other human behaviours within the context of the mission using a constructive simulation framework. This approach can be utilised to explore existing defence capabilities or new technologies and concepts. The DST Group-developed Combined Helicopter OPerational and Performance Analysis (CHOPPA) constructive simulation framework supports Monte-Carlo simulation and analysis of complex mission scenarios at timescales that are orders of magnitude faster than real-time. Friendly, neutral and enemy platforms, weapons, sensors, communications effects, human behaviours and the operating environment are all mathematically modelled in CHOPPA at varying levels of fidelity. The results of these constructive simulations facilitate a robust statistical analysis to inform tactics development for the RAN.

By using these tools to examine operational issues for the Romeo, DST Group is directly contributing to improving operational effectiveness, enhancing Australia's military capability and ensuring value for money for the RAN.

This paper presents a summary of the SHARP and CHOPPA simulations, their complementary use and the type of study outcomes produced in an example study exploring Romeo tactics development.

Keywords: *Human-in-the-loop simulation, constructive simulation, modelling, operations research, elicitation*

An Exploratory Study Using Agent-Based Distillations to Investigate Reconnaissance Scenarios in Support of Higher Fidelity Combat Simulations

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Abstract: Combat simulations and wargames form part of a suite of tools used to analyse complex military problems. The fidelity of this suite of tools varies in terms of their representation of both physical parameters and military doctrine. Higher fidelity models often have associated resource and computational constraints which makes exploring large regions of the parameter space infeasible. An approach known as operational synthesis employs low fidelity agent based distillation (ABD) models to rapidly search this parameter space in order to identify areas of interest for further exploration in higher fidelity models.

In this study we use the Map Aware Non-Uniform Automata (MANA) ABD model to gather additional insights for a reconnaissance study that was conducted in a higher fidelity combat simulation known as COMBATXXI (CXXI). The CXXI study investigated the potential impact of variations to platform mobility, sensors and signatures on the effectiveness of land combat vehicles conducting an observation task against an airfield and a river crossing point. An existing MANA scenario was used to explore the impact of factors not considered in the CXXI study, specifically, variations to both observation post placements and schemes of manoeuvre.

The MANA model identified the same trends in relation to mobility and signature that were identified in the CXXI study. The results from the additional variations performed in the MANA model showed a significant difference in the number of observations when a more aggressive and direct scheme of manoeuvre was employed and where alternative observation post locations were used. We explore these results further by implementing them in CXXI in order to provide greater confidence in the findings and further insights into the magnitude of the differences.

Keywords: *Agent-based modelling, Defence, simulation, operations analysis*

No Fifteen Thousand Men: An Agent-Based Replication of Pickett's Charge

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Abstract: The assault known as Pickett's Charge (at the Battle of Gettysburg, on 3 July, 1863) was a key event in the US Civil War, ruling out a victory by the Confederate States of America. Being well-documented, it is also a good candidate for replication using simulation.

Confederate General James Longstreet had advised Robert E. Lee against this assault, saying "General, I have been a soldier all my life... and should know, as well as any one, what soldiers can do. It is my opinion that no fifteen thousand men ever arrayed for battle can take that position." Although the eventual assault involved fewer than 15,000 men, events were to prove Longstreet correct.

To demonstrate the utility of agent-based simulation for modelling military engagements, we have constructed an agent-based simulation of Pickett's Charge in NetLogo, beginning after the end of the (largely ineffective) Confederate artillery barrage (see Figure 1), and using realistic estimates of unit strength. Key model parameters were:

- *union-musket* and *confederate-musket* – the effectiveness of Union and Confederate musket fire;
- *canister-hits* and *artillery-hits* – the effectiveness of Union canister and long-range shell fire; and
- *ave-withdraw* – the mean casualty level at which a unit will withdraw.

Model error was assessed using five numbers calculated by George Rippey Stewart in his 1959 book *Pickett's Charge*: Confederate musket casualties, Confederate long-range shell casualties, Confederate canister casualties, Union musket casualties, and the number of Confederate troops crossing the "high-water line" (historical values 5,000, 500, 1,000, 1,500, and 300, respectively). We performed 100 runs for each of 378 parameter combinations, some of which are shown in Figure 2.

The parameter combination with the lowest model error gave a good fit to the casualty figures (see Figure 3). However, out of 1,000 runs, only 45.6% had Confederate troops crossing the "high-water line," with an average of 345 troops making it across in those cases (i.e. an overall average of 157 troops), compared to the historical value of 300. This suggests that the ability of Confederate troops to cross Union lines at all was either an accident of fate, or the result of the (unmodelled) leadership ability of General Lewis Armistead, who led the Confederates across the stone wall marking Union lines.

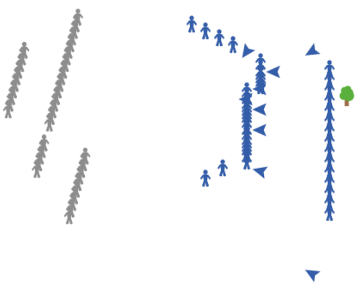

Figure 1. Initial agent positions in the NetLogo model. Arrow symbols show Union cannon, while the tree marks the "aim point" for Confederate troops.

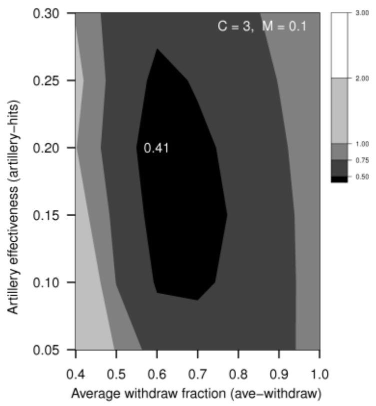

Figure 2. Values of the overall model error for some parameter combinations of *artillery-hits* and *ave-withdraw* (averaged over 100 runs each). Here *canister-hits* = 3 and *union-musket* = *confederate-musket* = 0.1.

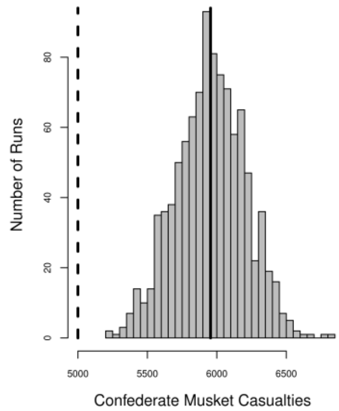

Figure 3. Confederate musket casualties for 1,000 runs with parameters giving the lowest model error. The mean of 5,955 ± 8 (solid vertical line) is close to the historical value of 5,000 (dashed line). Other casualty scores have similar results.

Keywords: *Pickett's Charge, Gettysburg, agent-based simulation, military simulation, NetLogo*

From System Thinking to Capability Thinking using the Thinking Capability Analysis Technique

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Abstract: System Thinking (ST) attempts to understand how different system components come together to form the overall whole of a system. This has proven to be a very valuable approach to study and understand complex systems; especially, complex socio-technical systems. In this context, a system exists for a purpose. This purpose is usually defined in the eyes of the beholders: external observers that need to make a judgement on what the purpose of the system is.

A capability is the capacity to generate an effect. It is made up of building-blocks of systems known as fundamental inputs to capabilities (FICs). In essence, a capability is a system of systems. A capability definition departs from a system definition in that the purpose of a capability (effect generation) is an integral part of the definition; that is, a capability can't be defined in isolation of the effects it is meant to generate. In essence, the type of effects a capability needs to generate needs to be part of the design and should not be merely left for an external observer's judgement. Therefore, CApability Thinking (CAT) focuses on how systems build the energy and capacity required in a system of systems to generate effects.

In this paper, CAT will be explored and discussed through similarities and differences to ST. We will then present The Thinking Capability Analysis Technique (TCAT) which extends the Function Analysis System Technique (FAST) in System Engineering. FAST has demonstrated a great deal of success as a decision aiding tool to map out functional interdependency for Requirement Engineering. TCAT replaces the *how* question in FAST with *enablers*, it extends the notations to include *responsibility* or the *whom* question to simultaneously establish a line of accountability, and increases the flexibility of the representation to cover multiple scopes. TCAT will be illustrated using an example on soft capabilities.

Keywords: *Capability thinking, system thinking, thinking capability analysis technique*

Feasible Scenario Spaces: a new way of measuring capability impacts

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Abstract: The future is unknowable, but organisations can still prepare for it. Traditional scenario methods do this by constructing a set of scenarios representing the critical uncertainties associated with the future. Scenarios are points or small regions within a large multi-dimensional space of possible futures. Options are tested against these scenarios to determine how they perform. For example, the Australian Department of Defence tests proposed capability sets using the Australian Capability Context Scenarios (ACCS), representing hypothesised critical uncertainties about future operations.

The ACCS represent only a small part of the space of all possible futures and any assessment against them provides only a limited view of how a capability will perform in the future. Rather than evaluating options against proposed scenarios we propose asking "what parts of the scenario space does a given capability set allow you to achieve with acceptable risk?" defined as the Feasible Scenario Space (FSS).

Unfortunately, as you move further into the future, the scenario space gets larger as there is more uncertainty of what the future might look like. This makes defining the FSS through exploration of the scenario space much more resource intensive. To make the assessment of options tractable we propose focusing on the scenarios (the key approved futures), the ACCS in the case of Defence, as the seed locations to start this search. The options are then compared based on the size of the hyper-volume surrounding the scenarios in which a given capability set presents an acceptable risk. The edges of this hyper-volume are estimated by testing options against points along each of the critical uncertainties moving out from each given seed scenario until a breaking point is found.

The FSS is defined as a surface which covers the set of scenario parameters for which a given capability set can achieve success, within acceptable levels of inherent risk.

This paper provides a detailed definition of the FSS and explains how to describe it within a multi-dimensional scenario space and how to test for the risk boundaries. An illustrative example is provided to show of how this approach would be applied.

Keywords: *Force design, scenario analysis, modernisation*

EXTENDED ABSTRACT ONLY

The Application of the Australian Defence Architecture Framework to Maritime Force Assessment

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Abstract: A Maritime Force Assessment Framework (MFAF) has been proposed to provide a consistent ontology for Operational Analysis (OA) that addresses Australian Defence capability needs. The MFAF provides a standardised framework to facilitate collection of information and presentation of consolidated results to senior decision makers. It should support the systematic and consistent evaluation of the capability of current and future (out to 20 years) maritime force structures and other inputs to capability, to deliver mission outcomes. It is desirable that the MFAF is compatible with emerging Australian Defence Organisation (ADO) standards, in particular the Australian Defense Architecture Framework (AUSDAF 2.0). Project activities that change the state of the military system itself, for example the activity of designing a ship, are outside the scope of this work. This paper discusses some experiences gained in developing and applying the MFAF.

The MFAF development was informed by the US Department of Defense Architecture Frameworks Meta Model (DM2). AUSDAF 2.0 is completely consistent with DoDAF 2.0, being directly derived from it, and hence the MFAF is assessed to be consistent with AUSDAF 2.0. A number of Core Entities were selected from the DM2 which were useful to the definition of maritime capability needs such as Activities, Desired Effects and Conditions. Combinations of these were formed to define additional, composite, entities also used when conducting OA. Examples of these composites were Scenarios, Allocated forces, Missions and Critical Operational Issues.

The Maritime Capability Analysis Branch has conducted a number of workshops to collect information from Subject Matter Advisors (SMA). SMA's identified and prioritised potential issues with current and future Navy force capability; these issues then became candidates for further OA studies. The entities used in the data collection framework were selected to match the needs of the SMA and senior decision makers. Combinations of MFAF entities were needed to make them compatible with the way they view the problem domain. However the combinations of core entities being used must be identified clearly. Desired Effect is a DM2 core entity defined as "A desired state of a Resource". An example of the sort of combination used in practice is "Defeat Enemy Submarine at a Choke Point". This is a combination of a Desired Effect; "Defeated" (Desired State), "Submarine" (Resource) and in addition a Location entity "Choke Point".

Entities used for the workshops included a Scenario (defined as the set of conditions under which activities are conducted for an operation), an allocated blue force and a blue force course of action (defined in DM2 as "A path towards a goal"). Another essential entity was the "Mission", defined in DM2 as "The task, together with the purpose [Desired Effect] that clearly indicates the action [Activity(s)] to be taken and the goal [Desired Effect]".

Many of the composites discussed above are directly useable in the workshops. However for some, including Activities and Effects, non-ideal combinations were required to take account of the way the stakeholders viewed the domain. The Activities to be undertaken and Desired Effects must be specified, however to make these comprehensible to the stakeholders these needed to be combined with other entities. Conversely it was necessary to separate out the Desired Effect from the Mission. A Mission Type entity was therefore created; with a Mission being defined as a combination of a Mission Type and a Desired Effect.

In the past, some activity taxonomies (task lists) have been produced on an ad-hoc basis. These all have issues in that none are purely activities, as defined by DM2, but are often inconsistent combinations with other entity types or may not obey principles regarding hierarchies. A hierarchal set (taxonomy) of Activity and other Entity combinations has been devised using Australian Joint and Maritime doctrine; these have been used and refined in a number of assessment activities. The latest list is the Maritime Operations Tasks (MOTS) Version 4.0.

Keywords: *Maritime Operations, taxonomies*

Beyond why to what and how: the use of systems thinking to support problem formulation in systems engineering applications

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Abstract: Systems thinking is a transdisciplinary research field which provides a powerful framework (i.e. theories, methodologies, and methods) for systems engineers to deal with the complexities of problem formulation. In this paper, we are motivated by the valuable benefits that systems thinking can contribute to theory and practice of requirement engineering. At a theoretical level, systems thinking is an intellectually rich domain of theoretical stances on how to build a systemic understanding of complex situations. Each of these theories offers a unique perspective on the problematic situation. For practice, using a systems approach offers a variety of approaches and techniques to serve different purposes (e.g. exploring purpose, bringing in different viewpoints, building consensus) and problem framing phases (e.g. identify issues, assess alternative solutions). This paper is intended for system engineers (researchers, practitioners, students) who are interested to know about systems thinking, and how it may contribute to understanding and framing complex situations, and identifying stakeholders' needs. First, we review the literature on systems thinking in the systems engineering field. We provide a discussion of these studies as there have been limited discussions and understanding of the use of systems thinking in the systems engineering literature. The overview of literature shows a gap in applications of the systems thinking ideas and methods in literature. Second, we develop a preliminary framework which brings together a holistic repertoire of systems thinking concepts and methods from different paradigms. The primary purpose of the framework is to: (1) provide a systems thinking-grounded view of the requirement elicitation process, (2) raise awareness about the variety of available systems thinking, their theoretical background, and how they can contribute to the process, and (3) provide insight into the practice aspects of these methods, including their: strengths, limitations, expected outcomes, and potential of combining them with other methods. The framework is based on critical systems practice theory. In practice, whenever faced with a task in a particular situation through inquiry process, a practitioner who is aware of the various theories and is equipped with an armory of methods and tools, will be able to assess the fitness of methods to the context. As the situation changes, some issues disappear and new issues emerge, the analyst will continually cycle around the phases of creativity, choice, and implementation in an ongoing quest for learning about the situation and the purpose of the proposed solution. The presented framework is theory-driven, and has not been applied and tested in real-life systems engineering applications. Future applications will help improve the framework based on an empirical understanding of 'what works' and 'what does not work' in 'what context'.

Keywords: *Systems thinking, systems engineering, critical systems thinking, requirements elicitation, needs analysis*

Improvements in Analysing Failure of Defence Systems for Operations Analysis

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Abstract: Fault Tree Analysis (FTA) is an established process for predicting the results of events on systems. Defence Science and Technology (DST) Group apply FTA to analyse the efficacy of helicopter Tactics, Techniques and Procedures (TTPs). In this context FTA allows the consequence of individual damage to be quantified. For example, what is the consequence of damage to the aircraft's left engine, ammunition bay and communications equipment? This provides quantified answers to the question 'does the TTP result in a higher chance of the aircraft completing its mission safely'.

This paper uses standard FTA terminology, consistent with the 'fault tree' analogy. The 'root' of the tree is the desired answer ('will the aircraft complete its mission safely?'), the 'leaves' of the tree are 'basic events' (e.g. the left engine has failed), the 'branches' of the tree are 'intermediary events' depending on multiple basic or intermediary events ('both engines have failed') and the logical gates for combining events to form new events are where the branches of the tree split. Conventionally when drawn as a diagram the 'tree' is usually drawn upside down with the 'root' at the top of the diagram.

Defence application of FTA is different to civilian application of FTA as Defence failure modes which result from adversarial intent differ from civilian failure modes. As Defence needs have developed it was necessary to build a more capable FTA suite, **FAU**lt **N**etwork **A**nalysis (FAUNA). FAUNA introduces NOT, INHIBIT, N of M and TRUTH gates that enable the analysis of more detailed questions and produce results with more impact. Examples of why these new gates are required are provided using the Armed Reconnaissance Helicopter as a case study.

FAUNA is available to DST Group staff on request, and has also been adopted by the Defence Science and Technology Laboratory (Dstl) in the United Kingdom. FAUNA is also available under commercial agreement.

Keywords: *Fault tree, system analysis, Defence, tactics, failure*

Towards Defence Strategic Data Planning

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Abstract: Defence generates and receives vast quantities of data in relation to the specification, development and intended operation of its capabilities and related decision processes. As an organisation, Defence has made good progress in the collection and availability of these types of data; however, the growing pace of technological advancement and the rapid evolution of the spectrum of potential adversaries mean that Defence must become even more effective and efficient in its data analytics to ensure agile decision making at all levels of the organisation. Achieving this objective requires focused strategic data planning, rigorous data design, speedy and accurate data collection, and effective data validation, processing, and management. Current Defence data management practices in Australia do not, for example, provide a unified asset identification number, nor a unified asset naming convention, leading to confusion and ambiguity in the provision of timely and accurate advice to decision makers. This is in part due to the lack of rigorous definitions, data structures and effective data management mechanisms and policies, making universal data integration difficult. This also increases the risk of inconsistencies between Defence's many data repositories. Based on reviewing data management practices of Defence organisation internationally, the authors argue that the Australian Defence Organisation needs an improved strategic data planning mechanism in order to develop a more holistic and effective approach to managing its capability-related data. We propose a framework based on review of the literature and best practices internationally, as well as our experience in analytical support of Force Design and capability-related decision processes, albeit being mindful of the evolving structure of Defence as the implementation of First Principles Review is taking shape. The value proposition of the framework is four-fold: (1) it proposes an iterative strategic data planning process that helps to improve the effectiveness and efficiency of data management in support of effective decision making, (2) it provides a set of guidelines for developing a strategic data plan, helping to facilitate and streamline data management across the organisation, (3) it provides guidelines for data design, collection, and management, as well as resource planning, and (4) it helps develop consistent capture of 'quality' information and other critical data required for Defence capability planning. Our framework is intended to be useful to strategic data planners and data managers working at different levels of Defence, and will also better support robust analytics for capability planning. This can, in turn, help reduce costs in data management but, more importantly, enhance Defence's capability development and trade-off decision processes.

Keywords: *Information management, data planning, strategic management, capability management*

Supporting Force Structure Review through graph visualisation and capability view improvements

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Abstract: Program Viewer is a prototype Defence decision support tool for whole of portfolio capability management that focuses on schedule, cost, personnel and capability. The tool has already supported a number of decision-making activities in Defence including the current and previous Force Structure Reviews. Close interaction with stakeholders has enabled access to a rich source of Defence portfolio data for populating a Unified Profile for DoDAF and MODAF (UPDM) (Hause, 2010) compliant repository. So far, Program Viewer has facilitated understanding of project costs and slippage, scheduled milestones and milestone relationships between projects, and potential issues (Bulluss et al., 2014, Lo et al., 2015).

Our software tool has been augmented herein with temporal graph visualisation (Lo et al., 2011, Lo et al., 2009) to support exploratory analysis of the taxonomy of Defence capabilities and capital acquisition projects juxtaposed with cost information. Through employing the Java universal network/graph (JUNG) toolkit (O'Madadhain et al., 2005), the prototype supports graph visualisation through (a) spring, (b) Fruchterman-Rheingold (1991), (c) Kamada-Kawai (1989), (d) circle and (e) Inverted Self-Organising Map (Meyer, 1998) layouts. Temporal mode enables users to visualise the graph evolving over time, gaining an improved understanding of relative budget allocation to projects on a year-by-year basis. By scaling node areas proportionally to project costs (total or on a yearly basis), relative budget allocation to projects can be quickly gleaned from the graph. Customisable node shape and colour, and ability to zoom and filter out data by context promote greater understanding of data from different perspectives.

An adapted capability view (CV-3) based on the DoDAF viewpoints has also been implemented. As project numbers within the repository increased, the understanding of project dependencies and inter-relationships has correspondingly become more complex. The CV-3 provides an improved contextual understanding of projects mapped against capability, simplifying the visualisation for decision-makers.

Our prototype tool provides a unique capability that merges data that is typically held locally within Defence groups, processes the information and provides visualisations that improve management of the whole-of-life capability systems lifecycle. The First Principles Review (2015) recommendations for enhancing performance and accountability of Defence capability acquisition and sustainment, and enterprise-wide information management have highlighted the need for improved focus in the area that Program Viewer seeks to innovate in.

Keywords: *Program Viewer, graph visualisation, adapted capability view, Defence portfolio-level decision-making*

Application of desktop human in the loop simulation to study air operations

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Abstract: While supporting the 2006 North West Shelf capability trial, Defence Science and Technology Organisation (DSTO) staff observed a Northrop Grumman virtual trial in which a surveillance scenario involving a simulated RQ-4B Global Hawk unmanned aerial vehicle (UAV) was conducted. From this trial DSTO identified a requirement to utilise human-in-the-loop (HITL) simulation to support acquisition and inform the development of tactics and concept of operations (CONOPS) for Project AIR 7000.

Development of an indigenous HITL simulation capability received endorsement through consultation with the AIR 7000 S&T Strategy Group and became the Synthetic Human-in-the-loop AIR 7000 Research Program (SHARP). The SHARP is now developed and managed by the Aerospace Capability Analysis (ACA) branch within the Joint and Operations Analysis Division (JOAD) of DSTO. The ACA has partnered with industry and used an agile development process to develop a mature, reconfigurable HITL simulation capability based on a distributed architecture and a standardised integration framework. The SHARP has become one of the analytical tools within an operations analysis process, which DSTO employs to assist the Australian Defence Force (ADF) to:

- develop tactics and CONOPS;
- model maritime intelligence, surveillance, reconnaissance and response (MISRR) roles;
- perform capability assessment;
- conduct problem exploration;
- investigate human factors issues;
- model operator inputs for constructive simulation; and
- validate constructive simulation outputs.

The CONOPS and tactics development life cycle (CTDL), is one of the main processes by which the ACA branch conducts operations research. It is an iterative process that integrates HITL and constructive simulation. The HITL simulation is used in the phase of problem development, where human operators are exposed to the military problem context within a simulation environment. The HITL simulation functions as a forum for military operators and researchers to resolve the problem into specific tactical options and their variants. The set of tactics and respective variants become inputs for the constructive simulation phase which performs robust analysis using Monte Carlo techniques. The output from the constructive simulation is passed through HITL simulation to test the veracity. This paper reports on the application of the CTDL within the ACA branch and provides examples where the SHARP has served as the HITL simulation capability. The paper also provides a summary of the design features within the SHARP that are used to achieve an agile desktop HITL simulation capability.

Keywords: *Human-in-the-loop, simulation, air operations, distributed architecture, agile*

Building and using an experimental Hadoop cluster

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Abstract: The volume of data being generated by real world sensors and simulations continues to increase. As the amount of data passes into the tens of gigabytes and beyond the ability to conduct even simple queries on a single machine is slowed greatly by disk read times. Over the last few years much work has been undertaken in developing ways to address this problem by developing systems such as “Apache Hadoop” and the “Amazon Elastic Compute Cloud”.

However, acquiring an off-the-shelf Hadoop system can cost hundreds of thousands of dollars and other solutions may not be available. For example, Defence is unable to transfer classified data into the Amazon Cloud. One popular approach amongst analysts who are also amateur computer scientists, is to build small Hadoop clusters from surplus hardware. This approach was adopted by a small team in the Defence Science and Technology Group where a cluster of 14 desktop computers was built for a very modest investment in new hard drives and RAM.

The first part of this presentation covers the development of the experimental system providing lessons learned and recommendations for others considering a similar cluster. Our experience suggests that the properties of the desired system can be determined by considering the following, in order:

1. Determine a desired number of CPU threads based on the desired speed-up factor
2. Determine the memory required per thread based on the maximum minimum efficient size of a map-reduce task
3. Determine the number of HDD per thread based on expectations about whether tasks will be CPU or read-write bounded
4. Determine the total HDD capacity required based on an estimate of the total data to be held
5. Keep the properties of all the nodes consistent to ease the cluster management burden
6. Determine the most cost effective way (CPU type, memory type, etc) to meet this requirement
7. Additionally, invest in a low-spec manager system.

Having developed a cluster using the above criteria, it has been used to support a number of studies. As such, this presentation will also discuss performance benchmarks and compare run-times of actual analytical tasks against a single machine and include a discussion of the impact of these improvements. These tasks have included the processing of more than 1 TB of simulation logs and conducting an analysis on tens of GB of sensor data.

Keywords: *Big data, analytics, Hadoop*

Defining and Developing Soft Capabilities within Defence

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Abstract: Capability is broadly agreed to mean the capacity or ability to achieve an effect. In military circles, effect is more precisely defined as desired operational effect. This is to ensure that capability has a purpose. A certain quantifiable usefulness that allows capabilities to be deconstructed, costed, compared and developed. Capability development, certainly within the well-recognised capability life cycle model used in various militaries and business, is founded on the premise that a capability is measurable. They are hard, tangible and generally easily recognised. But what about the capabilities that are not obvious? How do we describe those capabilities that generate tangible effects however are not themselves directly quantifiable?

Quantifiable hard capabilities are simple enough to understand, though perhaps complicated to develop. When designing and developing hard capabilities, organisations are travelling down a well-travelled highway lined with information, models, exemplars and warnings. A model commonly used to describe the development of capability, to achieve a specific effect, describes the Fundamental Inputs to Capability (FIC). FICs are used to describe the building blocks required for specific capabilities and, while they vary slightly between models, generally include people, organisational design, facilities, support structures, other major systems, common or collective training and policies. The use of these labels is a convenient way to understand the important building blocks however are FICs common across all types of capabilities?

Soft capability though, whilst intuitively understood by many, is not well defined in current literature. This paper seeks to present a synthesised understanding of soft capability from a range of subject matter experts in capability development. The study explored the characteristics, inputs and examples of soft capability as understood by experts in the field. The results of the research demonstrate that soft capability is different to other capability types commonly referred to in literature. The conclusion is that soft capability is a valid capability type that has, to date, been ignored in literature.

Keywords: *Soft capability, capability development, military capability, soft operations research, operational effects*

Exploring the Intrinsic Dimensionality of Survey Responses

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Abstract: We recently completed an organisational study of a branch within a busy operational military headquarters. This paper explores methodological issues of survey design in the light of statistical analyses carried out on responses to the survey.

While at the outset of the study senior branch management perceived that various issues impacted on performance, there was no clear problem definition. In designing the study we thus needed to examine the branch's workflows, processes and interactions at the individual, team, section and whole branch level; acknowledging the importance of teamwork, this became a particular focus. With no clear statement of the problem, the survey also had to be exploratory in nature, attempting to uncover various issues that may have an effect on performance. The survey comprised seven initial themes – resources, empowerment, cognitions, culture, communication climate, information flows and teamwork – plus two further themes (strategy/goals/objectives and sections) that emerged as salient issues following preliminary analysis. In total the survey consisted of 76 statements, each of which was associated with a particular theme; the 74 respondents were asked to indicate their strength of agreement with each statement on a five-point 'Likert' scale (plus Not Applicable).

Completing a lengthy survey was an added burden for our time-poor respondents. We noticed that respondents appeared to be giving less thought to their answers towards the end of the survey and we thus endeavoured to improve our instrument design for future surveys by exploring whether similar insights might be obtained with fewer questions. As a first step we investigated latent factors underlying the survey responses, finding that three dominant orthogonal factors accounted for 83.5% of the total variance and that each of these factors was heavily loaded on a single theme. The intrinsic dimensionality was thus much smaller than our choice of nine themes suggested. We further found that respondents' average choices for the three themes associated with the dominant factors could be used to estimate (better than chance) their averages for the remaining six themes. The variance of the actual averages here was 0.49 (on the Likert scale of 1 through 5) versus 0.21 for the variance of the difference between the actual and estimated averages.

There were unexpectedly large pair-wise cross-correlations between some of the themes. Part of this could be attributed to the interdependencies between themes revealed by factor analysis. A further contribution apparently arose from the tendency of some respondents to 'cluster' their answers within a rather limited range of the Likert scale in the latter part of the survey (as if they were giving less thought to their answers). A non-parametric two-sample Kolmogorov-Smirnov test showed that the range of answers for the first half of the survey was significantly greater than the range for the second half ($p < 1\%$). This tendency towards greater uniformity of answers as respondents progressed through a lengthy survey was previously observed by Galesic and Bosnjak (2009), who further noted that participation rates tend to decrease as surveys lengthen.

Our explorations suggest that with complex surveys, and when the research questions are not already well-defined, the dimensionality of the situation being investigated may well be somewhat smaller than implicitly assumed. In this case, if through pilot studies the most-important and relatively independent themes can be identified, then the number of questions may be able to be reduced without compromising the survey outcomes. Indeed, with time-poor respondents there may be a trade-off between the quality of responses and the length of the survey. Out of the 76 statements in the current survey, for example, only 30 of these fell within the themes on which the three dominant factors were most-heavily loaded.

Keywords: *Survey design, survey analysis, organisational study, factor analysis*

A Resilience Approach to Defence Critical Infrastructure

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Abstract: Defence is critically dependent on its own and national infrastructure for energy, water, information, transport, telecommunications and emergency services. The degree of interdependence between defence and national infrastructure varies across these basic services. This combination creates a very complex dynamic system. Review of Defence locations usually start with the logical system boundary the fence that surrounds the site. Infrastructure considerations which link and support the sites, these are viewed as external to Defence and as such beyond the Defence Organisational influence, missing the strong interdependency found "over the fence". This paper describes an approach to understand the dependencies and fragilities which impact defence resilience.

This resilience approach identifies potential impacts on defence capability, points/areas of failure when data sets are combined from both internal and external sources. A number of themes emerged from the analysis including strategic shocks, chronic stressors (e.g. perpetually under-resourced areas), divergent views (e.g. alternative lines of command / priorities), vulnerabilities, graceful degradation (e.g. aging assets) and future plans.

In order to achieve this, we extracted data from many Defence inputs such as: the industry policy statements, estate management, logistics supply chains and the Force Structure Review / force mix assumptions and scenarios. In addition, external data was accessed from sources such as Northern Territory government, Australian Bureau of Statistics, Attorney Generals Department / Critical Infrastructure Protection Modelling Agency, Engineers Australia, and Geoscience Australia. This dataset was used to cross reference the subject matter expert (SME) views collected at workshops and via surveys. This allowed SMEs to provide the impact the historical events that impacted Defence activities, and for those impacts to be categorised into themes, case studies and exemplars.

This work demonstrates the impact of critical infrastructure on Defence capability, and highlights the importance of a resilient infrastructure. Actions that bring about change in a specific area often lead to unanticipated and potentially unwanted consequences elsewhere. Treating resilience as a component of the defence system recognises that our world is changing and that changes occur often in an interlinked way.

Keywords: *Decision support systems, critical infrastructure, resilience*

Building a Model and Theory of Joint

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Abstract: Australian Defence Force (ADF) doctrine and strategic guidance emphasise the importance of 'Joint' capability for future operations. The aspiration of Joint however, is not to supplant or diminish the individual Services, but to enhance and augment their effectiveness by connecting personnel, capabilities and systems across the Service boundaries. While the goal of a joint ADF has been long standing, progress towards it has been at times slow and sporadic. The lack of a cohesive and coherent "Theory of Joint" underpinning a shared understanding of Joint across the Department has been identified by some as a potential issue. The focus is on gaining a holistic view of the joint space that provides a unifying context within which decisions can be made.

In support of this effort, around 70 one-star officers across the ADF, were surveyed to investigate their branch's degree of 'jointness'. Three dimensions of joint were identified from the survey data; Coordination and Organisation (C&O) – The extent to which an organisation element works towards its own or joint goals; Social Capital (SC) – The collective or shared benefits available to the whole enterprise and the premise that social networks have value; and Optimisation of Socio-technical systems (STS) – Optimising interactions between personnel and technologies across organisational boundaries. These dimensions can be used to visualize a 3D Joint Space (Fig 1). Cluster analysis of the data identified five clusters relating to different joint roles.

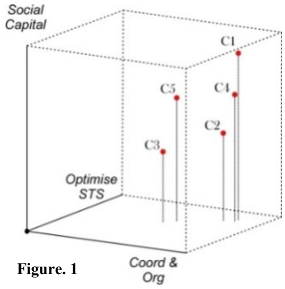

Figure. 1

Cluster	Description
Leaders (C1)	Highly joint and comprises branches that lead joint.
Specialist Joint (C2)	Manages or supports specialist joint capabilities (e.g. ISR).
Disconnected (C3)	Sits on the periphery of joint.
Supporters (C4)	Branches heavily focused on supporting joint activities.
Contributors (C5)	Single service focused branches.

A Joint operation will potentially involve branches from across the five clusters. Hence, not all branches need to be joint leaders, but the nature of their contribution will need to be understood. Analysis of cluster composition identified branches that appear to be in the wrong cluster when their stated role and function is considered. It also showed a need for joint branches to lead joint functions, but interestingly this is only the case currently for the conduct of operations and not for the other departmental functions (i.e. manage the current force, deliver the future force).

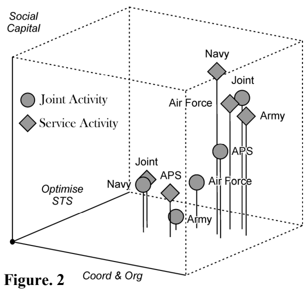

Figure. 2

The data collected also provides a visualisation of the 'location' of the various services within the joint space in regards to their 'focus' on service (◆) or joint (●) activities (Fig 2). While the current study has limitations (e.g. results represent only the branches surveyed, not the entire Service), the potential utility of a survey instrument and the 3D representation of the joint space (i.e. ability to differentiate between branches and services) has been demonstrated. The most important outcome of the study perhaps, is the need to represent Social Capital in any model of 'joint' effectiveness.

Arising from this 3D view of the joint space, a model of the Joint Organisation has been proposed. In addition to the three pillars of Structure, Capital and Capability, the larger conceptual model includes the functional outputs and dynamic processes associated with Joint. A set of preliminary tenets and guiding principles for joint has been derived from this model. The 3D visualisation and model can lend itself not only to joint within the ADF but could also be useful in considering the development, management and employment of agencies in the broader Joint, Interagency, Intergovernmental, and Multinational (JIIM) environment.

Keywords: *Joint, operations, culture, socio-technical systems*

Development of Agreeable Models for Army Intelligence, Surveillance and Reconnaissance in Support of Concept Development

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Abstract: Intelligence, Surveillance and Reconnaissance (ISR) is an integral function of the Australian Army, providing information and intelligence to decision makers at all levels. Army's ISR system comprises the equipment, personnel, processes and organisation that conduct collection activities. However, it has been noted that there is a lack of a guiding concept for future development, resulting in unease in acquisition, a lack of integration, and questions over whether the ISR system is being employed as effectively as possible. Accordingly, Army Headquarters (AHQ) has identified a need for a future Land ISR concept, to be supported by analysis from DST Group. This paper focuses on the problem structuring component of that support.

This problem structuring for Army ISR concept development covered the scope, the actors, the current situation, key themes and what the concept is intended to achieve. To do this effectively, it is important to be able to understand, explore and improve the system, and modelling is an important means to represent the system in a way that stakeholders and analysts can agree with, and understand.

Given the nature of the problem, Soft Systems Methodology (SSM) was identified as the most appropriate technique due to its focus on finding out about the problematic situation, which will support development of a range of models. The researchers worked with Army stakeholders to develop a SSM rich picture of the ISR system, an analysis of stakeholder roles, and a set of root definitions that could be developed into activity models. This SSM investigation was supplemented by development of an ISR functional model.

The majority of the data collected came from a series of three facilitated workshops with AHQ subject matter experts (SME), where the analyst could ask relevant questions of SME to learn about the situation, and present and refine models. Discussion in these workshops covered the role, scope, actors, key themes and functionality of the Army ISR system. The ISR system rich picture was added to and refined at each workshop to describe the ISR system from capability to effects. Models were used to represent and easily modify what relationship each actor had to the ISR concept, and what they wanted from the concept. A model of ISR functionality was also produced as a framework for analysis of concept options.

Root definitions, or PQR statements, of the form "do P, by Q, in order to achieve R", were developed based on the discussion to capture key points for the concept to address. These statements can also be used as measures of effectiveness for the concept. To be effective the concept must address the PQR statements produced, so that it guides capability decisions, considers future systems, describes how capability provides effects, aligns terminology and addresses key themes.

This report demonstrates the application of SSM as a basis for problem structuring complex military systems, in order to support development of a range of models that can provide guidance to a military concept writing process.

Keywords: *Soft systems, concepts, ISR, modelling*

Cyber - Concept to Force Development

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Abstract: Military concept development is a structured process that considers alternative ways of achieving strategic objectives, which is particularly relevant for military force design in a cost-constrained environment. Military concepts describe the way in which a particular Defence element, a Defence system, or the whole Defence enterprise, intends to operate to pursue military objectives. Forward-looking concepts centre on the kinds of effects that might be needed to deal with a range of potential future military problems, and help formulate capability development options to operate in the future environment.

In mid-2014 a systematic approach was used for the development of the cyber concept. The core of this concept comprises high-level capability statements that articulate capability goals for military objectives pertaining to the cyber domain. This set of around thirty capability statements are spread across themes such as policy, legal, operations, intelligence, workforce, acquisition, technology and relationships, with detailed characteristics supporting each statement. This, essentially, forms the 'design' of the future cyber domain. This cyber concept 'design' is now being utilised for 'development' of the cyber capability aided by three structured complementary techniques described below. 'Development' involves generating requirements, acquisition and implementation of capabilities, based on the 'design'.

About two hundred detailed cyber characteristics from the concept were clustered and aligned to the six Joint Warfighting Functions (Command, Situational Understanding, Force Generation, Force Application, Force Protection, and Force Sustainment). These enduring military functions are a useful taxonomy as they enable decomposition to more granular military roles. The result of the alignment was a list of fifteen high-level objectives with associated planning tasks and end-states. For each objective, risks and opportunities were considered in terms of the Fundamental Inputs to Capability (Personnel, Training, Organisation, Command & Management, Support, Facilities & Training, Supplies and Major Systems,). The planning tasks with end-states form the cyber development plan, which has explicit links to the cyber concept design.

A cost-benefit assessment, focusing on prioritisation of interdependent planning objectives, assessed across time and cost axes, assisted in the formation of a development plan across the cyber domain. This method favours pragmatic solutions in a limited resource environment, by encouraging participants to develop smarter proposals to address the risks posed in achieving objectives. The assessment was made more encompassing by a subjective assessment, conducted by stakeholders, of the impacts and value of strategic factors such as industry, government priorities, budget, technology trends, high-level threats and contribution to alliances.

Cyber-specific vignettes were developed as part of the 2014 Force Structure Review. These vignettes were considered across the Strategic Response Options (Understand, Shape, Deter, Deny, Defeat and Assist) to generate specific tasks which formed the scenario-specific demand for cyber capabilities, including workforce requirements, and capacities. SMEs then provided an assessment of workforce numbers and skills on the supply side, which when used with organisational responsibility mapping, yielded a cyber organisational structure across workforce categories. Cost envelopes across a ten-year period, together with training and recruitment pipelines, provided a realistic buildup of the cyber organisation.

Noting the lack of an accepted repeatable methodology to developing a concept and translating the concept into an implementation plan, this structured approach offers a systematic method to the development of solutions; and a consideration of how the solutions might be implemented. This approach, incorporating a range of complementary techniques, provides a clear and logically defensible method that has resulted in stakeholder buy-in and appreciation of concepts for force design and capability development. This process of focusing on developing a conceptual design to comprehend whole-of-domain issues, including strategic factors, before initiating the acquisition and implementation of capability also provides the coherence, contestability and assurance aspects for force design.

Keywords: *Cyber concept, military concept development, force design, force development*

EXTENDED ABSTRACT ONLY

Framing Analysis for Cyber within Joint Warfare

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Abstract: Cyber warfare is an emergent national threat that has become a key security determinant across many developed and developing economies. In response, programmes to counter 'Cyber warfare' have been established and expanded into the national security domain. Much of what is categorised as Cyber warfare is poorly defined from a Defence perspective. A complicating factor is that Cyber is both a distinct domain of warfare and an enabler within other (physical) warfare domains. The framing of Cyber warfare in a logical, structured and intuitive manner is crucial to inform strategic and operational level decision making. There is a distinct lack of appropriate analysis frameworks that capture the uniqueness of the Cyber conflict space with those that do exist being limited to very narrow problems, such as defining the point at which nefarious Cyber actions constitute war.

In the past it has been possible to frame warfare debates along a series of mutually exclusive lines of enquiry to simplify analysis of contributions to effects. These approaches have developed an overarching argument to capture the essential elements of the problem space in order to aggregate the outputs from these distinct discussions into a comprehensive thesis. Cyber warfare displays complexities that cannot be easily unpacked through such a reductionist framework. A more nuanced approach is necessary; one which creates a structure that is able to support strategic and operational decision making.

This paper does not purport to develop or present such a framework; instead it seeks to take a step in that direction by establishing a set of conjectures with which to frame the debate. These conjectures provide distinct lenses for exploring and analysing the Cyber conflict space. Distinguishing between the strategic and operational level contexts facilitates greater clarity and cohesion in discussion. Linking the conjectures and contexts in a structured manner informs strategic activities such as policy settings, metric definition and scenario development.

Utilising various Judgement-based Operations Research techniques, an appreciation for Cyber warfare within a Defence context is established. Using a set of enduring themes within the Cyber conflict debate we examine a conjecture for each theme. Each of the conjectures is, in effect, a context dependent, open-ended statement where various stances can be taken depending on a particular circumstance. The relationship between one context and another can provide an understanding of distinctions within the Cyber problem space. An important point is that the conjectures are points of significant dispute within the broader Cyber narrative; that is, the critical variables.

Our initial thematic analysis identified fourteen distinct themes, from which we postulate an equal number of conjectures. This has led to a structured approach to develop and test plausible concepts for Cyber warfare. Through the development of attributes and metrics this allows a level of consistency when undertaking analysis that incorporates other elements of Joint Warfare.

Keywords: *Cyberspace, joint warfare, strategic planning, conjectures*

Military inventory capacity and stock planning with surge and warning time and supplier constraints

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Abstract: Linear programming has since its inception, always been strongly applied to inventory management. Linear programming has also been used extensively in many military stockage problems. In a military context, two general events test and shape the supply chain. The first is the development of inventory control: stockholding and infrastructure capacity policies to meet demands associated with ongoing raise, train and sustain requirements. In this case, the military inventory policies have very similar characteristics to stockholding in a commercial supply chain, where demands are forecasted and corresponding procurement takes place.

The second event that shapes the structure of the supply chain is the occurrence of a contingency demands, often termed a surge demand. In the second case, a contingency will have a planned demand, sustainment period and corresponding warning time. While the demand and sustainment period are critical to stockholding decisions, it is the warning time, which in conjunction with the vendors constraints on supplying at surge rates that is critical to developing inventory holdings, capacity and reserve stocks, often called war reserve materiel in the United States Department of Defence. One can often summarise the vendors constraints in supplying at a surge rate through the Contingency Provisioning Lead Time (CPLT), which is defined as that time the vendor can supply at the required contingency throughput rate. The CPLT may be greater than the warning time, indicating the vendor cannot supply at the required throughput rate at the start of the contingency.

With the basic input parameters of raise, train and sustain demands; contingency demand; warning time; CPLT; and maximum order quantities; we form a linear program that optimises the infrastructure capacity, reserve stocks and nominal inventory holdings at a Defence logistics installation. This linear program is extended to include an "anytime" contingency, where the inventory constraints are formed assuming contingency surge demand can occur at any time during the raise, train and sustain cycle.

The linear program is solved and sensitivity analysis is conducted over variation in CPLT and warning times. A further extension of the linear program is developed which includes constraints on bulk delivery lead times.

Finally, we discuss stochasticity in demand, supply and warning times. Inevitability, there is uncertainty in each of the aforementioned parameters. To address this, we discuss a two-stage stochastic linear program. In this construct, the first stage decisions are the optimal infrastructure capacity; raise, train and sustain inventory holdings; and reserve stock inventory holdings. The second stage variables are the procurement decisions required to ensure sustainability under different demand, supply and warning time scenarios. Approaches to solving the stochastic linear program exactly or approximately through the Monte-Carlo based stochastic average approximation algorithm are also discussed.

Keywords: *Inventory management, military logistics, linear programming, stochastic linear programming*

Analysing Truck-Trailer-Flatrack Mix for a Given Road Network with Known Supply and Demand

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Abstract: A flatrack is a modular, flat transport structure that can be seen as a larger version of a pallet. As compared to a pallet, a flatrack can accommodate a higher load volume and weight for transportation or storage, under specific supply and safety conditions. Their structure is durable, hence they can be reused many times like shipping containers. A loaded or empty flatrack must be carried by a truck or trailer for transportation from one location to another. The flatracks can be loaded onto a vehicle and unloaded from a vehicle together with its cargo via a mechanical arm integral to the vehicle. As such they act as a module to the trucks and trailers and facilitate rapid loading and unloading of cargo.

We consider an organisation that intends to include flatracks in their vehicle fleet of trucks and trailers for transportation of cargo, from their own sources to destination locations, through specified road networks within given time windows. The loaded flatracks are unloaded (from the trucks and/or trailers) at their destinations as a single unit with their cargo, and as such they are not free for reuse until they have been emptied of cargo. This means that the flatracks may remain at the destination location for some time, and then the empty flatracks can be collected and returned to the source location for further use. A truck and trailer can carry multiple empty flatracks. Any delay in cargo removal from a flatrack and in empty flatrack collection may require the use of more flatracks in the system. On the other hand, frequent flatrack collection with partial vehicle loads might require more convoys to be operated. So a compromise between these two strategies is likely needed.

The purpose of this research is to determine the number of flatracks required as part of a fleet composed of a given number of trucks and trailers, such that the fleet can adequately perform a set of predefined tasks. We have undertaken a simulation based study to analyse the performance of the system with three different flatrack recovery policies. Here, we assume there are adequate supplies at the supply nodes and the demands at the demand nodes are known in advance with their required time windows. Further the road network is fixed and given. With limited representative data, the simulation results show interesting insights that are useful for decision making.

Keywords: *Simulation, flatrack, logistics, vehicle fleet mix, fleet management*

Testing aircraft fleet management policies using designed simulation experiments

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Abstract: The Australian Defence Force is in the process of receiving several new capabilities following recent acquisition decisions. In an era of declining government – and thus military – spending, there is an increasing imperative to maximize performance within existing Defence budgets. Therefore there is a desire – indeed obligation – to seek to manage these new aircraft fleets in the most efficient way possible. In practice, this translates into areas such as better maintenance processes and increased operational availability.

In this work we consider a new fleet of 24 MH-60R Seahawk naval combat helicopters being delivered to the Royal Australian Navy. The fleet is required to maintain eight aircraft embarked on ships at sea every day, and to achieve a certain number of ashore flying hours (across two squadrons) and embarked flying hours each year, over a 30 year life. Good fleet management would suggest that not only should these three primary requirements be met, but also the flying hours across the fleet should be somewhat balanced. In that way, no individual aircraft is too far ahead or below the rest of the fleet regarding total flying hours. Aircraft too far ahead would ultimately have to be retired early, reducing the fleet size. Similarly, each aircraft should have a reasonable split of embarked and ashore hours, as aircraft wear more rapidly when embarked due to increased exposure to corrosive salt-laden environments and the higher deployed operational tempo.

A fleet simulation model has been developed to test the capability of the fleet to meet these requirements. The model represents individual aircraft moving between various states, such as between ashore and embarked, and between serviceable (able to fly) and different types of maintenance, from regular short inspections to depot-level maintenance. Unscheduled maintenance is included as a random effect, with both the time between failures and the repair time represented as probability distributions. The model also incorporates various fleet management policies, to see which are most effective in meeting the three main requirements as well as the desire to provide a reasonably balanced fleet. Six policy types are tested: daily flying allocation; daily maintenance allocation; maintenance crew rotations within squadrons; tail rotation between squadrons; balancing the flying hours across the fleet; and sharing squadron resources.

There are a large number of inputs in the model, and while many are fixed, others are more ambiguous, such as the range of flying hours that an aircraft and the fleet may fly each day. When combined with the uncertainty in the values of the unscheduled maintenance distributions, as well as the range of fleet management policies described above, there is a large parameter space that can be explored. Given this, a simulation experimental design approach has been applied to this problem. This allows a thorough exploration of the parameter space in fewer runs than would otherwise be required. We apply this design to eleven continuous variables, two discrete variables, and the six fleet management 'policies' listed above. Each of these policies may have between two and five options. Ultimately, 1040 design points are used, with 50 replications at each point – by contrast, a full factorial design would require around 1E33 points.

The results show the strong influence of varying unscheduled maintenance on the ability of the fleet to meet the ongoing requirements, particularly if the frequency is greater than anticipated. It also demonstrates that particular fleet management policies, such as those that share squadron resources and rotate maintenance crews within squadrons, can be used to counteract an increase in unscheduled maintenance. For the requirements to balance the embarked, ashore and total flying hours across the fleet, tail rotation policies that enable more frequent rotations are most effective overall, especially for balancing embarked hours.

Overall, the experimental design technique provides insights to decision makers. In this fleet management example, it identifies the variables and policies of greatest influence. It thus assists decision makers in determining the best policies, and targeting the areas that may negatively impact on meeting requirements.

Keywords: *Aircraft fleet management, simulation, experimental design*

EXTENDED ABSTRACT ONLY

Statistical Modelling and Analysis of Logistics Data for Land Vehicle Fleet Management

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Abstract: The management of Land materiel capability encompasses a breadth and complexity of issues that often can be aided by statistical modelling and analysis. This is due to standard reporting mechanisms limiting decision makers to considering a narrow view of a fleet from high level descriptive statistics. In-depth modelling and analysis of a fleet can therefore better inform decision makers, managers and logisticians on the fleet characteristics of key land vehicle fleets, giving both a holistic and detailed overview. As such, a study was undertaken on a fleet to investigate: the observed level of demand and issue of stock, along with the 'Fulfilment Time' performance from inventory data; and the 'reasons for unavailability' from availability data. The study employs statistical methods to characterise fleet performance to provide stronger evidence of performance discriminators that are not available through standard reports.

The methods for the study are founded on data management practices, statistical analysis, and data analysis of transactional datasets, and the use of social science techniques (interviewing and consulting written report) expanded the methodologies. Customised data tables were obtained and extracted from the Military Integrated Logistics Information System (MILIS) via the Standard Defence Supply System interface. Data wrangling processes were applied to tidy, clean, transform, merge and reshape the datasets to ready it for analysis. A range of classifications were developed, to characterise the inventory dataset, including: Demand Priority; Demanding Organisation; Stock Owner; Inventory Segment; Subsystem; Delivered in Full on Time (DIFOT); Delivered by Standard Delivery Date; and Cost of Items Issued. Also, the 'Fulfilment Time' (wait) was calculated, as a proxy for demand. Furthermore, a classification for operational availability, and another for the 'reasons for unavailability' were developed based on operational availability data. Visualisation and Modelling of the datasets were then performed to understand the relationship between the variables within the inventory dataset, and the variables within the operational availability dataset. Non-parametric tests (e.g. Kruskal-Wallis test, and Chi-Square Tests of Homogeneity and Independence) were run to statistically analyse the data. Data analysis methods include data and text mining to: convert long text fields into succinct categories, such as those found in technical inspections of vehicles; and transform nearly 1,000 stock keeping units into 15 subsystems to detail each vehicle in the fleet. Other qualitative data sources, personal interview and written report, were used in the study to gather firsthand insight from subject matter experts and their experiences with the fleet.

The results include a range of graphs and tables for both aspects of the study (the inventory results and the operational availability results). Statistics were compared and tested across the categories of performance discriminators. Quantitative results from both avenues were also qualitatively compared, i.e. findings from 'reasons for unavailability' and DIFOT performance at subsystem level. The qualitative accounts from subject matter experts were also compared with the findings from the inventory characteristics and operational availability to validate these quantitative results.

A principle result from the comparison revealed how the same subsystems/parts were found to have the same opportunities for improvement through all avenues of enquiry, as the results matched within and across quantitative and qualitative methods. The validation of the qualitative accounts with the quantitative results demonstrated how the combination of methodologies: enriches understanding; corroborates quantitative and qualitative results from multiple sources; and increases confidence in results, which also demonstrated method triangulation. The comparison of both quantitative results from the textual analysis of operational availability and the statistical analysis of inventory data provides an evidence-based example of their relationship and how the same results arise across the logistics supply chain. Hence, it shows how for this fleet, the maintenance elements and issues requisitioning elements revealed the same supply chain performance; the impact of administrative and logistic delay time on inventory fulfilment time and fleet availability.

Keywords: *Fleet performance management, logistics supply chain, statistical analysis, qualitative analysis, data analysis*

Min/Max Inventory Planning for Military Logistics

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Abstract: Military logistics is concerned with the projection and sustainment of forces in accomplishing a mission. A critical part of force sustainment is supply chain planning (SCP), which involves determining the sources of supply and defining the distribution networks that will be used to meet the sustainment requirements of the force. Although supply chain planning is well-researched in the commercial sector, the military are driven by different criteria and use different planning processes on which there is limited research.

In the military domain, supply chain planning involves determining the deliveries required to meet the expected demand of a particular mission by calculating suitable delivery times and supply quantities. This process is typically done using a system called Min/Max, which calculates the deliveries using minimum (Min) and maximum (Max) inventory levels and a number of other constraints. The basic idea is to resupply the inventory of a node (location) when the stock level approaches, but doesn't fall below, the Min inventory level and order enough supplies to bring the stock level up to the Max stock holding capacity. This is traditionally a manual process that can take a group of military planners several hours or days to complete, depending on the size of the problem, and the results are susceptible to human error.

This paper presents the Min/Max Planning Algorithm (MPA) which can perform automated supply chain planning using the Min/Max system. Given an SCP problem with an expected profile of demand, the MPA uses the constraints defined for each node and the expected demand to calculate a suitable order profile for that node. Each node's order profile is combined with the profiles of its dependants, providing a complete picture of the supplies that a node will require to sustain itself and its dependants over the course of the mission. These combined order profiles are then converted into a list of deliveries which provides an overall solution to the SCP problem.

The MPA has been evaluated using four SCP problems of increasing complexity, which are representative of typical planning problems encountered by the Australian Defence Force. The results show that the MPA is able to solve all of these problems and keep the expected minimum stock level above a defined threshold, which provides a suitable buffer against uncertainty when the calculated deliveries are actually executed. The algorithm is also computationally efficient, being able to solve large SCP problems in less than a second. This is a significant improvement on the hours or days that it could take a military planner to perform the same calculations by hand.

Keywords: *Supply chain planning, inventory planning, min/max, military logistics*

Logistics Management Issues for Military Systems approaching the End of Service Life

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Abstract: Many concepts and models have been proposed and implemented to support the logistics management of physical assets through their service life. These concepts and models generally focus on a 'steady state' or 'mature' phase of the idealised asset life-cycle, and as such make a number of appropriate simplifying assumptions. As an asset approaches the end of its service life many of these assumptions become questionable and new logistics and fleet management issues begin to arise which potentially require the consideration of new concepts and models. A military system fleet approaching the end of its service life will continue to need ongoing support, which potentially includes support in operations. For this, fleet managers need to continue to invest in inventory to meet preparedness requirements and address potential obsolescence, phase out demand and discontinued supply issues; despite the fact that the fleet has a looming end of service life date. However, the desire not to over invest in inventory as an asset approaches the end of service life is balancing against these needs, as this can tie up financial resources and potentially add to labour, warehousing, transport and eventual asset disposal costs. These matters create tensions between effectiveness and efficiency considerations as system fleets reach the end of their service life. Past experience often suggest these issues are a secondary consideration in fleet management.

This paper will explore a range of end of service life logistic issues including approaches to the inventory management functions of requirements determination, and replenishment planning. We will consider some standard approaches to these functions and highlight how end of service life considerations may require new management heuristics and process models. In particular, we investigate efforts to integrate a spare parts management (SPM) phase out strategy. This includes seeking a process for developing options, and goal setting the final state of the spare parts inventory at the asset's end of life date. This can then modify demand forecasting selection processes and calculations for replenishment actions. Importantly, inventory segmentation can play a role to determine how to treat various asset spare parts based on factors such as supply characteristics, demand, cost, stock on hand and relationships to other parts of the asset sustainment system. How these factors can be integrated into a management model for decision policy is a focus of our discussion. We then present a management process model to indicate which replenishment actions suit particular items in the inventory based upon phase out segmentation analysis and a desired end of service state. In doing so, a number of key end-of-service life policy options can be proposed. This can aid military planners to oversee inventory management of assets that are approaching end of life.

Keywords: *Spare parts management, segmentation, phase out, end-of-life, replenishment*

Modelling the Performance of Positive P/E firms and Negative P/E firms

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Abstract: This paper evaluates whether performance of positive P/E firms are significantly different from negative P/E firms. It also investigates the characteristics of positive P/E firms and negative P/E firms and determine whether the differences in characteristics are statistically significant. Both Mood Median test and Kolmogorov–Smirnov (K-S) test are used in this paper to examine the significance of results on data gathered for four Asian countries (China, Japan, South Korea and Singapore) for the period from 2004 to 2014. Findings of this study show that the performance between positive P/E firms and negative P/E firms was significantly different, especially in terms of stock price returns, EBIT margin, current ratio, cash, assets turnover, EPS growth, EBIT growth, revenue growth, and market capitalization. Such results are partly consistent with previous studies and contribute to this area of study by examining new characteristics between firms with positive P/E and negative P/E.

Keywords: *Price Earnings ratio, performance, investment, fund management*

A Nonparametric Option Pricing Model Using Higher Moments

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Abstract: A nonparametric pricing model of European call options that includes non-Gaussian characteristics of skewness and kurtosis is proposed based on the cubic market capital asset pricing model. It is an equilibrium pricing model but risk-neutral valuation can be introduced through return data transformation. The model complies with the put-call parity principle of Eurpoean option pricing theory. The properties of the model are studied through simulation methods and compared with the Black-Scholes model. Simulation scenarios include cases on nonnormality in skewness and kurtosis, nonconstant variance, moneyness, contract duration, and interest rate levels. The proposed model can have negative prices in cases of out-of-money options and in simulation cases that are different from real-market situations, but the frequency of negative prices is reduced when risk-neutral valuation is implemented. The model is more adaptive and more conservative in pricing options compared to the Black-Scholes model when nonnormalities exist in the returns data.

Keywords: *Derivatives pricing, skewness, kurtosis, capital asset pricing model, European call options*

Agricultural commodities prices – fractional and integer differencing approach

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Abstract: In this paper the time series of two important agricultural Brazilian *commodities* are investigated, namely, the soybean and the corn. Time series can exhibits long-range dependence or persistence in their observations. Long memory process has become a useful tool in studies involving hidrology, climatology, geophysics and, particularly, in economics and finance. One of the most compelling motivations concerning the importance of long memory, fractionally integrated process is related to the rate of decay associated with the impulse response coefficients of a process. One attraction of long memory models is that they imply different long run predicitions and effects of shocks to conventional approaches. The ARFIMA (Auto Regressive Fractionally Integrated Moving Average) process is one the best-known classes of long memory models. It is a generalization of the ARIMA (Auto Regressive Integrated Moving Average) process. In this work, ARIMA and ARFIMA models were developed for the aforementioned *commodities* using the software R for both, spot price composition and future price prediction. The data were obtained from CEPEA/ESALQ/USP and the time interval for the *commodities'* series was taken from 2009 until May 2015. The Augmented Dickey Fuller Test (ADF) is used in order to identify the stationarity of the time series and find out the number of differencing required. The autocorrelations (ACF) and partial-autocorrelations (PACF) within the specified time series is evaluated providing the values for the parameters required. It is adopted the Schwartz and Bayesian information criterion (BIC) which indicates its applicability and its efficiency for determine or predict the *commodities'* prices. Comparisons between the performances of the ARIMA and ARFIMA models are evaluated. The results show that the fractionally integrated model has a better performance for the future prices forecasting when compared to the integer model. The proposed study also includes as goal to contribute to guide strategies and serve as a starting point for useful actions and decision-making more efficient for agribusiness in Brazil.

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Keywords: *Auto Regressive Fractionally Integrated Moving Average (ARFIMA), fractional integration, commodities, package R, Brazil*

A State-Space Estimation of the Lee-Carter Mortality Model and Implications for Annuity Pricing

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Abstract: A common feature of retirement income products is that their payouts depend on the lifetime of policyholders. A typical example is a life annuity policy which promises to provide benefits regularly as long as the retiree is alive. Consequently, insurers have to rely on "best estimate" life tables, which consist of age-specific mortality rates, in order to price these kind of products properly. Recently there is a growing concern about the accuracy of the estimation of mortality rates since it has been historically observed that life expectancy is often underestimated in the past (so-called longevity risk), thus resulting in longer benefit payments than insurers have originally anticipated. To take into account the stochastic nature of the evolution of mortality rates, Lee and Carter (1992) proposed a stochastic mortality model which primarily aims to forecast age-specific mortality rates more accurately.

The original approach to estimating the Lee-Carter model is via a singular value decomposition, which falls into the least squares framework. Researchers then point out that the Lee-Carter model can be treated as a state-space model. As a result several well-established state-space modeling techniques can be applied to not just perform estimation of the model, but to also perform forecasting as well as smoothing. Research in this area is still not yet fully explored in the actuarial literature, however. Existing relevant literature focuses mainly on mortality forecasting or pricing of longevity derivatives, while the full implications and methods of using the state-space representation of the Lee-Carter model in pricing retirement income products is yet to be examined.

The main contribution of this article is twofold. First, we provide a rigorous and detailed derivation of the posterior distributions of the parameters and the latent process of the Lee-Carter model via Gibbs sampling. Our assumption for priors is slightly more general than the current literature in this area. Moreover, we suggest a new form of identification constraint not yet utilised in the actuarial literature that proves to be a more convenient approach for estimating the model under the state-space framework. Second, by exploiting the posterior distribution of the latent process and parameters, we examine the pricing range of annuities, taking into account the stochastic nature of the dynamics of the mortality rates. In this way we aim to capture the impact of longevity risk on the pricing of annuities.

The outcome of our study demonstrates that an annuity price can be more than 4% under-valued when different assumptions are made on determining the survival curve constructed from the distribution of the forecasted mortality rates. Given that a typical annuity portfolio consists of a large number of policies with maturities which span decades, we conclude that the impact of longevity risk on the accurate pricing of annuities is a significant issue to be further researched. In addition, we find that mis-pricing is increasingly more pronounced for older ages as well as for annuity policies having a longer maturity.

Keywords: *Mortality modeling, longevity risk, Bayesian inference, Gibbs sampling, state-space models*

The GJR-GARCH and EGARCH option pricing models which incorporate the Piterbarg methodology

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Abstract: Knowledge of the risk-neutral distribution of the cumulative return with respect to the model used, is needed in European option pricing. GARCH models are known to provide superiour performances when cal-culating asset returns. There is a plethora of GARCH models and unfortunately their risk-neutral distributions are not known in all cases. Duan, Gauthier, Simonato and Sasseville (DGSS) provided an analytic approxi-mation model for the case where an EGARCH or a GJR-GARCH specification is used to describe the asset price dynamics. The DGSS model requires the risk-neutral pricing methodology of the Black-Scholes-Merton (BSM) option pricing model.

The Global Financial Crisis (GFC) exposed the shortcomings of the risk-neutral option pricing methodology. In particular, it became apparent that the the use of one risk-free interest rate is totally inadequate for option pricing. Various asset pricing models that extend the BSM model have been introduced since the GFC to address the over simplified interest rate assumption that prevailed prior to the GFC.

In this paper, the DGSS option pricing models are extended to incorporate the Piterbarg methodology. The Piterbarg methodology entails three unique interest rates to price options. Additionally, the price of options under this methodology depend on collateral payments throughout the lifetime of the option. The risk-neutral measure is replaced by by a measure in which the underlying asset drifts at the rate earned on a repurchase agreement, and not the risk-free interest rate. Therefore the risk-neutral asset price return dynamics under the risk-neutral measure provided by DGSS do not hold, and a new asset price return dynamic is derived in order to price options using GARCH processes to model the underlying assets returns in the Piterbarg methodology.

The Piterbarg adapted GARCH processes are then used in a Monte-Carlo simulation, in which the future expected asset price at the time of the maturity of the option is found and used to price options. The option prices are then converted to the Piterbarg implied volatility in order to compare the option prices on the FTSE/JSE Top 40 index using two different GARCH processes, namely the GJR-GARCH and the E-GARCH processes, which model the underlying assets volatility. The implied volatility is found using the Newton-Raphson method.

Keywords: *Asset pricing, EGARCH, GJR-GARCH, Piterbarg model*

Variable Annuity with GMWB: surrender or not, that is the question

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Abstract: A variable annuity contract with Guaranteed Minimum Withdrawal Benefit (GMWB) promises to return the entire initial investment through cash withdrawals during the policy life plus the remaining account balance at maturity, regardless of the portfolio performance. We assume that market is complete in financial risk and also there is no mortality risk (in the event of policyholder death, the contract is maintained by beneficiary), thus the annuity price can be expressed as an appropriate expectation. Under the optimal withdrawal strategy of a policyholder, the pricing of variable annuities with GMWB is an optimal stochastic control problem. The surrender feature available in marketed products allows termination of the contract before maturity, making it also an optimal stopping problem.

Although the surrender feature is quite common in variable annuity contracts, there appears to be no published analysis and results for this feature in GMWB under optimal policyholder behavior - results found in the literature so far are consistent with the absence of such a feature. Recently, Azimzadeh and Forsyth (2014) prove the existence of an optimal *bang-bang* control for a Guaranteed Lifelong Withdrawal Benefits (GLWB) contract. In particular, they find that the holder of a GLWB can maximize a writers losses by only ever performing non-withdrawal, withdrawal at exactly the contract rate, or full surrender. This dramatically reduces the optimal strategy space. However, they also demonstrate that the related GMWB contract is not convexity preserving, and hence does not satisfy the bang-bang principle other than in certain degenerate cases. For GMWB under optimal withdrawal assumption, the numerical algorithms developed by Dai et al. (2008), Chen and Forsyth (2008) and Luo and Shevchenko (2015a) appear to be the only ones found in the literature, but none of them actually performed calculations with surrender option on top of optimal withdrawal strategy. Also, it is of practical interest to see how the much simpler bang-bang strategy, although not optimal for GMWB, compares with optimal GMWB strategy with surrender option.

Recently, in Luo and Shevchenko (2015a), we have developed a new efficient numerical algorithm for pricing GMWB contracts in the case when transition density of the underlying asset between withdrawal dates or its moments are known. This algorithm relies on computing the expected contract value through a high order Gauss-Hermite quadrature applied on a cubic spline interpolation and much faster than the standard partial differential equation methods. In this paper we extend our algorithm to include surrender option in GMWB and compare prices under different policyholder strategies: optimal, static and bang-bang. Results indicate that following a simple but sub-optimal bang-bang strategy does not lead to significant reduction in the price or equivalently in the fee, in comparison with the optimal strategy. We also observed that the extra value added by the surrender option strongly depends on volatility and the penalty charge, among other factors such as contractual rate, maturity and interest rate etc. At high volatility or at low penalty charge, the surrender feature adds very significant value to the GMWB contract - the required fair fee is more than doubled in some cases; thus it is critical to account for surrender feature in pricing of real products. We also performed calculations for static withdrawal with surrender option, which is the same as bang-bang minus the "no-withdrawal" choice. We find that the fee for such contract is only less than 1% smaller when compared to the case of bang-bang strategy, meaning that the "no-withdrawal" option adds little value to the contract.

Keywords: *Variable annuity, optimal stochastic control, optimal stopping time, bang-bang control, Guaranteed Minimum Withdrawal Benefit*

Forecasting Leading Death Causes in Australia using Extended CreditRisk$^+$

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Abstract: Recently we developed a new framework in Hirz et al. (2015) to model stochastic mortality using extended CreditRisk$^+$ methodology which is very different from traditional time series methods used for mortality modelling previously. In this framework, deaths are driven by common latent stochastic risk factors which may be interpreted as death causes like neoplasms, circulatory diseases or idiosyncratic components. These common factors introduce dependence between policyholders in the annuity portfolios or between death events in population. This framework can be used to construct life tables based on mortality rate forecast. It also provides an efficient, numerically stable algorithm for an exact calculation of the one-period loss distribution of annuities or life insurance products portfolios and associated risk measures such as value-at-risk and expected shortfall required by many regulators. Moreover this framework allows stress testing and, therefore, offers insight into how certain health scenarios influence annuity payments of an insurer. Such scenarios may include improvement in health treatments or better medication. In this paper, using publicly available data for Australia, we estimate the model using Markov chain Monte Carlo method to identify leading death causes across all age groups including long term forecast for 2031 and 2051. On top of general reduced mortality, the proportion of deaths for certain certain causes has changed massively over the period 1987 to 2011. Our model forecasts suggest that if these trends persist, then the future gives a whole new picture of mortality for people aged above 40 years. Neoplasms will become the overall number-one death cause. Moreover, deaths due to mental and behavioural disorders are very likely to surge whilst deaths due to circulatory diseases will tend to decrease. This potential increase in deaths due to mental and behavioural disorders for older ages will have a massive impact on social systems as, typically, such patients need long-term geriatric care.

Keywords: *Extended CreditRisk$^+$, stochastic mortality model, life tables, annuity portfolios, Markov chain Monte Carlo*

Using a Bayesian approach to evaluate the accuracy of economies of scope: Examples from Australian public universities

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Abstract: The point estimate of economies of scope is a nonlinear combination of estimated coefficients from an empirical model. This estimate usually involves out-of-sample predictions when calculating the separate costs (as a part of the calculation of economies of scope). These difficulties make it hard to give the precise prediction and to calculate the standard deviation of this estimate along with its confidence intervals. In this paper, we demonstrate methods for constructing the confidence interval for economies of scope to allow researchers to draw inferences from estimated economies of scope. We review the common approaches such as delta method or bootstrap adopted by previous studies. In contrast to the above approximation methods, this study also proposes an alternative method, Bayesian approach, to produce full predictive distribution for this measure with the posterior distribution. To demonstrate these three approaches, we use a balanced panel data including 37 Australian public universities over the period 2003-12. Our Bayesian approach uses a quadratic cost function with two outputs. Estimates of economies of scope will be calculated with the sample data and estimated parameters from the model.

Keywords: *Bayesian inference, Delta method, bootstrap, economies of scope, confidence interval*

Local Government Debt and Regional Growth in Indonesia

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Abstract: This study analyses the impact of local government debt on growth and attempt to determine the threshold level of local debt-to-GRP for 33 regions in Indonesia over the period of 2008 to 2013. To investigate the impact of the level of local debt-to-GRP (Gross Regional Product) on growth, we utilized a generalized economic growth model augmented with the debt variable. The empirical growth model is generally based on an equation that relates the real GRP per capita growth rate to the initial level of income per capita augmented with the variable of local government debt-to-GRP and a squared term of local government debt-to-GRP.

There are five control variables in this study. The first control variable is population growth rate to capture the effect of population in the region on local economic growth, which is expected to have a positive coefficient. A higher population creates higher aggregate demand in the region; therefore it is expected to have a positive effect on local growth. The second variable is the Human Development Index (HDI). The HDI is a composite index consisting of life expectancy, education and income indicator. The higher value of HDI represents better quality of life and education; thus it is expected to have positive sign. The third control variable is total investment of domestic and foreign investment. A higher value of investment would have a positive impact on infrastructure development as well as on the local growth, thus it is expected to have a positive coefficient. We also consider including fiscal capacity ratio (FISCI) as a control variable as it is used to assess the health status of local finance to take domestic and foreign loan. Even though, region with higher fiscal capacity ratio would have better ability to borrow and repay loan, we expect the sign of FISCI to be negative as region with higher fiscal capacity ratio is usually a more matured region with stable and lower local economic growth. The fifth control variable is the customer price index (CPI) to capture the impact of price level dynamics at the regional level. We expect the sign of CPI is negative, as rapid increase in the price level of goods and services will generally hamper local growth.

We first apply Ordinary Least Square (OLS) regression to examine the linear impact of the local debt-to-GRP variable on growth. We take into account of linear form of the local government debt-to-GRP ratio into equation. The coefficient of local debt-to-GRP is significant at the level of 1 per cent. To evaluate the nonlinear relationship between local debt and growth, we estimate a nonlinear regression model augmented with a squared term of debt variable. The coefficient of the debt variable and a squared term of debt variable are both significant at the level of 1 per cent and 5 per cent respectively. The sign of a squared term of debt-to-GRP variable is also negative as we expect. The negative sign of a squared term of debt variable reflects the concavity or the inverted U-shape relationship between local government debt level and growth.

The Hausman test is used to determine the preferred panel model between Fixed Effect (FE) and Random Effect (RE). The results show that FE model is preferred over the RE. In the linear FE model, the coefficient of debt-to-GRP variable is significant at the level 1 per cent. In the nonlinear FE model, the debt-to-GRP variable is all significant at the level of 1 per cent and a squared term of debt-to-GRP is significant at the level of 10 per cent.

Our results suggest that there is a nonlinear relationship between local government debt and growth. The turning point or debt threshold ranges from 57 to 75 per cent. The coefficient of the quadratic form of local debt-to-GRP is a negative, indicating a concave or inverted U-shaped relationship between local debt and growth. The results confirm the theoretical assumption that at low debt levels the impact on growth is positive, but beyond the debt threshold an adverse effect on growth prevails.

Keywords: *Local government debt, regional growth, debt threshold, panel model*

Volatility Spillovers Between Energy and Agricultural Markets in Theory and Practice

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Abstract: Energy and agricultural commodities and markets have been examined extensively, albeit separately, for a number of years. In the energy literature, the returns, volatility and volatility spillovers (namely, the delayed effect of a returns shock in one asset on the subsequent volatility or covolatility in another asset), among alternative energy commodities, such as oil, gasoline and ethanol across different markets, have been analysed using a variety of univariate and multivariate models, estimation techniques, data sets, and time frequencies. A similar comment applies to the separate theoretical and empirical analysis of a wide range of agricultural commodities and markets. Given the recent interest and emphasis in bio-fuels and green energy, especially bio-ethanol, which is derived from a range of agricultural products, it is not surprising that there is a topical and developing literature on the spillovers between energy and agricultural markets. Modelling and testing spillovers between the energy and agricultural markets has typically been based on estimating multivariate conditional volatility models, specifically the BEKK and DCC models. The purpose of the paper is to evaluate the theory and practice in testing for volatility spillovers between energy and agricultural markets using the multivariate BEKK and DCC models, and to make recommendations as to how such spillovers might be tested using valid statistical techniques. Three new definitions of volatility and covolatility spillovers are given, and the different models used in empirical applications are evaluated in terms of the new definitions and statistical criteria.

Keywords: *Energy and agricultural markets, volatility and covolatility spillovers, univariate and multivariate conditional volatility models, definitions of spillovers*

Full and Partial Volatility and Covolatility Spillovers Between Energy and Agricultural Markets

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Abstract: Modelling and testing spillovers between the energy and agricultural markets has typically been based on estimating multivariate conditional volatility models, specifically the BEKK and DCC models. A serious technical deficiency is that the Quasi-Maximum Likelihood Estimates (QMLE) of a full BEKK matrix, which is typically estimated in examining volatility spillover effects, has no asymptotic properties (specifically, consistency and asymptotic normality), except by assumption, so that no valid statistical test of volatility spillovers is possible. However, the scalar and diagonal BEKK models can be derived from a stochastic process with appropriate regularity conditions, so that the QMLE of these models have appropriate asymptotic properties. Some papers in the literature have used the DCC model to test for volatility spillovers. However, it is well known in the financial econometrics literature that the DCC model has no regularity conditions, and that the QMLE of the parameters of DCC has no asymptotic properties, so that there is no valid statistical testing of volatility spillovers. The purpose of the paper is to evaluate the theory and practice in testing for volatility spillovers between energy and agricultural markets using the multivariate BEKK and DCC models, and to make recommendations as to how such spillovers might be tested using valid statistical techniques. Three new definitions of volatility and covolatility spillovers are given, and the different models used in empirical applications are evaluated in terms of the new definitions and statistical criteria.

Keywords: *Energy markets, agricultural markets, full and partial volatility and covolatility spillovers, univariate and multivariate conditional volatility models, BEKK*

Modeling Longevity Risk for Multiple Populations: The Role of a Roughness Penalty

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Abstract: Stochastic mortality models have a wide range of practical applications. For instance, governments rely on projections made from such models to engineer social security systems and demographic policies. Insurance companies depend on such models to quantify the value of and the risk associated with life contingent liabilities.

In recent years, stochastic mortality models for modeling multiple populations have gained considerable attention among researchers and end-users. Multi-population mortality models can be used to ensure the consistency of a national mortality projection with the mortality experiences observed in neighbouring countries that possess similar demographic characteristics. By incorporating data from a larger population, multi-population mortality models may also be used to enhance the credibility of the mortality projections for small populations (e.g., a pension plan of a small firm) with thin volumes of death and exposure counts. Multi-population mortality models also permit us to project future mortality of both genders jointly. The resulting projections are particularly helpful to actuaries working in jurisdictions where gender-neutral pricing is enforced.

Researchers have recently introduced a number of multi-population stochastic mortality models. Among these models, the augmented common factor (ACF) model introduced by Li and Lee (2005) has been considered very often in the literature. Mathematically, the ACF model for $n_p \geq 2$ populations can be expressed as

$$\ln(m_{x,t,i}) = a_{x,i} + B_x K_t + b_{x,i} k_{t,i} + \varepsilon_{x,t,i}, \quad i = 1, \ldots, n_p,$$

where $m_{x,t,i}$ is population i's central rate of death at age x and in year t, $a_{x,i}$ is a parameter measuring population i's average level of mortality at age x, K_t is a time-varying index reflecting the overall mortality level of all populations being modeled at time t, $k_{t,i}$ is another time-varying index that applies to population i only, B_x and $b_{x,i}$ respectively measure the sensitivities of $\ln(m_{x,t,i})$ to changes in K_t and $k_{t,i}$, and $\varepsilon_{x,t,i}$ is the error term that captures all remaining variations.

In spite of its popularity, the ACF model is subject to a significant limitation: it may result in forecasted mortality rates that exhibit a jagged pattern rather than a smooth relationship with age. The unwanted jaggedness arises from the erratic variations in the estimates of B_x and $b_{x,i}$. These irregularities typically carry no demographic meaning, which means that they are likely consequences of sampling errors. A mortality projection with a jagged pattern across ages appears to be anti-intuitive, because it is difficult to justify, for example, why mortality rates at adjacent ages change at very different speeds.

In this paper, we attempt to mitigate this problem by generalizing the work of Delwarde et al. (2007) to a multi-population setting. The generalization involves $(n_p + 1)$ smoothing parameters, one for the common trend and one for each of the n_p individual populations. The smoothing parameters are determined by using a leave-one-out cross-validation, which is more sophisticated than that entailed in the original work of Delwarde et al. (2007) due to the increased number of smoothing parameters.

We illustrate the proposed extension of the ACF model with real mortality data from a collection of national populations. It is found that compared to the original ACF model, the proposed extension produces mortality forecasts that are more reasonable, with less jagged patterns across ages.

Keywords: *Augmented common factor model, Lee-Carter model, Mortality forecasting, population basis risk, stochastic modeling*

A Discussion on the Innovation Distribution of Markov Regime-Switching GARCH Model

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Abstract: Markov Regime-Switching Generalized Autoregressive Conditional Heteroskedastic (MRS-GARCH) model is a widely used approach to model the financial volatility with potential structural breaks. The original innovation of the MRS-GARCH model is assumed to follow the Normal distribution, which cannot accommodate fat-tailed properties commonly existing in financial time series. Many existing studies point out that this problem can lead to inconsistent estimates. To overcome it, the Student's t-distribution and General Error Distribution (GED) are the two most popular alternatives. However, a recent study points out that the Student's t-distribution lacks stability. Instead, this research incorporates the α-stable distribution in the GARCH-type model. The issue of the α-stable distribution is that its second moment does not exist. To solve this problem, the tempered stable distribution, which retains most characteristics of the α-stable distribution and has defined moments, is a natural candidate. In this paper, we conduct a series of simulation studies to demonstrate that MRS-GARCH model with tempered stable distribution consistently outperform that with Student's t-distribution and GED. Our empirical study on the S&P 500 daily return volatility also generates robust results. Therefore, we argue that the tempered stable distribution could be a widely useful tool for modelling the financial volatility in general contexts with a MRS-GARCH-type specification.

Keywords: *GARCH Model, regime-switching, fat-tailed distribution, tempered stable distribution*

Modelling Volatility Spillovers for Bio-ethanol, Sugarcane and Corn

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Abstract: The recent and rapidly growing interest in biofuel as an energy source has raised concerns about its impact on the prices, returns and volatility of related agricultural commodities. Analyzing the spillover effects on agricultural commodities and biofuel helps commodity suppliers hedge their portfolios and manage the risk and co-risk of their biofuel and agricultural commodities. In the past, there have been many papers concerned with analyzing crude oil and agricultural commodities separately. The purpose of this paper is to examine the volatility spillovers for spot and futures returns on bio-ethanol and related agricultural commodities, specifically corn and sugarcane, using the multivariate diagonal BEKK conditional volatility model. The daily data used are from 31 October 2005 to 14 January 2015. The empirical results show that in 2 of 6 cases, there were significant negative co-volatility spillover effects, specifically corn on subsequent sugarcane co-volatility with corn, and sugarcane on subsequent corn co-volatility with sugarcane. In the other 4 cases, there were no significant co-volatility spillover effects. There are significant positive co-volatility spillover effects in all 6 cases, namely between corn and sugarcane, corn and ethanol, and sugarcane and ethanol, and vice-versa for each of the three pairs of commodities. It is clear that the futures prices of bio-ethanol and the two agricultural commodities, corn and sugarcane, have stronger co-volatility spillovers than their spot price counterparts. These empirical results suggest that the bio-ethanol and agricultural commodities should be considered as viable futures products in financial portfolios for risk management.

Keywords: *Biofuel, spot prices, futures prices, returns, volatility*

EXTENDED ABSTRACT ONLY

How are VIX and Stock Index ETF Related?

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Abstract: As stock market indices are not tradable, the importance and trading volume of Exchange Traded Funds (ETFs) cannot be understated. ETFs track an index and attempt to replicate the performance of a specific index. Numerous studies have demonstrated a strong relationship between the S&P500 index and the Volatility Index (VIX). However, few empirical studies have focused on the relationship between VIX and ETF returns. The purpose of the paper is to investigate whether VIX returns affect ETF returns by using vector autoregressive (VAR) models to determine whether daily VIX returns with different moving average processes affect ETF returns. The ARCH-LM test shows conditional heteroskedasticity in the estimation of ETF returns. The diagonal BEKK model is used to accommodate conditional heteroscedasticity in the VAR estimates of ETF returns. The paper uses daily data on ETF returns that follow different stock indices in the USA and Europe. The empirical results show that daily VIX returns: (1) have a significant negative effect on European ETF returns in the short run; (2) have a stronger significant effect on single market ETF returns than on European ETF returns; and (3) together with ETF returns on U.S. stocks, VIX returns are less significant than S&P500 returns.

Keywords: *Stock market indexes, Exchange Traded Funds, Volatility Index (VIX), vector autoregressive (VAR) models, Moving average processes*

The operationalization and applications of the concept of "sustainability" in the accounting and finance

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Abstract: In any survey of literature on the study of "sustainability" or "sustainability" related issues in recent years, one would find that definitions of "sustainability" involve many levels of arguments, domains and context, some of which are more subjective than others. These multifaceted levels and dimensions generate complex arguments, sometimes at crossed purposes, rendering a widely acceptable definition of "sustainability" unattainable in a practical sense. For example, the following popular "definition" is one that reflects the sense and the spirits of "sustainability" that few could argue against: "sustainability is the ability to endure" (Sustainability, 2015). While the definition encompasses the essential and general truths of sustainability, it is difficult for managers to "make it work" in order to make the concept useful in an everyday sense. The authors of the Brundtland Commission Report of the United Nation in 1987 were arguably content to leave the task of a definition to posterity, providing a report based on "sustainable development" which it defined as "development that meets the needs of the present without compromising the ability of the future generations to meet their own needs." Since then authors have lamented that "almost every article, paper or book on sustainability bemoans the fact that the concept is broad and lacks a broad consensus, … and is usually followed the authors' own preferred definition which in turn add to the lack of consensus!"(Bell & Morse, 2008)

Clear and crisp definitions serve as the foundation for meaningful discourse and enable decision-makers to make coherent and consistent decisions. Having a well-defined concept or object of discourse goes a long way to promote understanding and advance discussions about a given concept. In such a context, issues that arise can be communicated more effectively and efficiently, given that everyone understands the domain of discourse. As Bell & Morse (2008) stated "…how can we do something unless we know what we are trying to do, … If we don't know what we are trying to get, how do we know if have it?" This is even more true when politicians join the "bandwagon" of sustainability and raise the issue to a higher level of public awareness, creating in turn an increased level of confusion. Even so, given the dominant role that sustainability has assumed in the international development space and given that some of the motives for promoting sustainable development are less than benign, a working definition is greatly needed to indicate the success or failure of projects that are touted as "sustainable

Hence, we suggest here, as a working proposition and definition, that focuses on examining sustainability as a *process* rather than as a *state* to be attained which will induce clarity of meaning. In so doing, we can look at "sustainability" through its dynamics as a progression toward a yet-to-be defined ultimate state rather than having to stand moribund or to lapse into descriptive platitudes. For the research on sustainability to continue and to advance, it is not desirable and, indeed necessary, to wait for the elusive universal consensus of some "master" sustainability definition which can both satisfy the rigours of scientific research, and be intuitively simple enough to be acceptable across all levels and domains such as those suggested by the "three circle model of sustainability" as suggested by Scott Cato (2009) and more recently by Paul James (2015)

Keywords: *Sustainability measurement and indicators, sustainability and growth models*

Technological innovation of China's pharmaceutical industry

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Abstract: Based on the perspective of the innovation value chain, technological innovation process of pharmaceutical manufacturing industry is divided into two stages--technological development and technological transformation. This paper explores the technical innovation efficiency of China's pharmaceutical manufacturing industry and the determines of technological innovation efficiency by using SFA method. The authors analyze the effect of market competition, enterprise scale, government's policy supports and profits on the technological innovation efficiency of China's Pharmaceutical manufacturing industry. The results show that the overall inno-vation efficiency of China's pharmaceutical manufacturing is not high, but emerges upward trend. The efficiency of technological achievements transformation is slightly higher than that of technological development, in-ter-regional differences are obvious. There are significant positive relationships between market competition, enterprise scale and technical innovation efficiency, while the government's policy supports and profits have significant negative impact on the efficiency of technological transformation.

Keywords: *Pharmaceutical manufacturing industry, technological innovation efficiency, SFA, innovation value chain*

An Empirical Study on China's Regional Innovation Network Co-evolution State from Self-organization Perspective

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Abstract: According to the self-organization theory, this research analyzs the self-organization characteristics of regional innovation network. On this basis, from the view of systematic, this paper parses the system structure of regional innovation network and divides the system into four sub-systems. Then this paper models the order parameter of regional innovation network co-evolution and measurs the status of the regional innovation net-work co-evolution. Finally, this paper evaluates and conducts analysis on the status and differences in regional innovation network co-evolution of 30 provinces and then we have drawn a figure of regional innovation net-work co-evolution status.

Keywords: *Self-organization, co-evolution, regional innovation*

A volatility impulse response analysis applying multivariate GARCH models and news events around the GFC

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Abstract: This paper features an application of the Hafner and Herwartz (2006) approach to the analysis of multivariate GARCH models using volatility impulse response analysis. The data set used features ten years of daily return series for the New York Stock Exchange Index and the FTSE 100 index from the London stock Exchange, taken from 3rd January 2005 to January 31st 2015. This period captures both the Global Financial Crisis (GFC) and the subsequent European Sovereign Debt Crisis (ESDC). The attraction of the Hafner and Kerwartz (2006) approach is that it involves a novel application of the concept of impulse response functions, tracing the effects of independent shocks on volatility through time, whilst avoiding typical orthogonalization and ordering problems. Volatility impulse response functions (VIRF) provide information about the impact of independent shocks on volatility.

Hafner and Herwartz's (2006) VIRF extends a framework, provided by Koop et al. (1996), for the analysis of impulse responses. This approach is novel because it explores the effects of shocks to the conditional variance, as opposed to the conditional mean. Hafner and Herwartz (2006) utilise the fact that GARCH models can be viewed as being linear in squares, and that multivariate GARCH models are known to have a VARMA representation with non-Gaussian errors. They use this particular structure to calculate conditional expectations of volatility analytically in their VIRF analysis. Hafner and Herwartz (2006) use a Jordan decomposition of Σ_t in order to obtain independent and identically defined (hence i.i.d.) innovations. One general issue in the approach is the choice of baseline volatilities. Hafner and Herwartz (2006) define VIRF as the expectation of volatility conditional on an initial shock and on history, minus the baseline expectation that only conditions on history. This makes the process endogenous, but the choice of the baseline shock within the data set still obviously makes a difference. We explore the impact of three different shocks, the first marks the onset of the GFC, which we date as 9th August 2007, (GFC1). This began with the seizure in the banking system precipitated by BNP Paribas announcing that it was ceasing activity in three hedge funds that specialised in US mortgage debt. It took a year for the financial crisis to come to a head, but it did so on 15th September 2008, when the US government allowed the investment bank Lehman Brothers to go bankrupt (GFC2). Our third shock point is May 9th 2010, which marked the point at which the focus of concern switched from the private sector to the public sector.

A further contribution of this paper is the inclusion of leverage, or asymmetric effects, after Engle and Ng (1993). Our modelling is undertaken in the context of a multivariate GARCH model featuring pre-whitened return series, which are then analysed via a BEKK model using a t-distribution. A key result is that the impact of negative shocks is larger, in terms of the effects on variances and covariances, but shorter in duration, in this case a difference between three and six months, in the context of our particular return series. An effect previously reported by Tauchen et al., (1996), who use a different theoretical set up.

Keywords: *Volatility Impulse Response Functions, BEKK, asymmetry, GFC, ESDC*

Quantile regression, VaR and CVAR. An empirical beta comparison of the techniques in relation to credit risk.

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Abstract: This study focuses on the credit risk of Australian financial institutions relative to that of the US. These two countries are chosen because the study is undertaken in Australia, and because Australia is widely considered to have fared far better than the US during the Global Financial (GFC) in terms of both share market volatility and credit defaults, our comparison involves two countries experiencing very different circumstances. The key questions addressed by the paper are firstly, the extent to which the credit risk of Australian financial institutions compares favourably (or otherwise) to the US, and secondly whether credit risk of financial institutions increases (decreases) in a similar fashion over varying time periods. As part of the analysis we will look at a number of aspects. Firstly we will examine the relative financial institution capital levels of the two countries. Although bank capital covers a number of different risks, credit risk is an extremely important component of capital adequacy, and higher credit risk should be reflected in higher capital levels. Secondly we will examine relative levels of credit risk for these countries using non-performing loans and fluctuating asset values, applying various metrics, including Value at Risk (VaR), Conditional Value at Risk (CVaR) and quantile regression.

Following the Global Financial Crisis, there has been much criticism leveled at risk management techniques which measure volatility below a specified threshold. One such technique is Value at Risk (VaR). A major criticism is VaR says nothing of the risk beyond that threshold. Conditional Value at Risk (CVaR), on the other hand, measures extreme risk, those risks beyond VaR. Quantile regression divides a dataset into parts, allowing the extreme quantiles to be isolated and measured. Using these techniques, we compare the credit risk of two data sets (US and Australia) over an eleven year time period from 2004 to 2014. This period includes a range of economic circumstances, spanning pre-GFC, GFC and post-GFC. For credit risk we use non-performing loans, as well as a Merton type model which measures volatility in the market asset values of borrowers. We derive a beta which measures credit risk relative to a benchmark. We then compare relative beta changes over time for the two countries.

There are a number of important elements and findings highlighted by the paper. Firstly, on an absolute capital basis (equity to assets), as measured by the World Bank, Australian financial institutions have low capital in comparison to their global peers, with a capital ratio that is about half that of US banks. However, the ratio improves substantially on a risk-weighted basis (per the Basel approach), to one that is much closer to US Banks. Australian Banks have a very high home loan component, with home loans attracting a low risk weighting for capital adequacy requirements. Thus there is a much bigger differential between absolute capital ratios and risk weighted capital ratios for Australia than for the US. Secondly the credit risk of Australian financial institutions as measured by the World Bank for non-performing loans is very low in relation to global banks, and is about half that of the US. Thirdly, when we apply measurements such as VaR, CVaR and quantlile regression to non-performing assets and conduct a Beta analysis to measure fluctuations in credit risk, we find that risk for Australian financial institutions moves in line with that of the US. During the GFC, the risk for Australia increased by very similar levels to that of the US, although off a much smaller base. The findings can be important to banks and regulators in understanding credit risk in these countries as well as choosing modelling techniques which are able to measure extreme risk and respond to changing economic circumstances, and thus provide early warning signs of changes in credit risk.

Keywords: *Quantile regression, Conditional Value at Risk, credit risk*

Modelling and Simulation of Directional Financial Time Series

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Abstract: A stationary time series model is directional if it has properties that are not symmetric with respect to time, for example if, after the expected value is adjusted to 0, the expected value of the product of the variable squared and the following variable differs from the expected value of the product of the variable and the following variable squared. Marked directionality in time series is apparent from a comparison of time series plots in chronological order and in reverse order (time-to-go), but formal quantitative tests are needed to determine the strength of evidence against an assumption of reversibility (no directionality). Linear time series models with Gaussian noise (LGN models) are reversible whereas linear models with other noise distributions and non-linear models are directional. Evidence of directionality in time series can be found in many disciplines including financial time series. Examples of directional financial time series are presented, together with values of directionality statistics. A method of calculating the p-values of the directional statistics, corresponding to a null hypothesis of reversibility, using simulation is presented. The time series are then modelled by threshold autoregressive models, with noise distributions, which can be non-Gaussian, fitted to match the empirical distribution of the residuals. The fitting criterion is a weighted sum of the error sum of squares and a measure of discrepancy between values of the directionality statistics in the time series and long simulations from the potential model. Strategies for determining suitable weights for the criterion will be investigated. The directional time series models will be assessed in terms of the distribution of extreme values of the time series, which is a feature that was not used in the fitting process. The assessment will be made by comparing the distribution of extremes from: the observed time series; a long simulation from the fittted directional model; and a long simulation from a LGN model fitted to the time series on the basis of the Akaike information criterion (AIC).

Keywords: *Directional time series, reversibility, financial time series, randomization test, threshold autoregressive models*

Is it optimal to combine forecast with a simple average?

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Abstract: This paper proposes a unified framework to study the theoretical properties of forecast combination. By setting up the forecast combination problem as a panel data model, the paper obtains the necessary and sufficient conditions for optimal weight as well as the necessary and sufficient conditions for the simple average to be the optimal weight under Mean Squared Forecast Errors (MSFE). These conditions are consistent with existing results in the literature but the derivations are much simpler due to the proposed framework. In addition to existing results, this paper also establishes two useful theoretical results. First, it derives the necessary and sufficient conditions for a single model to outperform simple average of forecasts. As argued in the paper, it is unlikely that any individual model would satisfy these conditions in practice and therefore, it explains the empirical observation that simple average of forecasts often outperforms any single model. More importantly, it provided a theoretical explanation on the superiority of forecast combinations, at least in the MSFE sense. Second, the paper also shows that the MSFE of simple average of forecast decreases as the number of model increases. This implies that a single model is unlikely to be superior over simple average of forecasts if the number of models increases in the combination.

This paper shows that the proposed framework is also useful in studying the forecast combination puzzle. The paper verifies the existing view that the puzzle may be a result of estimation error in the optimal weight but more importantly, it identifies an additional cause of the puzzle. Specifically, the MSFE may be an inconsistent estimator of the forecast variance and thus, it may produce inconsistent results on the forecast performance of different models with different weighting schemes. A series of Monte Carlo experiments provided overwhelming support of this explanation. An important implication of this results is that selecting optimal model based on naïve comparison of MSFE values without further statistical test may produce inconsistent results.

Keywords: *Forecast combination, averaging, optimal weights, mean squared error*

Modelling Body Mass Index Distribution using Maximum Entropy Density

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Abstract: The objective of this paper is to model the distribution of Body Mass Index (BMI) for a given set of covariates. BMI is one of the leading indicators of health and has been studied by health professionals for many years. As such, there have been various approaches to model the distribution of BMI. Furthermore, there are numerous studies which investigate the association between an individual's physical and socio-economic attributes (covariates) to their BMI levels. This paper proposes the use of Maximum Entropy Density (MED) to model the distribution of BMI using information from covariates. The paper shows how covariates can be incorporated into the MED framework. This framework is then applied to an Australian data set. The results show how different covariates affect different moments of the estimated BMI distribution.

Keywords: *Maximum entropy density, body mass index*

Can Multivariate GARCH Models Really Improve Value-at-Risk Forecasts?

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Abstract: This paper evaluates the performance of multivariate conditional volatility models in forecasting Value-at-Risk (VaR). The paper considers the Constant Conditional Correlation (CCC) model of Bollerslev (1990), and models that allow dynamic conditional correlation such as the Dynamic Conditional Correlation (DCC) model of Engle (2002) and the Time-Varying Conditional Correlation (TVC) model of Tse and Tsui (2002). While the underlying assumptions vary between these models, their common objective is to model volatility for multiple assets by capturing their possible interactions. Thus, they provide more information about the underlying assets that could not be recovered by univariate models. However, the practical usefulness of these models are limited by their complexity as the number of asset increases. The paper aims to examine this trade-off between simplicity and extra information by applying these models to forecast VaR for a portfolio of the Australian dollar with twelve other currencies. This provides some insight into the practical usefulness of the additional information for purposes of risk management.

Keywords: *Value-at-Risk (VaR), Multivariate GARCH*

Quantitative measurement of contagion effects during a Global Financial Crisis: Evidence from selected countries

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Abstract: This paper investigates the existence and extent of contagion effects among international stock markets during the Global Financial Crisis (GFC), and if these financial contagion effects exist, it explores the differences of contagion effects in different sub-periods of pre, during, and post Global Financial Crisis. In a financial definition, the "domino effect" among international stock markets has been referred to as contagion, which draws much academic attention nowadays. Investigating contagion effects among stock markets helps us to study the inner relationship among global stock markets and to further prevent the devastating impact of similar catastrophes such as the Global Financial Crisis.

Keywords: *Global Financial Crisis, Financial contagion effects, micro, small and medium enterprises, India, Credit constraints*

A comparison of adaptive management and real options approaches for environmental decisions under uncertainty

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Abstract: Two approaches to sequential decisions under uncertainty in the environmental management - adaptive management and real options analysis – have evolved independently over the last decades.

Adaptive management, or learning by doing, originated from adaptive control. Adaptive management is acknowledged as one of the best-practice methods to manage biological systems under structural uncertainty. Adaptive management has been used for the management of renewable natural resources (such as fisheries and waterfowl) and the conservation of species (such as assisted colonization, restoration and threatened species management). In this context, stochastic dynamic models and historical data would be valuable for describing and predicting responses of management decisions, but these are either non-existent or severely limited in their scope.

Real options analysis originated from mathematical finance and is based on financial options pricing theory. The real options analysis can be viewed as both sequential decision-making and project valuation in a highly uncertain environment with non-stationary dynamics. Real options analysis has most often been used for industrial applications (such as mining, asset management, infrastructure, energy, defence, and agriculture). In this context, reasonably good stochastic dynamic models and historical data exist for describing and forecasting the behaviour of risk factors.

In mathematical terms, both adaptive management and real options approaches are based on stochastic optimal control and Markov decision processes. In environmental decision-making both enable practitioners and managers to make optimal decisions under uncertainty. However, the numerical methods of solving adaptive management versus real options problems are different, as their development has been motivated by the different needs of respective application areas. An important feature of adaptive management is the presence of and need to account for a small number of hidden variables. In contrast, real options focus on the development of techniques capable of dealing with high-dimensional problems with multiple stochastic risk factors.

Limited for a long time by the inefficiency of the solution methods, recent advances in both adaptive management and real options now allow us to solve more realistic environmental decision problems under uncertainty, widening the scope of their applications. Growing availability of data in the environmental management arena and an emerging need to conduct industrial operations in the proximity of conservation areas will require new decision-making approaches that can combine recent advances in adaptive management and real options.

This paper reviews recent advances in both adaptive management and real options methodologies, and compares methods for solving decisions under uncertainty problems based on the type of uncertainty they are addressing, the type of decision-making approach, important assumptions, and the size of the problems they are capable of dealing with. This paper proposes new areas of development that could inspire future research and better-informed environmental decisions under uncertainty.

Keywords: *Sequential decisions under uncertainty, stochastic optimal control, environmental decisions*

Switching Surfaces for Optimal Natural Resource Extraction under Uncertainty

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Abstract: The flexibility to revise managerial and/or operational decisions over time in response to uncertain market conditions can significantly increase the value of a project. In order to maximise the project value, the operational decisions need to be made sequentially, in an optimal manner, in response to the evolution of uncertainties. Although dynamic strategies brings substantial improvements of the project, its complexity from stochastic control algorithm makes modern real option theory rarely adopted by industry. Thus it calls for a methodology to display graphically the results obtained by real options analysis. An intuitive display of the information about the boundaries between the regions of different optimal decisions (called switching boundaries) would greatly assist industry with optimal sequential decision-making under uncertainty.

This paper presents a methodology to construct switching boundaries/surfaces for optimal natural resource extraction under uncertainty, based on the regression Monte Carlo approach. We extend previous research by (1) incorporating recently proposed advanced techniques (such as adaptive local basis and memory reduction methods) that allow considerable improvement of the accuracy of the switching boundaries; and (2) constructing and analysing the higher-dimensional switching boundaries.

We illustrate how to construct and use switching boundaries using a classical model of a copper mine with flexibility to delay, temporarily close, reopen or completely abandon the mineral extraction in response to the stochastic behaviour of the copper price. For such a model, the switching boundaries are the critical copper prices that trigger a change of operating regime. For this example, the switching boundaries are two-dimensional copper price surfaces that depend on the remaining reserve and the remaining time horizon. We display and analyse these surfaces using both 3D graphs and dynamic 2D graphs.

The paper demonstrates several benefits of the switching boundaries. They can be used by mining companies:

1. as a simple and intuitive decision support tool for identification of optimal operational strategies and for optimal management of resources projects;
2. to gain insight into optimal strategies under different market conditions and project settings;
3. to benefit financially from dynamic strategies.

Keywords: *Real options, stochastic optimal control, least-squares Monte Carlo, memory reduction method, stochastic switching*

On the valuation of natural resource investments using optimal stochastic switching

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Abstract: Complexity and technical difficulties associated with mineral extractions together with significant uncertainty surrounding mining operations require sophisticated stochastic control algorithms suitable for high-dimensional problems to optimise operating strategies under uncertainty.

Minerals extraction problems have attracted significant interest from researchers in the fields of stochastic control and real options since the 1980s. Numerous approaches have been suggested in the literature to treat such problems. Over the last decade, the least-squares Monte Carlo approach, originally motivated by financial applications, that approximates value function by linear combinations of a set of basic functions, has become very popular in the stochastic control problems in minerals applications. While such approach reduces computational complexity of the problems, it has two significant drawbacks. Specifically, (1) a choice of basis function is problematic; and (2) increasing the size of the basis may cause oscillations if the sample size is small.

Recently, a new algorithm known as Convex Stochastic Switching (CSS) has been suggested. The algorithm approximates a convex value function by piecewise affine linear convex functions in terms of sub-gradients. The linear dynamics of the state space and the Bellman recursion are utilised to estimate the value functions through operations on the sub-gradients. These value function approximations converge to the true values uniformly on compact sets with probability one. The method is completely free from the drawbacks of the least-squares Monte Carlo. This paper presents the first application of the new CSS algorithm to natural resource investment problem.

Keywords: *Convex switching systems, natural resource investments, real options*

New Regression Monte Carlo Methods for High-dimensional Real Options Problems in Minerals industry

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Abstract Mining operations are affected by significant uncertainty in commodity prices, combined with geological uncertainties (both in quantity and quality of the available reserves). Technical difficulties and costs associated with ore extraction together with a highly uncertain environment present significant risks for profitability of mineral projects. Optimising operating strategies in response to changing market conditions and information about the available reserves is crucial for project profitability in the face of uncertainty.

A natural resource extraction problem can be viewed as a stochastic optimal control (real options) problem, with extraction rate representing a control variable. In a finite horizon, finite reserve setting, an additional complexity arises from the need to consider a large number of feasible remaining reserve levels, which significantly increases the computational complexity of the algorithms.

Extraction of a natural resource problems have attracted the attention of researchers in the fields of real options and stochastic optimal control since the 1980s. However, there is still no computational framework available that would allow realistic high-dimensional real options problems in minerals industry to be solved.

Over the last decade, the approach based on value function approximation via basis functions has attracted significant attention from financial applications, and has given rise to a class of methods known as regression Monte Carlo methods. Regression Monte Carlo is a very versatile simulation-based technique. It can deal with a rich description of the mining problem, and very elaborate models for the risk factors.

In this paper, we propose to combine several crucial improvements to make the regression Monte Carlo method practical for multi-dimensional models:

1) Firstly, we avoid the discretisation of reserve level by using the control randomization technique. First, the reserve is replaced by a dummy random factor during the forward loop. Then, this variable is included into the regression factors during the backward loop, and optimised. Randomization also allows dealing with geological uncertainties in the estimated reserve.

2) Then, to avoid the full storage of the sample paths, we implement a memory reduction method. The idea is to store the seeds of the random number generator during the forward loop, in order to reproduce the paths exactly during the backward loop. This drastically reduces memory consumption.

3) Finally, to solve once and for all the problem of choice of regression basis, we perform non-parametric adaptive local regressions, which automatically adapt to the data and the function to regress. Its numerical efficiency is ensured by a novel fast implementation of the method.

We explain how these efficient implementation techniques allow us to tackle a stylized mineral extraction problem under both price and geological uncertainties. One key advantage of the proposed improvements is that they are easily extendable to higher dimensions and make it possible to tackle realistic multi-dimensional real option problems. For the mining industry, this means better estimates for the value of a mine, with geological and price uncertainties taken into account. Beyond that, it means better dynamic strategies for mine operation, with explicit rules on how to deal with changing circumstances.

Keywords: *Real option, stochastic control, Monte Carlo, control randomization, memory reduction*

Choosing crop rotations under uncertainty: a multi-period dynamic portfolio optimization approach

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Abstract: To achieve good crop yields, farmers are aware of the importance of good rainfall during the growing season. However, their choice of crop to plant may not necessarily be the optimal choice when climate uncertainty exists. Indeed, current cropping allocations may be driven more by historical trends and tradition than by the future forecasts of climate scenarios and commodity prices. In a digital agricultural future, farmers may instead use information on crop yields and water usage to make cropping decisions each year that optimize their cash flow under the uncertainty of climate conditions and commodity prices.

In this paper, we apply dynamic portfolio optimization techniques to the development of a simulation-based numerical method for making dynamic optimal cropping decisions. This method relies on a backwards recursive approach developed to solve the American option pricing problem. At each time step backwards from the end of the decision time period, the optimal expected future cash flow, or the so-called continuation function, is determined by using the Least Squares Monte Carlo method. As an example, we use a representative farm in Australia with four paddocks that can grow wheat, rice, barley and canola, and we also regard the corresponding commodity prices as stochastic variables. We compute the optimal crop rotations each year under different rainfall scenarios that maximise the expected utility over a fixed time period of 20 years. We evaluate the performance of the dynamic cropping strategies by comparing the expected value and standard deviation of future cash flows against those generated from static cropping strategies.

Keywords: *Crop rotation, rainfall, portfolio optimization, Least-squares Monte Carlo, approximate stochastic dynamic programming*

Optimal Asset Liability Management for Post-retirement stage with Income Protection Product

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Abstract: Australia has a compulsory defined contribution retirement provision system, whereby employers must con-tribute a proportion of the pre-tax salary of their employees towards an individual account which cannot be accessed until retirement except in extraordinary circumstances. These funds are generally invested in a port-folio of financial assets from which the retiree may draw throughout retirement. Retirees under this system face two key problems when making investment and withdrawal decisions regarding this portfolio. Firstly, retirees must manage their superannuation investment portfolio to maximise their risk-adjusted returns and thereby best financially provide for their own retirement. Secondly, retirees must optimise their withdrawal pattern from the superannuation account throughout retirement so as to maximise their post-retirement lifetime utility given the need to minimise the risk of portfolio ruin prior to death.

We model this issue as a dynamic stochastic optimisation problem with constraints. The market value of the portfolio is a function of the annual contributions invested by the individual throughout their career and the returns derived from their investment in uncertain financial markets. The post-retirement lifetime utility function is a function of discounted annual income throughout retirement and is therefore subject to market and inflation risk. We model the financial market uncertainties as correlated stochastic processes as projected by a variant on the Wilkie stochastic investment model developed within CSIRO, the SUPA (Simulation of Uncertainty for Pension Analysis) model. We also define an income protection asset (an inflation index linked annuity) which is available to the individual as a tool to hedge inflation risk. We then solve the dynamic super-annuation/pension portfolio optimisation problem using a numerical approach that is based on the stochastic control algorithm to calculate the conditional value functions of investors for a sequence of discrete decision dates. The algorithm provides optimal decisions for portfolio asset allocation in financial markets and the optimal amount to shift towards the annuity product on an annual basis to achieve maximum post-retirement lifetime utility whilst minimising the risk of portfolio ruin prior to death.

Keywords: *Portfolio optimization, least-squares Monte Carlo, approximate stochastic dynamic programming, optimal asset allocation, asset liability management*

Towards Dynamic Financial Valuation of Social Licence to Operate under Uncertainty

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Abstract: The concept of a Social Licence to Operate (SLO), first introduced in the minerals industry, has significantly evolved over the last decade and is currently viewed as a broad, ongoing approval and acceptance of business activities by society and stakeholders. It is gaining prominence outside the minerals industry, in the energy and manufacturing sectors.

SLO is broadly recognized as crucial for profitable and sustainable mineral resource extraction operations. Recent research shows that the reduction in project value due to the lack of the SLO can be as high as 70%. This motivates a strong interest from industry to assess the financial value of SLO to the company, in order to prioritise the SLO investments alongside other operational investments and to connect SLO with the project value, business risk and decision-making. However, there are still no accepted methodologies available to achieve this.

The consensus emerging in the literature is that the quality of company engagements with stakeholders/communities is among the most important factors influencing the SLO outcome. However, there are other factors affecting SLO outcome, such as existing and future economic, environmental and political conditions in the region; environmental and social impacts generated by mining operations; the company's ability to anticipate future risks and their proactivity in engagements with stakeholders and communities. The long timeframes for mining operation (>30 years) also mean that technological innovation can drive significant change in the value of economic, environmental and social assets over the life of a mine. Capturing this requires systematic quantitative work with deep qualitative grounding in context. Combining quantitative and qualitative analysis is a major challenge in SLO research.

In this paper, we discuss the possibility of quantitative modeling of SLO and propose several quantitative approaches and a novel integrated conceptual framework for dynamic financial valuation of SLO that accounts for such important SLO features as:

- Complex and non-linear interactions between industrial operations, communities and stakeholders responses, business decision making and company's value;
- Dynamic nature of SLO and its evolution over the lifecycle of mineral operations;
- Multiple uncertainties surrounding mining operations and SLO outcomes;
- Importance of flexibility and timing of business decisions in SLO management;
- Importance of anticipating future risks and proactive engagements with stakeholders/community;
- Unknown response to managerial actions from community and stakeholders.

The proposed framework is based on the integrated real options, adaptive management and risk analysis approaches.

This paper lays the foundation for development of decision support tools in which economic, social and environmental challenges are addressed simultaneously during the lifecycle of the minerals extraction operations, to achieve sustainable operations with robust SLO.

Keywords: *Financial valuation, social licence to operate, real options, adaptive management, resilience*

Modelling the Linkages between Dividend Policy and Future Earnings

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Abstract: The motivation of this study is to investigate whether the strength of payout ratios able to explain expected earnings. More definitely, do higher dividend payout ratios direct to higher return? The hypothesis is that higher dividend payout is a signal of optimism that leads to higher likelihood of subsiding agency cost and thus resulting to higher growth in expected earnings. In other words lower payout ratio leads to inefficient empire building or even funding in less than ideal projects whereas higher payout ratio leads to more carefully chosen projects leading to higher subsequent growth in earnings. This study aims to explore the relation of dividend policies with expected earnings in 5 major Asian countries - Australia, Singapore, China, Japan and South Korea. The motivation is the inevitably dissimilar environmental characteristic of these Asian countries. Other than that, most of the empirical studies on this subject are conducted in either developed US or EU capital markets. The 5 countries are different in their legal setup, taxation policies and financial structures. All these factors have visible impact on their payout policies. The fixed effect model of regression on 10 year data from 2003 through 2012 reveals some mixed results. We found that the common law followers (Australia and Singapore) have higher mean values for payout ratios whereas the civil law followers (China, South Korea, and Japan) have lower mean value for payout ratios. For all the countries, we found that the large firms tend to have lower future earnings growth. More importantly, we found significant positive relation between dividend payout ratios and future earnings growth in Australia, Singapore, Japan and South Korea. The pervasive positive relationship means that high dividend payout ratios lead to strong growth in subsequent earnings. We found strong positive evidence in favor of free cash flow theory to explain this relationship in Japan. However, China's findings as a negative relationship of dividend payout with future earnings growth is opposing to the inclusive inference.

Keywords: *Dividend, earnings, mean reversion, free cash flow, fixed effect*

Forecast foreign exchange with both linear and non-linear models coupled with trading rules for selected currencies

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Abstract: The importance of forecasting exchange rate is evident both academically and practically, but it is not an easy task to perform as the foreign exchange market has long been considered complex, erratic and exhibits apparently random behavior. The challenge is posited in a number of studies that highlight the poor out-of-sample forecasting performance of a variety of structural exchange rate models and conclude that none of these models could significantly outperform a simple random-walk model in both short- and medium-terms. An extensive subsequent literature using non-linear econometric techniques, different currencies, data periodicity and samples also draw similar conclusion that exchange rates, just like other financial time series, can be well modeled using a random walk model.

In this paper we attempt to employ a "hybrid" model to investigate the effectiveness of monetary fundamentals and other macroeconomic variables in predicting the bull and bear market longer-term trends (macro-cycles) and in forecasting the exchange rate movements. In particular, we intend to use a combined model of both parametric Markov Logistic model and a nonparametric multilayer feedforward neural network coupled with technical trading rules to predict the macro-cycles of the selected currencies by using the macroeconomic fundamental variables as inputs. When applying the linear models, most existing studies seem to use the same specification for estimation and forecasting, but the dynamic impact of the concerned variables is ignored. In this study we allow for variations in model specification throughout the forecasting period to address this stylized fact, and, furthermore, we combine the linear model and nonlinear neural network model by adopting both an equal weighted approach and a profit weighted approach to capture both the linear and nonlinear components of the exchange rate mechanism. It is expected that the combined hybrid models will outperform those single models in terms of predicting power and trading advantage in different market condition. We choose three pairs of currencies including the US dollar (USD), the Japanese yen (JPY) and Canadian dollar (CAD) in this study. The USD and JPY are one of the mostly traded currencies in the world, and the Canadian dollar is chosen because of its close economic ties to the United States. The bilateral exchange rate of CAD and JPY is studied as it is interesting to see if our model works for the less traded currencies, and also to complete the "triangle" of the three currencies.

The results confirm that the combination models have a significant predictive and market timing ability and outperform the benchmark models in terms of returns, even although their advantage diminishes in the periods of central bank intervention.

Keywords: *Forecasting exchange rate, equal weighted composite model, profit weighted composite model, trading macro-cycles, multilayer feedforward neural network*

An Empirical Study of the Impacts of Geographic and Cultural Distance on Chinese ODI

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Abstract: Since the reform and opening-up started in the end of the 1970s, especially after Deng's southern tour in the early 1990s, China has achieved remarkable success in attracting foreign direct investment (FDI), and become one of the top destinations in the world for FDI since 2003. By 2013, the utilized FDI in China has reached USD118.7 billion from nearly null level. The recent UNCTAD report shows that China became the top destination for inward FDI again in 2014, with an estimated amount of over US$128 billion of FDI received, despite concerns of China's economic slowdown. With China's rapidly integrating with the global economy, its outward FDI has also picked up rapidly in recent decades, especially since China's WTO entry in 2001, to make overseas acquisitions to gain technology and market access and international experience. Over the past few decades China has transformed into a major source country of FDI in the world, and become the third largest source of foreign direct investment after the United States and Japan since 2012.

In this study we attempt to investigate empirically the impacts of geographic and cultural distance on Chinese outward direct investment (ODI). It is found that Chinese ODI is negatively correlated with both geographic and cultural distance based on the tests using the full sample of all the recipient countries. Furthermore, we investigate the mechanisms through which the impact of cultural and geographic distance is exerted. The results indicate that geographic distance bears significantly negative impacts on ODI in the countries of low geographic distance, while it encourages OFDI into countries with high geographic distance. In addition, cultural distance is found to discourage OFDI through its impact on bilateral trade.

Keywords: *Outward foreign direct investment, Chinese economy, geographic and cultural distance*

EXTENDED ABSTRACT ONLY

A multi-functional large pumped storage scheme for New Zealand in support of renewable energy development?

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Abstract: Results are presented from a current PhD project at the University of Waikato, concerned with simulating a large seasonal pumped storage scheme in New Zealand's South Island. New Zealand presently has no pumped storage and about 65% of power generation is derived from hydro sources. There is also a small but growing contribution from wind energy. The total hydro storage capacity is only a little greater than 4,000 GWh - approximately 2 month's typical hydro power generation. Security of power supply is thus susceptible to extended droughts and further wind power development is likely to create grid instability in the absence of backup fast-response generating capacity.

The proposed scheme has energy storage which could be expanded to as much as 10,000 GWh with an installed capacity around 1,300 MW, using an upper reservoir in the Onslow schist rock basin in Central Otago. The operation of the scheme is being simulated using daily values of (i) recorded river flows (1994-2012) (ii) pump/generation operation (iii) existing hydro power station operation, to evaluate impact on both the New Zealand electricity system and changes to existing major hydro storage lake operations. The simulations indicate the scheme would permit partial reversion of existing scenic hydro lakes away from hydro storage to more natural seasonal water level variations. In particular, South Island hydro storage lakes would no longer hold back summer high flows as storage for winter power, but instead release the water in summer for both power generation (to pumped storage) and expanded irrigation use. The simulations show spill reduction from hydro dams would offset pumping/generating inefficiencies with a small net power gain. Fig. 1 shows a simulation result with spill reduction at two existing hydro power stations on the Clutha River.

The specific national advantage to the Onslow scheme, however, is that it would provide grid stability by buffering the power fluctuations from future major wind power development, enabling progression toward a national goal of 90% renewable electricity generation by 2025. This aspect is still being incorporated into the simulation process.

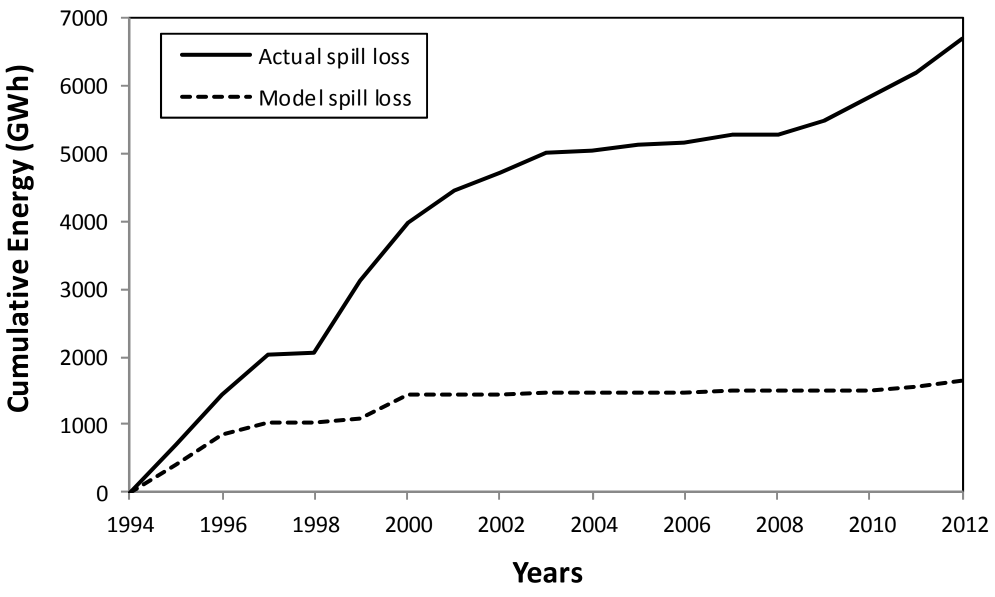

Figure 1. Cumulative energy loss from spill from Clyde and Roxburgh dams (combined): actual and as simulated (1994-2012) with the Onslow pumped storage scheme in operation. Mean extra power ≈ 30 MW.

Keywords: *Pumped storage, wind power, grid stability, climatic buffering*

Additive versus Multiplicative Seasonality in Solar Radiation Time Series

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Abstract: Several approaches have been developed for the forecasting of solar radiation on various time scales. The approaches range from use of Artificial Neural Networks (ANN) using raw solar irradiance to several methods utlizing first some type of seasonal adjustment. This seasonal adjustment is either in the form of multiplicative deseasoning such as using clearness index or a clear sky model, or additive deseasoning using Fourier series or wavelets. This article focuses on comparison of various methods of seasonal adjustment, but first let us examine the range of forecasting tools subsequent to this process of the modelling. The tools range from ANN to Adaptive Autoregressive to Exponential Smoothing. As well as these single method approaches, several authors utilise what might be called hybrid models, like wavelets plus ANN , and the Coupled Autoregressive and Dynamical Systems (CARDS) model of the present author and colleagues. This is not an exhaustive list but it gives the idea of the wide range of possible methods used for short term forecasting of solar radiation. There are essentially two methods of dealing with the seasonalities inherent in climate variables. One can deal with it in a multiplicative or additive modelling framework. Interestingly, though The multiplicative approach is problematic, it is the approach most often used for solar forecasting models in particular. There are two versions of the multiplicative approach with respect to solar radiation, calculating the clearness index, and estimating the clear sky index. There is this distinction in terminology since to form the clearness index, one divides the global solar radiation by the extraterrestrial radiation, a quantity determined only via astronomical formulae. On the other hand the clear sky index involves dividing the global radiation by a clear sky model. Note that the wind resource is not as seasonally dependent as the solar radiation, and both multiplicative and additive versions of dealing with seasonality are used. Additive de-seasoning is enacted through subtracting a mean function from the solar radiation, that function formed usually through the addition of terms involving a basis of the function space. Arguments are presented to support the conjecture that the appropriate way to perform this operation is through the use of a Fourier set of basis functions. As well as specifically dealing with how appropriate this approach is for solar radiation, it will discussed with reference to modelling ambient temperature. There are occasions when the bivariate modelling of temperature and solar radiation is needed. For example, a solar photovoltaic cell loses efficiency as the temperature increases, and so for evaluating the expected performance of a PV cell, it would be useful to be able to model temperature and solar radiation together. It is not possible to deal with temperature seasonality via a multiplicative approach. It would be difficult to construct a bivariate time series model where one dealt with the seasonality with a multiplicative approach with one variable and an additive with the other. This is another compelling argument for dealing with the solar radiation seasonality using Fourier series.

Keywords: *Time series, Additive seasonality, multiplicative seasonality, Fourier Series, Clear Sky Index*

EXTENDED ABSTRACT ONLY

How can decentralised generators influence distribution networks loads?

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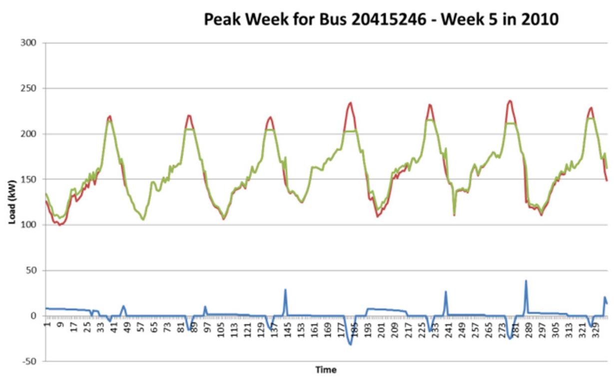
Abstract: With an increased number of decentralised generators on the network (e.g. rooftop solar panels, small-wind turbines) and a decline in monetary incentives for the output they feed back to the grid, small battery systems are expected to see a sudden increase in uptake as individual owners will aim at maximising their usage and revenue. Understanding how these decentralised generators might impact the grid at different locations is important for distribution network companies who need to ensure safe and reliable delivery of electricity at all time. To help with assessing the potential impact of these decentralised generators on the traditional grid, an agent-based model of a distribution network has been developed.

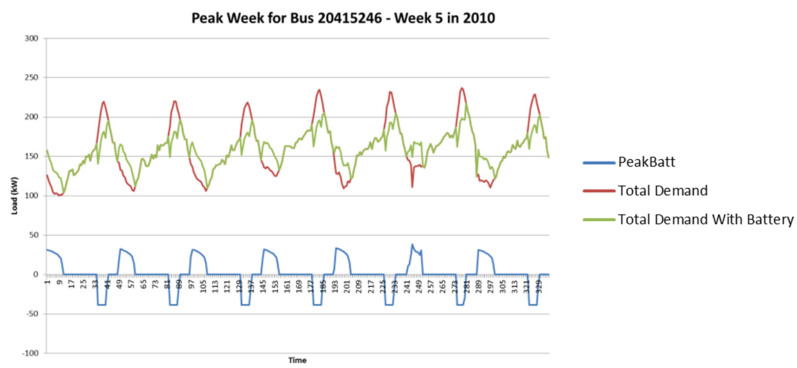
The agents of this model represent the different elements of a network (e.g. premises, transformers, lines, solar panels, batteries), and their behaviour. Many implementations of an agent's behaviour can be used, so that alternative behaviours can be evaluated when the aim of a simulation is to assess their impact on the network.

An example of alternative behaviour of agents is for battery systems that can have different control algorithms, depending on where they might be placed on the network, and what their purpose is. Two types have been implemented: a) at the individual premise level, where individual owners aim at maximising their renewable generator output for their own benefit, b) the grid level where the storage systems can support the network with fluctuating load and voltage levels. For both these battery types, alternative behaviours implementations can also be tried. Looking at the different ways batteries can be used offers some insight into how the overall system might work, and also provides an avenue for planners to put incentives in place so that these individual batteries can also support the network.

Simulations have shown how varying a few parameters describing the use of batteries can greatly influence the network outcomes, overall, but also over localised areas. The example below illustrates the use of a battery at the network level using two different control algorithms for the same week, where a peak was observed on a given bus. This shows that depending on the chosen algorithm, the peak load can be more or less reduced. Also, battery usage profile can vary greatly, leading to a reduction in battery life that, in some cases, might not warrant the gain in peak reduction. While these results are based using network batteries, equivalent results can be obtained with individual batteries when efficient incentives are put in place.



Control algorithm using variable discharge time based on consumption knowledge of the day before, and peak shaving aim of 10%.



Control algorithm using constant discharge time (17-20) and recharge times (0-5) with load following.

Keywords: *Agent-based models, electricity distribution networks, batteries*

Least cost combination of renewable generators, storage devices and transmission system in the NEM

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Abstract: There are differing views on how to achieve a high penetration renewable power system in the Australian National Electricity Market (NEM). The limited hydro resource in Australia makes it more challenging to achieve a 100% renewable power system than other hydro resource-rich countries, as pumped-hydro plants could act as peaking power plants and provide relatively cheap energy storage. Given the variability and diverse location of wind and solar resources, augmentation of the transmission network and placement of energy storage devices may be key considerations under a high penetration renewable power system.

The model in this paper estimates the least cost combination of renewable technologies, storage devices and transmission infrastructure to meet the projected demand in the NEM in the year 2030. The simulation uses historical data of NEM demand, regional interconnector capacity limits, weather data for wind and solar resources, and monthly hydro plant generation data as a benchmark. Genetic Algorithm (GA) is used as the optimization algorithm to seek the least cost combination of renewable generators, storage devices (existing pumped hydro and new grid-scale batteries) and transmission network upgrades to meet the electricity demand for all NEM regions at hourly temporal resolution.

The results in this paper suggest that the electricity cost of a 100% renewable power system in the NEM would be ranged from \$100/MWh to \$163/MWh. Significant flows of power between regions may occur frequently and this will require significant investment in the transmission system. Deployment of battery storage devices along with investment in transmission infrastructure greatly increases the utilization of wind farms and solar power systems.

Keywords: *Energy modelling, optimization, renewable energy*

A Simple Model for Estimating the Diffuse Fraction of Solar Irradiance from Photovoltaic Array Power Output

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Abstract: Given the rapid proliferation of data recording equipment for distributed photovoltaic (PV) arrays globally, there exists a new opportunity to use the power output from these systems for the purpose of surface solar radiation assessment. Direct measurements of the beam and diffuse irradiance represent the best methods for producing such assessments, however the equipment required for these observations are expensive and require routine maintenance, which therefore mean that the measurements are quite sparse globally. Satellite derived solar radiation estimates, meanwhile, have global coverage with increasingly fine resolution, but still require surface measurements of radiation in order to assess the performance of their solar radiation estimation algorithms (e.g. Heliostat). Therefore, it is global horizontal irradiance measurements recorded by a pyranometer, which have become the most common measurement of surface radiation. Pyranometers provide accurate surface radiation observations and are relatively inexpensive. As such, models which separate the diffuse and beam components in a global measurement have been discussed and developed vigorously in recent decades, with many modern models now accepted as the state of the art. This paper posits that the power output from PV systems is not altogether different from that recorded by pyranometers, and could be used in place of, or in supplement to, radiation observation equipment. This would greatly increase the density of the surface radiation measurement network, allowing for the many millions of PV systems reporting power output measurements globally to be applied to this purpose. PV system power output has a first order relationship with incoming solar radiation, but is confounded by additional second order interactions such as losses related to temperature, module efficiency, DC-AC conversion, soiling and shading, etc. Recently, research work by the first author has demonstrated that the individual nuances of PV systems can be accommodated through normalisation of their power output to their simulated clear sky performance. This normalised variable is termed the clear sky index for photovoltaics, K_{PV}. We use this value as the primary input to a logistical regression model in place of the traditional input, the clearness index K_t, and explore the use of additional predictor variables to optimise accuracy. PV power output was collected from 18 sites in two Australian cities (Adelaide and Melbourne) in which Bureau of Meteorology solar radiation measurement stations are deployed. This allowed us to fit and test K_t and K_{PV} based models to the observed diffuse radiation, and directly compare these approaches. Surprisingly, initial results suggest a K_{PV} based model has nearly equivalent performance to that of the traditional, pyranometer based K_t model. This paper will explore this relationship more fully, and provide the first simple model available for this purpose

Keywords: *Solar radiation, solar energy, photovoltaics, DNI, diffuse fraction*

Assessment of solar and wind synergy in Australia

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Abstract: Australia's growing renewable energy industry aims to meet local electricity demands while reducing the dependence on fossil fuels. Solar energy and wind energy are the two most viable sources of renewable energy resources available. However, intermittency caused from the unpredictable nature and dependence of these resources due to climatic and weather conditions affect the systems energy performance. Solar power is largely affected by the movement of clouds, while wind power variations can be associated with moving weather fronts. These variations occur at different temporal and spatial scales causing intermittency in the generation of power and significantly affect the scheduling and transmission operations of the grid operators. Thus, efficient short-term forecasting of stand-alone solar and wind energy production becomes vital unless the unpredicted generation is well catered by system reserves. Interestingly, intermittency relating to stand-alone solar and wind energy system can be mitigated by integrating these two resources to complement each other. Optimizing both of these resources for the generation of power is crucial.

Hybrid Solar-Wind power generation systems can boost energy production if greater complementary characteristics exist at potential sites. This study uses reduced hourly time averaged diagnostic fields from Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis data over Australia. The boundary layer flux data has been used to construct wind profile at 80 m turbine hub heights. The Wind Power Density (WPD) and surface incident shortwave flux (also available from MERRA surface flux data) were used to assess the feasibility of wind and solar energy, respectively.

The complementary characteristics of solar and wind energy were investigated temporally at hourly and daily scales. Hourly anti-correlations in solar and wind energy were significant in northern Australia during morning, central Australia at noon and western Australia in the afternoon. Regions near the eastern, western and south-western coast dominate the frequency of daily anti-correlations. Further assessment of the complementary characteristics of usable wind (WPD >240 Wm^{-2}) and solar (GHI >0 Wm^{-2}) energy showed potential locations of hybrid solar-wind power generating systems. Wind complemented solar along the western and southern coast, whereas solar complemented wind along the eastern and northern coast. Overall, the synergy between solar and wind energy in Australia is within 30-60% of all days within the period of 1979-2014. A hybrid solar-wind power generating system is most feasible in the south-east region where solar and winds complement each other on > 50% of the days within the last 36 years.

Also, a region of interest was selected (near Capital Wind farm) and correlations of wind/solar energy flux and NSW energy demand were investigated for 2010. Interestingly, on 76% of days during all of 2010, wind and solar energy supplemented each other (correlations more than 0.5), whereas with 10% of all days in 2010 wind and solar energy complemented each other. On 85% of days in 2010 the energy demand and wind energy were positively correlated, whereas the energy demand and solar energy were 100% positively correlated, except the correlations decreased during winter. A hybrid solar-wind power generating system is highly feasible at this location.

Keywords: *Hybrid solar-wind, synergy, MERRA*

Discovering the effect of RES on risk premia in electricity markets

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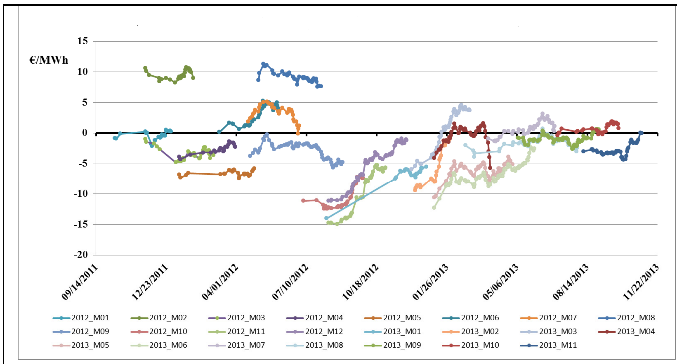
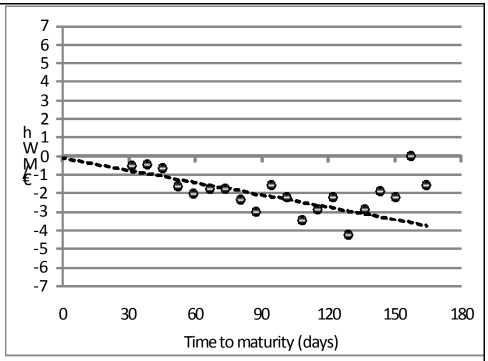
Abstract: This paper is part of a broader project aimed at discovering the effect of Renewable Energy Sources (RES) on electricity markets. The recent massive RES production in Europe is relatively recent: it started since 2009-2010 due to system of incentives introduced in almost all European countries. Nowadays, the technologies are consolidated and even though the incentive system has stopped (due also to the economic crisis), RES produce energy and have contributed at lowering (at least in the wholesale markets) prices. However, the effect of RES production on risk premia is still quite elusive and requires deeper analysis. In this exploratory and preliminary paper, we develop an ex post analysis on risk premia on the Italian futures market. The peculiarities of the electricity markets make electricity futures very different than financial or commodity futures. In fact, it is well known that a consequence of non-storability of electricity is that the only possible delivery in a forward or futures contract is through a supply over a period of time. The entire lifecycle of a standard futures/forward contract on electricity can be divided in a *trading period* and a *delivery period*. Differently from the classical case, the convergence of futures price to spot prices does not hold here. Indeed, at the end of the trading period futures expire, yet the spot price continues evolving during all the delivery period. Parties can open positions on forward and futures contracts only before the delivery period. At maturity (T), that is at the end of the delivery period H, contracts expire. Our work contributes to the existing literature on futures in electricity markets by analyzing empirically the deviation of futures prices from observed spot prices. The analysis is carried on the Italian forward base load monthly contracts (2008-2012). The results show, case by case, a clear non convergence of futures to the underlying spot prices or average of them (see Figure).



Trajectories of the payoff of monthly base load futures premia on Italian market from 2012_M01 to 2013_M11



Average performance of monthly baseload futures premia on Italian market vs time to maturity

However, at an aggregate level, a positive risk premium is found, which is somehow coherent with findings in the literature (see Figure). Moreover, given the absence of convergence of futures to spot prices at the end of trading period, a positive variance of the payoff is found at delivery. The results show that more research should be done on modelling average spot prices and futures, since most of the rules valid for other financial and commodity markets do not hold here. In fact, the underlying price is the average of ex post prices over the delivery period, which can last one month, three months or even one year. Modelling such a price can be even more challenging than modelling spot price and we know that modelling spot prices in electricity markets is a demanding task and still in progress.

Keywords: *Risk premia, electricity markets, futures and forwards*

Modelling the Likelihood of Urban Residential Fires Considering Fire History and the Built Environment: A Markov Chain Approach

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Abstract: In this paper, we address the complex question of how the occurrence rate of residential structure fires in Melbourne city are influenced by built-environment structural forms and/or the recent history of fire incident occurred within the neighbouring areas. Numerous studies have used the socio-demographic and economic characteristics to explain the spatial variability in residential fire occurrence rates. There is however less published research that links spatio-temporal variation of residential fire occurrences with patterns and changes in the built environment, or which seeks to quantify the spatial effect of fire events on the subsequent rate of incidents within the local area.

We develop a spatio-temporal model of residential fire occurrence based on a range of spatial characteristics and past fire occurrences within neighbourhood. These spatial characteristics include the Index of Relative Socio-economic Advantage and Disadvantage (IRSAD), residential density (i.e. the relative number of dwelling per unit area), percentage of owned dwellings, percentage of privately rented dwellings, percentage of publicly rented dwellings, percentage of residents moved in the last five years, and percentage of residents moved in last year. The model is fitted to fire incidence data from Melbourne, Australia, gathered over a 10-year period. Results show that the distribution of residential structure fires across Melbourne is a complex pattern and is associated with spatially-varying indicators. The inner suburbs of the Melbourne region are more fire prone than others. Those areas have high probability of fire occurrence. This naturally follows not only from built environment and socio economic characteristics, but also correlates with recently-located residents as the tenure status in those areas. Households that have recently moved into an area, and households consisting of temporary residents, have been demonstrated in prior studies to exhibit an elevated likelihood of fire occurrence. The analysis also capture that there is a neighbourhood "memory" effect of fires, with respect to fire occurrence rates.

The results contribute to an evidence base which may be useful for emergency planners and fire agencies seeking to build appropriate strategies to mitigate fire effects on communities. It also aids in assessing and classifying areas in terms of fire occurrence likelihood, and in determining when to circulate fire safety information to residents so as to retain preparedness and awareness of fire incidents.

Keywords: *Residential fire, urban ecology, built environment, Markov chains*

Improved numerical weather predictions by using optimised urban model parameter values and satellite derived tree heights

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Abstract: About 90% of the Australian population lives in urban areas yet numerical weather prediction (NWP) systems poorly represent urban areas. The Australian Community Climate and Earth System Simulator (ACCESS) uses a simple urban model with only three parameters; heat capacity, albedo and aerodynamic roughness length (Best, 2005). The urban model parameters are set fixed to the same values at all urban areas, worldwide. This urban model was developed in the United Kingdom and consequently the default urban parameter values are unlikely to be appropriate for Australia. A previous study (Best et al., 2006) has used observations of surface fluxes from Mexico City and Vancouver to evaluate this urban model and concluded that much better estimates of the sensible heat flux are provided when a significantly smaller value for the urban heat capacity parameter is used. This urban model contains no information about the three dimensional morphology of the buildings and consequently the urban heat capacity parameter is not well defined and cannot be measured.

The ACCESS NWP system simply assumes that over most of Australia, including urban areas, trees are 28 metres tall. ACCESS NWP assumes that the heat capacity of trees increases with tree height and follows a power law while the aerodynamic roughness length increases linearly with tree height (Essery et al., 2001). A halving of model tree heights causes the heat capacity of model trees to reduce by a factor of almost six.

In this study we use revised urban model parameter values that are more appropriate for Australia and a global dataset of forest canopy height derived from satellite LIDAR measurements to improve the ACCESS NWP system. Experiments show that the use of the new urban model parameters and tree heights results in significantly improved forecasts of air temperature at a height of 2 metres above the surface (screen level).

Keywords: *Urban, weather, heat capacity, Albedo, roughness length*

Modelling infrastructure interdependency at a local scale: value, methodologies and challenges

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Abstract: Natural hazards such as floods, bushfires, cyclones or hurricanes, can cause significant damage that disrupts our infrastructure systems. Climate change is making such extreme events more frequent and more severe. In addition, infrastructure systems have become more interconnected and interdependent. By interconnected, we mean that infrastructure systems use each other's output and operate together to provide joint services. The interdependence of two systems or components, on the other hand, refers to the effect of a decline of the performance of one system or component on another. Hence, a disruption to one infrastructure system may propagate into others and eventually affect various services that are critical for the well-being of communities. In recent years, cascading failures of infrastructure systems at a national scale have attracted significant attention. However, our understanding of these failures at a local scale remains limited. During major disasters, communities frequently face the challenge of disruptions that are locally triggered and propagated. Therefore, applying a systems-based analytical approach is likely to be beneficial for local authorities when making decisions on infrastructure planning and operations. To this end, the ability to model inter-connectedness of local infrastructure systems needs to be strengthened. The goal of this paper is to discuss the value of applying a systems approach to the analysis of infrastructure systems and their interdependencies and present and appraise various methodologies that can be used in implementing such as an approach. The paper is divided into four parts.

First, fundamental elements of interdependency analysis are presented. The differences between interdependency modelling at national and local scales are discussed and illustrated. One important difference is that coarse spatial resolution of models at a national scale prevents them from yielding information that is useful for locally-triggered and locally-propagated disruptions. For example, in a national-scale model, the entire water or power distribution system for a local government area may be represented by a single node reflecting its role in, and effect on, the national network, without incorporating an understanding of its internal operation.

Second, we describe the likely decision-making contexts within which infrastructure planning and management are conducted. Different local stakeholders with diverse concerns related to investment, planning, designing, and operations and management of infrastructures are usually involved in, and/or affected by, infrastructure decision-making. These stakeholders include local governments, infrastructure operators and utility companies, local businesses, households, individuals and local communities.

Third, we review different methodologies available for modelling infrastructure interdependencies at a local scale. We discuss their suitability in light of the specific analysis goals and identify their respective strengths and weaknesses. We propose a preliminary framework for selecting appropriate methods for modelling infrastructure performance depending on the underlying decision-making context.

Finally, we discuss important challenges present when tackling interdependency issues at a local scale. These challenges include lack of a comprehensive methodological framework linking different models, lack of a consistent benchmark and relevant datasets for judging the suitability of a method, and lack of a better understanding of the broader socio-economic impacts of infrastructure disruptions on local communities.

Keywords: *Infrastructure interdependency, local government, infrastructure planning, cascading failure*

TraNSIT: identifying optimal infrastructure investment

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Abstract: The Transport Network Strategic Investment Tool (TraNSIT) was conceived and developed by CSIRO, co-funded by the Office of Northern Australia, Queensland Government, NT Government and WA Government to provide a holistic view of the costs and benefits infrastructure investments and policy changes for the northern Australian livestock industry. Its initial application to the northern Australia's livestock herd of 12 million cattle, TraNSIT accommodated the movement of over 50 million cattle between 52,000 enterprises (2007 to 2011). This provided a baseline for transport costs and provided insights never before seen into freight flows and density of trucks on roads (Higgins et al 2015; Higgins et al 2013; McFallan et al 2013).

TraNSIT performs a mass optimal routing of vehicle movements between the thousands of enterprises, and scales up to provide industry, domain or locality wide logistics costs. This provides the ability to run scenarios and test logistics opportunities that benefit thousands of enterprises. Understanding what those scenarios may mean to supply chain flows and transport costs across all enterprises and the road network is critical to optimising the best value achieved from the investment options available.

With support from Meat & Livestock Australia, CSIRO has recently extended TraNSIT to the broader Australia road network for livestock movements for the 20 million strong herd. The tool provides stakeholders with information on both small- and large-scale investments in the supply chain through analysis of range of possible future industry scenarios. Several scenarios were developed via projects undertaken by the industry and state and federal governments including:

- Analysing the impact of road upgrades, where the financial benefits to enterprises, industry as a whole and the broader network are quantified;
- Optimising the use of road versus rail transport;
- Introducing new supply chain infrastructure facilities at optimal locations;
- Testing potential outcomes for changes in policy: alignment of driver and animal welfare stops; truck limitations for road classes;
- Identifying infrastructure investment and regulatory-change opportunities that maximise transport cost reductions for a given (limited) investment budget.

TraNSIT is modularised, and is currently set up with a beef module. By adding new modules we are able to inform management of investment in agricultural and horticultural supply chains across all of Australia, for existing and potential future industries. Further to this, new cost attributes are being developed to provide a multi-dimensional output allowing an understanding of the impact of potential changes on various social and environmental as well as economic variables. Our presentation will provide an overview of the methodology behind TraNSIT, along with a few transport infrastructure case studies.

As a result of the Northern Australia and Agriculture Competitiveness White Papers, which were launched by the Prime Minister in mid 2015, TraNSIT is being extended in two major initiatives. The first is to inform the Federal Government allocation of $100m investment into northern Australian roads to improve transportation of livestock, by identifying opportunities that achieve the best bang for buck. The second initiative is the extension of TraNSIT to over 95% of agriculture volume transported each year, covering 25 agriculture commodity/classes. The initiative will provide a baseline of transport movements of over 50 million tonnes of Australian agricultural and horticultural output between farms, storage, processors and to markets across Australia. TraNSIT is fast becoming the national platform for evaluating infrastructure investments and regulatory changes to improve supply chain efficiencies in agriculture transport.

Keywords: *Transport, optimization, agriculture, investment*

Modelling ad-hoc DRT over many days: a preliminary study

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Abstract: Traditional transport models focus on commuter traffic in private vehicles or public transport. However, new methods of travel are gaining traction, both in discussions and implementation: carsharing, shared taxis/buses, autonomous vehicles. Modelling these requires more attention on the interaction between people and place than traditional modes.

As part of a larger project on mobility on demand, shared flexibly-scheduled vehicles (also known as demand-responsive transportation, DRT) have been explored using simulations. These schemes can be designed in different ways with respect to the resolution of stops and timings, and the potential patronage. In a pure ad-hoc scheme, there will be no timetable or route. These schemes are attractive in areas where mass transit cannot provide a reasonable level-of-service in a financially and environmentally sustainable manner, such as fringe areas and small towns, however could also find a niche providing access to mass transit in larger cities.

One still-outstanding problem is predicting demand for DRT. Previous experiments have focused on trips, but have rarely looked into the choice to (continue to) use a service, especially when wait and travel times could change from day to day depending on the passengers using the service, and the effects on medium-term demand. Can an equilibrium point be found between supply and demand? If too many people use the service, wait and travel times increase too much for it to be a feasible option for some passengers, and so they take other modes or decide not to travel. However, the then decreased demand leads to good level-of-service for the remaining passengers; other customers might then return, which leads to worsening level-of-service, and so on. Another case occurs when an initially demand-responsive service starts to become “regular” in its routes and timings, in which case it is more efficient to create a fixed-route service.

Using agent-based modelling, we explore how demand for DRT changes on a daily basis. Passengers make decisions about whether to use DRT to participate in an activity, using information and satisfaction levels from previous trips and publicly-available information about service levels. Results reported include the activity levels and locations of the population, as well as the performance of the transport network. Experimenting with a simplified environment shows that mismatched supply and demand lead to fluctuating performance of the DRT systems.

Keywords: *Demand-responsive transportation, agent-based modelling, multi-day*

Challenges and opportunities for integrating land use, transport, and socio-economic models

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Abstract: The notion that economic, transport, and land use change processes interact, is common knowledge. How to simulate this interaction in (integrated) models is not that straightforward. Individual disciplines have co-existed for decennia and every discipline has developed its own concepts and (modelling) paradigms. When integrating models from these different disciplines, underlying assumptions and limitations of the existing individual models are passed on to the integrated model. A proper integration therefore requires a thorough understanding of the underlying theories of each of the models. Over the past decade, several attempts have been made to integrate socio-economic, land use, and transport models. However, focus tends to be on solving the software challenges more than on dealing with the scientific challenges.

We present and discuss an integrated spatial decision support system (ISDSS) for simulating urban and regional dynamics, for which prototypes have been applied to the Auckland and Wellington regions in New Zealand. The aim of this ISDSS is to support long-term integrated policy development and planning by taking into account land use, transport and socio-economic developments. An important aim of the approach is to show the trade-offs that need to be made when deciding about future development directions and therefore simulating the impact of alternative scenarios on the economy as well as the environment was found crucial.

The ISDSS has a temporal resolution of one year and a time horizon of 40-50 years into the future. The spatial resolution is 50 m. for Auckland and 100 m. for Greater Wellington and its extent is the greater metropolitan area; in both cases about 150 x 150 km. The ISDSS includes an ecological economic model, a demographic model, a land use model and a transport model. The first three components are integrated into one software system, while a loose coupling is made with the transport model. The demographic model used in the ISDSS is an age-cohort model that calculates population projections for the entire modelled region according to birth, mortality and migration figures which feed into the macro-economic and land use model. Macro-economic processes are represented using the Region Dynamic Economy Environment Model (RDEEM) input-output model which feeds into the land use model. Changes in land use are simulated with the Activity Based Metronamica model. This model simulates the competition for space at local level and hence the spatial allocation. It is an extension of the traditional cellular automaton (CA) based Metronamica as it includes population and jobs at cellular level in addition to land use classes. It provides the production and attraction for the transport model and in addition uses the zonal accessibility from the transport model as one of the factor for land use allocation. Transport and mobility processes are simulated with a four step transport model that calculates the production and attraction of trips, their distribution amongst the various transport zones, the modal split and finally the assignment of trips to the network.

The various individual models have been developed for different purposes, are built using different modelling paradigms and operate at different spatial and temporal scales and resolutions. While technically outputs from one model can be configured in such a way that they can be used as input into another, this does not overcome the conceptual challenges related to paradigms and scales, such as the integration of equilibrium approaches with dynamic simulation approaches, or the level of detail in model results that can meaningfully be provided at various scales.

The presentation discusses the challenges faced in the integration of the various models and focusses especially on the issues experienced resulting from the different modelling paradigms and different spatial and temporal scales and resolutions for which the models were originally developed and are now being applied.

Keywords: *Integrated strategic planning, integrated modelling, landuse-economic-transport interaction, modelling paradigms*

Integrated modelling to aid strategic urban and regional planning

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Abstract: Most of the current regional planning models rely on feed-forward trend analyses. However, economic, demographic, land use and infrastructure systems are far from isolated linear systems. They are in fact interdependent dynamic systems where a change in one systems impacts all other interdependent systems. Therefore, a change such as the addition of a new expressway to the transport network not only will bring changes in the transport system, but also in other systems like land use and demographic. Vision Illawarra is a modern tool that follows the system dynamics approach to incorporate these feedback loops between systems. Planners and policy makers can use Vision Illawarra to understand the holistic change a planning or policy decision will bring to the regional setting, thus enabling them to make smart strategic decisions for the benefit of the region.

Keywords: *Urban planning, land use, transportation, input-output model, synthetic population*

Novel spatial analysis of residential resource consumption via the Melbourne train network

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Abstract: Urban data volumes are increasing and becoming more accessible at a rapid rate. Therefore, novel approaches are required to synthesise and analyse the data in a meaningful way. The Australian Urban Research Infrastructure Network (AURIN) is providing tools and is negotiating data access to key datasets about cities to facilitate research on urban issues. Through AURIN, a number of datasets around urban settlements have been made available to researchers and policy analysts, including on demographics, housing, and resource consumption. These datasets are aggregated to geographic regions such as Australian Bureau of Statistics statistical areas, local government localities or postcodes in order to cater for the purpose of these regions. However, this can be a challenge when performing contextual analysis over a given region, as the data is not easily compared between spatial aggregations. Although this is a wealth of information, we argue that these regions are less intuitive to the general public compared with regions located around a familiar local landmark, such as a train station. Therefore, using landmarks like these as the basis for performing spatial analysis of its surrounding region may provide improved understanding of urban issues. In this paper, we explore the use of Melbourne metropolitan train stations as landmarks to explore the functional relationship between key co-variates such as population, house size, income and dependent variables water and electricity consumption for areas in Greater Melbourne. To achieve this, *Thiessen* polygons are used to define catchment areas and data is aggregated to these regions surrounding each train station. By presenting the data spatially for these regions in Melbourne, we demonstrate the use of a novel approach to spatial visualisation data. Results show strong associations between income and electricity consumption, and between measures of urban density with resource consumption.

Keywords: *Water and energy consumption, demographics, housing, spatial data analysis*

Improving Social Media Monitoring and Analysis Tools for Emergency Management

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Abstract: Open source data from social media platforms is becoming a critical source of intelligence to inform situational awareness in the emergency management domain. However, the use of social media data in emergency management organisations is not yet widespread. This paper reports on findings from four interviews with social media subject matter experts from Australian emergency management organisations. The first goal of the interviews was to understand how social media monitoring and analysis tools are used to meet the information needs of emergency services organisations. A second goal of the interviews was to capture their insight as to how such tools could be improved, to inform the ongoing development of CSIRO's Emergency Situation Awareness (ESA) tool. The ESA tool provides crowd sourced information in near-real-time from Twitter about all-hazard types for emergency managers. ESA collects Tweets from Australia and New Zealand and processes them to: identify unexpected incidents, monitor ongoing emergency events and provide access to an archive to explore past events (Power et al. 2014).

This paper reports on the findings from these interviews. All four interviewees were using a range of social media monitoring and analysis tools such as Geofeedia and Signal as well as the ESA tool. Our analysis revealed that participants valued the following characteristics when analysing social media data for emergency management: saving time, triangulation of multiple sources of information, "More eyes on the ground", geographic and temporal context, information about individuals, collaborative tools and cost minimisation.

However, as one participant noted: "*there is no one product that suits all our needs*". We spoke to participants about how the current social media monitoring and analysis tools could be improved. The key features they sought were:

1. Automated evaluation of information sources
2. The ability to follow social media content from specific individuals
3. Geographic representation of search results
4. Access to real-time feeds across multiple platforms, and
5. Flexibility to retrospectively modify searches.

We conclude by describing how these recommendations have been used to improve the delivery of CSIRO's ESA tool.

Keywords: *Emergency management, situational awareness, social media, Twitter*

Modelling the impacts of current patterns of urban form expansion in Kuwait with the use of ABM and GIS

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Abstract: During the last six decades Kuwait City has experienced a rapid and unpreceded population growth with only a small increase in the respective urban area. This is largely due to the discovery of oil and arrival of thousands of new immigrants. The alarming rise in the urban density has caused issues for the residents' lifestyle, the economy and the environment. Historically, urban planning decisions in Kuwait were based on a series of "Master Plans" implemented by the government. Generally the plans, the last of which was formulated in 1997, promoted concentrated high density development in the city's Central Business District (CBD), and resulted into a low density urban sprawl expanding outwards in a radial fashion.

A significant disadvantage of this top-down approach is the lack of inclusion of the citizens' suggestions and opinions, unlike similar expansion and planning policies in Western cities. Furthermore, the plans failed to incorporate measures to successfully accommodate the increase of vehicles and high traffic density, resulting into severe congestion issues and commuting times. Additionally, land development constraints set by the plans in combination with the increase of Kuwaiti citizens eligible to apply for housing welfare, caused a considerable increase of waiting times for receiving the government grants and drove property prices to levels out of reach for the majority of population. Pressure caused by these matters, has caused several protests in Kuwait, making the analysis of the impacts of current patterns of urban form expansion critical.

To predict the future effects of the continuation of the existing pattern of urban growth in Kuwait on congestion and housing shortage a series of simulations based on Agent Based Modelling (ABM) and Geographical Information Systems (GIS) is proposed. ABM provides a mean to evaluate decisions by different citizen groups on their settlement patterns and interactions with other groups, such as the developers and the government. The simulations are able to receive and overlay GIS data inputs related to land use, transport networks, and demographics. The simulations have a horizon of 35 years (up to 2050).

This paper discusses the rationale, design methodology and parameterisation of the ABM and the agent groups that constitute the framework. The base set of rules governing the behaviour of the agent groups was derived after analysing real data from historical Kuwait archives. The analysis findings are outlined in this paper. The findings imply that there are significant inherent correlations between urban form expansion and urban transportation quality as well as land use distribution.

Using the historical trends as a guide for future expansion and assuming linear development along the current transportation networks it is possible to obtain five yearly predictions for the future state of:

- Land use and development ratio
- Accessibility to transportation networks, work, shopping centres, services and infrastructure
- Population growth, distribution patterns and density.

The analysis of the simulation outputs will enable the generation of a set of predictions for the impacts on congestion and housing shortage in Kuwait. The outputs of the model will also enable the evaluation of the centroid urban form expansion and can form a basis for reference for developing alternative urban planning and expansion policies not just in Kuwait, but in other modern cities especially ones that experienced rapid radial growth around their CBD.

The proposed model with appropriate modifications will also be applied for simulating two alternative scenarios of urban form expansion in Kuwait in future work, hence allowing a quantitative comparison of urban planning strategies.

Keywords: *Agent based modeling (ABM), urban form, Geographical Information Systems (GIS), congestion, land use*

Dynamic Modelling of Energy Transitions Using a Coupled Modelling-Narrative Approach

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Abstract: Energy transitions are a matter of competitions between multiple emerging systems and a dominant, established system. Understanding the complex dynamics of these interactions can assist better-informed decision making and policy interventions. This paper presents a coupled modelling-narrative approach, consisting of a System Dynamics (SD) model interlinked with a narrative transitions-theoretical framework. The approach is geared at understanding the dynamics of emerging on-grid electricity sources, such as renewables, in power sector transitions.

The value of implementing such a coupled approach is twofold. Firstly, it empowers the SD modelling process. As SD modelling itself is agnostic to the conceptualisation of the (societal) system under study, it is left to the modeller to design an appropriate SD structure – i.e. Causal Loop Diagram. The approach presented in this paper provides a narrative theoretical framework based on the state-of-the-art of Sustainability Transitions literature and a generic SD model (applicable to similar energy transition cases) which directly translates the key concepts and dynamical hypotheses. The theoretical framework enables the creation of highly structured narratives that not only provide a clear overview of the case, but also assist the identification of case specific boundary conditions, parameters, feedback loops and therefore in setting up and validating the SD model. Secondly, the close connection between the narrative theoretical framework and the SD model enables considerable explanatory power that cannot be obtained from simply using a model or a narrative. Where the narrative case description, for example, outlines the developments following a certain policy intervention, the SD model allows interrogating the detailed interactions of the chain of causes and consequences following the intervention. SD models are able to represent and reproduce complex causal relations including feedbacks, non-linearity, threshold effects and time delays – dynamics which are impracticable to analyse with human mental models alone.

This paper presents how the SD model is structured based on the core concepts of the narrative theoretical framework. Examples from an existing application by the authors of the framework on the case of the emergence of on-grid solar electricity in India are used to illustrate how the coupling of the SD model with the narrative theory helps addressing questions going beyond modelling or narrative analysis in isolation.

Keywords: *Transition modelling, sustainability transition, system dynamics approach, renewable energy*

Stochastic Differential Equations for Point-Specific Traffic Flow Modelling in Regional Australia

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Abstract: The reliability of vehicular networks is defined as the probability that the maximal flow can be assigned to the network with a minimal loss of functionality. With rapid developments in deployment of intelligent transport systems, the literature on short-term traffic flow modelling has undergone great development recently to help with better traffic management and control. The stochastic differential equation (SDE) technique is discussed in the current study for modelling point-specific traffic flow. This approach is then applied to the traffic counts in the Illawarra Region-Australia. Roads and Maritime Services (RMS) in NSW-Australia uses automatic tube vehicle counting in certain stations. For a targeted RMS traffic count location in the Illawarra Region, the hourly traffic counts are recorded from January 2010 until June 2014. This data is used in this study. A SDE approach is presented for time-specific traffic modelling and prediction in a regular weekday and weekend for the targeted location.

The Illawarra region is an area of New South Wales (NSW) located to the south of Sydney, with urban development mostly provided along a narrow coastal area including the major regional city of Wollongong which is the third-largest in the state. South of Wollongong is the large natural feature of Lake Illawarra with a number of other urban centres located around the lake including Dapto to the west, Warrawong to the east and Shellharbour to the south. There are two major north-south road corridors of comparable travel distances and times located along each side of the lake, with the M1 Princes Motorway being the primary inter-regional road transport link provided around the western extent, and the B65 Grand Pacific Drive route located between the lake and the coastline to the east which generally caters for local and intra-regional trips. Whilst both of these corridors provide multi-lane, high capacity road links along their full length, the M1 route is mostly comprised of high-speed freeway apart from a lower-speed urban section through Albion Park Rail and Oak Flats which can often suffer from considerable congestion during peak periods. Alternatively the B65 route is lower-speed and generally urban along its full length, although does not carry as much traffic as the M1 route and tends to have less overall congestion during peak periods.

Once the traffic flow is modelled, a mathematical user equilibrium model is then developed for formulating the toll pricing problem on the targeted routes considering that different travellers may have different value-of-times (VOTs). The models examine quantitatively the effect of different toll levels on the efficiency (in terms of the total generalized travel time and generalized travel cost of all travellers) and equity (in terms of the ratio of generalized travel cost among different traveller classes). The proposed models can serve as a useful decision-support tool for NSW Roads and Maritime Services.

Keywords: *Equilibrium model, stochastic differential equation, traffic flow, value-of-time, vehicular networks*

Modelling Demographic Relationships

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Abstract: This paper is based on adapting the Leslie population model to show the relationship between an aging population and immigration. The recent Government Report (Intergenerational Report, 2015) raised a major concern about the future standard of living in Australia with an aging population in the years 2015 to 2055. Unfortunately, the Report predicted falling living standards but neglected to study the effects of other parameters on these predictions. Quite a simple analysis using the modified Leslie model shows a different picture, including both the dynamics and long term effects of immigration on living standards. The assumptions about life expectancy in the Leslie model can be varied to allow for a large proportion of the population living to one hundred years of age. The results are described and also show how immigration can be of advantage in future Australian living standards.

Another simple model (Piketty, 2014) shows the effects of the changing role of Capital since 1945 and provides an insight into the likely distribution of wealth and income in the years 2015 to 2055 in Australia. The predictions of the two models (Leslie and Piketty) are combined to provide a more complete picture of living standards of an aging population in Australia in the years 2015 to 2055.

Keywords: *Aging population, immigration, Leslie model*

EXTENDED ABSTRACT ONLY

Revealing the Emergence of Future Urban Pattern in a Post-Industrial Region – Cells and Agents in Interaction

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Abstract: During the 20th century, the environment of Central Europe was shaped by extensive growth of urban areas, leading to sprawling urban agglomerations. Morphological growth of cities is still ongoing in, but currently a second major trend is superimposed on this process: urban decline. Accordingly, the largest urban agglomeration in Central Europe – the Ruhr (North Rhine-Westphalia, Germany) – faces a suite of socioeconomic problems common to all members of the 'rusty' fellowship in Europe: a demographic decline, an aging population, high unemployment rates, an incipient 'brain drain', and a lack of incentives to attract prosperous 'new economy' service sector companies. These negative characteristics contrast with the physical extension of the Ruhr's 15 cities and districts. Between 1975 and 2005, the region expanded in area by approximately 37,022 ha, with a total urban area increase from 94,990 ha to 132,012 ha. The modeling of both growth and decline trends is essential for estimating their social and ecological impacts. Since the beginning of the millennium, artificial intelligence (AI) techniques as cellular automata (CA) and multi-agent systems (MAS) have been incorporated into land-system simulations to address the complex challenges of transitions in urban areas as open, dynamic systems.

The presented study integrates the strengths of two complementary artificial intelligence techniques in order to simulate urban sprawl and demographic decline in the Ruhr at once. While the CA SLEUTH is one of the best-assessed spatially-explicit urban growth models applied in numerous studies all over the world, ReHoSh (Residential Mobility and the Housing Market of Shrinking City Systems) is an MAS catching the interactions between stakeholders of housing markets and the development of potential residential areas. SLEUTH is an acronym of the model's initial input factors of slope, land use, exclusion, transport, and hillshade. Five growth coefficients (dispersion, breed, spread, slope, road gravity) define the four growth rules of SLEUTH: spontaneous growth, reflecting the random emergence of new urban areas, new spreading center growth, edge growth depicting urban sprawl, and road-influenced growth. Again, the MAS ReHoSh focuses on the dynamics of interregional housing markets to infer the development of population patterns, housing prices, and housing supply in shrinking city agglomerations. The households and the cities themselves represent the agents. The most important driving factor of ReHoSh is the proactive search of the household agents for a new housing place.

The contribution presents the concept of semi-explicit urban weights for moderating between the cells and agents. They are defined as the simulated dwelling supply, varying on community level, assigned to cells identified as potential residential areas. The ReHoSh simulation was carried out within the context of a standardized 'business-as-usual' development scenario implemented to predict and update actual conditions for the year 2025. The simulated supply of residential areas in the Ruhr is divided by the potential residential areas extracted by the GMES Urban Atlas. This map is introduced into SLEUTH. Subsequently, two other scenarios of changing housing preferences are simulated for the year 2025. They illustrate what happens if the preferences for newly developed housing is decreased or increased by 5 % in different groups of household sizes. Thus, they should reflect the dissemination of sustainable thinking among stakeholders versus the steady dream of owning a house in sub- and exurban areas. While urban areas in the Ruhr have had an extent of 132,012 ha in 2005, it is 136,007 ha in 2025 in the 'business as usual'-scenario. The 'sustainable thinking'-scenario reduced the growth rate to 2,273 ha to an extent of 134,285 ha in 2025. The 'dream of owning a house' evokes a rate of 8,129 ha and an extent of 140,141 ha. Higher growth rates which are depicted in the other two scenarios lead to a more extensive urban land conversion even in rather remote areas. The question of how the scenarios influence the spatial extension of the Ruhr's urban growth is analyzed with the concept of urban DNA. Here, the simulation outcomes are transferred into a digital petri dish reflecting a synthetic environment with perfect conditions of growth. The integrated SLEUTH-ReHoSh simulation of the 'synthetic Ruhr' reveals a tendency to edge growth and a high influence of the road network. Low probabilities cannot avoid the urban growth along the street network. In contrast, they avoid a sprawled disperse pattern as postulated for a 'sustainable thinking'.

Keywords: *Cellular automata, multi agent system, urban growth*

Modelling urban social, economic and demographic systems for small areas: a joined model approach

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Abstract: Urban environments are becoming more important in developed and developing countries. In 2014, the UN reported that 54 per cent of the world's population lived in urban areas, and this was expected to increase to 66 per cent by 2050.

Cities provide a more efficient distribution system for the essentials of life like water, food and sewerage, and they create efficiencies in employment and industry through agglomeration. However, as the population increases, more food, water, employment and land for housing is required. As more people move in, land in the centre of the city becomes more expensive, so people with lower incomes are forced to the outer suburbs for housing, and efficient public transport systems are then needed.

Planning for this population growth will be important for future cities. Thinking about how much water, employment, transport, land, and the capacity of the sewerage, road and public transport systems will be essential for the future wellbeing of urban residents.

The issue of population sustainability was tackled at a world level in 1972 with the Limits to Growth modelling (updated in 1995 and 2005). However, decisions on building infrastructure like water storage, sewerage systems and roads are made at the city level, not the global level. The limits to growth model also used a single model (a systems approach) which suffers from using one method to estimate effects across a number of domains – social, economic and environmental. This one model then needs to be tested and validated. There may be models in the economic domain which could be linked to models in the social domain and models in the environmental domain, all of which are best practice in their own fields, and have been validated and tested. This may be a better approach to modelling across a number of domains.

In thinking about this problem, one solution may be to develop a synthetic population of each city. This synthetic population can then be used in a number of bottom up models (for example, agent based models, microsimulation models, heat consumption models, etc); or could be aggregated to use in aggregated models (like an economic Input/Output model). The model could also have a spatial element within the city by assigning individuals to houses in the city, allowing new suburbs in growth areas; or urban infill. Population densities could be adjusted according to the local Government planning proposals.

This synthetic population could be derived using a spatial microsimulation technique. This technique derives a synthetic census for each small area in the city. Imputation and modelling can then be conducted using this dataset, including making the model dynamic through population ageing and migration; and adding real life decisions made by human agents, like housing choice, partnering and children.

This synthetic population could then be used with Input/Output, agent based and regression models to incorporate economic and social behaviour. This combined model then provides a powerful tool for modelling the social, economic and demographic characteristics of urban populations.

This paper introduces the concept of spatial microsimulation modelling, and then outlines how a dynamic spatial microsimulation model using synthetic data could be used with other macro models (like Input/Output models) and micro-data models (like agent based models and regression models) to provide complex models of urban life. We will also discuss how results and analysis of this spatial model can be best presented to policy makers and planners, and what types of indicators as an output from the model will be important in assisting city policy makers and planners.

This is a large and complex model, which does not yet exist. The concept requires modellers from different disciplines to work together, as well as experts in presenting and analysing spatial data. These researchers will need to overcome disciplinary barriers and combine a number of modelling frameworks and techniques to present and analyse the results. This paper also discusses how this could be done.

Keywords: *Sustainability, microsimulation, input/output, agent based, cities, spatial data presentation*

Are people living in greener neighbourhoods happier? An Australian case study using microblog data

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Abstract: Although the links between environmental factors and wellbeing in urban settings are of great interest, evi-dence for the existence of such is limited. Among few studies conducted on this aspect, findings are sometimes contradictory, particularly between tropical and temperate locations. Two studies conducted in Australia and in the UK found a positive correlation between urban greenspace and happiness, while a study conducted in Singapore reported a lack of evidence to claim a significant relationship between the happiness and greenery. Hence, scientists stressed the need for further research in this area. Unlike in the past, acquiring suitable data that help quantify the level of happiness from the public is now possible due to the popularity of microblog sites. In this study, we utilise this new data source to gain insights into the greenery-happiness relationship.

With the rise of social media, microblogging websites have evolved to become a vital data source, particularly for measuring public opinions. This is due to nature of microblogs on which people post real time messages about their experience and opinions on a variety of topics. Consequently, there is an increasing traction in wide array of disciplines to use this relatively new and publicly available data source for variety of purposes including measuring public sentiment. Sentiment analysis has been handled as a Natural Language Processing task at many levels of granularity. Starting from being a document level classification task, it has been handled at the sentence level and more recently at the phrase level.

Besides the challenges traditional sentiment analysis systems face, such as ambiguity, handling of negation, detection of sarcasm and opinion spam, sentiment analysis of microblogs have to handle the additional difficulties. The first issue when dealing with microblog posts is that usually the text length is very short while such posts often have spelling variation, special tokens, topic variation, and multilingual contents. These difficulties do not apply to sentiment analysis exclusively, but are also of concern for other natural language processing tools, such as part-of-speech taggers, parsers and the like.

Twitter is currently the most popular microblogging service of which the data is publicly available. With several hundred million users in its user-base, the content produced currently amounts to 58 million tweets per day on average. Twitter also offers an easy to access application programming interface (API), which can be used to interact with the service easily, for example, to download tweets of interest. For these reasons almost all previous research on sentiment analysis of microblogs has been carried out on Twitter data, which is also the case for this work. In this study, we use geotagged tweets for major Australian cities that have been collected over two years. These tweets are classified into positive, negative and neutral sentiment. In case of positive or negative type, we also quantify the degree of sentiment. For these cities, we then measure the greenness and calculate area-specific vegetation indices using satellite imagery. Statistical significance of the correlation between greenness and happiness is then evaluated.

Keywords: *Twitter data, sentiment analysis, vegetation index*

Modelling hydrology and sediment transport in grass strips

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Abstract: Grass buffer strips impact the hydrology of flow and consequently the fate of sediment. The two processes of increased roughness and infiltration enhance trapping of sediment particles upstream and within grass strips. A number of models have been developed to predict the performance of grass strips in removing sediment. Although these models have helped decision makers in adopting the technology, the models are not yet capable of accurately and explicitly describing the sediment transport and deposition processes in time and space. A complex process-based model is developed to predict flow characteristics as well as sediment deposition and transport upstream, and within grass strips. The following assumptions have been made in developing this model:

- The inflow is steady and subcritical,
- Deposition and re-entrainment (detachment of deposited sediment by overland flow) are the two main processes occurring concurrently that change sediment concentration along the path.
- As the length of backwater is short and the permeability of bare soil is dramatically lower than that of vegetated ground, infiltration is neglected in the upstream region.
- Particles are trapped because of infiltration regardless of their size.
- Deposited mass due to infiltration settles on the soil top and does not percolate within.
- Vegetation is non-submerged.

The model is capable of estimating the proportion and amount of different sediment particle size classes in the outflow. The modified Green–Ampt equation was used to simulate infiltration. Gradually varied flow and kinematic wave approximation were used to model flow characteristics upstream and within grass strips. The GUEST model approach has been modified in order to use its basic approaches in sediment transport module in grass strips. Model predictions agree well with the results of two sets of controlled experiments. The bias, coefficient of model efficiency and the root mean squared error of the modelled efficiency of grass strips in reducing sediment concentration were 0.93–0.99, 0.58–0.99 and 8.9–12.7, respectively. The sensitivity analysis showed that the initial soil moisture and flow rate are the most sensitive parameters in predicting runoff loss. Increasing the slope steepness and flow rate dramatically decreases the efficiency of grass strips in reducing sediment concentration and mass.

Keywords: *Model, sediment, vegetated strip, hydrology, buffer strip*

Modelling the effect of vegetation and soil on streamflow at a catchment scale

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Abstract: There is a need to better understand, and accurately simulate the influence of land attributes and land use on stream flow. The aim of this study was to quantify the effect of different vegetation types and soil characteristics on stream flow in the Flowerdale catchment, northwest Tasmania, Australia. The catchment has a total area of 15,100 ha, with three main land-uses in which 30% had been converted mainly from native forest to plantation forest, predominately *Eucalyptus nitens*, during the past three decades. Catchment water balance were measured and modelled in four sub-catchments, along with biomass production from plantation forest. Two sub-catchments with areas of 421 ha and 220 ha were covered predominantly (more than 90% of the sub-catchment area) with *Eucalyptus nitens* plantation (age 2-12 years), one catchment with native forest (179 ha), and one with planted pasture (96 ha). Rainfall, streamflow, soil moisture variability and vegetation growth were measured for a period of three years. Streamflow for the entire catchment had been continuously measured for more than forty years (station 14215, DPIPWE).

The water balance of a widely used one-dimensional process-based forest productivity model 3-PG (Almeida and Sands, 2015, Landsberg and Waring, 1997) was adapted to spatially predict forest and pasture water use (rainfall interception, soil evaporation, transpiration, soil moisture, drainage, runoff) and vegetation growth at daily and monthly time steps. After accounting for daily water use by vegetation (ET), we used the topographic index to simulate water accumulation and movement in the catchment. Sub-catchment discharges were routed to the outlet using linear routing principles. The model was applied to each monitored sub-catchment and to the entire catchment.

Results of the measurements and modelling show that landscape characteristics such as soil effective depth, soil texture, and topography, as well as vegetation type, strongly affected the monthly runoff coefficient (RC). This energy limited catchment has a high average annual RC of 0.53 (range 0.37-0.69) with 60% of the average 1400 mm annual rainfall occurring during the months of May to September. Pasture and native forest RC was 0.46 and 0.34, respectively. The shallow soil, higher elevation, *Eucalyptus* plantation sub-catchment had a RC of 0.37 and mean annual increment of wood growth (MAI) of 10 m^3 ha^{-1} $year^{-1}$; the deep soil, lower elevation *Eucalyptus* plantations produced a RC of 0.25 and MAI of 22 m^3 ha^{-1} $year^{-1}$. These results demonstrate that, as expected, the pasture used less water than plantations or native forest under similar conditions of soil and climate. Variability of RC and tree growth between the two plantation catchments was explained by landscape variability and climate characteristics. Higher plantation productivity used more water, which was more available in the deeper soil, and warmer temperatures favoured growth. Shallow-rooted pastures could not utilise water stored deep in soils, which led to high base-flow from the pasture catchment. Daily time-step modelling produced more accurate estimates of discharge (R^2 = 0.87) than running it at a monthly time-step (R^2 = 0.80). The model warrants more diverse testing, e.g. deeper soils, tropical climates, contrasting vegetation and changes of land-use over time.

Keywords: *Water-use, streamflow, catchment, soils, vegetation*

EXTENDED ABSTRACT ONLY

Modelling land use efficiency in supplying multiple ecosystem services

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Abstract: In land systems, policy and governance responses are required to ensure the efficient supply of multiple ecosystem services given growing competition for land between multiple land uses and ecosystem services. Carbon markets are creating incentives for change in land use from agriculture to other uses such as reforestation. Other growing demands from land systems are occurring at the same time including: urban development, amenity, and recreation; mining; energy, food production; water resources; and biodiversity services. Change in land use alters the supply of some ecosystem services relative to others, and synergies and trade-offs may occur. Managing competition between land uses requires efficiency in land allocation. Hence, policy needs to enhance ecosystem services with minimal trade-offs and achieving efficient provision of ecosystem services from land use requires quantitative, integrated modelling and analysis.

Using the LUTO model of Australian land use and ecosystem services, we modelled the potential competition for land and the efficiency in supplying multiple ecosystem services in Australia's agricultural land under global change from 2013 to 2050. LUTO is a spatio-temporal model that runs at 1.1km grid cell resolution and an annual time-step. We considered competition between agriculture, fast-growing *Eucalyptus* monocultures termed *carbon plantings*, and a mix of local native tree species termed *environmental plantings*, and the impact on emissions abatement, agricultural production, water resources, and biodiversity services. The impact of uncertainty in global drivers was assessed through four future scenarios (termed *global outlooks*). We also assessed sensitivity to uncertainty in the rate of agricultural productivity growth and in land use change adoption rates. We created production possibility frontiers (PPFs) for carbon sequestration and agricultural production, water resources, and biodiversity services and quantified the efficiency of carbon markets relative to the PPFs. We calculated the costs and benefits associated with increasing productive efficiency via goal programming based first on dual objectives, then on all four objectives.

The presence of markets for agricultural commodities and carbon produced efficient outcomes for agricultural production and emissions abatement. However, land use allocations did not efficiently supply either water resources or biodiversity services due to weak price signals. When two objectives were considered as is typical in efficiency assessments, efficiency improvements could be achieved through alternative land use configurations. However, significant unintended trade-offs occurred for the other objectives, and substantial opportunity costs were incurred. When multiple objectives were considered simultaneously, land use arrangements were identified that were efficient across multiple ecosystem services (Figure 1). By adjusting the metric used to combine multiple services, efficient land use arrangements could be achieved that meet society's preferences for ecosystem service provision from land systems. Market incentives are needed that effectively price multiple ecosystem services to increase the efficiency of land use arrangements and effectively manage competition for land.

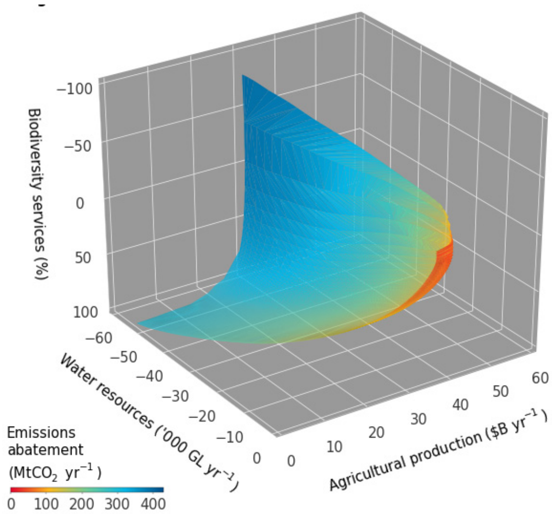

Figure 1. Example of a 4-dimensional production possibility hypersurface (emissions abatement weight 0.05). Created by maximising the weighted supply of multiple ecosystem services.

Keywords: *Trade-offs, ecosystem services, land use change, climate change, scenarios*

Forecasting urban growth patterns: a non path-dependent modeling approach for spatial planning support

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Abstract: Monitoring and modeling land use and cover changes (LUCC) associated with urbanization are of great importance in understanding how these changes interact with ecological, social and economic processes. Prospective modeling helps decision-making of the stakeholders through exploring a range of possible futures and alternatives of urban development. Supporting medium and long-term strategic planning of land-use policy options needs advanced modeling approaches and appropriate simulation tools. Numerous modeling techniques and tools have been developed by the scientific community to better understand and predict urban growth. This extensive research has significantly improved the predictive ability of models over recent decades. However, the place of modeling in prospective planning practice and decision-making process is still in its early stages because of several unresolved implementation issues. One of the main limitations of existing models comes from their dependency on past LUCC trends. Such path-dependent models, which assume stationary processes, aim at reproducing past land changes into the future. Most of them show strong constraints to simulate contrasted prospective scenarios. To overcome this drawback, the SLEUTH spatially explicit model has been modified in order to be used in a fully controlled forecasting mode. Our objective is to spatially allocate both the amount and patterns of urban growth, accordingly to predefined prospective scenarios and assuming a non path-dependency. The SLEUTH model is selected thanks to its ability to simulate four urban expansion patterns: spontaneous growth, new spreading centers, edge-growth and road-influenced growth. This improved version of SLEUTH is a "scenario-based" model (SLEUTH*) allowing: (i) the definition of – exogenous – expected amount of change regardless of past trends; (ii) the specification of the contribution of each urban growth patterns with respect to scenario hypothesis; (iii) the addition of an economic factor (attractiveness map) that contributes to urban growth. Finally, this version is designed to execute automatically prospective scenario composed by sub-periods showing different spatial dynamics.

Examples of application to Toulouse metropolitan area (France) are provided to illustrate the contribution of the modified SLEUTH model to spatially deal with prospective scenarios based on a non path-dependent modeling approach. Seven systemic and contrasting scenarios were built from 2010 to 2100 based on urban planning, adaptations technology, local trends, major global trends, and climate scenarios. Furthermore, the impact of urban growth following the different scenarios on urban climate is assessed.

Keywords: *Urban growth, prospective modeling, amount of change, spatial patterns, path-dependent model*

Predicting response of state-wide stream condition to changes in land-use across Victoria to prioritise restoration effort

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Abstract: Land use change has been extensively linked to declines in stream condition, but there is limited understanding of how condition varies at landscape scale and how a widely used management action, *i.e.*, riparian vegetation restoration, improves condition. The use of modelling to predict patterns of stream condition at landscape scale is a developing field due to the complexity involved in modelling within the stream network. Very few studies have sought to simulate flow-on effects of land-use change in this complex environment.

Riparian vegetation restoration can mitigate effects of land use and improve water quality by reducing nutrient and sediment inputs and increasing shade, leaf-litter inputs, and instream habitat heterogeneity through fallen branches, trees, and stumps. Macroinvertebrates are used globally to indicate stream health because more sensitive taxa and more diverse assemblages are found in less degraded streams, which in turn have feedback effects on food webs and therefore overall ecosystem biodiversity and processes. However, response of biological indicators to riparian restoration have been mixed. Several reviews suggest that area, configuration, and connectivity of restored vegetation patches can influence and limit the response of these indicators, which highlights a clear need for spatial analysis in the planning of riparian restoration. In this study, we first predicted stream condition across the state of Victoria, then simulated different riparian restoration strategies, in particular, addition of vegetation of varying lengths and configurations. We produced a baseline of condition against which future condition can be compared in conjunction with strategies that can help guide planning of intervention works in Victoria.

We used Boosted Regression Tree (BRT), an additive regression tree method, to quantify the spatial relationship between macroinvertebrate indices and the upstream environment. Indices included SIGNAL2, EPT, and family richness and community composition derived from ~120 macroinvertebrate family distribution models. Upstream predictors included rainfall, flow variability, and vegetation and land use (grazing, cropping, and urbanisation) variables. We used 16,144 macroinvertebrate samples collected at 2174 sites across Victoria between 1990 and 2012. Vegetation and land use variables were exponentially weighted by hydrologically active distance both overland and upstream to account for greater influence of impacts closer to the site. Transferability of the model to unsampled reaches was assessed by means of 10-fold cross-validation. Samples were split into ten independent but representative groups, then models were built from 90% of the data and tested on the remaining 10%. The correlation coefficient of cross-validated models was consistently above 0.85 using observed vs predicted data from the test group only, indicating a highly transferrable model. The models were used to predict macroinvertebrate indices and family occurrence for ~50,000 reaches across Victoria in the Bureau of Meteorology's Australian Hydrological Geospatial Fabric (Geofabric).

Presence of upstream dense vegetation explained 41% of the variation in SIGNAL2, followed by total annual rainfall (30%), and instream habitat (riffle or edge, 20%). Partial dependent plots show SIGNAL2 is highest where both the riparian zone and much of the upstream catchment are covered with dense vegetation, annual rainfall is high, flow is stable, and within riffle habitats.

Vegetation and land use variables were manipulated to simulate the response of macroinvertebrate indicators to different riparian revegetation strategies for all reaches across Victoria. The comparison of these strategies will help define future riparian restoration works by minimizing the risk of both working in unresponsive streams or rivers and at ineffective scales or patterns.

Keywords: *Macroinvertebrate indices (SIGNAL2), Boosted Regression Tree (BRT), restoration, river condition, river health*

An integrated model of land-use trade-offs and expanding agricultural processing centres

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Abstract: Climate change and demand for greener energy alternatives are putting increased pressure on the use of agricultural land for not just for food and fibre production but also biofuels, carbon sequestration, biodiversity and other non-traditional uses. A key question is how this competition might impact on not only future land use but also on the composition of the supply chains that process the products of the land. In this paper we address a major part of this question by considering the location of processing centres alongside land use change in an integrated optimisation model. CSIRO has previously developed a model of land-use trade-offs that considers the possible evolution of agricultural land areas in Australia over the next 40 years. This can be modelled as a large scale multi-stage linear programming problem. Here we consider in addition the construction of some processing centres for bio-fuel, bio-energy, livestock facilities and so forth, which introduces a new combinatorial aspect to the model. The decisions of land use and the location of processing centres are interlinked, because transport costs based on distances are often instrumental in determining the economic viability of some of the land uses and conversely economies of scale are necessary to justify investment in processing plants.

In this paper we introduce a model containing both problems of a land allocation and a facility location simultaneously which results in a large scale mixed integer linear programming (MILP) problem and therefore is computationally difficult to solve. We suggest an algorithm to solve the problem which utilises some decomposition techniques including aggregation and disaggregation, column generation and a concept of clustering. Furthermore, some numerical results are provide to empirically show the computational feasibility of the suggested solution methodology.

Keywords: *Mixed integer linear programming, land use management, facility location*

Modelling Biodiversity Benefits and Opportunity Costs of Timber Harvesting: A Case Study of *Pinus radiata*

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Abstract: Biodiversity provides a wide range of ecosystem services to human well-being. Forests, including native and planted forests, are home to more than half of the known terrestrial plant and animal species; and deforestation is the major cause of biodiversity loss. To increase species diversity in plantation forests, foresters need to use alternative forest management strategies, such as the extension of rotation age and the application of different harvest sizes, among others.

New Zealand is one of 25 global biodiversity hotspots and yet plantation forests are common at 7% and 22% of land surface and of total forest area, respectively. As a result, the New Zealand forestry sector contributes 3.4% to annual GDP and is the third largest export industry in New Zealand. Although established mainly for production, *Pinus radiata* plantations still support a wide range of indigenous understorey species. Native beetle communities found in mature plantations are very similar in composition to those in native forest, and a lot of threatened species occur in exotic plantations.

According to the Convention on Biological Diversity's target to 2010 [25], at least 30% of all production plantations should be managed in a suitable manner in order to conserve plant diversity. To help meet this target (and to achieve other ecosystem services for people), the diversity of the associated plant community in plantation forests is worth valuing. This study modelled the potential biodiversity benefits and the financial opportunity costs of a patch-clearcutting harvesting strategy over a clear-cutting strategy in plantation forests (*Pinus radiata* D. Don) in New Zealand (across all regions) using optimisation techniques. Using a species-area relationship and economies of harvesting scale, the net present values (NPV) under alternative management strategies were calculated. In order to calculate the NPV, the forest-level optimisation model by Nghiem 2013 was extended to include uncertainty in timber growth, plant diversity, and harvesting costs. Various sensitivity analyses of the model to the key model inputs were performed.

The results suggested biodiversity benefits from the patch-clearcutting strategy over the clear-cutting strategy for understorey plant species (ie, 59 vs 11 species but with a maximal difference of 72 vs 11). This was achieved at a financial opportunity cost of 27 NZD (18 USD) per extra plant species per forest plantation (95% CI: 23—31 NZD/species, or 15—20 USD/species). This equated to 1250 NZD (820 USD)/ha (95% CI: 1060–1470 NZD/ha, or 690—960 USD/ha). These opportunity costs increased with a decrease in discount rate, the exponent of species diversity, the exponent of harvesting cost, an increase in stand size, older stand age (that generates more favourable habitat conditions) and stand age cutting restrictions.

This research can inform local decision making, such as financial compensation to foresters or laws on harvesting strategies by governments. In some cases, policy makers may also wish to consider carbon sequestration associated with different forestry practices, such as reducing erosion, reducing flood risk and improving fresh water quality in all plantation forests. In such cases they might wish to pay private foresters even more to change forestry practices (or else buy up forests for the government or even pass laws that require a certain type of forest management). But such work may also inform international payments to conserve biodiversity in developing countries with plantation forests involving *P. radiata* or other plantation species (eg, via the Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanism).

Keywords: *Opportunity cost of biodiversity, modeling, optimization, New Zealand, optimal forest rotation*

Formulating chemical fugacity for general circulation models

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Abstract: Fugacity is identical to the partial pressure of an ideal gas in air, however, for real gases fugacity is much more accurate than partial pressure in chemical equilibrium calculations. Since the first use of environmental chemical fugacity models in the late 1970's they have been utilised extensively in the study of the local and global partitioning and distribution of chemicals in the environment. Global climate models are becoming an increasingly important tool in understanding the effects of climate change. Climate models are now being applied to understanding the distribution of persistent organic pollutants (POPs). POPs are a class of toxic chemicals that can bioconcentrate, bioaccumulate and biomagnify. Chemical fugacity is being used to calculate the inter-phase fluxes, however, the intra-phase fluxes are still being calculated using chemical concentration.

Here we formulate equations that are suitable for the solution of intra-phase chemical fluxes in general circulation models using a chemical fugacity approach. Using a relaxation experiment in a one-dimensional (in the vertical) ocean, we examine how the the fugacity approach compares to the standard approach of using chemical concentration. We find that there are two major differences. Firstly, in the equilibrium calculation the standard method homogenises the concentration in the water column, while the fugacity approach has a depth dependent concentration with a uniform fugacity. Secondly, the timescale of equilibration is different, even though the turbulent diffusivity is the same in both simulations. These results suggest that climate models that model POPs should use a fugacity approach for the calculation of intra-phase fluxes, and not only inter-phase fluxes.

Keywords: *General circulation model, fugacity modelling, persistent organic pollutants*

Parameter Estimation in Complex Plankton Models using the Boundary Eigenvalue Nudging – Genetic Algorithm (BENGA) Method

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Abstract: The analysis of trophically complex mathematical ecosystem models is typically carried out using numerical techniques because it is considered that the number and nonlinear nature of the equations involved makes the use of analytic techniques virtually impossible. In particular, building such models is a notoriously difficult task; most competing populations in many ecosystem models collapse (i.e. have multiple spurious extinctions). This is a realisation *in silico* of the Principle of Competitive Exclusion (Gause 1932, 1934) that stipulates that only as many competing populations can coexist as there are resources to support them. The incongruity of Gause's laboratory findings with the natural world led Hutchinson (1961) to propose the Paradox of the Plankton. This paradox articulated the observation that many populations of plankton coexisted in the ocean in apparent contradiction of Gause's Principle and the predictions of the simple theoretical models of the day. Whilst many solutions to the Paradox of the Plankton of varying robustness have been proposed (for example, Huisman and Weissing 1999, Schippers et al. 2001, Cropp and Norbury 2012b) the parameterization of complex ecosystem models remains a significant practical challenge (Cropp and Norbury 2013) that applied modelers need to overcome (for example, Gabric et al. 2008).

The conservative normal (CN) framework articulates a number of ecological axioms that govern ecosystems by exploiting the properties of systems that are written in Kolmogorov form. Previous work has shown that trophically simple models developed within the CN framework are mathematically tractable, simplifying analysis. By exploiting the properties of Kolmogorov ecological systems it is possible to ensure models have particular properties, such as all populations remaining extant, into an ecological model. Here we demonstrate the usefulness of analytical results known for models of Kolmogorov form to construct a trophically complex ecosystem model. We also show that the properties of Kolmogorov ecological systems can be exploited to create ecosystem models with structural coexistence, that is, models for which no population goes extinct for all realistic (i.e. positive) parameter sets. We utilize this property in conjunction the key attribute of Kolmogorov systems, that closed form analytical expressions for the eigenvalues associated with populations that are zero at an equilibrium point are trivially obtained, to provide a computationally efficient method for the refinement of model parameters.

Genetic Algorithms (GAs) are commonly used to estimate parameter sets that allow ecological models to reproduce observed data or theoretical objectives (Kristensen et al. 2003). It is a well-known property of GAs and other optimization approaches that convergence slows as the dimension of the solution space increases (Fournier et al. 2011), that is, as the number of parameters required to be estimated increases. We combine the properties of Kolmogorov systems with a GA to increase the rate of convergence by preconditioning the problem to a region of the solution space where desirable solutions reside. The method can be used to precondition parameter values used in standard optimization techniques, such as genetic algorithms, to significantly improve convergence towards a target equilibrium state. We use an equilibrium state community composition as this is an observed property of systems with structural coexistence, and provides a useful and easily derived goal function in the absence of measured data. However, the method is equally applicable to any chosen point in the solution space of a model.

Keywords: *Boundary eigenvalue nudging, genetic algorithm, Kolmogorov system, parameter estimation*

Queensland Storm Surge Forecasting Model Design Using Sensitivity Analysis

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Abstract: Storm surge is a destructive and life threatening natural hazard associated with tropical cyclone (TC) events with the Queensland (Qld) coastline being particularly vulnerable. In a disaster management context, understanding the full range of possible scenarios that may arise from an impending event is critical for informed evacuation decision making. Tropical cyclones are difficult to forecast in terms of track and intensity, and storm surge magnitude is highly sensitive to the specific direction and location of peak cyclonic wind forcing in interaction with the local bathymetry. Here we investigate the optimal design of the next-generation storm surge forecasting system using a sensitivity analysis approach.

The storm surge forecasting system, QSurge consists of a web-based probabilistic hazard mapping interface drawing from a large database of pre-simulated events. The aim of this paper is identify the appropriate increments of various tropical cyclone parameters necessary to capture the full range of possible storm surge outcomes whilst minimising computational run time. Sensitivity modelling experiments were conducted, consisting of simulating a range of TC parameter values within a parametric wind field model and then simulating storm surge using the Coral Sea MIKE21 hydrodynamic model established for this study and implemented on high performance computing. Detailed analysis of the results was undertaken for the study sites of Cairns, Cardwell and Townsville in North Queensland, and used to determine the optimal range of values for the various cyclone parameters. The number of scenarios necessary to complete a full ensemble database for landfall locations between Cooktown and the Whitsundays was initially estimated as 2,165,240. This was reduced to a set of 664,335 scenarios using polynomial relationships between peak storm surge magnitude and TC parameters such as central pressure and radius of maximum winds. Such a simulation set is achievable using high performance computing and given the optimised run time of the numerical model.

Keywords: *Storm surge, tropical cyclone, numerical modelling, sensitivity testing, optimisation*

Advancing Dynamical Understanding in the East Australian Current through a Regional Reanalysis using 4-Dimensional Variational Data Assimilation

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Abstract: The East Australian Current (EAC) is the Western Boundary Current (WBC) of the South Pacific Subtropical Gyre, playing a primary role in the transport of heat poleward along the coast of Eastern Australia. The current has a significant impact on the weather and climate of the most densely populated region of the country and its associated coastal upwelling and eddy entrainment is a major driver of productivity in an otherwise nutrient-devoid WBC system. The EAC is one of the most dynamic oceanic regions on the planet making its circulation very difficult to predict. In particular, predicting separation of the current from the coast and the formation and behaviour of mesoscale eddies in the Tasman Sea is a major challenge. This study uses a variety of observations to develop a reanalysis of the region, providing new insight into the complex EAC dynamics.

As with weather forecasting, effective state-estimation and prediction of the dynamically unstable mesoscale ocean circulation requires data assimilation techniques, which combine ocean observations with a dynamical model to provide an ocean state estimate that is more useful than either alone. In this project we use the ROMS (Regional Ocean Modeling System) 4-Dimensional Variational (4D-Var) data assimilation tools to combine the available data streams with the model fields providing a reanalysis of the EAC region at 3-6km resolution over a 2-year period (Jan 2012- Dec 2013). 4D-Var is an advanced data assimilation technique that minimises the difference between the model solution of the time-evolving flow and all available observations over the assimilation interval, based on prior assumptions of the errors in the observations and the model background state.

In addition to the traditional data streams (satellite derived SSH and SST, Argo profiling floats and XBT lines) we exploit the newly available Integrated Marine Observing System observations in the region. These include velocity and hydrographic observations from the EAC transport array and the SE Qld and NSW mooring arrays, surface velocity measurements from the Coffs Harbour High-Frequency radar, and hydrographic observations from shelf and sea gliders.

By combining a state-of-the-art modelling system, an array of traditional and newly available data streams and an advanced assimilation method, the reanalysis provides an estimate of the 3-dimensional ocean state over the 2-year period with an optimised representation of the temporal and spatial evolution of the mesoscale field. The data assimilation constrains the modelled solution to provide an improved fit to the observations while maintaining a dynamically consistent solution. Comparison of the reanalysis to independent, non-assimilated, observations from shipboard CTD casts, taken on three separate cruises, shows a marked improvement in the model's representation of the subsurface ocean state. The reanalysis allows us to quantify EAC transport and kinetic energy and perform detailed analysis of the circulation dynamics, including current separation. We find that eddy kinetic energy in the Tasman Front is positively correlated to EAC transport upstream, with an eddy shedding frequency of 100-120 days.

Keywords: *Data assimilation, reanalysis, state estimation, modelling, observations*

Modelling wind-wave induced sediment resuspension in Sydney estuary

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Abstract: Surficial estuarine sediments are susceptible to resuspension by physical (tides, currents), chemical (diffusion), biological (bioturbation) and anthropogenic (dredging, trawling) processes. Resuspension is a significant process in Sydney estuary, New South Wales, Australia, affecting approximately 30% of surficial sediments in the water way at any given time and occurring daily during the summer. Bottom sediments in the estuary are contaminated by a suite of chemicals due to urbanisation and industry, in particular the heavy metals copper, lead and zinc. Resuspension of these sediments consequently increases the availability of these metal contaminants to aquatic biota and facilitates their spread across the estuary into less contaminated regions and therefore poses a significant environmental threat. However, the mechanisms responsible for natural sediment resuspension in this estuary due to meteorological and hydrological influences are not well understood. Therefore, the present work aimed to monitor, characterise and model the role of wind-waves in the resuspension of contaminated sediments in Sydney estuary and thus assess its importance in the major problem of heavy metal contamination in this estuary.

The present work studied wind-induced sediment resuspension in three embayments of Sydney estuary: Chowder Bay, Mosman Bay and Iron Cove, each representing a unique section of the estuary that responds differently in the resuspension of their sediments due to seasonal prevailing wind regimes. Wind velocity and direction were logged using an ultrasonic wind sensor, wave height using a pressure gauge and turbidity using a water quality Sonde with an attached backscatter probe. The Sonde also logged temperature, salinity, pH and depth. All devices deployed in the estuary logged data at ten minute intervals during summer and winter months over three years. Water samples were also collected to determine concentrations of suspended particles in the water column as well as concentrations of metals.

Data analysis of field monitoring results and subsequent construction of a predictive resuspension model were carried out on Matlab™. Data for wind velocity, direction, wave height, tide height and turbidity (as both NTU and mg/L) were detrended, cross-correlated and underwent linear regression analysis. Results demonstrated that wind-wave induced resuspension events occurred daily and were related to increases in wave height and wind velocity as well as shallower water depth. North-easterly winds during summer were related to the resuspension of sediments in the north-east-facing embayment (Iron Cove), while southerly winter winds were related to resuspension in the south-facing embayment (Mosman Bay) and this was expected due to the longer fetch lengths for these wind directions in each of the respective embayments. Resuspension in the open, high energy embayment located near the mouth of Sydney estuary (Chowder Bay) was not influenced by wind, but were related to waves. The predictive resuspension model was able to satisfactorily capture the wind-wave-resuspension process and adequately predict turbidity in the water column based on wind speed/direction and tide height information. In future, the present model may be coupled to other models such as sediment transport and biological metal uptake for a complete, comprehensive understanding of sediment and metal contaminant dynamics in Sydney estuary.

Keywords: *Sediments, resuspension, Sydney estuary, metals, winds*

Numerical simulation of the morphodynamics of the Gold Coast Seaway

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Abstract: Sediment transport and morphological change in the Gold Coast Seaway area, located on the east coast of Australia, were studied numerically. The main reason for the study was to understand the pattern of morphological evolution in the area with a focus on the ebb-tidal delta to examine the processes leading to its morphological change and gradual growth; despite the fact that a sand bypassing system has been implemented and operated since the entrance stabilization in 1986. The model used was MIKE 21 which is a depth averaged flexible mesh model which couples flow, wave and sediment transport. The model was run for a ten month period during which significant morphological evolution and delta growth was observed based on two subsequent bathymetry surveys. Model sensitivity to various input parameters such as wave directional standard deviation, wave breaking coefficient, sediment grain size and wave theory formulation were discussed. The simulated accumulative longshore sediment transport showed a good agreement with previous estimates. Although the model was unable to account for the movement of sediment resulting from the artificial sand bypassing system, it still simulated gradual natural sand bypassing around the offshore edge of ebb-tidal delta consistent with studies of other ebb-tidal delta locations devoid of an artificial bypassing system. The predicted trend of seabed level changes during the ten months, ignoring the artificial sand bypass system, also showed a tendency for northward migration of the inlet channel due to the dominant direction of the littoral current. This finding was consistent with the previous historical analysis of the entrance before stabilisation. During low energy wave conditions, the majority of the littoral drift accumulated to the south of the jetty. This resulted in erosion of the downstream coastline as well as the central part of the ebb-tidal delta. The cross shore distribution of the littoral drift confirmed the occurrence of a significant volume of longshore sediment transport further offshore from the seaward end of the bypassing jetty as well as the southern training wall, especially during storm events. It is suggested that this leakage partially passed the ebb-tidal delta through natural sand bypassing, but was mainly trapped on the ebb-tidal delta in response to the interaction of longshore, wave induced and ebb currents. Therefore, it is suggested that the growth of the ebb-tidal delta is mainly due to the leakage of littoral drift past the sand bypassing jetty and southern training wall. The results also showed that storm events, and in this case mainly the East Coast Low (ECL) in May 2009, play a major role in controlling the morphological evolution of the ebb-tidal delta. The model skill was therefore assessed quantitatively for simulated bed level changes in response to ECL 2009 event in comparison with the observed morphological changes over the ten month period using an adjusted Brier Skill Score. The skill results in this comparison show that the model performed well.

Keywords: *Morphological simulation, ebb-tidal delta, Skill Score, sediment transport*

Modelling sea level and East Australian Current co-variability using the Hilbert-Huang transform

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Abstract: Sea-level rise is one of the most important consequences of global warming, and has global and regional im-pacts. Studying changes in sea level on a regional scale is essential to the development of more-reliable coastal adaptation plans. On a regional scale, there is a superimposition of a number of factors, which complicates the analysis: oceanographic data are usually non-stationary and non-linear.

In this study we use the Empirical Mode Decomposition (EMD)/Hilbert-Huang Transform (HHT) method to analyse East Australian Current (EAC) transport and sea level data from Fort Denison, Sydney. The focus of this study is the long-term time scale consequences of climate change. The results show a rise in sea level of about 1.2 mm/yr over 98 years, and an increase in the total EAC transport in the Sydney region of about 8.75 Sv in over 61 years. These preliminary results also indicate a statistically significant (7 years) lagged correlation of $r = 0.84$ (p value $< 10^{-4}$) between the multidecadal variability in EAC and sea level. However, it is possible that this apparent correlation may in some part be an artifact of the modelling methodology.

Nevertheless, the EMD/HHT methodology provides a way of decomposing non-stationary data into various intrinsic modes, which can be compared with the known behaviour of various physical drivers of sea level variability. Moreover, it allows comparison of different aspects of the ocean system and can be used to infer the existence of interrelationships, which can be used to improve understanding of local ocean dynamics. These aspects of the methodology are explored in the paper.

Keywords: *Sea level rise, East Australian Currents, regional sea level rise, Hilbert-Huang Transform, empirical mode decomposition*

Quarantine and surveillance strategies for plant pathogen detection and control

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Abstract: Incursions of plant pests and diseases pose serious threats to food security, agricultural productivity and the natural environment. One of the challenges in confidently delimiting and eradicating incursions is how to choose from an arsenal of surveillance and quarantine approaches in order to best control multiple dispersal pathways. Anthropogenic spread (propagules carried on humans or transported on produce or equipment) can be controlled with quarantine measures, which in turn can vary in intensity. In contrast, environmental spread processes are more difficult to control, but often have a temporal signal (e.g. seasonality) which can introduce both challenges and opportunities for surveillance and control. This leads to complex decisions regarding when, where and how to search.

Recent modelling investigations of surveillance performance have optimised the output of simulation models, and found that a risk-weighted randomised search can perform close to optimally. However, exactly how quarantine and surveillance strategies should change to reflect different dispersal modes remains largely unaddressed.

Here we develop a spatial simulation model of a plant fungal-pathogen incursion into an agricultural region, and its subsequent surveillance and control. We include structural differences in dispersal via the interplay of biological, environmental and anthropogenic connectivity between host sites (farms). Our objective was to gain broad insights into the relative roles played by different spread modes in propagating an invasion, and how incorporating knowledge of these spread risks may improve approaches to quarantine restrictions and surveillance.

We find that broad heuristic rules for quarantine restrictions fail to contain the pathogen due to residual connectivity between sites, but surveillance measures enable early detection and successfully lead to suppression of the pathogen in all farms. Alternative surveillance strategies attain similar levels of performance by incorporating environmental or anthropogenic dispersal risk in the prioritisation of sites.

Our model provides the basis to develop essential insights into the effectiveness of different surveillance and quarantine decisions for fungal pathogen control. Parameterised for authentic settings it will aid our understanding of how the extent and resolution of interventions should suitably reflect the spatial structure of dispersal processes.

Keywords: *Modelling, simulation, fungal pathogen, horticultural management, detection*

Models to test and operationalise control strategies for crown-of-thorns starfish on the Great Barrier Reef

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Abstract: Coral cover on the Great Barrier Reef (GBR) has declined by half over the past 30 years, a large proportion of which has been attributed to predation by the crown-of-thorns starfish (COTS). While COTS are endemic to the region, they have periodic outbreaks that can devastate large areas of reef. The current control program uses divers to deliver lethal injections. Given that more than 2500 individual reefs make up the GBR, there is a strong argument for such a program to be highly targeted at reefs that are either of particularly high value (social, economic or ecological) or those with the most potential to spread outbreaks through the reef network.

We will describe two novel modelling tools designed to support the existing control program and test alternative control strategies.

1. The Connectivity Interface (CONNIE) is an online model (www.csiro.au/connie2) that uses hydrodynamic modeling (calibrated against available temperature, salinity and sealevel data) and particle-tracking approaches to estimate the potential for COTS larval dispersal and settlement throughout the GBR system. The approach has also been extended to explicitly capture multigenerational connectivity using network analysis techniques. In addition to physical dispersal, the model has options to include biological processes such as larval swimming behaviours. CONNIE is currently being used by reef managers to identify potential upstream sources of outbreaks and downstream reefs at most risk of future outbreaks. Importantly, it can also be used to help identify those coral populations that are most critical to recovery of damaged reefs.
2. Over the longer term, reef managers are looking at alternative COTS control and coral recovery strategies. In response, we have developed a dynamic Coral and COTS Network model (CoCoNet) that includes fast and slow growing corals, and an age structured COTS population. Trophic interactions on individual reefs have been parameterised by fitting to long-term monitoring datasets. Tropical cyclones are another major influence on coral cover in the GBR and their inclusion is allowing exploration of cumulative impacts within the modeling framework. Model results show periodic outbreaks of COTS whose magnitudes and frequencies are sensitive to the levels of inter-reef larval exchange. Parameterisation of alternative management interventions is now a focus for ongoing development of the model.

Keywords: *Coral, crown-of-thorns starfish, connectivity, larval dispersal, COTS control*

Modelling habitat suitability and connectivity of feral pigs for exotic disease surveillance in northern Australia

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Abstract: Feral animal hosts such as pigs (*Sus scrofa*) could play an important role during incursions of several high priority exotic animal diseases by facilitating disease establishment and spread. In northern Australia, vulnerable to disease incursions and with large feral pig populations, this threat is particularly evident. Consequently, feral pigs have been a focus of significant disease surveillance efforts through the *Northern Australia Quarantine Strategy*. However, spatially-explicit knowledge of feral pig populations at the regional and national scale to inform risk-based early detection surveillance reimains limited.

It has been suggested that landscape ecological approaches commonly used in conservation biology are currently underutilized in biosecurity applications. For example, in feral pigs, a contagious disease would establish in locally growing populations with prolific social interaction; disease spread would depend on contact between local populations within the broader landscape through regional dispersal processes. Hence, spatial models of suitable breeding habitat (facilitating disease establishment) and population connectivity (facilitating disease dispersal) could serve to more effectively target limited surveillance resources.

We modelled habitat suitability of feral pigs across tropical northern Australia using a novel approach that linked probabilistic modelling in Bayesian networks with spatial moving window analysis. Models were calibrated from experts' functional understanding of the drivers of feral pig habitat suitability. This allowed us to overcome issues of data availability and extrapolate predictions to the regional scale. Habitat suitability was found to be influenced by four key habitat requirements: water and food resources as well as protection from heat stress and disturbance. As the seasonal availability of each requirement varied considerably, we calibrated two scenarios capturing conditions during the late dry season (October to November), when availability is most restricted, and the late wet season (March to April), when resources are abundant. Suitable feral pig breeding habitat retracted to core "source" habitat under poor conditions and expanded widely during favourable conditions. Preliminary validation against independent, seasonally-specific data of feral pig occurrence indicated that models which accounted for feral pigs' mobility and resource utilization at the landscape scale had the highest predictive performance.

In subsequent work, we will use results from these seasonal models to delineate contiguous patches of suitable breeding habitat and, in conjunction with further expert elicitation, to parameterize landscape resistance surfaces, which describe the permeability of the surrounding unsuitable habitat to feral pig dispersal. We will then model functional connectivity corridors between habitat patches using a network graph approach based in circuit theory that measures patch connectivity as a function of landscape resistance across multiple dispersal pathways.

Our research provides, for the first time, a complete and coherent picture of areas most at risk of disease establishment (via host availability) and spread (via host interaction) at the regional scale. The approach is transparent and flexible and could readily be applied to other host species. Spatial predictions in the form of habitat suitability and connectivity indices can be incorporated as an improved variable into existing surveillance frameworks that also consider risk factors other than feral animal hosts.

Keywords: *Landscape ecology, biosecurity, feral animal host, Bayesian network, graph theory*

Using connectivity networks to estimate and allocate the efforts needed to control the crown-of-thorns starfish outbreaks on the Great Barrier Reef

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Abstract: Many of the world's ecosystems and associated industries are threatened by rapidly spreading invasive species, pests, and pathogens. In complex habitats, such as marine environments connected by ocean currents, populations will actively expand their range across vast areas and often also spread simultaneously from multiple locations. In contrast, the eradication and surveillance efforts that aim to control these large-scale problems are often logistically limited to targeting specific locations at specific points in time. This gap between the scale of the problem and the scale of the available response creates a growing need to provide recommendations on the best available practices to the managers and stakeholders who need to decide where to focus their current efforts in order to limit the future spatial distribution of these species.

To this end, we developed a risk assessment framework to guide the allocation of localised eradication efforts that aims to limit the range expansion of unwanted species. We simulate the process of metapopulation emergence with the help of a probabilistic network model in which the nodes represent habitat patches and the links represent the colonisation probabilities. This model creates an array of possible future distributions which can then be used to predict key range expansion pathways, and therefore to identify populations and/or patches that need to be prioritised for surveillance or eradication in order to best restrict the species' future distribution. Critically, our method is adaptive, as it actively reassesses possible future distributions as new information on the system becomes available and correspondingly updates the targeting priorities for future surveillance and eradication strategies. The framework can also be used to develop contingency plans if there is a reason to suspect that current containment or eradication efforts could fail.

We then demonstrate how this framework could be applied to control the ongoing infestations of crown-of-thorns starfish on Australia's iconic Great Barrier Reef (GBR) which is threatening both the health of the GBR ecosystem and its A$5billion tourism industry. We use oceanographic models of the GBR (~3800 reefs/nodes) to simulate the dispersal probabilities of starfish larvae (simulated larval trajectories from multiple seasonal spawning events translated into probabilistic network links) spreading from reefs with known starfish outbreaks (~60 reefs/nodes with outbreaks) to other reefs of the GBR (unaffected reefs/nodes) in order to assess future infestation risks and prevent unaffected reefs from experiencing outbreaks. We will discuss how this approach can be used to:

1) determine the potential of the ongoing starfish outbreaks to spread across the ecosystem in the long-term;
2) identify the best locations where limited resources available for eradication should be allocated, and therefore estimate the resources needed to implement an effective control campaign;
3) assess the risks to the as-of-yet unaffected reefs, identifying priority locations for future surveillance efforts and an implementation of an early warning system;
4) reconcile sometimes conflicting management objectives, such as saving economically *vs.* ecologically important reefs.

A preliminary version of this model is currently being trialled by the managers to evaluate the risks from the ongoing starfish outbreaks.

Keywords: *Adaptive management, decision theory, spatial network, network analysis, connectivity*

CLIMEX Version 4: New tools for visualizing the dynamic nature of climate suitability

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Abstract: Species niche modeling and species distribution modelling have traditionally dealt with species potential ranges as a fairly static phenomenon. Lip service has sometimes been paid to the notion that species ranges could be dynamic, but this has usually been in the context of an apologetic comment on a map of a species range map. Despite such throwaway comments, the bioclimatic modeling paradigm has been firmly characterized by stationarity. Typically, a muster of distribution points in space (all known up to the start of the modelling exercise are used to train a model in relation to (static) Bioclim variables in the case of correlative models, or climate normals in the case of CLIMEX. It is worthwhile remembering that these modelling paradigms evolved in a period in which climate station data was barely digitized into computer-readable format, and the splining techniques were only just becoming available to develop credible gridded datasets of long-term climate normals. This set of techniques was warmly embraced by the developers of climatologies. It wasn't until the CRU produced a 0.5 degree gridded monthly climatic time-series in 2000, and subsequently at a finer spatial resolution, that for the first time, there was a means to look at the role of interannual variation in climate suitability on biophysical systems at a global scale. Surprisingly, as far as we know there have been no attempts to exploit this dataset to explore seasonal and interannual variation in climate suitability. In CLIMEX Version 4, we introduce a new model (Compare Locations/Years). This model allows users to apply the species parameter sets for Compare Locations models to a time series of monthly climate data. The output can be visualized within CLIMEX as either a weekly or annual time-step time series, which can be saved out as an AVI format video. The state variables available for mapping in the time series are those that describe climate suitability within a CLIMEX Compare Locations model.

The results are most revealing. Seasonal changes can be seen unfolding in waves. The effects of stochastic phenomena such as heavy rainfall associated with cyclones or frontal systems can be visualized in terms of their timing, extent and duration. The annual timestep time-series reveal the potential dynamism in species ranges if unconstrained by dispersal limitations and non-climatic factors. In addition to the visualization tools, CLIMEX provides the ability to save out results in NetCDF format for subsequent analysis.

The new Compare Locations/Years model in CLIMEX provides an important tool for exploring species range dynamics, and should spur interest in a phenomenon that has remained obscure for so long.

Keywords: *CLIMEX, range boundaries*

Risk mapping as a valuable tool for surveillance and eradication of invasive species

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Abstract: Management of an invasive species requires understanding of how it interacts within its new environment, both directly and indirectly. Risk maps show where invasive species are likely to establish and persist. Risk mapping underpins surveillance and eradication. Risk maps help in surveillance by identifying where establishment can occur for trap placement or monitoring for seedling establishment. Risk maps can assist in eradication programs through design and resourcing of delimitation surveys. However, risk maps can be generally basic with the primary focus on key environmental factors or dispersal modelling. In this presentation we describe a risk mapping approach that can incorporate all available knowledge of the pest using a holistic ecosystem approach, including the effects of management strategies, and demonstrate how it can guide both surveillance and eradication programs using an invasive weed and a pest species as diverse case studies.

In the invasive weed example, a Chilean needle grass (*Nassella neesiana*) (CNG) model was built to guide eradication effort in southern Victoria and southeast Queensland. Management options are not always captured in environmental or dispersal studies but were included in the model. The differences in weed management resulted in different risk maps for each region. The Queensland model outcomes showed overall risk for serious impact was less than previously considered, that there were no natural barriers to spread that could be used to aid containment, and that regional-scale changes in roadside verge management (through slashing) posed the greatest threat to ongoing spread.

Another example, the European rabbit *(Oryctolagus cuniculus),* is an invasive pest affecting the environment and agricultural productivity in southern Queensland. Risk maps incorporating key environmental variables and management allows for better planning for surveillance and eradication. A 555 km barrier fence acting as a containment line has been maintained since the 1930s to keep rabbits out of productive agricultural areas in southeast Queensland. Our modelling identified suitable habitat on both sides of the fence, indicating priority areas for surveillance on either side of the fence, and a better understanding of the potential persistence and direction of source populations that could also be targeted for eradication programs.

Risk maps provide a visual stimuli that allows ease of interpretation of model results in areas familiar to stakeholders. The maps should be displayed at an appropriate scale relevant to their intended use. In many cases, risk maps alone are sufficient to guide surveillance and eradication efforts. However, they can easily be used as a baseline for dispersal modelling and optimisation of surveillance and eradication activities to increase effectiveness of pest management.

Keywords**:** *Risk mapping, invasive species, pest management, Bayesian networks*

Using dynamic spatial simulation modelling to help keep the skeleton in the closet

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Abstract: Invasive organisms such as pests, weeds and pathogens can pose serious threats to agricultural and natural systems. Understanding and predicting how their populations vary across space and time, and how human management actions will affect these population dynamics and spread, can help design effective surveillance strategies and eradication plans. Environmental effects, such as the way that populations are affected by heterogeneous landscape features, are often important; this adds extra complexity. Some populations or sub-populations may evolve new characteristics over time, such as resistance to chemical pesticides, and these characteristics may then spread spatially through dispersal and gene flow; this adds still further complexity. Dynamic spatially-explicit computer simulation modelling provides a valuable tool for dealing with these complexities by integrating knowledge and hypotheses regarding lower-scale processes in order to generate higher-level understanding and make higher-level predictions.

This presentation will summarize some recent spatial simulation modelling of pests, weeds and pathogens carried out to help address key crop protection issues related to surveillance and eradication in Australian agricultural systems. For example:

- skeleton weed is slowly spreading across and negatively impacting the key Western Australian grain producing region – a combination of wind-dispersal modelling and biological modelling can provide predictions of where surveillance teams should search for new infestations each year;
- populations of red-legged earth mite are evolving to be resistant to synthetic pyrethrum pesticides – spatial ecological modelling incorporating resistance population genetics can predict how different management options will affect the spread of this resistance across and between farms;
- many crop pathogens are dispersed by wind and/or rain splash – modelling can unravel the complex interactions between environmental and biological factors, where moisture may trigger spores to be released at certain times, and the timing of release can strongly affect the direction and distance of dispersal;
- populations of annual ryegrass are now appearing that are resistant to the world's most important herbicide, glyphosate – simulation modelling can predict whether declaring glyphosate-resistant ryegrass to be a noxious weed and providing compensation to farmers for eradicating it may be an economically viable management option.

Together these examples will help show how spatial computer simulation modelling can help inform surveillance and eradication of invasive species and deal with the threats that pests, weeds and pathogens all pose to agriculture.

Keywords: *Dynamic spatial simulation modelling, pests, weeds, pathogens*

A general model to simulate how an invading organism's dispersal characteristics influence its spread, and the implications for surveillance strategies

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Abstract: Invading organisms do not all exhibit the same dispersal characteristics. Some may spread at a constant rate across the landscape, in a process similar to diffusion, typically modelled with 'thin-tailed' or non-leptokurtic dispersal kernels. For others, dispersal may include occasional long-distance dispersal events that allow them to quickly expand into new areas at a rate that increases with time. This kind of dispersal is typically modeled with 'fat-tailed' or leptokurtic dispersal kernels. These varying dispersal characteristics are likely to affect the dynamics and spatial patterns of spread of a new invader, and are thus likely to have implications for the effectiveness of surveillance strategies.

Spread models allow us to predict the spread of invasive organisms to help evaluate the efficacy of different surveillance strategies. Many spread models assume non-leptokurtic, constant-rate diffusive spread, possibly because including long-distance dispersal events through leptokurtic dispersal kernels adds to the computational complexity of the spread model. Modelling only non-leptokurtic, constant-rate dispersal, risks overlooking important aspects of the dynamic nature of how real organisms spread. This may in turn affect the results when the model is used to assess surveillance strategies. In particular, we predicted that models that do not incorporate leptokurtic dispersal might underestimate the spread of an invasion and thus overestimate the efficacy of standard surveillance strategies. Therefore, the aim of this study was to design a general model of the spread of a new biological invasion that accounts for varying dispersal characteristics, including both leptokurtic and non-leptokurtic dispersal. Then use this model to assess how the dispersal characteristics influence the dynamic and spatial patterns of spread, and provide insights into the potential implications of leptokurtic dispersal for surveillance strategies.

We simulated the spread of a new biological invasion using two types of dispersal kernels, a non-leptokurtic kernel (exponential) and a leptokurtic kernel (Weibull) with varying degrees of leptokurtosis. We then assessed if the spread of the invasion and its potential to move beyond the simulated area differed between the dispersal types and distances over the same time period. We showed that over the same time period, leptokurtic dispersal models predicted spread over greater distances and area than the non-leptokurtic dispersal models. This suggests that surveillance options will need to be different in regards to survey density and frequency in order to detect the invasions at a similar extent of spread. We also determined that species with high degrees of leptokurtic dispersal may be difficult to contain with buffers around an invasion site, as they consistently moved beyond the simulated area. Non-leptokurtic and leptokurtic models with low degrees of long-distance dispersal did not often, if ever, go beyond the simulated area, suggesting that organisms with these dispersal characteristics can be contained with a buffer. The dispersal type and distance of the invading organism impacted its spread, and will likely impact the efficacy of different surveillance strategies. Thus, when using spread models to evaluate and improve surveillance strategies, it is important to simulate the spread of invasions with models that account for species-specific dispersal characteristics.

Keywords: *Biosecurity, diffusion, dispersal kernels, invasion biology, leptokurtic*

Incorporating wind-borne dispersal into biosecurity risk modelling

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Abstract: Wind is an important pathway for pest spread, both into and within Australia. A wide range of biosecurity threats can be dispersed by wind, including pests, pathogens (such as fungal spores and viruses), disease vectors (such as aphids, mosquitoes and midges) and new genes (such as for insecticide resistance) that are important to agriculture, animal production and human health.

For wind-dispersed organisms modelling wind-borne dispersal can be used to help design surveillance programmes and eradication responses. A wide range of simulation models are available that combine atmospheric physics with outputs from global atmospheric circulation models to reconstruct or predict wind-borne particle movement. However, these mostly require considerable expertise and time to use. Also, most are designed for tracking point-source pollutants. This means that modelling widely dispersed pests is difficult, and the biology of the organism, such as survival in the air column, is not explicitly considered.

We have developed a new application called *TAPPAS*: the Tool for Assessing Pest or Pathogen Airborne Spread to overcome these barriers. TAPPAS is a web application developed in collaboration with BOM to analyse the risk of long distance wind dispersal by biosecurity threats. Users can conduct sophisticated analyses through a web-browser, with simulations being undertaken on a supercomputer using global wind data and the particle dispersion model HYSPLIT, with synthesis dispersal maps being returned. Analyses can include forward projections (what areas are at risk given the current distribution of a pest?) and backward projections (where might a new incursion have arrived from?).

When conducting a scenario users enter values, or accept default values, for various attributes that are specific to the simulation. These attributes are then transformed into a JSON string that is parsed to the Australian Bureau of Meteorology HYSPLIT API (Application Programming Interface) and starts the running of HYSPLIT on a high performance computer located at the National Computing Infrastructure (Canberra, Australia). HYSPLIT output is created in a binary file which is then transformed to a NetCDF and a zipped KML. Data is retrieved by TAPPAS and loaded to a PostgreSQL database while the actual data files are downloaded and stored on the TAPPAS server. Within TAPPAS users can retrieve previously run simulations. HYSPLIT itself has already been widely used and tested in modelling passive dispersal of organisms. However, in future we hope to also give TAPPAS users access to alternative particle dispersion models.

TAPPAS Version 1 was released in October 2015. It is available through registration which is currently available for existing and prospective collaborators and co-investors. Development of additional functionality will be ongoing. This will be prioritised to meet the needs of co-investors. In addition, we are now looking, with collaborators, to test and apply TAPPAS to biosecurity problems and other discipline areas. This presentation will include a demonstration of TAPPAS, and provide an overview of how TAPPAS can guide surveillance and eradication efforts. TAPPAS has a generic architecture. We therefore expect it to be readily adaptable to a wide range of other applications where wind dispersal is important, such as the movement of allergens.

Keywords: *Particle dispersion modeling, global circulation models, HYSPLIT, TAPPAS*

Continuing with agent based models to aid decision making in weed management. A case study of buffel grass; a weed dispersed by vehicular wind turbulence

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Abstract: Previously we developed an agent-based weed dispersal model in NetLogo to allow pest managers to determine the costs and benefits of different control scenarios on a real weed infestation in southeast Victoria. That model focused on a relatively wide spread weed in Victoria, Serrated tussock, which is primarily wind dispersed. We now have developed a similar model for a new weed invading along roadsides in north-western Victoria, buffel grass. Buffel grass (an invasive grass from Africa and Asia) has recently been recorded spreading along roadsides in the Mallee in North West Victoria. Propagules were most likely from infestations in South Australia. However, unlike serrated tussock, buffel grass is primarily dispersed along roadsides by vehicular wind turbulence.

Model parameters were determined and verified on historic South Australian buffel grass infestations and then applied to Victorian infestations in the Mallee region.

We discuss the development of parameters for the dispersal kernel (Weiball compared to lognormal distributions), suitability and susceptibility of landuses, as well as the process for verification of the final model parameters. We discuss the issues with validation of the observed and modelled dispersal patterns as well as the outlining suitable management scenarios.

Six different management strategies were compared to each other and a null or "do nothing" scenario. The six different strategies with various levels of detection and control on major and minor roads within the Victorian Mallee were analysed over a 15-year period.

We found that all of the control strategies had significant beneficial impacts on the future spread of the weed. Initial control of known infestations appeared to be the key factor in slowing the spread of the weed. Follow up annual control on new infestations on major roads gave good longer-term control and is an effective management strategy. Detecting and control of infestations along minor roads is much more costly but gives long-term suppression of the weed. We discuss options for management along major and minor roads.

Keywords: *Weed management, scenarios, verification and validation of models*

Simulating freshwater ecosystem health in Flanders by using the ELMO toolbox

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Abstract: In this study, we present the ELMO toolbox, which is used to predict spatio-temporal changes in freshwater ecosystem health and support river management actions in Flanders. Flanders, the northern geographical region of the federal state Belgium, has a heavily modified and complex river system which is exposed to multiple stress factors (e.g. wastewater disposal, hydromorphological alternations, ...) that deteriorate the ecological status. In the light of the European Water Framework Directive (EWFD), which aims to restore the ecological status of all water bodies in Europe, the ELMO toolbox is developed to support decisions in restoration management. Essentially, the toolbox estimates what the effect of a certain river restoration action will be on the present biological community and thus ecosystem health. The ELMO toolbox is based on a coupled simulation model that employs abiotic conditions to predict macroinvertebrate presence and the coupled ecological water quality. In order to do so, simulations of species distribution models (SDMs) are coupled to an ecological water quality assessment index, the Multimetric Macroinvertebrate Index Flanders (MMIF). The model structure of these SDMs is based on ecological filter theory, where distributions of individual taxa are modelled by applying constraints on an initial source pool. In this particular study, the applied constraints on the source pool are abiotic and geographical constraints. The coupled simulation model is applied with physical-chemical, hydromorphological and macroinvertebrate data of the Flemish Government Agency. This data set comprises records over more than 400 sites located in Flanders, with a span of 12 years. These data were used to construct 92 macroinvertebrate SDMs and from the simulations of these SMDs, the MMIF was calculated. The results show that 30 % of the SDMs perform fairly well, where the Cohen's Kappa (K) is higher than 0.3 with a maximum of 0.82. The other 40 % and 30 % of the models respectively have a moderate ($K \in$[0.15,0.30]) and low ($K <$0.15) performance. Additionally, it was observed that the performance increases by 10 % when the geographical filter is applied together with the abiotic filter compared to when only the abiotic filter is applied. In general, the SDMs with a lower performance are models constructed with fewer data and knowledge. With respect to the coupled simulations of the ecological water quality, the calculations of the MMIF show that the higher ecological water quality classes are simulated well, whereas the performance for lower classes is in general low. The over prediction observed in most SDMs is the main reason for the lower performances in the lower ecological water quality classes. Clearly, the performance loss in the SDMs causes a lower performance in the ecological water quality assessment index. In order to increase performance of the simulations, further research should focus on improving the individual SDMs. These efforts should focus on the integration of other sources of data and knowledge, but also on model structural elements. Improvements to the model structure could involve the application of biological constraints (i.e. species interactions) and fine tuning of the geographical constraints. With these model elements, we except to better understand the key processes driving the biological communities, and with that the human impacts on freshwater ecosystem health.

Keywords: *Species distribution models, ecological water quality assessment, macroinvertebrates, freshwater ecosystems, river management*

Determination of physical–chemical conditions to predict macroinvertebrate communities in Machangara River (Southern Andes, in Ecuador)

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Abstract: This research presents habitat suitability models (HSM) as decision support tools (DST) to predict the ecological quality of the Machangara River (Southern Andes, Ecuador). The DST aims to predict the ecosystem health by modelling macro invertebrate species as a function of physical-chemical water parameters. The data was collected during February and March of 2012 and comprise 33 samples of macro invertebrates and physical-chemical parameters at different locations along the basin according to land use. Thirty nine different macro-invertebrates taxa were identified in the different sampled locations.

Fig.1: Location of Machangara Basin in Ecuador – South America.

First, the Biological Monitoring Working Party Index adapted to Colombia (BMWP-Col) was used to calculate the Ecological Status in the stream. This index calculation for the 33 locations gave the following distribution: bad (3), poor (6), moderate (15) and good (9) ecological water quality. Poor water quality results were obtained along the parts where the river flows through Cuenca City and after a dam in the Machangara Hydroelectric Project. In contrast, good water quality results were found in the upstream locations of the basin with low human presence.

Second, to unravel the relationship between macrobenthos and physical – chemical parameters, Pruned Multi-target Clustering Trees (PMCT) were used. The presence of the *Hyalellidae* (Crustacea), *Scirtidae* (Coleoptera), *Perla* (Plecoptera) and *Leptophleibiidae* (Ephemeroptera) were well predicted by this model. The model of the latter taxon had the best fitting with a value of Correctly Classified Instance (CCI) equal of 79% and Kappa statistics of 0.45. In the analysis, this taxon is present when Biochemical Oxygen Demand 5 (BOD_5) in the water is less than 0.4 mg/l, Organic Nitrogen is less than 0.4 mg/l and the Conductivity is less or equal of 83µS/cm.

Third, a generalized linear model (GLM) with binomial fitting was used to determine the relationship between taxon and water quality conditions. The taxa of *Scirtidae* (Coleoptera), *Baetis* (Ephmeroptera), *Leptoceridae* (Trichoptera) and *Trycorythidae* (Ephemeroptera) showed good adjustment with this kind of model. The best fitting with this analysis was with *Leptoceridae* taxon, which had an explained deviance equal to 68% and the Akaike Information Criterion (AIC) was 27 units. The GLM function related to that taxon has been found to depend on the concentration of the following five variables: Fecal Coliforms (FCol), Flow Velocity (FV), BOD_5, pH, Chemical Oxygen Demand (COD) and Conductivity, as shown by the next equation:

$$f = \frac{e^{(50.4797+6.4095\times Log_{FCol}-12.2656\times FV-12.4040\times BOD5-5.3051\times pH-1.1153\times COD-0.0775\times Conductivity)}}{1+e^{(50.4797+6.4095\times Log_{FCol}-12.2656\times FV-12.4040\times BOD5-5.3051\times pH-1.1153\times COD-0.0775\times Conductivity)}}$$

Finally, the presence of these taxa was analyzed with respect to the earlier determined BMWP qualification index. Thus, the results suggest that the HSM can be employed to predict either presence or absence of a taxon, and its relationship with the ecological status of the stream. Furthermore, these models can be potentially used as decision support tools for river basin management and water policy development.

Keywords: *Biological Monitoring Working Party Index, Pruned Multi-target Clustering Trees, generalized linear model with binomial fitting, Ecuador, environmental modelling*

An assessment of current and critical nitrogen and phosphorus losses from European agricultural soils

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Abstract: Since the early 1940s, European agriculture has intensified greatly, resulting in large inputs of nitrogen (N) and phosphorus (P) to soil by fertilizers and manure. This has led to an increase in crop growth and soil fertility in terms of elevated N and P contents. However, the increased application of fertilizers and manure also induced adverse effects, such as: (i) loss of biodiversity in natural ecosystems due to increased emission and deposition of ammonia, (ii) increased levels of nitrogen in drinking water reservoirs due to leaching of nitrate to ground water and (iii) eutrophication of surface waters due to increased runoff of N and P. Main aim of this study therefore was to identify regions where N and P loads used for agricultural production lead to the adverse impacts listed above. This was assessed by comparing current N and P losses from agriculture with critical losses, calculated at a high spatial resolution for the entire European Union using the INTEGRATOR model. Current N and P losses were based on calculations using current detailed agronomic and biophysical data. Critical N and P losses were based on critical NH_3 emissions, NO_3 leaching rates, as well as N and P runoff rates. Critical NH_3 emissions were related to national emission ceilings in view of biodiversity loss. Critical leaching and runoff levels were derived from critical N and P concentrations in view of drinking water quality and eutrophication, respectively. Calculated current (2010) N and P balances show that they are highly spatially variable and largely related to the livestock distribution. The critical P runoff to surface waters is most often exceeded followed by N runoff to surface waters and NO_3 leaching to groundwater.

Keywords: *N and P balances, agriculture, nutrient losses, leaching, NH_3 emission*

Modelling the effect of work related mobility on air pollution exposure in the UK

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Abstract: The quantification of population level exposure to ambient air pollution is typically based on static population distributions inferred from the postcode of residence, and annual average concentrations of priority air pollutants at that location. Contemporary atmospheric chemistry transport models (ACTMs) are capable of providing air pollution concentration fields with high spatial and temporal resolution, for instance generating 1 km × 1 km gridded maps at hourly time steps. In addition, the 2011 UK Census has generated a novel population data product accounting for the location of the workplace, the so-called 'workday population' distribution, which accounts for the location of individuals during working hours. This 'workday' or 'daytime' population maps include usual residents, as well as others present in an output area during regular working hours and does complement the regular maps of residents, without double-counting of populations.

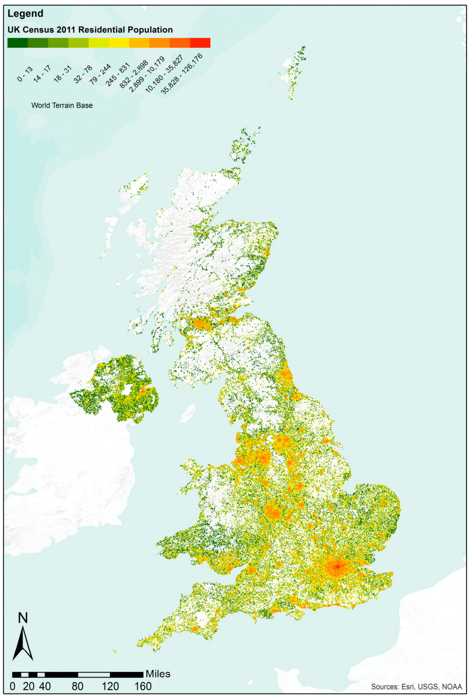

Fig. 1. UK population based on the UK Census 2011 dataset, gridded to 1 km × 1 km cells using Land Cover Map (LCM) 2007 information on urban and suburban land use. Population data for the UK, including the devolved administrations Northern Ireland, Wales and Scotland, was included on output area (OA) level (min. OA size: 40 resident households and 100 resident people, but the recommended size was rather larger at 125 house-holds), consisting of > 200,000 polygons of varying size. Using the Feature Manipulation Engine (FME, Safe Software), LCM 2007 land use parcels and OAs were intersected and population allocated by area weights for urban and suburban land use only. In a final step, spatial mapping of the population on a model grid with 1 km cell size (British National Grid) was to conducted using ARC GIS.

By combining the latest (2011) residential and workday population statistics for the whole of the UK with high resolution data on urban and suburban land use classes from the UK land cover map (LCM) 2007, a vector map, a set of 1 km gridded population density maps have been generated. Here, we demonstrate the impact of using hourly ACTM outputs and distinguishing between working hours and times off work on the modelled population exposure for the UK. This allows, for the first time, to illustrate the bias introduced by the use of static population representations in quantifying public health impacts from air pollution. Taking into account spatio-temporal variability of air pollutant concentrations and mobility of the population, accounting for population location more accurately will inform the design of air pollution control strategies, as addressing different source sectors with their underlying spatial patterns and temporal emission characteristics will potentially have profound implications for the resulting changes in population exposure.

We will show exemplary results for a primary pollutant (nitrogen dioxide) and secondary pollutants (fine particulate matter, ozone) to highlight different characteristics and how they affect the model results. Initial tests have already indicated substantial differences between primary (locally emitted) pollutants, and secondary aerosols (more regionally distributed) for individual exposures modelled. Workday population statistics for England, Wales and Northern Ireland have already been computed, while data for Scotland is due for release in August 2015, hence the result presented here are work in progress.

Keywords: *Air pollution, exposure, spatio-temporal variability, GIS*

Optimising seasonal environmental water decisions in complex regulated river systems: A case study using the Murrumbidgee River

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Abstract: Many freshwater systems worldwide and in Australia are severely degraded as a result of river regulation (e.g. operation of infrastructure) and the extraction of water for consumptive purposes (e.g. town water supplies, irrigation districts). One approach to redress this has been the purchase of environmental water entitlements, an approach which has required large public investment. However, management of this environmental water is a complex task, due to the multiple temporal and spatial scales associated with these decisions. Environmental managers are tasked with processing a vast array of information (including climate and streamflow, river operation, current and antecedent environmental conditions, as well as multiple and at times conflicting environmental objectives) to identify the best decisions around the delivery of this environmental water. The complexity of the decision space makes it very challenging to do this in an efficient and transparent way. A potential approach to assist environmental water managers understand and assess this complex decision space is optimisation.

Optimisation involves determining optimal decisions given pre-defined objectives (e.g. maximisation of ecological health) and constraints (e.g. operational constraints) and has been used widely in water resource management. In this study, the seasonal environmental water decision support (SEWDS) tool is presented using the Murrumbidgee River as a case study. The Murrumbidgee River, located in New South Wales, provides an ideal case study due to to the presence of a variety of environmental assets (e.g. river channel, Mid-Murrumbidgee wetlands, Lowbidgee) and their spatial network as well as a range of potential environmental water decisions (e.g. releases made from multiple reservoirs, off-river storage, regulator diversions). This presentation outlines the challenges of representing such a complex hydrological system within a mixed integer linear optimisation model in a way that a user can follow the decision process rather than providing a "black box" tool. To do this, a simplified hydrological model is developed of the Murrumbidgee river system, which included specifying important environmental assets as well as the main factors that influence environmental watering decisions. This process of representation also included the challenge of identifying the main species that are targeted in the region and adequately predicting the ecological response of each. To do this, conceptual models were developed to link the ecological health of each species to key flow components. The SEWDS tool is then used to determine the optimal environmental watering decisions (i.e. release, store and divert) over a given year. The results suggest (i) that the simplified representation of the system provides adequate complexity to inform environmental watering decisions, (ii) it sufficiently represents and predicts the ecological response, and (iii) how the tool can be used to investigate the trade-off between different environmental assets within the Murrumbidgee River system. Overall, the SEWDS tool provides valuable insight about the river system that will aid environmental water managers in making informed environmental watering decisions.

Keywords: *Seasonal environmental water decisions, optimisation, Murrumbidgee River, decision support, environmental flow*

There is more to the UK particulate matter than Saharan dust

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Abstract: The UK's geographical proximity to other densely populated countries such as Germany and The Netherlands make it vulnerable to the import of large concentrations of gaseous pollutants and particulate matter (PM). An elevated PM pollution event was observed across the UK between 26 March and 8 April 2014. Observations from UK monitoring networks showed markedly elevated PM surface concentrations during this period. The episode was widely reported in the UK news media with many reports associating the elevated PM episode with an enhanced surface concentration of mineral dust transported from the Sahara. The UK monitoring network registered values of PM of up to 100 µg m^{-3}, well above typical UK hourly concentrations. An atmospheric chemistry transport model, EMEP4UK version rv4.3 driven by the Weather and Research Forecast model (WRF) version 3.6, was used to simulate this PM pollution event over Europe and for the UK. The EMEP4UK model simulates the concentration of PM with aerodynamic diameter less than 10 µm (PM_{10}) and with diameter less than 2.5 µm ($PM_{2.5}$). The EMEP4UK model includes a suite of anthropogenic emissions in addition to dust emissions from Sahara and from other dust sources, such as roads. The model domain covers the whole of Europe at a horizontal resolution of 50 km x 50 km and a higher resolution inner nest over the UK at 5 km x 5 km. The model is widely applied and validated against ground-based measurements, see for instance Vieno et al. (2010, 2014). The results of this study highlight the importance of accurate source apportionment of elevated levels of ambient particulate matter, as a mis-classification of the origin (e.g. as Saharan Dust) will result in a lack of policy incentives to address more stringent reductions of agricultural ammonia emissions (the real culprit for these episodes). Atmospheric chemistry transport modelling and ground-based observations are both essential to identify source regions and sectors, and to validate the contributing species of PM.

Two distinct peaks are visible in the observed and the modelled surface PM concentrations for this period: one occurring on the 30th of March (called EP1 hereafter) and the second on the 3rd of April (called EP2 hereafter) as shown in Fig. 1. EP1 and EP2 are of similar duration and magnitude, although they differ somewhat in their simulated PM compositions, both peaks were dominated by secondary PM. EP2 had a larger component of Saharan dust, but for one day only (typically on the 3rd or 4th of April). Moreover, even in EP2 Saharan dust was present in substantial concentration only in the south of the UK (red values in Fig. 1). During EP1 an elevated PM plume composed mainly of nitrate aerosols was advected from continental Europe to the UK. Advection from Europe also dominated the PM during EP2, but with peak PM levels on 3rd of April further elevated by import of Saharan dust.

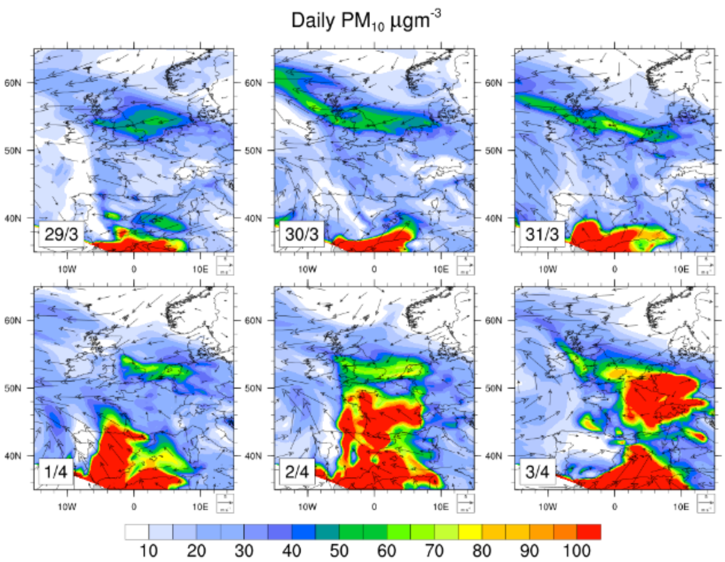

Fig. 1. EMEP4UK model calculated daily surface concentration of the PM_{10} surface concentration map for the period from the 29-Mar-2014 (***EP1***) until 03-Apr-2014 (***EP2***)

Keywords: *Air pollution, particulate matter, Saharan dust, atmospheric chemistry, meteorology*

Predicting the temporal response of seagrass meadows to dredging using Dynamic Bayesian Networks

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Abstract: Predicting temporal responses of ecosystems to disturbances associated with industrial activities is critical for their management and conservation. However, prediction of ecosystem responses is challenging due to the complexity and potential non-linearities stemming from interactions between system components and multiple environmental drivers. Prediction is particularly difficult for marine ecosystems due to their often highly variable and complex natures and large uncertainties surrounding their dynamic responses. Consequently, current management of such systems often rely on expert judgement and/or complex quantitative models that consider only a subset of the relevant ecological processes. Hence there exists an urgent need for the development of whole-of-systems predictive models to support decision and policy makers in managing complex marine systems in the context of industry based disturbances.

This paper presents Dynamic Bayesian Networks (DBNs) for predicting the temporal response of a marine ecosystem to anthropogenic disturbances. The DBN provides a visual representation of the problem domain in terms of factors (parts of the ecosystem) and their relationships. These relationships are quantified via Conditional Probability Tables (CPTs), which estimate the variability and uncertainty in the distribution of each factor. The combination of qualitative visual and quantitative elements in a DBN facilitates the integration of a wide array of data, published and expert knowledge and other models. Such multiple sources are often essential as one single source of information is rarely sufficient to cover the diverse range of factors relevant to a management task.

Here, a DBN model is developed for tropical, annual *Halophila* and temperate, persistent *Amphibolis* seagrass meadows to inform dredging management and help meet environmental guidelines. Specifically, the impacts of capital (e.g. new port development) and maintenance (e.g. maintaining channel depths in established ports) dredging is evaluated with respect to the risk of permanent loss, defined as no recovery within 5 years (Environmental Protection Agency guidelines). The model is developed using expert knowledge, existing literature, statistical models of environmental light, and experimental data.

The model is then demonstrated in a case study through the analysis of a variety of dredging, environmental and seagrass ecosystem recovery scenarios. In spatial zones significantly affected by dredging, such as the zone of moderate impact, shoot density has a very high probability of being driven to zero by capital dredging due to the duration of such dredging. Here, fast growing *Halophila* species can recover, however, the probability of recovery depends on the presence of seed banks. On the other hand, slow growing *Amphibolis* meadows have a high probability of suffering permanent loss. However, in the maintenance dredging scenario, due to the shorter duration of dredging, *Amphibolis* is better able to resist the impacts of dredging. For both types of seagrass meadows, the probability of loss was strongly dependent on the biological and ecological status of the meadow, as well as environmental conditions post-dredging. The ability to predict the ecosystem response under cumulative, non-linear interactions across a complex ecosystem highlights the utility of DBNs for decision support and environmental management.

Keywords: *Dynamic Bayesian Networks, predictive modelling, spatio-temporal modelling, seagrass, marine ecosystems*

Comparing drainage and NO_3^- leaching using the APSIM and NZ-DNDC models

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Abstract: APSIM and NZ-DNDC are both process-based models simulating C- and N-cycling in agricultural soils. Previous studies have shown that the fate of applied N simulated by the two models can vary considerably, with different proportions lost via plant uptake, NO_3^- leaching, and gaseous emissions. Understanding the reasons for these differences may provide a basis for improving the description of the modelled processes.

In this study we compared the predictions of drainage and NO_3^- leaching from the two models.[1] Simulation experiments were performed on 4 bare soils with different textures and SOC contents to a depth of 50 cm. Urine was applied at 600 kg N/ha in 4 different seasons and with weather from 2 different years: 1997 (~820 mm rain) and 2006 (~1170 mm rain). Using bare soil simulations enables the identification of differences on the basic description of water balance and solute transport without the complicating effects of plant interactions.

Results:

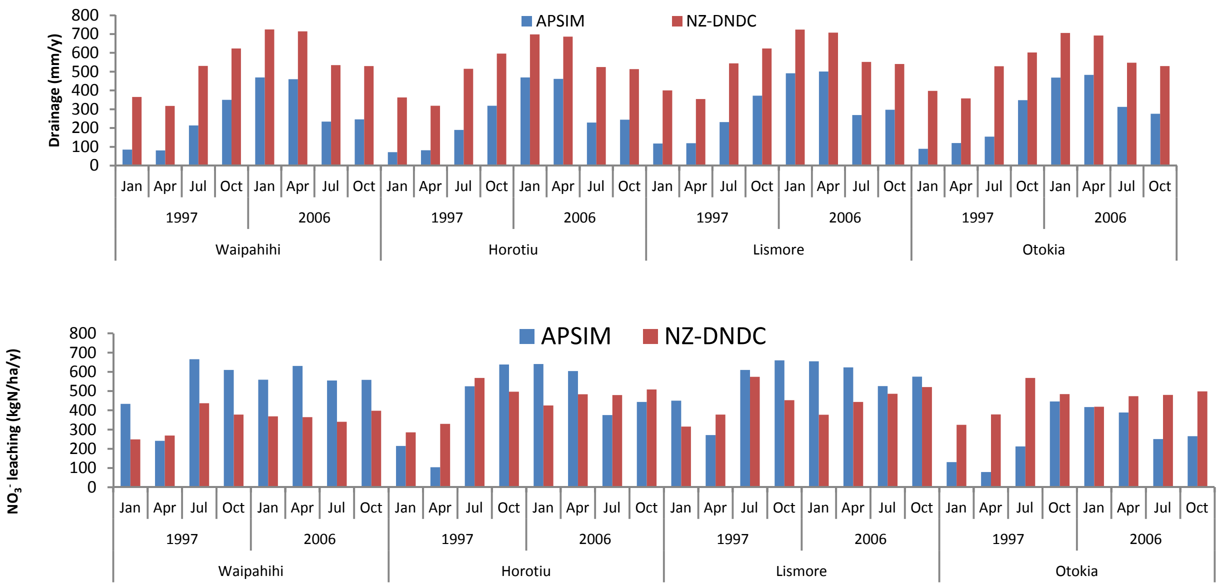

Figure 1. Annual total drainage (top) and NO_3^- leaching (bottom) at 50 cm following urine application on Jan, Apr, Jul or Oct, simulated by APSIM and NZ-DNDC.

Drainage was lower for APSIM compared with NZ-DNDC (Fig. 1, top), although both models showed a similar seasonal pattern. Soil type did not make much difference to total water drainage. APSIM generally simulated higher NO_3^- leaching than NZ-DNDC except in the Horotiu and Otokia soils (Fig. 1, bottom). The higher rates of volatilisation in NZ-DNDC (data not shown) would have contributed to the lower NO_3^- leaching. Note that graphs show only annual totals; daily patterns might be different for the different models and soils. Further details will be given in the conference presentation.

[1] The APSIM model used the SWIM sub-model for these tests

Keywords: *APSIM, NZ-DNDC, nitrate leaching, drainage*

Analysis of the Spatiotemporal Distribution of Soil Organic Carbon

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Abstract: Feedbacks between atmospheric and terrestrial carbon stocks remain unclear. Soil carbon stores are affected by a complex interaction among several biophysical and hydroclimatic processes, including the dynamics of soil moisture, insolation, and temperature. Studying the spatiotemporal distribution of soil organic carbon (SOC) and its dynamic changes is necessary for building a soil carbon pool inventory, as well as predicting the potential for soil carbon sequestration (Dorji et al., 2014). Many environmental controls on soil organic carbon have been analysed at site-specific plot-scales, while long term temporal studies of SOC dynamics are less common. The continued uncertainty of carbon cycle feedbacks, and the complexity of interactions of controls on, and transport of, soil carbon at regional scales, justifies further investigation. This study investigates the spatiotemporal relationships between surface SOC and a number of environmental variables across a catchment. The findings of this research will contribute to overall understanding of SOC distribution and controls for large regional scales.

The catchment for this study is located in the Upper Hunter Valley region of New South Wales, Australia. The study focuses on the Krui River catchment, having an area of 562 km^2. Soil samples were obtained across the catchment using a 1 km grid scale. Cores with a depth of 220 mm were obtained from 59 grazing sites in 2006 and from 52 grazing sites in 2014, with 41 of the sites common to both 2006 and 2014. At each sampling location, aboveground biomass (AGB), soil moisture, and soil temperature was sampled within a 0.25m^2 quadrat. Land use at each sample site was classified as either cropping or grazing.

For a comparison of the temporal variability in SOC concentrations, average SOC from the two sampling dates were compared using Student's t-test. To determine which variables were the most important, principle component analysis was performed for topographic (elevation, slope, aspect, plan curvature, profile curvature, TWI), soil (pH, Electroconductivity, clay %) and vegetation (sampled vegetation biomass, remotely sensed vegetation biomass) variables for the sample sites. SOC, elevation, Normalised Difference Vegetation Index (NDVI) and plan curvature were found to be the most important variables for the first 2 principle components. Linear regression and heteroscedasticity tests were applied to the strongest correlations between SOC and the other variables for both sampling periods.

The results of this study show that soil carbon was spatially and temporally stable over medium time scales (8+ years), with the variables of SOC, elevation and NDVI having strong, positive correlations with each other for both sampling periods. Strong, positive Pearson's r correlations were observed between SOC and NDVI, a surrogate for Aboveground Net Primary Production (ANPP), for both sampling periods. Thus regions of higher net primary production corresponding with higher concentrations of SOC. Grazing intensity, represented in this study by sampled AGB, did not affect SOC.

Topography strongly influences vegetation via its control on such climate variables as precipitation and temperature. Elevation was found to explain much of the variability in NDVI, and hence SOC, although slope and aspect also had weak to moderate correlations with NDVI. The relationship between SOC and aspect was weak. This study demonstrates that the variables of elevation and NDVI can be used to digitally map the spatiotemporal distribution of SOC across large (~500 km^2) catchments of elevations ranging from ~300 to ~1100 m. However, long term seasonal climate variability may affect the predictive ability of SOC using these variables.

The spatial and long term temporal stability of catchment SOC demonstrated here has major implications for soil carbon sequestration. SOC across the catchment appears to be at equilibrium, with minimal variation observed after 8 years of continuous grazing. Carbon sequestration methods would therefore require major changes in grazing land-use to achieve observable increases in soil carbon.

Keywords: *Soil temperature, catchment, geomorphology, NDVI*

EXTENDED ABSTRACT ONLY

Modelling the effects of fertilizer management on crop productivity and nitrogen balance in the North China Plain

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Abstract: In North China Plain, winter-wheat (*Triticum eastivum L.*) and summer-maize (*Zea mays L.*) are grown each year without a fallow period. The rotation generally has high N inputs and flood irrigation with groundwater. Over-application of nitrogen (N) fertilizers can contribute to environmental impacts in North China Plain. This study aims to compare crop yields, N use efficiencies (NUE) and N losses in a wheat-maize cropping system under different fertilizer practices and analyze the soil N balance to fertilizer managements.

Agricultural Production Systems sIMulator (APSIM) was first employed to characterize wheat-maize yield and N dynamics under different nitrogen rates at experimental stations in North China Plain. Four N application rates (100, 200, 300, 400 kg N ha^{-1} per season) and straw removal from the field were run from October 2001 to late September 2004. Daily rainfall, maximum and minimum temperatures, solar radiation and potential ET data were collected at a meteorological station on the experimental site. The depth of the root zone was 1.8m. Nitrogen moving beyond the lower boundary (root zone), was assumed to be lost and not used by crops. Soil water content measured at 5 to 7 day intervals, above-ground biomass, grain yield, crop N uptake and soil nitrate concentration from the 200 kg N ha^{-1} treatment were used for model calibrations. The other three treatments (N100, N300 and N400) were used for validation. The results show that:

- Evaluation of the N200 data set shows that the model can be calibrated to achieve a satisfactory agreement between simulated and measured crop growth development, aboveground biomass and grain yield (aboveground biomass: RMSR=1214 kg ha^{-1}, R^2=0.94; grain yield: RMSR=117 kg ha^{-1}, R^2=0.99);
- Change of soil water storage to 1.8 m during all six cropping seasons were predicted very well (calibration RMSR=3.1 cm, MRE=-0.36, R^2=0.85; validation RMSR=3.3 cm, MRE=-0.23, R^2=0.82);
- Simulated water contents in different soil layers showed good agreement with field-measured values, and had a RMSE less than 0.057 $cm^3\,cm^{-3}$;
- Simulated crop N uptake and soil residual N to 1.8 m were reasonable. The annual drainage and N leaching were consistent with the measured data for N200.

It was possible to calibrate the model to simulate crop grow and N uptake, N leaching, and N dynamics. The results also demonstrated that N deposition from atmosphere and ammonia volatilization losses should be taken into account in the APSIM model, especially in North China Plain on alkaline soils. The grain yield and crop harvest N under the N100 application rate (low N inputs) decreased by 12 and 23% after two years, without taking into account N deposition from the atmosphere, whereas soil nitrate accumulation under the N400 (high N inputs) treatment increased by 13%, without correction for ammonia volatilization.

Keywords: *Double crop rotation, APSIM model, nitrogen transport, nitrogen losses*

Litter decomposition under diverse environmental conditions: insights from isotope experiments

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Abstract: Litter decomposition is a central element of ecosystem dynamics, and has substantial effect on soil carbon (C) balance and global C budget. It is crucial to understand how litter decomposition responds to climate and management changes. To measure the rate of litter decomposition, litterbag experiment is one of the dominant approaches, in which changes in the litter mass in a bag with time were measured to derive the decomposition rate. However, this approach has many limitations, including changed microclimate by the litterbag, leaching of soluble compounds, possible loss of small litter fragments, and potential exclusion of soil fauna. These limitations are difficult to overcome in the field, and can result in uncertainty in the estimates. Laboratory incubation of ^{13}C or ^{14}C labeled substrate is an alternative approach. It enables the tracing of C fluxes evolved from the newly added substrate. Extensive data from such incubation experiments have become available, including various treatments of different C substrates across a broad range of environmental conditions, providing an opportunity to develop integrative approaches to infer litter decomposition across ecosystems.

We conducted a comprehensive literature search, and collated data sets from 103 isotope experiments that traced CO_2-C fluxes derived from ^{13}C- or ^{14}C-labelled substrates. For each experimental data set, a one-pool decomposition model (first-order decay) was fitted to estimate the decomposition rate constant *k* of the substrate C. The one-pool model was expressed as:

$$C_t = C_0 \cdot e^{-k \cdot t} + \varepsilon,$$

where C_0 is the measured substrate C amount (mg C) at the start of an experiment, C_t is the substrate C at time t (days in this study) from the start of the experiment, k is the decomposition rate constant (day^{-1}), ε is random error assumed to be normally distributed with mean 0 and standard deviation σ. For each set of substrate C data, the model parameter k was estimated through nonlinear regression. The results indicated that the one-pool decomposition model could well fit the substrate C dynamics. Pooling all data sets together, the model explained 85% of the variation in observed substrate C dynamics. Of the 103 individual experiments, the decomposition rate k ranged from 0.00029 to 0.39 day^{-1} with an average of 0.021 day^{-1}, which is comparable with the decomposition rate for fresh organic matter in most soil organic matter models.

After deriving k for each experimental data set, we further tested three related hypothesizes that were commonly proposed in the literature: 1) k is different not only between ecosystems (i.e. forest, grassland, cropland, and other) but also between substrate types (i.e. root-exudates-like and plant-residue-like), 2) stoichiometry of soil and substrate in terms of their *C:N* ratios have significant effect on k, 3) soil environment in terms of soil texture (i.e. sand and/or clay content) and soil pH have significant effect on k. A hierarchical regression model was performed treating ecosystems and substrate types as group categories..Our results show that rate of litter decomposition did not present significant difference between ecosystems, but decomposition of root-exudates-like substrates was significantly faster than that of plant-residue-like substrates. Detailed data assessment is being performed for other two hypotheses. The findings of this study will benefit effective estimation of the fate of plant litter across ecosystems under potential climate and land management changes.

Keywords: *Carbon cycle, litter decomposition, data assimilation, carbon model, incubation*

The effect of soil organic carbon on wheat: Quantifying the relative effects of nitrogen and water supply

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Abstract: Soil organic carbon (SOC) is an important component of the natural capital of soil through its effect on nitrogen (N) and water supply to crops. However, the relative contribution of these soil processes to grain yield is poorly understood. We used APSIM (v7.7) to investigate the effect of an increase in SOC on yields for a site at Brigalow, Queensland. Wheat was simulated for 50 years (1963 to 2012) in scenarios where increased SOC affected: (1) *Nitrogen Cycling* (i.e. N supply to the crop); (2) *Soil Physical Properties* (i.e. water holding capacity, saturation, hydraulic conductivity, and bulk density; which affect the water supply to the crop); or (3) *Combined Properties* (i.e. the combined effect of N cycling and soil physical properties). Pedo-transfer functions taken from the literature were used to quantify the relationship between SOC and soil physical properties, and values of those properties in the model were manually set for low (i.e. 1.2 %) and high (i.e. 2.2 %) SOC concentrations. Predictions from these three scenarios were compared to those with the lower SOC (termed the *Control*). Scenarios were simulated across five N fertiliser rates (0 – 200 kg N/ha). As the aim of this study was to compare different SOC levels, SOC, mineral N, water, and surface residue values were 'reset' to initial values annually.

At low N rates simulated wheat yields in the *Nitrogen Cycling* scenario were significantly higher than those in the *Control* (i.e. 0 or 50 kg N/ha; Figure 1a). In contrast, there was little difference between yields in the *Nitrogen Cycling* and *Control* scenarios at high N rates. The effect of increased SOC on yield was much smaller in the *Soil Physical Properties* scenario than in the *Nitrogen Cycling* scenario (Figure 1b). The median yields of the *Soil Physical Properties* scenario were lower than those of the *Control* scenario at low N rates, but were slightly higher at high N rates. The simulated yields of the *Combined Properties* scenario were similar to those of the *Nitrogen Cycling* scenario at low N rates (Figure 1c); however, both the simulated median yield and the range in predicted yields (i.e. the difference between the 25th and 75th percentiles) were lower. At high N rates, the simulated yields of the *Combined Properties* scenario were slightly higher than those of the *Control* and the magnitudes of the increases were similar to those in the *Soil Physical Properties* scenario. While this study only considered the effect of increased SOC for a single site at Brigalow, it is expected that the effects would be similar across sites.

Understanding the relative effect of SOC on N cycling or soil physical properties is important for valuing and managing SOC in Australian grains farms. APSIM currently only dynamically simulates the effect of SOC on N cycling, and varying soil physical properties requires user-intervention. The results indicate that APSIM may currently be overestimating the effect of increased SOC on wheat yield at low N rates as the effects of SOC on soil physical properties are currently not considered. Conversely, APSIM may be underestimating the effect at high fertilizer rates.

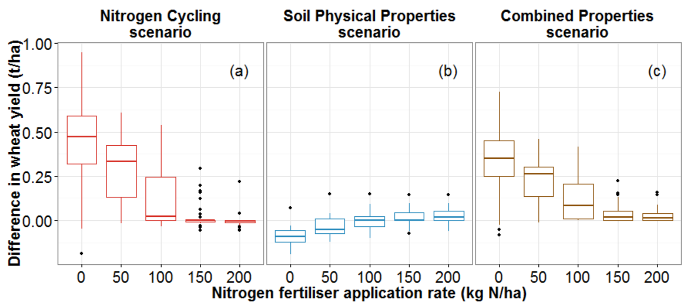

Figure 1. Box and whiskers plots of the difference in the simulated wheat yield between the *Control* scenario (SOC 1.2%) and the *Nitrogen Cycling, Soil Physical Properties*, and *Combined Properties* scenarios, given increased soil organic carbon (2.2 %) for a site at Brigalow under five N fertiliser rates.

Future development of APSIM could consider making soil physical properties dynamically responsive to SOC. That would allow the model to provide better estimates of (or insights into) soil and crop management.

Keywords: *Soil organic carbon, APSIM, wheat*

Modelling nitrous oxide emissions from grains and sugarcane cropping systems: Generation and mitigation of emissions

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Abstract: Nitrous oxide (N_2O) is a potent greenhouse gas: In Australia, agricultural production systems contribute 78.6 % of national emissions. Measured emissions range from 0.1 to 48 kg N ha^{-1} yr^{-1}, with the higher emissions in this range occurring in both sugarcane crops and in grain crops (in the high rainfall zone) after conversion from pasture, and lower emissions in this range occurring in dryland grain cropping systems in drier regions. Chemical (e.g. chemo denitrification) as well as biological processes have been suggested as a cause of the high emissions. Understanding the processes causing the high emissions is important for designing nitrous oxide mitigation strategies. We used the APSIM model to explore the possible causes, and mitigation of nitrous oxide emissions in a range of crops and environmental conditions.

The capacity of the APSIM model to simulate N_2O emissions and crop yields was evaluated by simulating experiments at nine sites in sugarcane (four sites) and grains (five sites) cropping regions in Australia. Experiments comprised different soils types and crops, and differing fertiliser, irrigation, tillage and residue management. The model could reproduce the experimental results with only small modification to the default representation of nitrogen, carbon or water cycling in the soil or crop modules of the model. In sugarcane cropping systems, RMSE of simulations of denitrification (i.e. N_2 and N_2O emissions) improved from 3.14 kg N ha^{-1} with the default value (6.0×10^{-4}) of the potential denitrification rate coefficient to 0.62 kg N ha^{-1} with higher value (13.8×10^{-4}). This parameterisation gave good predictions ($R^2 = 0.96$) of N_2O emissions at three sites subsequently modelled. In the five experiments in grains cropping systems, the frequency of denitrification events was lower in the experiment than predicted with the default parameterisation of the model. In simulation of a subset of the treatments from the experiments, this difference was attributed to the default value of threshold soil water content (or water filled pore space) above which denitrification starts. The default value (which was the soil water content at drained upper limit, DUL), had to be increased to ~1.1*DUL to match the patterns of denitrification events and N_2O emissions. After this change, N_2O emissions in 48 grain crop validation datasets were well predicted ($R^2 = 0.91$).

The simulation results provided insights into both the processes controlling N_2O emissions and potential mitigation of emissions at the study sites. The successful simulation of high N_2O emissions suggests that the biological processes represented in the model could be responsible for the high measured emissions. Thus, chemical processes (not represented in the model) may not have been making a significant contribution to these emissions. In the sugarcane cropping systems, simulated emissions were positively related to soil organic carbon. Also, N_2O emissions were affected by nitrogen fertiliser applications (impacting soil mineral nitrogen) and by the presence/absence of shallow water tables (impacting soil moisture). Of these factors, obviously the one most easily controlled by farmers is the management of nitrogen fertiliser and mitigation options should focus on this. For example, splitting of N fertiliser was predicted to reduce N_2O emissions by 10-20% over a wide range of sites. In grains cropping systems, N_2O emissions can be reduced by avoiding applying N fertiliser at rates in excess of the industry recommendations and reducing N application to rainfed crops in dry years. Contrary to the results in sugarcane, we did not find any effect of splitting N in grain crops. This study illustrates the value that modelling can bring to understanding carbon and nitrogen cycling in soil-plant systems.

Keywords: *APSIM, mitigation, denitrification, wheat, nitrogen fertiliser*

Intercomparison of soil organic matter dynamics models across land uses

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Abstract: Soil organic carbon (SOC) is the largest organic carbon pool in the terrestrial biosphere and has a great potential to drive future climate change. This makes it critical to understand how SOC changes (i.e. balance between vegetation carbon input into the soil and heterotrophic respiration) in response to environmental and management conditions. Models of the terrestrial ecosystems simulate, with varying complexity, both vegetation carbon input into the soil in forms of above ground and root residue and carbon loss through heterotrophic respiration during soil organic matter (SOM) decomposition. However, these models have adopted different conceptualization of SOM pools, decomposition rate constants, as well as response functions of decomposition rate to environmental drivers such as temperature, soil moisture and land use, which may lead to different projections of SOC for a given land use type.

In this study we examined how SOM pool structure, decomposition processes and environmental response functions are represented in five dynamics SOM sub-/models (APSIM, DayCent, DNDC, ECOSSE and LPJ-DyN) and how variations in these representations influence the simulated soil carbon change over time across a set of selected sites in Australia with varying land uses (agricultural, forestry and rangelands). These include sites where both increasing as well as declining soil carbon pools were observed as a result of different land uses. We compared how well the five models could reproduce the observed SOC changes across sites and land uses, with the aim to identify the key underlying processes that make it possible to replicate soil carbon behaviour.

These five SOM models were selected because they cover a range of complexities when representing surface and soil organic matter processes due to the scale and land uses they normally simulate.

- APSIM – mainly an agro-ecosystem model at the site scale, but can also simulate horticulture, grazing and forestry systems.
- DayCent – ecosystem model for grasslands, forests and croplands on site to regional scale.
- DNDC – mainly an agro-ecosystem model at the site scale, but can also simulate forestry and wetlands.
- ECOSSE – is a SOM model for long-term soil carbon dynamics on site to regional scale.
- LPJ-DyN – natural vegetation model (forest and grassland) on the regional to global scale.

To be able to compare the SOM models in the same environment, DayCent, DNDC, ECOSSE and LPJ-DyN have been implemented in the APSIM framework in parallel to the existing SOM module. In this way all models are affected by the same residue input, soil temperature and moisture, and N uptake.

Initial results show that the SOM models differ greatly in their assumption and resulting decomposition of plant residue pools, in terms of both decomposition rates and carbon efficiencies. These differences resulted in that some models overestimate soil carbon accumulation under forest land uses as a consequence of large influxes of organic carbon with high C:N ratios, which promoted immobilisation and consequently reduces SOM decomposition rates. For agricultural (declining SOC) and rangeland (stable SOC) land uses the models simulated similar soil carbon trend and matched better to observations.

From this study we hope to clarify which processes are important for Australian conditions and should be improved in soil organic matter dynamics models, in order to be able to adequately predict the interaction between future climate change and soil carbon dynamics in Australia.

Keywords: *Model Intercomparison Project (MIP), Soil Organic Matter (SOM), decomposition, land use*

Potential errors in estimating daily N_2O emission caused by measurement time and frequency

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Abstract: Static- and auto- chamber methods are most commonly used to measure nitrous oxide (N_2O) emissions from soils, especially, to examine differences between treatments. Often such measurements are used to calculate daily or annual total emissions. The static chamber method measures N_2O flux once or twice per day, while the auto-chamber method measures the flux multiple (6-8) times. The time of measurement during a day and the limited sampling frequency may cause large errors in the estimation of daily N_2O emissions. This study evaluates the potential errors caused by the frequency of sampling and the time of day the measurement occurs. We assume that the continuous N_2O flux data measured with the micrometeorological technique represent the N_2O emissions and the diurnal variations in emissions are similar to those measured by the chamber method in the same treatment. Errors caused by the micrometeorological and static chambers methodology is ignored in this study.

The results show that there is no constant pattern in the diurnal N_2O emissions during the measurement periods at the two sites. Consequently, any hour's measurement within a day has a low (<10%) probability of representing the daily average flux throughout the measurement period. When the N_2O flux was measured only once a day (frequency of most static chamber measurements), the estimates of daily N_2O emissions are subject to large errors as shown by average RMSE of 85 g N ha^{-1} d^{-1} and 47 g N ha^{-1} d^{-1} at Murwillumbah and Ginninderra, respectively. These values are equivalent to 108% of the average daily fluxes at Murwillumbah and 157% at Ginninderra. The accuracy in determining the daily N_2O emission was improved significantly by increasing the sampling frequency. For example, sampling 6 times per day (the typical measurement frequency of auto-chambers), the RMSE for daily flux estimates was reduced to 26 g N ha^{-1} d^{-1} and 15 g N ha^{-1} d^{-1}, corresponding to 32% and 51% of the mean daily total fluxes at Murwillumbah and Ginninderra, respectively. However, the uncertainty of estimated daily fluxes caused by measurement frequency needs to be considered because a sampling frequency of 12 times per time per day had a RMSE within 15-30% of average daily flux. These findings indicate that it is essential to consider the uncertainty caused by measurement time and frequency, especially when low frequency measurements are used to estimate daily N_2O fluxes or verify models.

***Keywords**:* *Nitrous oxide, sampling time, frequency, uncertainty*

Thoughts on spatio-temporal uncertainty metrics motivated by input sensitivity in the Spark bushfire spread model

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Abstract: Bushfires are highly complex events to both measure and predict. We want our models to predict certain observable features of fires, but which features to use is a question with many possible answers. It is important to understand both the skill of our bushfire spread prediction models, and the level of uncertainty inherent in their results. However, this can be difficult to quantify even when the desired features are known. One challenge is obtaining complete observed data. A second is knowing how to determine appropriate comparative metrics for predictions and observations that evolve over space and time. Further to this, we need to consider the intended use case of the metrics. Viability of a metric may depend on whether it is needed to inform: machine decision-making, researchers familiar with the subject area, or public stakeholders and decision makers. Here, we illustrate some problems and solutions that we have encountered in determining metrics appropriate to bushfire modelling, along with our proposed approach to measuring model skill. In particular we focus on metrics evaluating predicted bushfire perimeters, as opposed to other aspects of fire behaviour such as fire intensity, flame depth and height, etc.

We model the evolution of a bushfire perimeter through time, given sparse data and incompletely observed perimeters. Considering the intended use cases of our comparison metrics, we have to communicate our model skill with human stakeholders and also use these metrics to improve our models in a relatively automated way. This adds an extra layer of complexity in selecting and applying metrics. Rather than focusing on a single metric that will likely never meet all our needs, we instead propose a standard approach to the development of metric sets appropriate to a problem. Our work utilises ideas from goodness-of-fit testing in the context of posterior and prior predictive approaches. We use this approach to simultaneously develop metrics for both human stakeholder and computational model development purposes.

In this paper, we demonstrate both visual and computational two-dimensional metric solutions, as well as a scalar metric appropriate for different computational purposes. The scalar metric is one originally proposed in Baddeley (1992) which has been previously applied to weather forecasting (Gilleland et al., 2008). We also provide details on our standard approach, which could be extended to other spatio-temporal and complex models.

Keywords: *Model skill, goodness-of-fit, scientific communication, spatio-temporal, bushfire modelling*

Assessment of light history indicators for predicting seagrass biomass

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Abstract: Seagrasses are rapidly declining worldwide due to anthropogenic impacts on coastal environments. One major contributor to seagrass loss is the degradation of water quality which reduces light availability.

In this paper we use a data-driven approach to compare several indicators of light history for their ability to predict seagrass biomass. Data sets for daily light and seasonal biomass of seagrass (*Zostera muelleri*) meadows from two lakes (Lake Macquarie and Tuggerah Lake) in New South Wales, Australia, were analysed. The light history indicators were compared to seagrass biomass, for different periods of light history. Three indicators were tested: (1) an unweighted mean of the light history, (2) a weighted mean of the light history that places greater emphasis on the more recent light doses, and (3) a modified rolling average of light history.

For the time periods that maximised the correlation between seagrass biomass and light history (hereafter called the optimised light history periods), the relationships between seagrass biomass and the three measures of light history always showed high significance ($p<0.05$) but low predictive power ($R^2<0.5$). Our results consistently demonstrated that there was a significant and positive relationship between light history and biomass at the optimised light history periods. However, light availability was clearly not the only factor influencing seagrass biomass in the two lakes studied. The best correlations were identified for total and below-ground biomass in Lake Macquarie (R^2=0.47-0.49, $p<0.0001$); this was attributed to the high below-ground to above-ground biomass ratio and lesser influence of sediment and nutrient conditions in Lake Macquarie compared to Tuggerah Lake.

All three light history indicators yielded similar correlations between biomass and light history (maximum variation in R^2 was 0.05). Indicator 1 was slightly better than the other two because it produced higher R^2 values and lower p-values. Indicator 1 was also easier to calculate than indicator 2 and requires a shorter time period of daily light data to optimise than indicator 2. Indicator 3 is ideally suited for use as a tracer in large-scale modelling simulations, and thus may be used in these simulations if indicator 1 cannot be easily calculated. Hence we generally recommend indicator 1, although indicator 3 may also be suitable in some circumstances. For these two indicators, 1.5-8 months of daily light data was required to optimise the correlation between biomass and light history for the seagrass *Z. muelleri* in Lake Macquarie and Tuggerah Lake. These time periods provide an upper limit on the time that this seagrass species should be subjected to light deprivation before management actions are triggered.

Keywords: *Light history, biomass, management, monitoring, seagrass*

Data-based methods for temporal disaggregation of contaminant loads

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Abstract: Budget-based catchment models offer benefits of robustness and simplicity, but they do not provide information on seasonal or storm event loadings that are of more ecological relevance. We have therefore investigated data-based methods for temporal disaggregation of mean loads, with emphasis on ungauged sites. Measured load seasonal load fraction was calculated for nutrients at approximately 200 measurement sites in New Zealand. This dataset was used to predict the seasonality at ungauged sites using three data based methods – boosted regression trees, simple MARS (multivariate adaptive regression splines) regression, and catchment similarity. The resulting models provided satisfactory predictions for seasonality of TN and TP, but not for dissolved nutrients. The simpler MARS regressions methods and catchment similarity provided similar model performance to the regression trees, with additional benefits of improved model interpretability and ease of prediction. For event and daily loadings, we investigated methods for disaggregation based on generalising event load probability distributions and rating curves in conjunction with measured or modelled flow rates. Empirical probability distributions provided comparable prediction performance to parametric methods, due to difficulty in generalising the distribution parameters. The main gain in reducing prediction uncertainty arose from appropriate normalisation, while attempts to further resolve variability were of marginal success, as judged by cross-validation statistics. Hence a simple master curve of normalised probability distribution, along with characterisation of errors, was appropriate for events. Overall, these methods provide useful approaches for temporal disaggregation, but often entail considerable prediction uncertainty.

Keywords: *Hydrology, water quality, seasonality, data mining*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Extracting relationships from environmental data by means of partial information analysis

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Abstract: In recent years, the amount of environmental data being collected has increased dramatically. However, in many instances, much of the data collected on a routine basis by water authorities and Government agencies is archived without detailed analysis. This is despite the fact that such data can be invaluable in terms of developing a better understanding the dynamics of complex systems, identifying data errors and identifying inputs to data-driven predictive models. Consequently, there is a need for robust data analysis methods that enable maximum benefit to be derived from data sets, thereby value-adding to existing investments in data collection.

In this paper, an improved approach based on partial mutual information (PMI) is presented that enables the strength of non-linear relationships between variables in highly dimensional data to be determined, as well as the degree of redundancy of information in the data. While PMI approaches have been used extensively for the purposes of the identification of the most important inputs for data-driven predictive models, such as artificial neural networks, for some time, and have been proven to be extremely powerful, they have generally relied on the assumption that the data follow a normal distribution, which is unlikely to be the case for the majority of environmental applications.

In order to overcome the above shortcoming, an improved PMI approach is presented that is able to deal with data with different degrees of non-normality and non-linearity. This is done by addressing two aspects of the calculation of PMI, including how to best calculate the density needed for mutual information (MI) calculation and how to best calculate the residuals needed for the calculation of PMI. In relation to MI bandwidth estimation, different methods of obtaining the optimal kernel bandwidth are considered. In addition, different methods for boundary correction are considered to account for the extension of symmetrical kernels beyond the bounds of potential inputs, which results in the underestimation of kernel-based marginal and joint probability distribution functions. In relation to residual estimation, both kernel-based methods and kernel-free methods are considered. For the latter, different methods for obtaining the optimal bandwidth and different boundary correction methods are tried.

In total, sixteen different combinations of the above methods are applied to three synthetic case studies with varying degrees of non-linearity, for each of which data following distributions with varying degrees of non-normality are generated. The results indicate that by using improved methods of MI and residual estimation, input variable selection accuracy of PMI can be increased from between 25% and 95%, depending on the degree of non-normality of the data, when commonly-used methods for MI and residual estimation are used, to 100% when methods for MI and residual estimation are used that are tailored to the problem at hand. However, this comes at a significant decrease in computational efficiency.

Guidelines for the selection of the most appropriate methods for MI and residual estimation based on the degree of non-linearity and non-normality of the data are developed from the results on the synthetic case studies. These guidelines are tested on two semi-real case studies for which real input data are used, but calibrated artificial neural network models are used to generate the corresponding outputs so that the true inputs are known. The two case studies include the forecasting of salinity in the River Murray in Australia and the prediction of runoff in the Kentucky river basin in the USA. These case studies are selected as the data for the former are relatively linear and normally distributed, whereas the data for the latter case study are highly non-linear and non-normal. The results show that the proposed guidelines hold for these case studies and that the correct inputs are selected 100% of the time if these guidelines are followed.

Keywords: *Data mining, knowledge extraction, input variable selection, partial mutual information*

EXTENDED ABSTRACT ONLY

Synthetic data comparison of Ensemble Empirical Mode Decomposition (EEMD) and Complete EEMD

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Abstract: Ensemble Empirical Mode Decomposition (EEMD) is a noise assisted locally adaptive spectral analysis technique suitable for application to non-stationary and non-linear time series. Recently, Torres et al. (2011; IEEE ICASSP, 4144–4147) introduced Complete EEMD (CEEMD), a significant modification of the EEMD algorithm. In order to appreciate the improved features of CEEMD relative to EEMD and the original Empirical Mode Decomposition (EMD) we need to understand the background to these different methods.

EMD is a data-driven spectral analysis algorithm. When applied to a time series the EMD algorithm identifies a series of progressively lower frequency orthogonal Intrinsic Mode Functions (IMFs) and a residual, which when summed together form the original time series. Two features of EMD outputs: (1) mode mixing; and (2) non-robust IMFs led to further work to improve EMD. Mode mixing is when a signal is not captured within a single IMF, but is split over two or more neighbouring IMFs. The non-robustness of EMD IMFs is due to the nature of the EMD algorithm, which relies upon identification of local maxima and minima within the time series. Minor changes in the location of local maxima and minima within the time series result in a different decomposition with the magnitude of difference being amplified in subsequent IMFs. Thus EMD IMFs can vary depending on small changes in the initial time series.

EEMD was proposed as an improvement over EMD in order to overcome the two weaknesses in EMD. In EEMD an ensemble of EMD runs is performed on the original time to which normally distributed white noise has been added to each ensemble member. The white noise, scaled by the standard deviation of the time series, introduces perturbations in the timing of local maxima and minima within the ensemble member time series, which prompts a wide range of decomposition results. The first IMF from EEMD is formed by taking the average of all first IMFs from the ensemble members. Subsequent EEMD IMFs are formed in the same way as ensemble averages of subsequent IMFs. By taking the ensemble average the dominant IMF features are identified and the EEMD IMFs represent the most robust decomposition of the time series. During the averaging process the impact of the added white noise is largely averaged out, particularly if the size of the ensemble is large relative to the standard deviation scaling factor. Despite the benefits of EEMD over EMD two weaknesses remain: (1) mode mixing; and (2) non-completeness. In EEMD mode mixing persists due to the number of IMFs produced in each EMD run varying between ensemble members. Thus during the IMF averaging, say for the fifth IMF, IMFs with different frequency modes can be averaged together, which results in mode mixing in the final EEMD IMF. Non-completeness arises due to the added white noise not being averaged out – thus EEMD IMFs and residual do not sum to form the original time series.

CEEMD takes a different approach to EEMD. Rather than adding white noise to the time series and extracting all the IMFs using EMD for each ensemble member, in CEEMD noise is added to the time series at each IMF step, the first IMF is extracted using EMD and then the ensemble of first IMFs is averaged to obtain a CEEMD IMF. Once a CEEMD IMF is identified it is subtracted from the original series and the process repeats on the residual. In this way each IMF is the result of averaging of first IMFs, which reduces the likelihood of mode mixing. Furthermore, by subtracting the CEEMD IMFs from the original series, rather than the series + white noise, the problem of non-completeness is resolved.

Here I present the key differences between the EEMD and CEEMD and discuss the improvements introduced by CEEMD. I demonstrate the different methods and compare their performance when applied to synthetic datasets of known spectral and trend properties. The ability of each algorithm to identify known synthetic components within each dataset will be assessed. EEMD and CEEMD will be applied to the monthly Southern Oscillation Index (SOI) time series and a comparison of their respective spectral outputs will be made. Conclusions about the performance of EEMD and CEEMD will be drawn.

Keywords: *Complete Ensemble Empirical Mode Decomposition, synthetic data comparison, spectral analysis*

Geostatistical water table mapping: cautionary tales, tribulations and resolutions

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Abstract: The interpolation of sparse groundwater head observations to produce potentiometric maps is a fundamental approach for understanding groundwater dynamics. Traditionally, interpolation has been undertaken by manual estimation of contours, and more recently, numerical interpolation approaches, such as kriging, have been employed. Unconfined heads are, however, often a subdued reflection of the topography, with local variability influenced by rainfall, landuse and geology. These factors are therefore drivers of the observed head and can potentially be used as predictors in the interpolation. Kriging with external drift (KED) is a widely adopted approach to make use of such predictors and, to date, it has been used to include the land surface elevation as a predictor of head. The resulting potentiometric maps are often a significant improvement over ordinary kriging, showing plausible flow directions and gradients.

The KED does, however, have a number of unacknowledged fundamental weaknesses - specifically, excessive noise in the head (Fig. 1), sensitivity to observation errors and questionable estimation in uplands and in coastal regions dominated by radial flow. This paper illustrates these weaknesses by application of KED to various catchments and then proposes a multivariate localised colocated cokriging (ColCK) approach that locally reduces the excessive noise from KED and incorporates the coast line and streams into the estimation. Figure 1 shows a cross-section from application of the univariate ColCK (using only the DEM) and KED to the Murray Mouth, South Australia, and shows the observed bore data along the cross-section. It illustrates that ColCK considerably reduces the level of excessive noise and erroneous estimation from KED. However, both interpolation methods deviate from the observed head at a lower land surface elevation (approximately < 40 m AHD). While deviations can occur when observations are not located at the centre of a grid cell, the considerable departure from the observations illustrates challenges that arise when the surveyed bore land surface significantly differs from the DEM. With resolution of such data errors and the inclusion of the stream network, ColCK is a viable approach for gaining more insight from the nation's groundwater data.

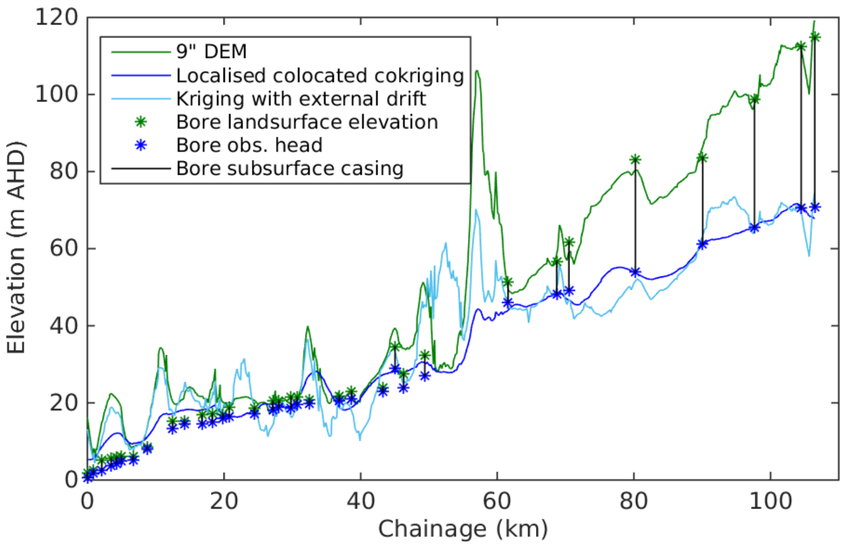

Figure: Cross-section from water table mapping for Autumn 2011 using localised colocated cokriging and kriging with external drift.

Keywords: *Water table mapping, groundwater, colocated cokriging, kriging with external drift*

The Groundwater Statistical Toolkit: an open source package for hydrogeological insights

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Abstract: Australia's groundwater monitoring network comprises of over 15,000 monitoring bores, has an annual operating budget of $29M and an asset replacement value of $136M (SKM, 2012). However, too often the data are only used for graphical analysis of, say, trends and it is only occasionally used for calibrating numerical groundwater models. To increase the value derived from the nation's groundwater data, this paper presents a highly flexible open-source groundwater time-series modelling tookit for deriving significantly more quantitative insights from the data (available at https://github.com/peterson-tim-j/Groundwater-Statistics-Toolbox).

The toolkit allows highly flexible construction of a wide range of groundwater time-series models and it already includes linear and nonlinear transfer-function noise models and double exponential smoothing models. The transfer function models have been used to decompose observed hydrographs into the impacts from climate variability and pumping drawdown, quantify hydraulic properties and identify dominant climate lag times; while the smoothing model has been used to statistically identify outlier observations at 33,000 observation bores throughout Victoria (note, many of these bores are no longer monitored).

In applying the toolkit to an observation bore, a model can be built using pre-defined components for the simulation of drivers such as recharge, phreatic evapotranspiration, groundwater pumping or landuse change. Moreover, new components can be easily defined and integrated into the toolkit using the object-oriented structure of the toolkit. This structure allows the flexibility of the toolkit to be preserved within a graphical user interface (Fig. 1), while also providing batch analysis of hydrographs and the use of the toolkit by those not comfortable with Matlab command line analysis. In presenting the Groundwater Statistical Toolkit, the structure of the algorithms will be detailed, the user interface will be presented and a number of case studies will be discussed.

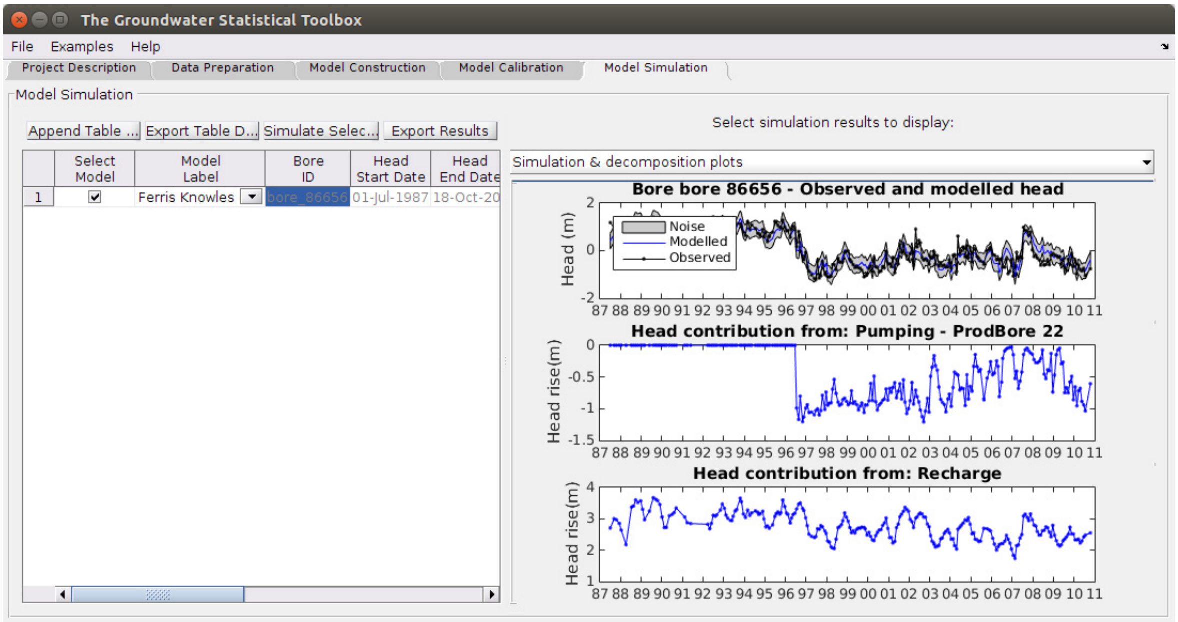

Figure 1. Screenshot of the *Groundwater Statistical Toolkit* user interface. The table (left) lists models available for simulation and on the right are simulation results for a shallow bore in Clydebank, Victoria, and its decomposition to the impacts from pumping and recharge.

Keywords: *Groundwater time-series modelling, groundwater modelling, object-oriented modelling*

A probabilistic approach to climate shift detection based on the Maronna-Yohai bivariate test

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Abstract: This paper presents an extension of a method from previously published work showing that discontinuous shifts, or step changes, are present in recent climate.

The global mean temperature (GMT) time series is a composite variable. It contains natural variability centered about Earth's biospheric heat. Historically, this has varied due to volcanic, geographic, solar and orbital effects. At the decadal scale, it has varied due to a complex set of internal variations, of which the Pacific decadal oscillation (PDO) and the Atlantic multi-decadal oscillation (AMO) are possibly the most influential. Anthropogenically-induced global warming, due to changes in land use, ozone depleting chemicals, and increasingly, greenhouse gases (GHG), leaves a complex signature in this time series. However, due to the need to convey information about climate change impacts to a wide and complex readership, the annual GMT series is regarded as the primary measure in monitoring the climate and its rate of change, and for comparisons with projections. Embedded in many projections, is the assumption that the rate of change should be largely free of discontinuities.

There is now an existing body of work based on a homogeneity test, the Maronna-Yohai bivariate test. This test was originally devised to assess single inhomogeneities in a serially independent time series. This paper describes an extension of this test to detect multiple shifts in the mean of a time series subject to external forcing. This has been achieved by the application of a set of decision rules designed to produce a robust set of results from noisy time series. It has been applied to estimated annual surface temperature at global, hemispheric, tropical, extra-tropical and polar scales

The procedure is presented as an objective test for determining the most likely time of change. The test's basis, equations and decision rules are described in some detail, and preliminary results are then presented, demonstrating that (a) climate regime shifts occurring at sub-global scale leave traces in the global record, and (b) recent shifts are at least as coherent as similar shifts found earlier in the instrumental record.

Keywords: *Maronna bivariate, global temperatures, shift, step change, regime change*

Joint multiple time-series modelling of groundwater hydrographs: an approach to overcome data paucity for the improved decomposition of hydrographs to individual drivers

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Abstract: Groundwater level observations are often the only available data for estimating the impacts of pumping or land use change. However, the groundwater level is often only observed after the pumping or land use change commences. This makes quantifying the impact of the pumping or land use change very challenging and trials of the Peterson & Western (2014) groundwater time-series model often result in poor model performance, ill-defined parameters and inconsistent estimates of the water level impact. This problem is addressed here by the joint calibration of the time-series model to two observation bores. Specifically, one bore with a long record is selected with minimal impact of the anthropogenic driver and the second bore is at the site of the impact and has observations only after the anthropogenic driver commenced. Next, the two bores are jointly calibrated using an extension of Peterson & Western (2014). In doing so, a fixed estimate of the spatial correlation between the two sites was used to iteratively inform the model parameters at one site by using the parameter estimates from the other site.

To evaluate the approach, it was implemented at two observations bores (86656 and 86654) at Clydebank, Gippsland, Victoria, where only 86656 is influenced by groundwater pumping; which is undertaken to control groundwater salinity. The time series model was first calibrated only to bore 86656 for the period of 1/1/2003 to 1/1/2007 (red line in Fig.1a) and evaluated on the remainder of the observation period (blue line in Fig.1a). Next, bore 86656 was jointly calibrated (again from 1/1/2003 to 1/1/2007) with bore 86654; which was calibrated from 1/1/1993 to 1/1/2007 (Fig. 2a). The results show that a joint calibration of bore 86656 significantly improved the coefficient of efficiency from 0.18 to 0.78 during the evaluation period. Additionally, the decomposition of the drivers from the joint calibration show that the joint calibration produced more plausible estimates of drawdown than from the single bore calibration. This trial highlights the potential effectiveness of the approach in overcoming data limitations for estimating anthropogenic impacts on groundwater resources.

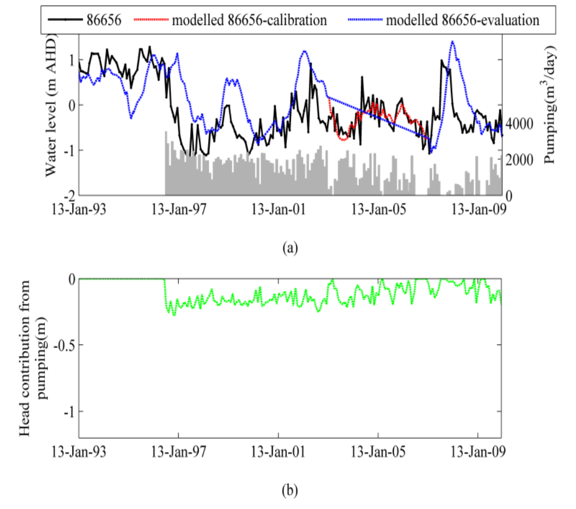

Fig. 1 (a) Single calibration of bore 86656 and **(b)** estimate of drawdown from pumping. In (a), the grey bars denote the daily pumping rate.

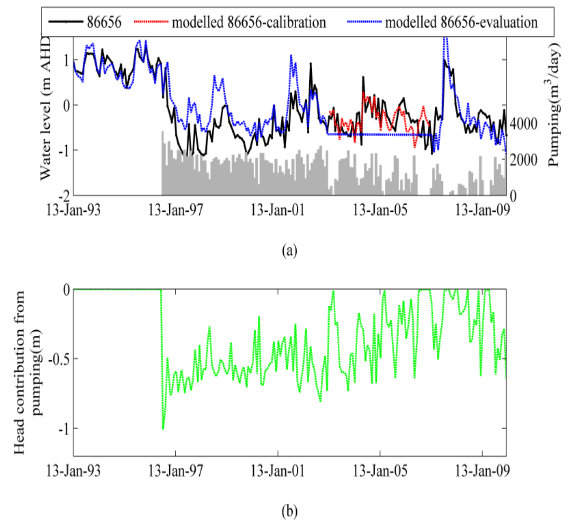

Fig. 2 (a) Joint calibration of bore 86656 using bore 86654. **(b)** Drawdown from pumping. In (a), the grey bars denote the daily pumping rate.

Keywords: *Groundwater time-series modelling, hydrograph decomposition, groundwater pumping*

Can recursive digital filters ever produce accurate baseflow estimates?

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Abstract: Improved methods that partitions streamflow into different fluxes, such as overland flow, subsurface flow and groundwater discharge, would enable deeper understanding of the underlying processes in river basins. Although there is a continuum of subsurface flow paths, it is common to consider only two components in the makeup of the total stream discharge, namely storm runoff and baseflow. In this work, the term baseflow is used to describe groundwater discharge from aquifers that reaches the stream. Even with this simplification ignoring slow drainage from other sources, the separation of baseflow from streamflow hydrographs at the catchment scale is difficult. There are numerous methods proposed to meet this challenge, and of which, various forms of recursive digital filters (RDFs) are widely used. These RDFs vary with complexity and underlying physical assumptions (where they are explicitly made) and the best choices among RDFs remain unclear. Moreover their ability to estimate accurate baseflow values is generally unknown due to inadequacies in observational data. Only recently have controlled numerical experiments, based on 3D surface water/groundwater models, been used to objectively evaluate their performance in synthetic settings, but they have not been sufficiently comprehensive to assess a wide range of RDFs.

Within this context, we unify the existing RDFs, namely the Chapman-Maxwell, Boughton-Eckhardt, IHACRES, Furey-Gupta, Boussinesq and Croke filters, through two theoretical frameworks. The first involves extending Croke's formalism to describe multiple quickflow and recharge/slowflow pathways in the filter construction, and the second invokes the signal processing theoretic for infinite-impulse response (IIR) filters. By nesting these existing RDFs within generalized RDFs, we can systematically increase the complexity of the generalized RDFs by increasing the flow pathways or equivalently, increasing filter orders. We therefore extend the previous evaluation studies to assess the RDFs collectively against modelled simulations from HydroGeoSphere. The model data set, recently produced by Li et al. (2014), contains daily streamflow and baseflow timeseries for tilted V-shaped catchments. Sixty-six representative catchments were set up by Latin hyper-cube sampled model parameter values relating to catchment geometry (area, slopes, and aspect ratio) and homogenous soil/aquifer properties (saturated hydraulic conductivity and Van Genuchten soil water retention parameters). The models were forced by rainfall and potential evapotranspiration measurements from 5 Australian cities, representing a range of climatic conditions.

We evaluate the ability of the generalized RDFs to reproduce daily baseflow through direct calibration against synthetic truth and split-sample evaluation. Our evaluation demonstrates that there is uncertainty in the best implementations (and thus, calibration) of the generalized filters. When the RDFs are implemented as a linear filter, the physical meaning of the filter parameters and construction is preserved but negative flows are generated. This is not the case when the RDFs were implemented with thresholds to avoid negative flows. The information gained from the RDFs can also become limited; especially during recession periods.

We systematically increased the complexity of the generalized RDFs and used Bayesian Information Criteria analysis to find optimal RDF order for reproducing synthetic baseflow. The simpler Eckhardt filter is not optimal for most catchments. However, it should be noted that the observed preference for higher-order RDFs over the simpler filters is conditional on having perfect knowledge of baseflow for calibration and the specific application of estimating daily baseflow.

Despite increasing the orders of the RDFs, there remains persistent, and at times substantial, disagreement between the synthetic and estimated baseflow for many catchments. Spearman correlation analysis shows that the RDFs perform poorly over catchments with small baseflow components, low saturated hydraulic conductivity, high streamflow coefficients of variation, and higher rainfall. The simplest explanation is that a low baseflow 'signal' in the streamflow data is hard to distinguish, perhaps regardless of the estimation method. The advantages of using more complex RDFs over the Eckhardt filter are also more striking at these catchments where the latter performs poorly. In conclusion, while the RDFs have systematic weaknesses, this study demonstrates that the generalized RDFs offer more flexible filter structures than existing methods and provide a means for further calibration.

Keywords: *Baseflow estimation, recursive digital filters, controlled experiments, Eckhardt filter*

Flexible and modular visualisation and data discovery tools for environmental information

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Abstract: Recent advances in environmental sensing, high-resolution satellite technology, advanced environmental modelling, information platforms, and virtual laboratories present significant opportunities for providing scientific communities and the general public with the ability to discover and gain insights into our ever-changing environment. However, barriers to realising the value of available environmental datasets exist, specifically, in the (lack of) streamlined access to datasets, and tooling to flexibly support the mash-up creation of various visualisations. In previous work, a Data Brokering Layer has been developed to support the streamlining of potentially heterogeneous access mechanisms and data formats.

The Data Brokering Layer provides functionality to handle data queries and access to registered datasets and data services, where in the past, visualisation portals would have required ad-hoc code to handle access to each dataset individually, thus limiting the extensibility of such data portals further. Thus, the Data Brokering Layer provides a basis on which a library of visualisation and data discovery modules can be developed. Such visualisation and data discovery modules provide flexible, reusable and mashable components for exploring datasets multiple contexts across multiple domains. Examples of visualisation modules include data portals, embedded visualisation panels, and real-time reports.

In this paper, we focus on the visualisation and data discovery capabilities developed in the context of the eReefs project which aim to provide an integrated information platform for discovery and visualisation of observational and modelled data of the Great Barrier Reef.

Keywords: *Great Barrier Reef, visualisation, data interoperability, data discovery, environmental information systems*

Sensitivity of the Hilbert-Huang Transform to interpolation methodology: examples using synthetic and ocean data

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Abstract: The Hilbert-Huang Transform (HHT) provides a way to decompose a signal into component functions and to analyse instantaneous frequency data. Moreover, it applies to nonlinear and non-stationary data, and so offers a practical alternative to more traditional methods such as the Fourier transform, which is not well-suited to such circumstances. Since its inception in the late 1990s, the HHT has been applied in a number of areas, including biomedicine, neuroscience, epidemiology, chemical engineering, finance, atmospheric turbulence, seismology and ocean dynamics. The HHT combines a data sifting process known as empirical mode decomposition (EMD) with Hilbert spectral analysis. The EMD process decomposes a signal into intrinsic mode functions (IMFs), which are analogous to the harmonic modes of Fourier analysis, but which can have variable amplitude and frequency throughout the time domain. A critical step in determining each of the IMFs involves constructing upper and lower envelopes of the local maxima and minima. In the original presentation of the HHT methodology, cubic spline interpolation was recommended to construct these envelopes. However, there does not appear to be any literature to support such a recommendation and so it is natural to wonder how employing alternative interpolation methods would affect the ultimate outcome of the HHT method.

In this paper we consider this issue by studying the HHT, and in particular the EMD procedure, as it applies to two synthetic data sets (one a noisy realisation of the other) and to a real geophysical data set, namely sea level data collected by a tidal gauge at Brisbane. IMFs for each of the data sets are derived separately using cubic spline and linear interpolation techniques and the resulting structures scrutinized for systematic differences.

The analyses of the synthetic data sets showed only minor differences between the results produced by the linear and cubic interpolation methods, with the linear interpolation method producing the most accurate of the underlying trend in the input signal. The cubic interpolation EMD method produced better estimates of oscillatory signal components, though these estimates suffered from larger errors near the boundaries when compared with those obtained from the linear EMD procedure.

Analyses of the noisy synthetic data set again showed only relatively minor differences in the performance of linear and cubic ensemble EMD. Both methods were affected by mode mixing issues, but the linear method again provided the more accurate estimate of the trend in the signal. The low frequency oscillatory component of the signal was estimated more accurately by the cubic ensemble EMD method, while the high frequency component was reproduced to a similar degree of accuracy by both linear and cubic methods. Overall, the choice of interpolation method used when applying the EMD procedure to the synthetic data sets only produced minor changes in the output.

Using the linear and cubic methods to estimate the long term trend in sea level at Brisbane produced similar results, but with differences that could be considered significant in the context of understanding the impacts of trends in sea level. One key point of difference was that the linear EMD method delivered a trend estimate with discontinuous derivative, which may be considered less desirable in some circumstances.

Keywords: *Non-stationary time series, Hilbert-Huang Transform, Empirical Mode Decomposition, interpolation, data analysis, Empirical Mode Decomposition*

Impact of meadow size and morphology characteristics on bistability in seagrass ecosystems

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Abstract: Distinct switches between alternative regimes are a feature of many aquatic ecosystems. Alternative stable states occur as a result of reinforcing feedbacks which (1) confer resilience to the highly productive, healthy ecosystem when it is present and (2) hinder recovery of this ecosystem following loss. However, the appearance of these alternative states may not be robust under all external environmental factors and biological characteristics of the ecosystem.

In this talk, we use a deterministic mathematical model to investigate how the spatial and biological characteristics of an aquatic ecosystem (seagrass meadows) affect the occurrence of alternative states induced by a positive feedback between seagrass presence and sediment resuspension. The model is solved under steady state conditions, and its parameters are obtained from reported literature values. Because hydrodynamic conditions vary widely in the estuarine and coastal areas that seagrass can colonise, we modelled the two extremes of hydrodynamic environments: (1) seagrass meadows subject to unidirectional flow with negligible wave action present, which represents the minimum water residence time of water in the meadow, and (2) seagrass meadows present in a wave-dominated environment with low net horizontal spatial water movement, which represents the maximum residence time of water in the meadow. This allowed us to determine the impact of the water residence time on the difference in water clarity induced by seagrass presence.

New formulations are introduced to account for edge effects at the boundary between seagrass meadows and bare areas, and leaf area index, which allow the results to be generalised across different morphologies and colonisation strategies. We show that the water residence time is a critical factor to determine whether the positive feedback between seagrass presence and sediment resuspension has the potential to induce alternative states in aquatic ecosystems. For environmental management of aquatic ecosystems, our results demonstrate that high water residence time in an area where seagrass can grow is a prerequisite for the feedback between seagrass and water clarity to significantly impact on whether seagrass is present or absent. Hence, the effects of this feedback can be disregarded in areas where the water residence time is low.

Alternative regimes in aquatic ecosystems are controlled by the coupling of highly variable physical and biological processes. Hence, "When are we confident in the parameterisation of these models?" is a question that we pose for debate in this session.

Keywords: *Alternative states, bistability, feedbacks, seagrass, sediment resuspension*

Indicators of changing connectivity within estuarine and coastal systems

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Abstract: Connectivity amongst estuarine and coastal habitats and human activities has long been recognised as a key process for maintaining healthy ecosystems and associated ecosystem services. However, indicator metrics that effectively capture the range of ecologically significant aspects of connectivity at appropriate temporal and spatial scales have not previously been available. Using Gladstone Harbour (southern Great Barrier Reef) as a test case, we developed and estimated novel connectivity indicators that relate directly to aspects of ecosystem health, such as water quality, contaminant dispersal, and ecological functions such as larval dispersal and settlement.

Three classes of connectivity indicator have been developed:

- *Flushing rate* provides an integrated measure of the exchange of water through the system and is already in common use as an indirect indicator of water quality.
- *Contaminant connectivity* provides an integrated measure of the potential for contaminants to enter other parts of the system.
- *Ecological connectivity* provides an integrated measure of the potential for exchanges between spawning areas and nursery habitats throughout the system.

All three connectivity indicators used detailed information on physical dispersal derived using a high-resolution hydrodynamic model of the estuarine system and particle tracking techniques. Particle retention and network analyses were applied to this data at the scale of established reporting zones in the harbour to generate both annual indicator distributions and corresponding baseline distributions for comparison. The baseline was derived from 4-years of data that included a wide range of environmental conditions (wind and river flow) as well as changes in bathymetry associated with dredging of shipping channels.

The final indicator scores represented statistical comparisons of annual and baseline distributions for each reporting zone. Indicator scores could also be combined to provide an overall connectivity score for each zone. Sensitivities of the indicators were calibrated by deriving scores for a number of historical years and two artificially constructed extreme years; the first derived by combining months of high-flushing rates and the second by combining months of low-flushing rates.

The three connectivity indicators were designed to capture different characteristics of the system and the derived scores confirm that their responses are independent. While this could result in quite complex responses across zones and indicators, aggregated scores revealed broader trends such as a tendency for overall connectivity in the main harbour zones to derive a net benefit from higher flushing conditions, while smaller estuaries and bays benefited from lower flushing conditions.

Keywords: *Connectivity, indicator, dispersal, flushing, estuary*

3D Hydrodynamics and Vertical Mixing in a Stratified Estuary

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Abstract: Estuaries are commonly classified by their flow characteristics and the extent of salt and fresh water mixing observed under normal conditions. Highly stratified, "salt-wedge" estuaries are characterised by a well-defined horizontal halocline, with a fresh surface water layer forming above the saline coastal water. Salt-wedge estuaries have large fluvial to tidal flow ratio and typically occur along microtidal coasts where the tidal range is less than 2 m. The mixing of fresh river water and saline coastal water in estuaries is primarily determined by turbulent mixing and to a much lesser extent molecular diffusion (e.g. Masselink and Hughes, 2003). Under low turbulent energy conditions the river and coastal water masses remain segregated. As turbulent mixing increases, such as during a flood event, the estuary may temporarily transition to a "partially" or "well-mixed" condition.

The hydrodynamics and vertical mixing in a stratified estuary has been explored using high-resolution datasets and numerical models. The hydrodynamics and vertical structure in the Yarra River estuary (Melbourne, Australia) was observed using a combination of ADCP (Acoustic Doppler Current Profiler) and EC/T (Electrical Conductivity and Temperature) instruments. The observed features of the estuary and position of the halocline were subsequently simulated using a 3D Non-Linear Shallow Water Equation (NLSWE) solver coupled with turbulent mixing and atmospheric exchange models. The key aspects of the numerical modelling approach required to accurately capture the vertical structure of the Yarra River estuary included:

- The inclusion of approximately 200 urban stormwater discharge inputs,
- A hybrid z-coordinate with surface sigma-layer model mesh vertical discretization, and
- Coupling of the 3D hydrodynamic model with a two-equation vertical turbulence scheme.

The coupling of the hydrodynamics with the vertical turbulence scheme was an essential component of the modelling system. Following this approach, the 1D (vertical) transport equations of momentum, salt and heat are calculated and used by NLSWE solver in the 3D circulation calculations. Efficient integration of the 3D NLSWE was achieved through a mode splitting scheme, whereby different components of the governing equations were updated using an appropriate timestep selected by taking into account physical and numerical convergence and stability considerations.

This model will ultimately form the basis for a 3D hydrodynamic-microorganism model through the coupling with the Aquatic EcoDynamics (AED^2) modelling library. It is anticipated that this tool will be used by industry partners (Melbourne Water) to make scientifically-informed management decisions for improvement of water quality in the Yarra River estuary.

Keywords: *Salt wedge intrusion, water quality, Yarra River, TUFLOW FV*

An attractor modelling approach to predicting system stability in barrier estuaries

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Abstract: An attractor modelling approach has been shown (Hinwood and McLean, 2015) to simulate the long term evolution and stability of barrier estuary entrances. From this a classification of estuaries, based on the stability of the entrance, may be made. For individual estuaries this modelling approach can be used to investigate system instability under different climate scenarios. Climate change will result in changed river flows and increased sea levels. These changes will affect the behaviour of barrier estuaries, which are frequently vulnerable to entrance instability or closure. To determine the effects of climate change on the entrance stability, extensive sets of simulations were made using a simple model of the estuary entrance dynamics.

The model used is based on a two-cell representation of the hydrodynamics and sediment transport in the entrance constriction. The attractors are found by running the model until a limit state is attained, usually about 2,000 tide cycles, for several thousand sets of initial conditions of non-dimensional river flow, Q, and entrance depth, h. The results of the modeling are shown on an "attractor map", which is a plot of Q against the final value of h. The map also shows the attractors, which are lines depicting the states to which the estuary evolves under the assumed conditions of tide, river flow and coastal sediment supply. For entrances where Q is less than a critical value, relatively small changes in river flow or sediment supply can push the estuary into the catchment of the river flow attractor and effectively close the entrance until a higher river flow or erosive wave condition scours the entrance.

The Snowy River Estuary is used as an application where we have previous 3D modelling results for similar scenarios. In this paper we use the attractor map to determine the effects of changes in the entrance stability and estuary regime for the pre and post Snowy Mountains Scheme plus predicted climate change scenarios that lead to changes in river flow and/or mean sea level for the years 2035 and 2100. The analyses show that the predicted rise in mean sea level is likely to reduce the stability of the entrances. The predicted reduction in catchment flow is likely to have a small impact on the stability of estuary entrance with the main effect being the rise in sea level which leads to an increase in marine sediment being supplied to the entrance. The attractor approach is shown to provide additional information on the response of an estuary to a range of conditions and can provide guidance on the selection of specific cases for detailed study.

The Pre-SMS entrance condition is shown to have been essentially stable but the removal of the upper catchment by the Snowy Mountains Scheme has increased the vulnerability of the entrance to closure. The effects of reductions in catchment flows predicted under climate change appear to have been exacerbated by expected increases in inter-tidal area in the estuary through sea level rise, which will lead to an increase in the influx of marine sand to the entrance. Thus, over the period up to 2100 the entrance will stay well within the vulnerable zone.

Attractor modelling has been shown as a useful tool to represent the entrance state and potential trajectory of barrier estuaries with a significant river inflow. The construction of an attractor map for an estuary can provide the basis for management decisions where periodic entrance constriction impacts on the amenity and function of the estuary. Attractor modelling can contribute strongly to the development of a Decision Support Structure that includes projected estuary state, expanding on the reactive measures possible when only monitoring methods are available.

Keywords: *Barrier estuary, attractors, modelling*

Wave parameter classification based on morphological changes around a small wave-dominated tidal-inlet using a schematized Delft3D model

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Abstract: The investigation of long-term morphological changes of a tidal-inlet using process-based models is a complicated and resource dependant task. To date, a number of input reduction techniques have been utilised to reduce the complexity of the modelling tasks; amongst them the wave condition has been shown to be of significant importance. Rapid and significant morphological changes generally occur as a result of a highly energetic waves occurring over a short period, whilst low energy waves can only be influential if they occur for a longer period. Therefore, research has been focused on methods to categorize a continuous time-series of waves into discrete events which, in combination, have an almost identical morphological outcome as the full time-series. Nevertheless, there is no clear agreement on a preferred categorization method based on an overall frequency of occurrence of wave parameters. Additionally, for a re-arranged, categorized wave dataset, the selected chronology of the events is a matter of further consideration as research has shown that the morphological outcome would vary. Moreover, despite some noteworthy research for coastal areas, the current literature is quite limited in regard to morphological changes around small tidal-inlet entrances. The first of the above-mentioned gaps was considered in this study and as such this article aims solely to determine important classes of wave parameters based on their relative morphological impacts on a wave-dominated, small tidal-inlet entrance. The effects of chronology, as well as the cumulative influence of consecutive wave events are therefore not further considered here.

For this study several categorization methods from the literature were investigated. The selected approach uses an offshore directional wave time-series to statistically classify wave parameters. Wave data is initially separated by wave period (e.g. Tp), to distinguish between seas and swell waves. Then, based on the frequency of the occurrence of particular wave height and direction ranges, data is classified into sub-groups. Later, the sub-groups with the combined total frequency percentage of occurrence of about 90% are identified to encompass the required classes of schematized wave parameters for modelling. The remaining sub-groups (i.e. with total 10% occurrence) are considered to be morphologically ineffective. Furthermore, for preparing the model boundary data, there needs to be representative wave parameters for each of the selected classes. For the representative wave direction and period, a simple algebraic average of data for each class could be used. However, the best practice to find the representative average wave height could be through averaging the energy of individual incident waves for each of the classes. All these classified parameters then are used as input for morphological model.

For the case study of this research, the wave classification procedure resulted in 20 classes of wave data. An existing, calibrated, validated, coupled Delft3d Wave and Flow model was used along with a simple harmonic tide at the boundary, to perform the necessary morphological modellings. In this research, the inlet entrance, its channel and the flood shoal of the selected case study area were the main focus. The modelling results showed that the wave classes which have undergone less refraction (i.e. cases with shore-normal offshore wave direction) were more prominent in transport of sediment all around the inlet entrance; irrespective of the wave height and period. Conversely, waves with a more oblique angle of incidence showed less transport in to the inlet inner lagoon; even for very large wave heights. The influence of wave period was also shown to be noticeable, as extensive erosion/accretion events based on larger wavelength of swell in comparison to sea waves was existent. The variation of depth averaged velocity, erosion/accretion and wave parameters at selected locations revealed that locations inside the inlet lagoon and at the entrance channel were less sensitive to different wave conditions. In contrast, the observation point offshore of the entrance, directly followed the changes to wave parameters. By having an insight in to the importance of each individual class of wave data, the classification procedure could be re-assured. Moreover, a particular wave class could be statically important but morphologically ineffective. Therefore, the output could assist in selection of an appropriate chronology for a cumulative morphological study.

Keywords: *Wave schematization, sediment transport, Delft3D, tidal inlet*

Effect of floristic niche width on community-level ecosystem function in the Wet tropics

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Abstract: Aim: It is argued that conserving different spatial and temporal dimensions of biodiversity is necessary for maintaining ecosystem functions under global change. Recent work has shifted the focus from spatially local (α-diversity) to macroecological scales (β- and γ-diversity), emphasising links between ecological specialisation and ecosystem functions. We test whether the ecological specialisation of vascular plant species in environmental space (environmental β-diversity) influences a key community-level ecosystem function - gross primary productivity (GPP) - under current environmental conditions.

Location: Wet Tropics biogeographic region, Australia (WT).

Methods: We summarised herbarium records for 4300 vascular plant species from the Wet Tropics. For all records of each species, we calculated the environmental niche width (95^{th} -5^{th} percentiles). Niche widths were quantified in three key environmental dimensions for vascular plants, using interpolated climate surfaces at 250m resolution (2001-2012): mean annual rainfall, maximum temperature of the warmest period and total soil nitrogen fraction.

Using the herbarium records, we calculate the average environmental niche width for all species occurring at 527 ecological survey sites (i.e. community level environmental niche width, cENW). Structural equation modelling is then used to quantify relationships between remotely sensed GPP (2001-2012), environmental conditions and cENW in all three environmental dimensions.

Potential implications: The influence of environmental β-diversity on GPP is unlikely to be as important as direct environmental effects under current conditions. However, the importance of community-level niche widths in influencing ecosystem functions may become more prominent over longer time scales under rapidly changing environmental conditions. Assessing these relationships at broad spatiotemporal scales will be important in ensuring macroecological processes can be adequately considered in the management of biodiversity and ecosystem functions under global change scenarios.

Keywords: *Niche width, vascular plants, gross primary productivity, rainfall, temperature, Australian Wet Tropics Bioregion*

Moving window analysis links landscape-scale resource utilization to habitat suitability models of feral pigs in northern Australia

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Abstract: Habitat suitability (or species distribution) models have been widely used to inform management decisions about species conservation, resource management or invasion control. We developed habitat suitability models of feral pigs across tropical northern Australia to enable more effective management of their negative impacts. However, when investigating wildlife-habitat relationships of highly mobile animals such as feral pigs, home range behaviour must be accounted for as these species can utilize scattered resources and fulfil their living and breeding requirements at different locations within the wider landscape that is accessible to them.

We developed a novel approach for incorporating landscape-scale utilization of resources and other habitat requirements into habitat suitability models of feral pigs via moving window analysis. Modelling followed three steps: (1) model pixel values for each of four key habitat requirements (water and food resources as well as protection from heat stress and disturbance) using probabilistic Bayesian networks that combine spatially-explicit explanatory variables, (2) transform them into landscape values via moving window analysis, and (3) model habitat suitability using a Bayesian network that combines all landscape values. Models were implemented in *Norsys Netica 5.12* and *AgenaRisk 6.1* software and calibrated using expert elicitation. Moving window analyses were implemented in the *R 'raster'* package and *ESRI ArcGIS 10.2* software.

Here, we present expert-elicited response functions describing the relationship between landscape-scale patterns of each habitat requirement and its sufficiency to sustain breeding in feral pigs. Two types of response mechanisms were described by each expert: a distance-dependent one where the sufficiency of a requirement diminishes with increasing distance, and a composition-dependent one where the sufficiency of a requirement diminishes with decreasing abundance. These functions were used to parameterize moving window analyses and calculate distance-dependent, composition-dependent and combined distance/composition-dependent requirement landscape values. Experts described three general shapes of response curve: linear decay, where sufficiency diminishes steadily with increasing distance/decreasing abundance; exponential decay, where sufficiency is strongly affected by initial increases in distance or decreases in abundance; and inverted exponential decay, where sufficiency diminishes little initially but strongly at large distances or low levels of abundance. Experts displayed considerable agreement when describing some responses but differed widely with others. Expert assumptions about the characteristic scale of the response, and hence the size of the moving window, also varied considerably.

We schematically illustrate that expert assumptions about the characteristic scale and mechanism of resource utilization had a considerable effect on computed sufficiency: Assuming distance-dependence dramatically increased sufficiency of a requirement. This effect became more pronounced at larger characteristic scales of resource utilization. Assuming composition- or combined distance/composition-dependence consolidated computed sufficiency to larger, more continuous resource aggregations and discounted utilization of isolated or scattered resources. These effects were equally more pronounced at larger characteristic scales. Hence, these assumptions require careful consideration when using them as an input into habitat suitability models and their effect on model performance must be validated. Our approach could readily be applied to other mobile species that respond to conditions at the landscape scale.

Keywords: *Species distribution model, spatial analysis, landscape ecology, home range behaviour, wildlife-habitat relationships*

Species richness, endemism and rarity under climate change using the Biodiversity and Climate Change Virtual Laboratory

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Abstract: The Biodiversity and Climate Change Virtual Laboratory (BCCVL; http://bccvl.org.au) is an integrated online tool for biodiversity-climate change modelling. It comprises five core components allowing researchers to (1) apply a suite of Species Distribution Models (SDMs), (2) combine SDM predictions using model ensembling, (3) project these SDMs into the future using alternate climate scenarios, (4) analyse species trait data, and (5) generate surfaces of biodiversity indices from the SDM outputs. The last component is the focus of this work.

Biodiversity indices over regional to continental extents are commonly calculated using digitised specimen data from museums and herbariums, with such "atlas" data being increasingly available through portals such as the Atlas of Living Australia (http://ala.org.au). However, atlas data are typically collected for taxonomic and genetic purposes, not spatial analysis, and thus species geographic distributions derived from them often have large gaps. Such gaps can be filled by using coarse spatial resolutions, such as 100 km cells, but at the cost of losing any fine scale detail in an analysis. The use of SDMs means that these sampling gaps can be filled in, and fine resolution patterns and relationships can be elucidated. SDMs also allow the forecasting of biodiversity patterns under future climate scenarios.

Using the BCCVL, users can calibrate SDMs for each of a set of taxa, and then analyse their collective distributions using indices such as species richness, endemism, rarity and sampling redundancy. Endemism and rarity are important indices for understanding biodiversity. Species richness is simply the count of species found in a given area, and does not take into account the commonness or rarity species. For purposes of conservation and understanding evolutionary history we are normally interested in those species that are rare or have narrow ranges and are possibly endemic. Weighted Endemism (WE) is a relative range-restriction measure in which widespread species are down-weighted. It can be treated as a range weighted richness score, and can also be expressed as a proportion of the total richness (Corrected Weighted Endemism, CWE). Endemism is essentially the footprint of the species distribution and is related to rarity except that it does not account for the spatial distribution of abundances. Rarity and sample redundancy are calculated in the BCCVL by using the SDM suitability or probability scores as pseudo-abundances. For all indices the user has the option to set very low values to zero to reduce any overestimation of species ranges.

These biodiversity indices are implemented in the BCCVL using the Biodiverse software (http://purl.org/biodiverse), allowing the addition of other indices as needed. The BCCVL itself is under continuous development, and is an open source project (https://github.com/BCCVL).

Keywords: *Biodiversity, endemism, rarity, species distribution model, climate change*

A GIS tool for land and water use planning in mining regions

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Abstract: Mineral rich regions can pose particular land use planning challenges due to economic pressure to mine that can face strong opposition from those concerned about social and environmental impacts. While fundamentally opposing values cannot easily be resolved, progress has been made in developing GIS planning tools that provide a common ground for analysis of scenarios and options. However, the complexity of integrating models across disciplines such as hydrology and ecology poses a considerable challenge.

This paper describes a GIS tool that highlights priority areas for biodiversity conservation and water provisioning services and then integrates both to characterize water provisioning ecosystem services (WPES). Biodiversity conservation priority areas were modelled with the spatial prioritization tool Zonation, and water provisioning services were assessed based on runoff, flow path length and the presence of vegetation. Zonation produces prioritisation in a balanced manner that maximises high quality habitats for all biodiversity features (e.g. species) in accordance to their rarity. The top priorities typically represent the full range of regional biodiversity within a relatively small area. These priorities were derived from spatial data describing the distribution of biodiversity features, including flora and fauna species and endangered ecological communities. Water provisioning services were calculated through modelling flow length with a digital elevation model in combination with runoff and spatial data on vegetation cover. Areas with longer flow length, in areas with higher runoff and vegetation cover, have higher values for water provisioning services. Spatial data for biodiversity and water provision services were then combined using a stream network to characterize the value of runoff generating areas in terms of their contribution to downstream riparian biodiversity.

A case study of land use planning in the Greater Hunter region, a mining and agricultural area of New South Wales, Australia, is used to demonstrate our approach to quantifying WPES. The impacts of potential future locations of surface coal mining were assessed by examining the spatial overlap of a coal seam geological layer with WPES. Our analysis identified areas that have high WPES value that may be affected by mining in the future. The aim of this research is not to present an end-point for a planning process but to demonstrate the value of and ways forward for incorporating system interactions by combining outputs of modelling tools. We conclude by discussing future research and the challenge of considering jointly water impacts and biodiversity impacts, including the need to evaluate interactions among the various GIS layers.

Keywords: *Mining, resource extraction, integrative modelling, strategic environmental assessment, cumulative impacts, land use planning*

Modelling Structures of Terrain Surface Using GIS in Loess Plateau

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Abstract: Terrain is a combination of several scales of structures, with those different structures being sensitive to different landscape process and influenced by DEM (Digital Elevation Model) resolution in different ways. It is important to separate these structures to investigate their characteristics. In this research, the spatial structure of a terrain surface Loess Hilly areas in the Loess Plateau was analyzed using a 10 m resolution DEM. A geostatistical model named Independent Structures Model (ISM) was built and used to model the semi-variance of different terrain structures with different spatial frequencies. Surface of each terrain structure was mapped by kriging. The result showed that: 1). The spatial components for elevation surface could be modelled through the modelling of semi-variance. In the study area, the elevation surface could be modelled to be three components with range of 82.5 m, 655.4 m and 1974.2 m and one trend component. The third component was the most important because the sill value was larger than the other two components. 2). The three components in the model could be shown to be consistent with half width of catchments with minimum catchment area of 0.1 km^2, 1 km^2 and 10 km^2. The result of this work are relevant for research into the scaling effect of terrain parameters and the relationship between terrain and soil erosion modelling, hydrology analysis and related fields.

Keywords: *Independent structures model, spatial structure, terrain*

Detecting vegetation groundwater use from satellite observations of surface temperature and surface energy balance modelling

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Abstract: Groundwater-dependent vegetation (GDV) are a critical component of the landscape, play an important role in the maintenance of biodiversity and actively regulate biosphere dynamics through contributions to the carbon and nitrogen cycles, the hydrological cycle and surface energy balance. GDV can be difficult to identify in landscapes, especially if only partially dependent on groundwater resources. Partial dependence is of equal importance where it is critical to the survival of vegetation during drought. Sustainable management of these ecosystems requires an understanding of their location as well as the frequency, duration and magnitude of groundwater use. Presently, several different approaches must be combined to achieve this level of understanding. This paper will (1) provide a brief overview of a novel model-data method which, through the comparison of modelled and observed land surface temperature (LST), aims to detect groundwater use by vegetation at a regional scale (~100 km^2); and (2) discuss how this methodology can be used to improve our understanding of ecophysiological processes and future sustainable management of GDV.

LST is directly related to heat fluxes whereby increased latent heat (or evapotranspiration) results in decreased LST. In water-limited environments, latent heat (and by association LST) is dependent on plant-available water, with cooler LST associated with abundant plant-available water. As near-surface soil moisture resources are depleted, GDV are able to supplement this water with groundwater resources, thereby maintaining cooler LST relative to non-GDV communities. In order to detect the groundwater component of LST ($T_{s.gw}$), a two-layer surface energy balance (SEB) model, driven by soil moisture, meteorological data and net radiation, was used to model instantaneous land surface temperature ($T_{s.mod}$), while coincident instantaneous satellite observations of radiometric land surface temperature ($T_{s.obs}$) were obtained from the MODIS sensor aboard the Terra satellite. $T_{s.obs}$ represents land surface temperatures as observed by the satellite sensor, reflecting all plant-available water resources while $T_{s.mod}$ reflect near-surface soil moisture resources (<30 cm depth) only. Thus the difference between $T_{s.mod}$ and $T_{s.obs}$ (temperature deviation) contains both $T_{s.gw}$ and model-data error. $T_{s.gw}$ was differentiated from systematic model-data error through the spatial and temporal application of an error threshold to temperature deviation data.

This novel model-data method can be used to estimate the location of GDV and the frequency, duration and magnitude of groundwater use by these communities. This is particularly pertinent in areas where groundwater resources have been or may be impacted through climate variability and/or anthropogenic activity, such as aquifer dewatering for mining, aquifer depressurisation for coal seam gas development, and over-extraction for agriculture, urban supply etc. In these and other instances, the model-data method could be used to retrospectively investigate impacts of historical water table decline; monitor for real-time changes in plant available water; or assess the likelihood of future impacts to GDV. The model-data method described in this paper consequently has broad-ranging application with respect to sustainable environmental and water resource management into the future.

Keywords: *Groundwater-dependent vegetation, land surface temperature, surface energy balance modelling, remote-sensing*

Hydrological links between cosmic-ray soil moisture retrievals and remotely sensed evapotranspiration across a semi-arid pasture site

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Abstract: Soil moisture and land surface evaporation, which includes soil evaporation, canopy interception and transpiration processes, are key factors affecting water cycle behavior and feedbacks between the land surface and the atmosphere at a range of scales. Measurement of soil moisture at intermediate resolutions is a challenge that has been addressed to a certain extent by the Cosmic Ray Soil Moisture Observing System (COSMOS). We present here a study to examine the link between the COSMOS soil moisture retrievals and evapotranspiration (ET) estimates obtained from remote sensing at a semi-arid pasture site near Baldry, in the central-west of New South Wales, Australia. COSMOS soil moisture was compared to ET estimates obtained by applying the PT-JPL method to remote sensing products of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. Ancillary data included air temperature, humidity, and radiation components. Use of Quartile-Quartile (Q-Q) plots and Analysis of Variance (ANOVA) with box plots provide a graphical estimate for the similarity of the distributions of the two quantities. The relationships were tested across the entire period of record, as well as across shorter periods in order to analyze local scale discrepancies. Results show that the COSMOS soil moisture, which is representative of much of the root zone of the pasture field, is well correlated with the modeled ET under most conditions. It was also noted that under high soil moisture conditions with low temperatures, the PT-JPL method produced ET values inconsistent with measurements from a local eddy covariance tower, and also with the COSMOS soil moisture. This leads to further investigations regarding appropriate models for particular conditions.

Keywords: *COSMOS, soil moisture, evapotranspiration*

Plant species identification in coastal dunes using ground images

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Abstract: Plant species identification and the assessment of coverage of each species are important for ecological studies. Previous studies using ground images mainly focused on the discrimination of plants using images taken in rather ideal laboratory/controlled condition. However, in the case of field studies, the discrimination of plant species needs to be performed from images taken in vague natural condition. For this purpose, the removal of the background "layer" (i.e. soil, or sand) is an important preprocessing step before species identification. In this study we introduced a sequence of discrimination models able to discern the background and identify plant species using simple color indices, and we assessed its validity.

Sample images were obtained on coastal dunes in Tottori, Japan where ground image sensing was applicable owing to the dominance of herbs and low shrubs. 140 images (10 images per species) were used to calibrate the model. We evaluated the proposed model in two steps. In the first step, test images (280 images) containing only plants (14 species) were processed. In the second step, test images (750 images) containing the same species with sand in the background were processed, thereby assessing the applicability of the model for natural field surveys.

We employed a discrimination model that combined the clustering based on color indices and linear discriminant analysis. The clustering based on color indices separated 14 plant species into two clusters based on the frequency distribution of the color indices of each species; and then, two linear discriminant functions were regressed for species identification in each cluster. Each species could then be described based on the characteristics of the frequency distribution of the red, green and blue components obtained from the images. Some color indices such as chromatic coordinates, and the excess green index (ExG) were calculated based on these three components, too. Three to six characteristic parameters, such as the median, 2.5 percentile and skewness in frequency distribution of each color component and index, were selected as potential variables of the discriminant function. Stepwise variable selections were used to eliminate variables and detect the ones effective in the species identification process.

The recall rate in the clustering of plant species using color indices was 1.0, which indicated that the indices we used were effective at discriminating the plant species. The global accuracy of the discrimination process was 0.739 (207 out of 280 images), and the accuracy of discrimination varied significantly between species. For example, the performance of the discrimination of *Elaeagnus umbellata*, *Fimbristylis sericea* and *Pinus thunbergii* was 20/20, 19/20 and 19/20, respectively. For 10 out of 14 species, both precision rates and recall rates were higher than 0.7. With sand in the background, 439 out of 750 images were correctly distinguished. The global accuracy of the discrimination process including sand identification was 0.585. On the whole, for most species, the identification process was less successful/accurate in the case of pictures featuring sand in the background than in pictures without.

Keywords: *Image analysis, plant species identification, ground images*

Evaluation of multiple satellite evaporation products in two dryland regions using GRACE

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Abstract: Remote sensing has become a valuable tool for monitoring the water cycle variables in areas that lack the availability of ground-based measurements. Integrating multiple remote sensing-based estimates of evaporation, precipitation, and the terrestrial water storage changes with local measurements of streamflow into a consistent estimate of the regional water budget is a challenge, due to the scale mismatch among the retrieved variables. Evapotranspiration, including soil evaporation, interception losses and canopy transpiration, has received special focus in a number of recent studies that aim to provide global or regional estimates of evaporation at regular time intervals using a variety of remote sensing input. In arid and semi-arid regions, modeling of evaporation is particularly challenging due to the relatively high role of the soil evaporation component in these regions and the variable nature of rainfall events that drive the evaporation process. In this study, we explore the hydrological consistency of remote sensing products in terms of water budget closure and the correlation among spatial patterns of precipitation (P), evaporation (E) and terrestrial water storage, using P-E as a surrogate of water storage changes, with special attention to the evaporation component. The analysis is undertaken within two dryland regions that have presented recent significant changes in climatology (Murray-Darling Basin in Australia) and water storage (the Saq aquifer in northern Saudi Arabia). Water storage changes were derived from the Gravity Recovery and Climate Experiment (GRACE) spherical harmonic (SH) coefficients. Six remote sensing-based evaporation estimates were subtracted from the Global Precipitation Climatology Project (GPCP)-based precipitation estimates and were compared with GRACE-derived water storage changes. Our results suggest that it is not possible to close the water balance by using satellite data alone, even when adopting a spherical harmonic filtering approach.

Keywords: *Evaporation, GRACE, dryland, spherical harmonics*

On the sensitivity of Land Surface Temperature estimates in arid irrigated lands using MODTRAN

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Abstract: Land surface temperature (LST) derived from thermal infrared (TIR) satellite data has been reliably used as a remote indicator of evapotranspiration (ET) and surface moisture status. However, in order to retrieve the ET with an accuracy approaching 10%, LST should be retrieved to within 1 °C or better, disregarding other elements of uncertainty. The removal of atmospheric effects is key towards achieving a precise estimation of LST and it requires detailed information on water vapor. The Thermal Infrared Sensor (TIRS) onboard Landsat 8 captures data in two long wave thermal bands with 100-meter resolution. However, the US Geological Survey has reported a calibration problem of TIRS bands caused by stray light, resulting in a higher bias in one of its two bands (4% in band 11, 2% in band 10). Therefore, split-window algorithms for the estimation of LST might not be reliable. Our work will focus on the impact of using different atmospheric profiles (e.g. weather prediction models, satellite) for the estimation of LST derived from MODTRAN by using one of the TIRS bands onboard Landsat 8 (band 10). Sites with in-situ measurements of LST are used as evaluation sources. Comparisons between the measured LST and LST derived based on different atmospheric profile inputs to MODTRAN are carried out from 2 Landsat-overpass days (DOY 153 and 160 2015). Preliminary results show a mean absolute error of around 3 °C between in-situ and estimated LST over two different crops (alfalfa and carrot) and bare soil.

Keywords: *Land Surface Temperature, MODTRAN, MODIS, reanalysis, agriculture*

Evaluation of a Soil Moisture Downscaling Algorithm Using the SMAPEx Data Set in Australia

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Abstract: Surface soil moisture is essential to global water cycle monitoring, weather forecasting, prediction of drought and flood, and modelling of evaporation. Radiometer remote sensing (passive microwave) is generally accepted as the most accurate technology for remotely measuring soil moisture. However, it suffers from being low resolution, around 36 km, placing limitations on hydro-meteorological applications such as regional weather forecasting, flood prediction, and agricultural activities that have a resolution requirement of better than 10 km. Conversely, radar (active microwave) remote sensing provides a much higher spatial resolution capability (better than 3 km), but is less sensitive to changes in soil moisture due to the confounding effects of vegetation and surface roughness. Consequently, NASA has developed a satellite to provide soil moisture data at 9 km resolution by combining a 3 km radar with 36 km radiometer.

This study evaluates a soil moisture downscaling algorithm that merges radiometer and radar observations to provide a medium-resolution soil moisture and thus overcoming their individual limitations. The downscaling algorithm used for this purpose is the Bayesian merging method, which is a non-linear algorithm based on the concepts of the Kalman filter. This soil moisture downscaling algorithm has so far only been tested using synthetic data. Consequently, this study presents an extensive evaluation of the soil moisture downscaling algorithm with an experimental data set collected from the third Soil Moisture Active Passive Experiment (SMAPEx-3) field campaign in south-eastern Australia. The medium-resolution soil moisture was obtained using background soil moisture estimates updated with observed and model predicted radar and radiometer values, and validated against a 1 km reference soil moisture map derived from 1 km airborne radiometer observations. The Bayesian algorithm results are also compared with linear downscaling algorithms including the baseline and optional algorithms from the NASA SMAP mission.

The main finding from this study was that the accuracy of the Bayesian merging method was affected by land cover types, e.g. the downscaling performance was better in the homogenous grassland than the highly vegetated area which contained more heterogeneous surface conditions. But overall the error of Bayesian merging method was 0.043, 0.029, 0.017 cm^3/cm^3 at 1 km, 3 km and 9 km respectively. In addition, the downscaled soil moisture was well correlated to the reference; at 9 km resolution the correlation coefficient (R^2) was 0.63. In comparison to the linear downscaling algorithms, the Bayesian merging method had slightly better results in terms of RMSE and correlation R^2 at 9 km resolution. The main limitation of the Bayesian method was the uncertainty of ancillary parameters involved in the radar forward model. It is expected that by using dynamic and more accurate surface roughness and vegetation parameters, the Bayesian merging method has the potential to retrieve an even more accurate soil moisture at medium-resolution.

***Keywords**:* *Soil moisture, downscaling, Bayesian, SMAPEx*

The fourth SMAP Experiment (SMAPEx-4): preliminary results

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Abstract: Microwave remote sensing at L-band (1 – 2 GHz) has been widely acknowledged as the most promising technique to monitor regional to global soil moisture, which is a key variable in many disciplines such as hydrology, agriculture, and meteorology. Consequently, the first soil moisture dedicated satellite mission, the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS), has applied an L-band (1.4 GHz) interferometric radiometer to provide global soil moisture with ~40 km resolution every 2 – 3 days. Subsequently the National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive (SMAP) mission has developed an innovative joint L-band (1.4 GHz) radiometer and L-band (1.2 GHz) radar system to provide global soil moisture retrievals at 9km resolution by combining 36 km radiometer data with 3km radar data. While SMOS was launched on 2 November 2009 and continues to operate beyond its design life, SMAP was launched on 31 January 2015 and has just successfully completed its commissioning phase on 30 April 2015. In addition to its downscaled soil moisture, SMAP has a radiometer-only soil moisture product at 36km resolution and radar-only soil moisture product at 3km resolution.

To verify the performance of SMAP, the Fourth SMAP Experiment (SMAPEx-4) was carried out immediately following the commissioning phase of SMAP. Consequently this airborne field campaign covered a 3 week period from 1st to 23rd May 2015. The experiment was conducted in the Murrumbidgee River Catchment in Australia, with a particular focus on the Yanco area where over 40 OzNet soil moisture monitoring stations have been installed in a nested framework, providing data at 3km, 9km and 36km resolution.

The main objectives of SMAPEx-4 were to: i) evaluate SMAP active-passive downscaled 9km radiometer observations; ii) inter-compare between airborne, SMAP, Aquarius, and SMOS radiometer and radar observations; iii) validate SMAP passive, active, active-passive soil moisture retrieval algorithms using airborne soil moisture retrieval results and monitoring network; and iv) further develop radar only soil moisture retrieval algorithms.

The airborne radar (1.2 GHz) and radiometer (1.4 GHz) observations were conducted over two flight areas covering SMAP, SMOS and Aquarius radiometer 3dB footprints, during nine flights in coincidence with overpasses of the satellites. Intensive ground soil moisture sampling was conducted together with airborne sampling over six 3km by 3km focus farms, in order to calibrate and validate soil moisture retrieval models. During non-flight sampling days, intensive vegetation and surface roughness sampling were conducted in focus farms, and regional point-based soil moisture sampling was conducted across the 36km by 36km ground sampling area to obtain soil moisture spatial patterns at SMAP 36km scale. Additionally, a vehicle based remote sensing system, including L-band radiometer, GNSS-R soil moisture sensor, thermal infrared radiometer, multi-spectral sensors, EM38, and EMI, was tested during the SMAPEx-4. The SMAPEx-4 data set will benefit SMAP post-launch calibration and validation under Australian land surface conditions.

Keywords: *Soil moisture, remote sensing, active and passive microwave, airborne field experiment*

Fine-tuning of unmanned aerial surveillance for ecological systems

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Abstract: Much of our understanding and management of ecological processes requires knowledge of the distribution and abundance of species. Reliable abundance or density estimates are essential for managing both threatened and invasive populations, yet are often challenging to obtain. Recent and emerging technological advances, particularly in unmanned aerial vehicles (UAVs), provide exciting opportunities to overcome these challenges in ecological surveillance. UAVs can provide automated, cost-effective surveillance and offer repeat surveys for pest incursions at an invasion front. They can capitalise on manoeuvrability and advanced imagery options to detect species that are cryptic due to behaviour, life-history or inaccessible habitat. UAVs may also cause less disturbance, in magnitude and duration, for sensitive fauna than other survey methods such as transect counting by humans or sniffer dogs.

The surveillance approach depends upon the particular ecological context and the objective. For example, animal, plant and microbial target species differ in their movement, spread and observability. Lag-times may exist between a pest species presence at a site and its detectability, prompting a need for repeat surveys. Operationally, however, the frequency and coverage of UAV surveys may be limited by financial and other constraints, leading to errors in estimating species occurrence or density.

We use simulation modelling to investigate how movement ecology should influence fine-scale decisions regarding ecological surveillance using UAVs. Movement and dispersal parameter choices allow contrasts between locally mobile but slow-dispersing populations, and species that are locally more static but invasive at the landscape scale.

We find that low and slow UAV flights may offer the best monitoring strategy to predict local population densities in transects, but that the consequent reduction in overall area sampled may sacrifice the ability to reliably predict regional population density. Alternative flight plans may perform better, but this is also dependent on movement ecology and the magnitude of relative detection errors for different flight choices.

Simulated investigations such as this will become increasingly useful to reveal how spatio-temporal extent and resolution of UAV monitoring should be adjusted to reduce observation errors and thus provide better population estimates, maximising the efficacy and efficiency of unmanned aerial surveys.

Keywords: *Surveillance, probability of detection, weed, pathogen, mammal*

The potential of unmanned aerial vehicles for providing information on vegetation health

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Abstract: The accurate and timely retrieval of agricultural water use, crop health and related plant biophysical parameters, represent key elements in delivering an effective crop management and monitoring strategy. In arid and semi-arid environments, where the availability of water is generally limited, determining the dynamics of these variables is especially important. With the rapid developments in unmanned aerial vehicles (UAVs), the capacity to develop customized retrievals of crop information now exists. While there remain challenges in the routine application of autonomous airborne systems, the state of current technology together with sensor developments provide an opportunity to further explore the operational potential. UAVs offer the capacity to bridge the spatio-temporal divide that exists between satellite and ground based sensing, offering new insights into process dynamics and behavior and providing the data necessary to produce a truly multi-scale framework for improved agricultural characterization. In this paper we will focus on the retrieval of vegetation parameters from UAV platforms, using high-resolution satellite data from RapidEye and Landsat sensors to evaluate retrievals. A focus on traditional parameters such as the Normalised Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) will be supplemented with estimates of thermal infrared based land surface temperature. We will also discuss how UAVs can support the development of farm-level monitoring, particularly in the determining crop water-use and crop health.

Keywords: *Unmanned Aerial Vehicles (UAV), NDVI, LAI, land surface temperature, agriculture*

Automated detection and segmentation of vine rows using high resolution UAS imagery in a commercial vineyard

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Abstract: Climate models predict increased average temperatures and water scarcity in major agricultural regions of Australia over the coming decades. These changes will increase the pressure on vineyards to manage water and other resources more efficiently, without compromising their high quality grape production. Several studies have demonstrated that high-resolution visual/near-infrared (VNIR) vineyard maps acquired from unmanned aerial systems (UAS) can be used to monitor crop spatial variability and plant biophysical parameters in vineyards. However, manual segmentation of aerial images is time consuming and costly, therefore in order to efficiently assess vineyards from remote sensing data, automated tools are required to extract relevant information from vineyard maps. Generating vineyard maps requires separating vine pixels from non-vine pixels in order to accurately determine vine spectral and spatial information. Previously several image texture and frequency analysis methods have been applied to vineyard map generation, however these approaches require manual preliminary delineation of the vine fields. In this paper, an automated algorithm that uses skeletonisation techniques to reduce the complexity of agricultural scenes into a collection of skeletal descriptors is described. By applying a series of geometric and spatial constraints to each skeleton, the algorithm accurately identifies and segments each vine row. The algorithm presented here has been applied to a high resolution aerial orthomosaic and has proven its efficiency in unsupervised detection and delineation of vine rows in a commercial vineyard.

Keywords: *Photogrammetry, image processing, precision viticulture*

Estimation of crop water stress in a nectarine orchard using high-resolution imagery from unmanned aerial vehicle (UAV)

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Abstract: Adequate and timely irrigation based on real-time monitoring of crop water status is critical for efficient and sustainable water use. However, detection of water status in large crop fields is not a trivial task as manual inspection can be time consuming and costly. Moreover, the symptoms of water stress are visually detectable only after the crops are already in a significantly water deficient stage. Consequently, capability of monitoring water status in crops on a regular basis could maximize productivity and water use efficiency. As an indicator, the crop water stress index (CWSI) has been widely used to estimate water status in the crop fields. CWSI can be derived from ground-based leaf temperature measurements, however, airborne or UAV-borne high-resolution thermal sensing provides a superior platform to cover large regions within a short time window. In this paper, UAV-borne thermal sensing was conducted to map plant water stress and spatial variability in water control and deficit plots over 1 ha of a nectarine orchard at an altitude of 100 m from ground level. Targets of ground control points (GCPs) were designed to suit the image spatial resolution as well as the visibility in the thermal infrared spectral range. The target was made of aluminium body marked with a black cross, which can be detected as a cool object in the thermal infrared image due to its low emissivity. Thermal infrared images were post-processed to generate single temperature-based orthomosaic image for the entire study field. CWSI map was computed using canopy temperatures at the centre of canopies from the mosaic image. Histogram analysis was used to estimate the lower boundary temperature (T_{wet}), representing the temperature of fully transpiring leaves. The upper boundary temperature (T_{dry}) was determined by air temperature + 6 ^{0}C. Ground measurements of midday stem water potential (SWP) and stomatal conductance (g_c) were collected concurrently with UAV operation and used to correlate the thermal measurement to crop biophysical parameters. Results showed that CWSI was in good agreement with both SWP and g_c with determination coefficients (R^2) of 0.92 and 0.97, respectively. Thus, remotely estimated CWSI from a UAV platform can play an important role in effective mapping of spatial variability of nectarine water stress and subsequently in optimal management of irrigation.

Keywords: *Unmanned Aerial Vehicle (UAV), thermal infrared imagery, Crop Water Stress Index (CWSI), canopy temperature, Stem Water Potential (SWP)*

Assessment of crop insect damage using unmanned aerial systems: A machine learning approach

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Abstract: Agricultural pests are responsible for millions of dollars in crop losses and management costs every year. In order to implement optimal site-specific treatments and reduce control costs, new methods to accurately monitor and assess pest damage need to be investigated. In this paper we explore the combination of unmanned aerial vehicles (UAV), remote sensing and machine learning techniques as a promising technology to address this challenge. The deployment of UAVs as a sensor platform is a rapidly growing field of study for biosecurity and precision agriculture applications. In this experiment, a data collection campaign is performed over a sorghum crop severely damaged by white grubs (Coleoptera: Scarabaeidae). The larvae of these scarab beetles feed on the roots of plants, which in turn impairs root exploration of the soil profile. In the field, crop health status could be classified according to three levels: bare soil where plants were decimated, transition zones of reduced plant density and healthy canopy areas. In this study, we describe the UAV platform deployed to collect high-resolution RGB imagery as well as the image processing pipeline implemented to create an orthoimage. An unsupervised machine learning approach is formulated in order to create a meaningful partition of the image into each of the crop levels. The aim of the approach is to simplify the image analysis step by minimizing user input requirements and avoiding the manual data labeling necessary in supervised learning approaches. The implemented algorithm is based on the K-means clustering algorithm. In order to control high-frequency components present in the feature space, a neighbourhood-oriented parameter is introduced by applying Gaussian convolution kernels prior to K-means. The outcome of this approach is a *soft* K-means algorithm similar to the EM algorithm for Gaussian mixture models. The results show the algorithm delivers decision boundaries that consistently classify the field into three clusters, one for each crop health level. The methodology presented in this paper represents a venue for further research towards automated crop damage assessments and biosecurity surveillance.

Keywords: *Unmanned aerial vehicles (UAV), machine learning, k-means, remote sensing, biosecurity*

Evaluating the effectiveness of UAVs for pest management

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Abstract: Advances in unmanned aerial vehicles technology offer an opportunity to detect pest species using high resolution, multi- or hyper-spectral images of either known incursions or high-risk areas. However, their benefits in terms of detection rates, cost effectiveness and any potential limitations have yet to be determined. A three-year Plant Biosecurity Cooperative Research Centre project, *Optimising Surveillance Protocols Using Unmanned Aerial Systems*, and an existing Victorian state government aquatic weeds project aims to investigate the capacity and effectiveness of UAVs and imaging technology in biosecurity surveillance.

The future of effective and efficient biosecurity surveillance programs and pest management in general, will require a higher level of automation and technical sophistication and an increased dependence on affordable technologies. Reliable yet effective sampling efforts are imperative to the future of plant biosecurity and food security in general

Biosecurity organisations will adopt new practices if compared to existing practices they are shown to have or are;

1. Increased detection rates
2. Cover larger areas
3. More cost effective
4. Compliments and improves existing practices.

This paper will discuss preliminary results from a number of experiments illustrating detection rates of existing surveillance practices, aerial imagery or the use of UAVs for a variety of pests, including alligator weed, hawkweed, crop pathogens and insect pests.

Keywords: *Detection, distance sampling*

Setting priorities for river restoration using habitat suitability models in Flanders, Belgium

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Abstract: In this study, we present a diagnostic modelling tool to prioritise river management actions and its application for the region of Flanders. Since the introduction of the European Water Framework Directive (WFD), river managers are required to achieve a good ecological status. To this end the reference condition approach was introduced, which describes the high ecological status through lists of reference taxa expected to be presented under these conditions. This concept showed much promise to move river restoration practice forward, since it allowed river managers to quantify the deviation from a high ecological status. Its practical implementation has proven to be difficult though, as it often remains unclear which pressures should be mitigated to remediate the ecological status of a water body.

Our diagnostic modelling tool implements the reference condition approach using habitat suitability models for individual fish or macroinvertebrate species. These models consider both physical-chemical and hydromorphological variables. Model construction has been grounded in ecological theory, and model calibration and validation has been done based on Flemish data and knowledge databases. The tool evaluates the existing biological community in a river against the list of species as defined by the reference condition (Figure 1). While the list used in our tool is based on the biological reference condition as defined in the WFD, it differs from the latter in the distinction between 'reference species' – generalist species that are part of the reference condition – and 'critical species' – sensitive species that only occur when a good ecological status is reached. For each missing species, the current habitat suitability for each abiotic variable is calculated, which results in an overall ranking of all abiotic variables that may limit the achievement of a good ecological status. Variables resulting in a lower habitat suitability for all missing species in the sample in general are considered more limiting. In this ranking, the distinction between critical and reference species is taken into account, by giving critical species a higher weight in the analysis.

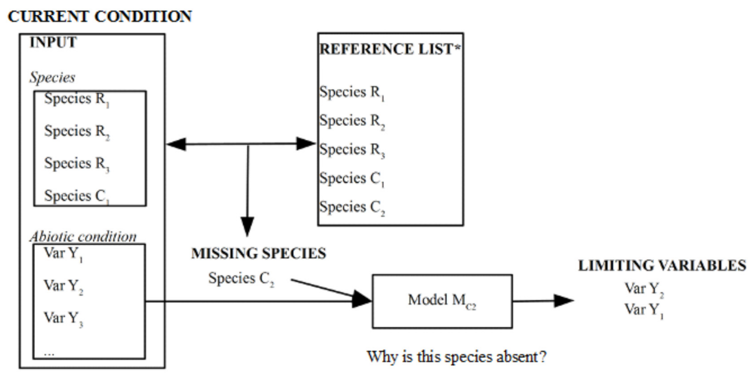

Figure 1. Overview of the diagnostic modelling tool where 'R-species'are reference species, 'C-species' critical species, Y_X an abiotic variable, and M_X the habitat suitability model for species X.

Application of the tool to the Flanders region results in a general ranking of stressors and an overview per water body of the stressors to mitigate as a priority: the most important stressors related to the decline in macroinvertebrates are nutrients and oxygen, whilst for fish the lack of natural substrates also is important. When applied to the catchment scale, combinations of measures can be scored according to their expected success towards achieving the good ecological status for each water body, by cross-tabulating the ranking output with information on the effect of management measures on individual abiotic variables.

Keywords: *European Water Framework Directive, decision support, river restoration, ecological modelling*

Integrated planning of linear infrastructure and conservation offsets

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Abstract: Linear infrastructure (e.g. roads, railways, utility corridors) is critical to the functioning of modern industrialised societies, but has profound impacts on ecological systems and their biological diversity. The ecological impacts of linear infrastructure may be exacerbated by the failure to anticipate and plan for them early on. Moreover, poor planning can lead to the costly redesign or abandonment of projects to avert unforeseen ecological impacts. Explicitly considering trade-offs between linear infrastructure development and conservation requirements (see Figure 1) at an early planning stage provides the greatest opportunities for achieving both routing and offsetting objectives cost-effectively.

Here, we combine route planning for linear infrastructure with strategic conservation offset decision making in a unified framework to identify efficient opportunities for both routing and impact mitigation. The routing component is spatially explicit and links two or more target nodes via a network of connected planning units with fixed costs while accounting for impacts on features of conservation concern. The offsetting component identifies efficient solutions for mitigating the unavoidable impacts of linear infrastructure. We demonstrate the benefits of solving both planning objectives simultaneously by contrasting the cost-effectiveness of the integrated solutions with those found by solving the problems sequentially.

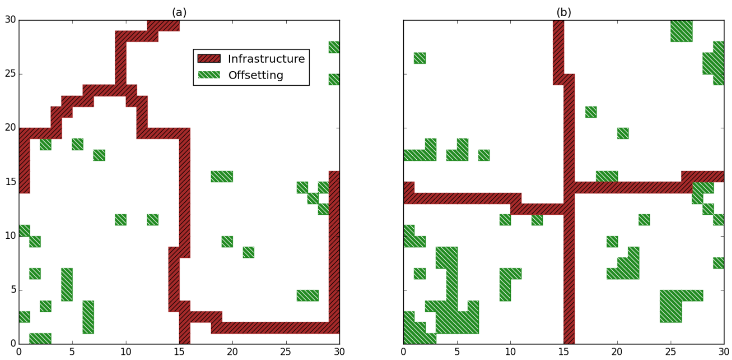

Figure 1. Solutions to a problem instance, favouring (a) offsetting and (b) infrastructure.

We formulated these planning problems in a mathematical optimisation framework in which space is discretised into planning units. Four sets of attributes were quantified for each planning unit as inputs to the optimisation problem: (i) the expected loss of conservation value resulting from linear infrastructure development for each of the conservation features (e.g. species); (ii) the cost of linear infrastructure development; (iii) the cost of offsetting; and (iv) the estimated benefit of offsetting with respect to the conservation features. The decision variables determine whether each planning unit is part of the routing solution, the offsetting solution, or neither. The mitigation effort is required to be sufficient to offset all of the impacts on biodiversity (no net loss) generated by the linear infrastructure development.

We describe an integer linear programming formulation of the optimisation problem and evaluate its efficacy through simulation. We find that solving both problems simultaneously can dramatically improve efficiency compared to solving the routing and offsetting problems sequentially. Furthermore, a sequential approach resulted in infeasible offsetting problems in 25% of cases. This work suggests both linear infrastructure and conservation offset planning could benefit from greater coordination in the early stages of the planning process.

Keywords: *Conservation planning, linear infrastructure, mixed integer programming, optimisation, offsetting*

Life on the fringe: choosing spatially explicit conservation actions for coastal ecosystems

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Abstract: With the growth of human populations there is an increasing urgency for coordinated management of land and ocean-based activities and of their influence on coastal marine ecosystems. There is mounting concern that biodiversity decline will result from fragmentation of ecosystem structure and alteration of the coastal land/seascape. Marine reserve design is increasingly being implemented for the dual purpose of managing biodiversity assets and fishery resources. However paradigms in reserve design for these two objectives are completely different. A comprehensive strategy for reserve design meets the dual objectives of fisheries and biodiversity while also responding to concerns over climate change and offering a socially-equitable distribution of benefits.

We use a structured decision-making approach to determine suitable development and management options to safeguard a productive near shore fishery whilst accommodating climate change and the associated human responses. Within-realm (either for the land or the sea) spatial action planning to maximise biodiversity benefits has been widely studied, but very little investigation has been made into three essential facets of integrated planning:

a) The land/sea interface, estuaries and near-shore marine systems;
b) Ecological processes e.g. self purification, delivery of ecosystem services to adjacent environs, and how they are affected by climate change;
c) Direct impact of climate change on interconnected realms.

Systematic conservation prioritization rarely explicitly accounts for connectivity. However, in the design of marine protected areas it is essential to incorporate both the influence of connectivity and climate change, and equally the effect of climate change on connectivity. The project addresses this gap.

Ecosystem connectivity for the persistence of life history stages has important consequences for reef and coastal organisms that have nursery habitats detached from reproductive populations. Climate change impacts e.g. increased ocean temperatures are expected to accelerate larval development, potentially leading to reduced pelagic larval durations and earlier settlement behaviour. Species distribution models linked to spatial prioritization can inform actions that quantify and synthesize explicit trade-offs between conservation investments in different locations accounting for threats. We developed a mechanistic model that incorporates survival, life history, growth and dispersal data to investigate impacts to populations and connectivity under climatic change. We apply this model to an Australian iconic fish species, the barramundi (*Lates calcarifer)* an economically important species in near shore tropical regions.

To develop robust plans for conservation, species-specific analyses explicitly defining responses to environmental change are incorporated into prioritization. We are developing a strategy for conservation action involving three integrated processes - reserve network expansion, zoning (i.e. land/seascape-use) and environmental impact avoidance. We use the Zonation conservation prioritization framework and apply our plan to the Mackay/Whitsunday NRM Region of North Queensland employing feature specific connectivity. Species and habitat types are the biodiversity features used in the analysis. We obtained data on commercial and recreational fishing and included a socio-economic component as opportunity costs. Specifically habitat types for finfish are estuary, inshore and offshore with combinations of these. With the use of a mechanistic model we can incorporate threats in conservation planning that produce habitat loss and species displacement e.g. land-use change and climate change thereby achieving a more efficient planning program.

Keywords: *Conservation planning, climatic change, coastal, modelling, spatial prioritization*

Representativeness of Protected Areas

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Abstract: Protected Areas (PAs) are a central part of biodiversity conservation strategies around the world. There are currently more than 170,000 PAs under IUCN designation and they cover *c*13% of the Earth's land mass. Recent global gap analyses have demonstrated that certain habitat types and biomes are systematically less well represented than others in the world's current PA network. This inequitable distribution of PAs means poorly represented habitat types and biomes could lose many species. Moreover, as the CBD's Aichi Biodiversity target 11 requires signatory countries to increase the amount of area protected in both their terrestrial and marine biomes to 17% and 10% respectively by 2020, this bias, if unaddressed, is likely to be perpetuated in the future.

Countries need to ensure that their PA network is comprehensive and representative. To be considered comprehensive, PA networks need to protect >0% of every single habitat types or ecoregions within a country. Representativeness is then a function of how much of each habitat of interest in protected. For example, countries can aim to protect the same amount of each habitat (fixed area representativeness); or they can aim to protect an area proportional to the total habitat within the country (proportional representativeness).

We propose a systematic approach to measure both kind of representativeness in PA networks called Protection Equality (PE). Our methods build on the work published by Barr and colleagues in 2011, who first described PE by adapting the Gini coefficient, which originally measures income inequality within countries. PE values range between 0, for perfect inequality, and 1, for perfect equality or representativeness. As such, PE values are comparable between countries and are a valuable tool to measure the performance of PA networks.

We illustrate the Protection Equality metrics with a case study by measuring the representativeness of the six largest countries in the world that have more than 90% of their PAs clearly delimited: Argentina, Australia, Brazil, Canada, Congo DRC and the United States. We also introduce a new R package to measure fixed area and proportional PE easily and systematically. We find that Australia outperforms all other countries in terms of both proportional and fixed area representativeness with PE values of almost 0.5 for both. While the US has the most area protected overall, its representativeness is similar to Brazil, Canada and Argentina. Our results provide transparency to the issue of PA representation and provide a starting point for further evaluation and testing of the metrics. Importantly, they highlight clear shortcomings in the design of PA networks.

We recommend that our metric should be used to measure representativeness at the country level to measure progress towards the Aichi target 11. By calculating PE today, we can use this value as a benchmark for progress in 2020 that goes further than simply measuring the amount of area protected.

As a next step, we aim to design an optimisation protocol for countries to select where to protect land by trying to maximise the PE values.

Keywords: *Protection Equality, complementarity and representation, habitat, decision-making*

Assessing the cost-effectiveness of invasive species management: a decision tool for biodiversity conservation

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Abstract: Invasive species threaten biodiversity in Australia. One of these species is the introduced root pathogen *Phytophthora cinnamomi,* which harms native and commercial plant species. Disease caused by this pathogen was listed as a key threatening process under the Commonwealth's Environment Protection and Biodiversity Conservation Act in 2000. There is considerable uncertainty regarding the best management strategies to address invasive species like *Phytophthora cinnamomi*; particularly where the efficacy of control methods is unknown. How should environmental managers decide whether management strategies are worthwhile or cost-effective? We demonstrate the use of a tool that can address these management challenges: the Investment Framework for Environmental Resources (INFFER). INFFER was designed to help environmental managers achieve the most valuable environmental outcomes with the limited resources they have available. The framework involves a systematic assessment of the trade-offs between variables such as asset value, likelihood that private individuals will adopt management or behavioural changes, delays in the realisation of benefits, and sources of uncertainty due to potential technical failure or socio-political risks. We present an application of INFFER to assess the cost-effectiveness of management strategies to address *Phytophthora cinnamomi* in the Fitzgerald River National Park, a national park in the South-West Botanical Province of Western Australia. The Fitzgerald River National Park is one of the largest parks in Australia, and has high conservation value because of its high floral diversity and numbers of endemic species. The model was developed in collaboration with park stakeholders, including park rangers, management and research officers, and members of a local natural resource management group. We found that despite uncertainty regarding the efficacy of existing containment and eradication methods, management strategies aimed at containing existing *Phytophthora cinnamomi* infestations and preventing future infestations, resulted in significantly greater benefits than costs (Benefit: Cost Index = 3.02). This result supports investment of public conservation funds to control *Phytophthora cinnamomi* in the Fitzgerald River National Park. A sensitivity analysis identified the need for better biophysical data to quantify the impact of management works, and demonstrated how uncertain funding environments prevent confidence in the accomplishment of project goals, through an inability to assure the future maintenance and upkeep of management works. Our analysis demonstrates the importance of using a rigorous decision support tool like INFFER to assess investment decisions when there is uncertainty regarding conservation benefits.

Keywords: *Benefit-cost analysis, biodiversity conservation, cost-effectiveness, natural resource management, stakeholder engagement*

A Reusable Scientific workflow for conservation Planning

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Abstract: In order to perform complex scientific data analysis, multiple software and skillsets are generally required. These analyses can involve collaborations between scientific and technical communities, with expertise in problem formulation and the use of tools and programming languages. While such collaborations are useful for solving a given problem, transferability and productivity of the approach is low and requires considerable assistance from the original tool developers.

Any complex scientific data analysis involves accessing and refining large volumes of data, running simulations and algorithms, and visualising results. These steps can incorporate a variety of tools and programming languages, and can be constructed as a series of activities to achieve a desired outcome. This is where scientific workflows are very useful. Scientific workflows abstract complex analyses into a series of inter-dependent computational steps that lead to a solution for a scientific problem. Once constructed, the workflow can be executed repeatedly and the results reproduced with minimal assistance from the original tool developers. This improves transferability, repeatability and productivity, and reduces costs by reusing workflow components for similar problems but using different datasets. Kepler is a popular open-source scientific workflow tool for designing, executing, archiving and sharing workflows. It has the ability to couple disparate execution environments on a single platform. For example, users can run analysis steps written in Python, R and Matlab on a single platform as part of a single analysis and synthesis experiment. Kepler provides a wide variety of reusable components that perform various tasks, including data access from databases, remote system, file system and web services, and data servers, and executes these processes in a local or distributed environment. Together these functionalities provide greater flexibility for researchers to undertake complex scientific analyses compared with traditional homogeneous environments.

In this paper, we will describe a new scientific workflow based on Kepler that automates data analysis tasks for Marxan, a widely used conservation planning software. Marxan is used by over 4,200 active users in more than 180 countries to identify gaps in biodiversity protection, identify cost effective areas for conservation investment and inform multiple-use zoning. Its use is expanding rapidly and this new functionality will improve the application of Marxan to various conservation planning problems. A Kepler workbench has been extended to provide functionality to invoke Marxan and execute it within a distributed environment using Nimrod/K. Our aim was to develop a reproducible, reusable workflow to generate conservation planning scenarios on the Kepler platform. The workflow components include data acquisition and pre-processing, construction of planning scenarios, generation of efficient solutions to the complex problem formulations and visualization of outputs. The workflow components are shared for reuse and re-configured to design and simulate other conservation planning applications. We also present a use case to demonstrate a Kepler Marxan workflow to design and implement conservation planning computational simulation experiments.

Keywords: *Conservation planning, scientific workflow, Marxan, optimisation*

The Biodiversity and Climate Change Virtual Laboratory: How Ecology and Big Data can be utilised in the fight against vector-borne diseases

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Abstract: Advances in computing power and infrastructure, increases in the number and size of ecological and environmental datasets, and the number and type of data collection methods, are revolutionizing the field of Ecology. To integrate these advances, virtual laboratories offer a unique tool to facilitate, expedite, and accelerate research into the impacts of climate change on biodiversity. We introduce the uniquely cloud-based Biodiversity and Climate Change Virtual Laboratory (BCCVL), which provides access to numerous species distribution modelling tools; a large and growing collection of biological, climate, and other environmental datasets, as well as a variety of experiment types to conduct research into the impact of climate change on biodiversity. Users can upload and share datasets, potentially increasing collaboration and cross-fertilisation of ideas and innovation among the user community. Feedback confirms that the BCCVL's goals of lowering the technical requirements for species distribution modelling, and reducing time spent on such research, are being met. We present a case study that illustrates the utility of the BCCVL as a research tool that can be applied to the problem of vector borne diseases and the likelihood of climate change altering their future distribution across Australia. This case study presents the preliminary results of an ensemble modelling experiment which employs multiple (15) different species distribution modelling algorithms to model the distribution of one of the main mosquito vectors of the most common vector borne disease in Australia: Ross River Virus (RRV). We use the BCCVL to do future projection of these models with future climates based on two extreme emissions scenarios, for multiple years. Our results show a large range in both the modelled current distribution, and projected future distribution, of the mosquito species studied. Most models (that were built using different algorithms) show somewhat similar current distributions of the species however there are three models that are obvious outliers. The projected models show a similar range in the distribution of the species, with some models indicating a fewer areas (and also areas with a lower probability of occurrence in specific areas) where the species is likely to be found under a climate change scenario. However, a majority of models show an expanded distribution, with some areas that have a greater probability of the occurrence of this species; this will provide a more robust indication of future distribution for policy makers and planners, than if just one or a few models had been employed. The economic and human health impact of vector borne diseases underline the importance of scientifically sound projections of the future spread of common disease vectors such as mosquitos under various climate change scenarios. This is because such information is essential for policy–makers to identify vulnerable communities and to better manage outbreaks and potential epidemics of such diseases. The BCCVL has provided the means to effectively and robustly bracket multiple sources of uncertainty in the future spread of RRV: this study focuses on two of these - the future distribution of a primary mosquito vector of the disease under two extreme scenarios of climate change. Research is underway to expand our analysis to take into account more sources of uncertainty: more vector and amplifying host species, emissions scenarios, and future climate projections from a range of different global climate models.

Keywords: *Biodiversity, climate change, virtual laboratory, species distribution modelling*

Providing context for the land-sharing and land-sparing debate

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Abstract: Agricultural and environmental policies that encourage multifunctional landscapes are referred to as land-sharing or land-sparing. While both strategies aim to improve biodiversity and production across landscapes, land-sharing aims for integration of production and biodiversity objectives within agricultural land uses, and land-sparing promotes separation and specialization of land uses for each objective. Numerous assessments of land-sharing and land-sparing exist, but preferences vary with different contexts (biophysical or socio-economic settings or conditions). Evaluations of "context" have predominately focused on variation of species types and describing biodiversity patterns across gradients of agricultural intensity. However, other potentially important contextual features have been rarely considered, for example baseline conditions, management options for both agricultural and spared land, and differences in objectives or decision criteria. Further, multiple contextual parameters have not been systematically varied. Comparisons between studies from different contexts are hindered by confounding variables, and the most important and influential variables are therefore unable to be identified.

We assess the impact of multiple contextual parameters using a simple, aspatial model of landscape change, and discuss results with reference to a targeted review of the land-sharing/land-sparing literature. Starting with a landscape consisting of 'agriculture' and 'other' land uses, land-sharing is simulated by increasing the biodiversity value of agricultural land, which in some scenarios comes at a cost to agricultural yield. Land-sparing is simulated by increasing agricultural yield, which in some scenarios comes at a cost to biodiversity value. Land-use allocations are then adjusted depending on whether objectives are to maximize biodiversity, or maximize agricultural production. The model determines total biodiversity value (species abundance) and total agricultural production as an aggregate of the scores from different land-uses in each scenario, and indicates a preference for land-sharing, land-sparing, the baseline condition (the initial land-use allocation and benefits), or a combination of these options, by a summation of biodiversity and agriculture scores. Our model is parameterized using a case study site in Central Kalimantan, Indonesia. We examined the importance of different contextual parameters in determining policy preference by applying random forests of conditional inference trees, and compare the results to the relative emphasis different contextual features have received in the literature.

Despite land-sharing and land-sparing being strongly driven by aims to understand the biodiversity-production trade-off, less than 10% of the assessed literature explicitly included impacts on yield or profit, and even less included comparisons that explicitly included the biodiversity value of spared land (e.g. set-asides). We found that past emphasis on different types of species is warranted, but also important in determining preferences are the proportion of the landscape initially allocated to agriculture, the management intentions for spared land, crop types, and level of policy effectiveness. Variations in objective and decision criteria were less important but still altered the policy preferences under some circumstances. Our results show an increased preference for sparing when the proportion of agricultural land is high, likely reflecting the disproportionate amount of biodiversity often found within remnant native fragments in such landscapes. Further, when land availability is finite there are limited opportunities for agriculture to expand to compensate for yield foregone in landscapes already high in agricultural area.

This study provides evidence that context warrants explicit inclusion in assessments of agricultural and environmental policy, to a much greater and more nuanced extent than has been addressed in the peer-reviewed literature. Our methodological approach is broadly applicable, but generalizations from this case to others should still be made with caution.

Keywords: *Agriculture, biodiversity, conservation, policy, wildlife friendly farming*

Distribution models of temperate habitat-forming species on the Continental Shelf in eastern Australia: setting the baseline to monitor and predict future changes

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Abstract: Habitat-formers (e.g. kelp beds, corals, sessile invertebrate assemblages) are key to the structure and functioning of reef ecosystems worldwide. In southeast Australia, a region identified as a global hotspot for climate-driven ocean warming, the structure and distribution of deep (> 30 m) benthic sessile communities are poorly known given these habitats are hard to quantitatively survey. Using high-resolution imagery of the seafloor from a recent national-scale AUV-based survey program, we establish a critical baseline about the latitudinal gradient in benthic community composition from 27°S to 43°S on the eastern seaboard of Australia.

Over >1,800 AUV images taken across the 7 different survey regions along the eastern seaboard of Australia, we estimated percentage cover of 51 pre-selected invertebrate morphospecies, including two ascidians, four bryozoans, seven cnidarians and 38 sponges. These morphospecies were chosen for their strong features (i.e. size, shape, colour), which facilitated their identification and detectability on the images. Three levels of details (i.e. group, shape, colour) were reported for each record, so as to test the sensitivity of our results to alternative invertebrate classification schemes of increasing resolution.

Large-scale latitudinal variability between three major community types (sub-tropical, warm temperate and cool temperate) mostly correlates with primary productivity and temperature climatology, while local scale variability relates well with depth.

Using environmental variables that capture past climatology both in terms of means and extremes (frequency and magnitude), we develop alternative distribution models for several habitat-forming species. Our models characterise the thermal tolerance of individual morphospecies in terms of suitable and/or critical boundary conditions. We compare model performance, discriminate between different types of latitudinal distribution (e.g. truncated or continuous), identify indicator morphospecies more likely to respond to climate-driven changes in ocean conditions, and discuss these results in the context of ongoing and future ocean changes. Our study provides an important benchmark to detect and predict future climate-driven changes in southeastern Australia, and our methodology has general applicability for monitoring of deep reef environments.

Keywords: *Autonomous Underwater Vehicle, East Australian Current, climate change, distribution modelling*

Delineating environmental envelopes to improve mapping of species distributions, via a hurdle model with CART &/or MaxEnt

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Abstract: Species distribution modelling (SDM) typically analyses species' presence together with some form of absence information. Ideally absences comprise observations or are inferred from comprehensive sampling. When such information is not available, then pseudo-absences are often generated from the background locations within the study region of interest containing the presences, or else absence is implied through the comparison of presences to the whole study region, *e.g.* as is the case in Maximum Entropy (MaxEnt) or Poisson point process modelling.

However, the choice of *which* absence information to include can be both challenging and highly influential on SDM predictions (e.g. Oksanen and Minchin, 2002). In practice, the use of pseudo- or implied absences often leads to an imbalance where absences far outnumber presences. This leaves analysis highly susceptible to 'naughty-noughts': absences that occur beyond the envelope of the species, which can exert strong influence on the model and its predictions (Austin and Meyers, 1996). Also known as 'excess zeros', naughty noughts can be estimated via an overall proportion in simple hurdle or mixture models (Martin et al., 2005). However, absences, especially those that occur beyond the species envelope, can often be more diverse than presences. Here we consider an extension to excess zero models. The two-staged approach first exploits the compartmentalisation provided by classification trees (CTs) (as in O'Leary, 2008) to identify multiple sources of naughty noughts and simultaneously delineate several species envelopes. Then SDMs can be fit separately within each envelope, and for this stage, we examine both CTs (as in Falk et al., 2014) and the popular MaxEnt (Elith et al., 2006).

We introduce a wider range of model performance measures to improve treatment of naughty noughts in SDM. We retain an overall measure of model performance, the area under the curve (AUC) of the Receiver-Operating Curve (ROC), but focus on its constituent measures of false negative rate (FNR) and false positive rate (FPR), and how these relate to the threshold in the predicted probability of presence that delimits predicted presence from absence. We also propose error rates more relevant to users of predictions: false omission rate (FOR), the chance that a predicted absence corresponds to (and hence wastes) an observed presence, and the false discovery rate (FDR), reflecting those predicted (or potential) presences that correspond to absence. A high FDR may be desirable since it could help target future search efforts, whereas zero or low FOR is desirable since it indicates none of the (often valuable) presences have been ignored in the SDM.

For illustration, we chose *Bradypus variegatus*, a species that has previously been published as an exemplar species for MaxEnt, proposed by Phillips et al. (2006). We used CTs to increasingly refine the species envelope, starting with the whole study region (E0), eliminating more and more potential naughty noughts (E1–E3). When combined with an SDM fit within the species envelope, the best CT SDM had similar AUC and FPR to the best MaxEnt SDM, but otherwise performed better. The FNR and FOR were greatly reduced, suggesting that CTs handle absences better. Interestingly, MaxEnt predictions showed low discriminatory performance, with the most common predicted probability of presence being in the same range (0.00-0.20) for both true absences and presences. In summary, this example shows that SDMs can be improved by introducing an initial hurdle to identify naughty noughts and partition the envelope before applying SDMs. This improvement was barely detectable via AUC and FPR yet visible in FOR, FNR, and the comparison of predicted probability of presence distribution for pres/absence.

Keywords: *Naughty-noughts, excess zeros, species distribution modelling, predictive performance, misclassification rate*

A spatially structured metapopulation model in a stochastic environment

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Abstract: The evolution of a population is governed by how individuals interact with other individuals in the population and how they interact with the environment. In many applications, the environment is assumed to be static. However, this excludes important changes such as breeding seasons, cold snaps and catastrophes. To better understand a population's evolution, models need to be enriched to account for dynamic environments.

Many changes in the environment cannot be predicted with a high level of accuracy. For example, the connectivity between populations can be abruptly reduced or even cut throughout various times of the year, or perhaps the suitability of a patch a population inhabits is drastically reduced when a disease infects the food source in the area. Occurrences like these are inherently hard to predict and, as such, are classified as stochastic influences in the system. Many models presented today cannot account for stochastic influences on the environment. The aim of this talk is to determine conditions for extinction of a population (or, more specifically, a population of J populations which each inhabit a patch termed a "metapopulation") which inhabits a stochastically changing environment.

To do this, a Markov population process, $n^N(t)$, (indexed by the total population ceiling N) with state space $S = \{0, \ldots, N_1\} \times \cdots \times \{0, \ldots, N_J\}$, where N_i is the population ceiling on patch i, is used (note that $N = \sum_i N_i$). The parameters in the transition rates of this process are allowed to change stochastically according to another underlying discrete state, continuous time Markov process, $C(t)$, which models which configuration the environment is currently in out of a finite set of possibilities $S_C = \{1, 2, \ldots, K\}$. A functional law of large numbers is applied to the *density process* $n^{(N)}(t)/N$, which shows that a piecewise-deterministic Markov process (PDMP) approximates the density process well as $N \to \infty$, under certain conditions. It is shown that the PDMP is a random dynamical system on $E = [0, M_1] \times \cdots \times [0, M_J]$, where $M_i = \lim_{N\to\infty} N_i/N$, generated by the system

$$\frac{dx(t, x_0)}{dt} = F(C(t), x), \qquad x(0, x_0) = x_0,$$

where $n^{(N)}(0)/N \to x_0$ in probability, $C(t)$ is the Markov process governing the environment and $F : S_C \times E \mapsto \mathbb{R}^J$ is an explicit function.

Using the theory of random dynamical systems, a condition that determines if the metapopulation will go extinct is calculated. This condition shows that extinction of the metapopulation is not entirely dependent on the birth and death rates of the species but also the migration rates between patches and also illustrates the complicated affect that an environment can have on a population.

Keywords: *Metapopulation, piecewise-deterministic Markov process, random dynamical system, Lyapunov exponent*

Towards an Ontology-based Soil Information System

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Abstract: Environmental information is critical to the sustainable use and management of the world's resources. Soils are a fundamental part of the environmental information requirement, and appropriate soil data and information are crucial to support evidence-based policy, planning and resource management decisions.

For data to be useful, one basic requirement is that they be interpretable. Sufficient information should be provided to allow data to be unambiguously interpreted and used. Examples of such information include the location at which the soil was sampled, the property that was measured, the unit of measure, and quality assurance and quality control information. Furthermore, data should be easily integrated with other data sources, which is required in many modelling applications. For example, simulation of crop production may require, besides soil data, also weather, crop and fertilizer data.

To meet these requirements, we have developed a soil ontology for modelling soil information. In this paper, we focus on the design of the ontology and its potential applications. We describe the use of the ontology to facilitate data access by mapping data to the ontology and making them available as Linked Data. We also discuss applications of the ontology for data integration, data classification and data validation.

Keywords: *Soil information, ontology, Linked Data, data integration, data classification*

Integrated approach to the optimal sequencing of urban water supply augmentation options under climate change

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Abstract: Urban water supply security is under increasing threat worldwide as a result of the impact of population growth and climate change. In order to meet this challenge, alternative urban water supply augmentation options are being considered, including the construction of desalination plants, the development of stormwater and recycled wastewater sources and the use of rainwater tanks. This complicates the assessment of which combination of augmentation options is most appropriate, necessitating an integrated approach that not only considers the interactions between potential sources, but also the views of stakeholders. In addition, given the long-range impacts of climate change, the significant investments associated with augmentation options and the generally inflexible nature of water supply infrastructure, the staging of potential augmentation options needs to be considered carefully.

In order to assist decision-makers with selecting the most appropriate long-term (e.g. 50 years) urban water supply augmentation plan under uncertainty in future conditions, including the impacts of population and climate change, a scenario-driven, multi-objective optimisation approach is presented. The approach includes (i) the identification of stakeholder defined plausible future scenarios (e.g. in terms of population growth and climate change), (ii) the determination of optimal sequences of augmentation options for each of these scenarios (future pathways) using multi-objective evolutionary optimization approaches, which enable complex water supply systems consisting of combinations of traditional and non-traditional sources to be modelled in an integrated manner and optimal trade-offs between costs and climate change related objectives (e.g. minimisation of energy usage or greenhouse gas emissions) to be obtained, (iii) the calculation of the sensitivity of these optimal augmentation plans to the plausible future conditions articulated in the scenarios, enabling trade-offs between objectives (e.g. minimisation of lifecycle costs and greenhouse gas emissions) and risk-based performance (e.g. reliability, vulnerability) to be examined by decision-makers.

The approach is illustrated for the southern portion of the water supply system of Adelaide, South Australia. The alternative water sources considered include desalination, stormwater harvesting and rainwater tanks and the objectives include the minimisation of the present values of cost and greenhouse gas emissions. Seven scenarios consisting of different combinations of future population and climate change (including emissions scenario and global circulation model) are considered over a 40-year planning horizon. A multi-objective genetic algorithm is used to develop optimal sequence plans for each of these scenarios at 10-year intervals and an integrated simulation model of the selected water sources is used to ensure the system is modelled in an integrated fashion during the optimisation process. Sobol' is used to perform a global sensitivity analysis of the optimal sequence plans, enabling trade-offs between the variation in costs, greenhouse gas emissions, system reliability and system vulnerability to be considered in selecting the most appropriate water supply augmentation sequence plan.

The results indicate that a 50GL desalination plant is required in 2020 under all population and climate change scenarios. The scenarios with lower forecast demands indicate that the capacity of this plant should be expanded to 100GL in 2050, while the expansion is required earlier for the scenarios with higher forecast demands together with an additional 50GL desalination plant being required by 2050. All but one optimal sequence contain some stormwater harvesting, but the actual schemes and their timing vary considerably, primarily accounting for the trade-offs achieved between cost and GHG emissions. The global sensitivity analysis shows that the system reliability is mainly dependent on variations in population growth, whereas the system vulnerability is sensitive to both variations in population growth and climate change forecasts.

Keywords: *Multi-objective optimisation, deep uncertainty, population growth, water infrastructure sequencing, climate change*

Modelling the effect of sea level rise on tropical cyclone storm surge impact

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Abstract: Across Northern Australia Tropical Cyclones (TC) present a major hazard for coastal communities. Improvements to building codes and investments in disaster planning have had demonstrable impact on the resilience of exposed communities however the hazard to life posed by Storm Tide inundation remains a major concern. Projected sea level rise due to climate change over the course of this century suggests that the impact of Storm Tide events will be more significant in the future as higher sea levels expose a wider area to inundation. While knowledge of climate change impacts on the frequency and intensity of Tropical Cyclones has implications for storm tide impacts Climate Change damage assessments frequently assume the relationship between storm tide impacts and sea level rise to be linear.

During Tropical Cyclone events, Storm Tide continues to increase in height in relatively shallow waters. This suggests that the nature of the relationship between sea level rise and Storm Tide impact may not be linear which has significant implications for climate change damage assessments and subsequent adaptation strategies proposed.

To examine the effect of sea level rise on Storm Tide impacts this paper presents the results of a storm tide inundation model of Cyclone Yasi run over varying water levels to simulate sea level rise. TC Yasi was a very destructive and powerful tropical cyclone that made landfall with a category 5 intensity on the southern tropical coast near Mission Beach, Australia between midnight and 1am early on Thrusday 3rd February, 2011. ArcGIS is used to assess the impact of inundation across various indicators such as area of land, population impacted and lengths of roads inundated. By comparing the impact of the inundation for the model runs at various water depths the relationship between Storm Tide Impact and sea level rise is identified.

Our study provides insight into the future behavior of Storm Surge events as sea levels rise that can inform climate change adaptation planning and vulnerability assessments.

This comparison of the modelled storm surge inundation depth for Cyclone Yasi considers cyclone wind and pressure fields generated with parametric techniques such as Holland et al. (2010) wind field profile. The storm tide was simulated using Mike 21 hydrodynamic software with offshore bathymetry obtained from multiple local, state and federal agencies and adjusted to AHD and the land elevation was obtained from 1-m LiDAR data supplied by the Queensland State government..

Keywords: *Climate change, storm tide impacts, sea level rise, natural hazards, inundation*

A novel coupled biokinetic-equilibrium model to assess metal uptake and bioaccumulation by an estuarine filter-feeder

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Abstract: Sydney estuary (Port Jackson) located in New South Wales, Australia, has been observed to have significantly elevated concentrations of metal contaminants in its sediment and in the soft tissues of numerous aquatic organisms. This indicates that the resuspension of contaminated sediment through the action of waves, winds, bioturbation and dredging is potentially a major mechanism of trace metal assimilation and bioaccumulation by suspension filter-feeders like the Sydney rock oyster (*Saccostrea glomerata*) via ingestion. These sediment resuspension and metal uptake processes are thought to be sensitive to climate change effects, particularly in extreme events, and may be impacted significantly in the future due to changes in winds, waves, tides, rainfall, water temperature, pH (CO_2) and salinity.

Trace metal bioaccumulation by an oyster is an intricate problem involving numerous chemical and biological processes. To help investigate the dynamics of sediment resuspension and metal bioaccumulation, a coupled biokinetic-equilibrium bioaccumulation model was developed in the software platform R. A first-order biokinetic model component was used to (1) simulate the sediment dynamics (i.e. settlement, resuspension, ingestion/efflux of sediment by oysters) and (2) simulate the uptake, assimilation and depuration of metals in *S.glomerata*. This biokinetic model was dynamically (i.e. data exchanged at each time step) coupled to an equilibrium model used to calculate the partitioning of the different metals between the dissolved and particulate phases, and between organic and inorganic ligands.

To provide calibration data for the coupled model, a laboratory-based mesocosm experiment was carried out. For a period of 60 days, farmed *S.glomerata* specimens were exposed to different combinations (scenarios) of low, medium and high sediment metal concentrations, and low, medium and high suspended sediment concentrations. Measurements of water pH, temperature, salinity and turbidity along with metal (Cd, Co, Cu, Mn, Ni, Pb and Zn) concentrations in the sediment and oyster soft tissue were conducted.

Due to parameter uncertainty, such as an incomplete list of physiological data available for *S. glomerata* and lack of specific information regarding water chemistry and metal speciation, a methodological approach was adopted to calibrate the model. The results of the model highlighted the importance of accounting for both the fast (equilibrium) and slow (kinetic) processes occurring in oyster-sediment interactions. Mn and Pb results from the model followed quite rapid uptake and loss by oysters and were good fits across the scenarios. Co and Ni demonstrated considerable depuration from tissues. Cu was underestimated in the model however this may have likely been owed to Cu's dependency on DOM and choice of dissolved copper speciation in the model. Lastly, Zn bioaccumulation was well fitted across all scenarios and performed the best in the model.

Keywords: *Oysters, metals, bioaccumulation, Sydney estuary, speciation*

Intelligent model to categorise mechanised water end uses

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Abstract: The current population boom has pushed demand on residential land in most world metropolitan cities to its extreme limit, and also imposed significant pressure on water security. To ease this problem, construction of residential apartment building has been the top priority of the governments. With the rapid advancement in technology, especially in water metering area, the next generation of these buildings is expected to not only offer their residents a comfortable living area but also make the water supply and management become much more effectively controllable. To contribute to this goal, the aim of this study was to develop an autonomous and intelligent system for residential water end-use classification that could interface with customers and water business managers via a user-friendly smartphone and web-based applications. The authors recently developed an intelligent application called *Autoflow*© which served as a prototype tool to solve the complex problem of autonomously categorising residential water consumption data into a registry of single and combined events. This model was developed using data collected in several cities in Australia, and when applied on single residential property, the achieved accuracy ranged from 86% - 96%. The only limitation of *Autoflow*© is that when being deployed overseas, a new water end use dataset must be collected to retrain the model to adapt to the new regions. The ultimate goal of this study is to develop the next *Autoflow*© generation, called *Autoflow*^{AB}, which can be applied in all future apartment buildings to help disaggregate water consumption autonomously into the six main categories including: shower, toilet, tap, clothes washer, dishwasher and evaporative air cooler without relying on any previously collected data for training. The key employed techniques are Dynamic Time Warping (DTW) and Decision Tree. The model has been tested on 150 residential properties in Australia where the accuracy ranges from 87 – 94 %, and also planned to be applied on 30 new 7-story buildings in the Commonwealth Games Village located in Gold Coast Australia.

Keywords: *Water end use event, residential water flow trace disaggregation, water micro-component, Hidden Markov Model, dynamic time warping algorithm*

Using marine models to road-test climate-smart management responses and strategies and prepare decision makers

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Abstract: Preparation for climate change and responding appropriately to extreme events and abrupt changes in the state and organisation of ecosystems, and their dependent societies, is aided by pre-testing of strategies and adaptation options. Simulation modeling can facilitate understanding of the underlying drivers and system responses as well as appropriate monitoring, and can assist in planning for both gradual and abrupt future change. Here we first present a framework to map the flows from changes in physical drivers impacting biological systems through to their impact on socio-economic systems. We then suggest actions that could be taken as a perturbation propagates through the system, and examine several modeling tools that are being used to road-test climate-smart management responses, strategies or to inform design of adaptation options. Through case study examples we focus on (1) the use of multispecies models to advance our ability to anticipate or deal with major ecosystem shifts, (2) illustrate how the outputs of models, such as seasonal forecast models, can be used to adaptively respond to changes, and (3) the use of management strategy evaluation (MSE) to account for uncertainties and test the performance of alternative marine monitoring and management strategies to detect and respond to ecological changes caused by climate change.

Our examples illustrate that models need not be overly complex to be useful. For example, we show that an intermediate complexity modelling approach assists in understanding the underlying mechanisms (e.g. non-linear changes in population parameters below critical prey thresholds may contribute to the responses of predators to changes in their prey) as well as in identifying early warning signals (e.g. increasing variance in population monitoring data may signal a forthcoming abrupt decline). Similarly, forecasting models can provide information on seasonal time scales, allowing proactive decision making by a range of users. Seasonal forecasting is already being used in Australia in a range of marine farming and fishing operations to reduce uncertainty and manage business risks. Species-specific habitat forecasts are also being used to assist fishers plan the timing of their harvest of wild fisheries such as southern bluefin tuna. These approaches may represent a useful stepping stone to improve decision making and industry resilience at longer timescales.

Ecological simulations of the resilience of marine ecosystems can similarly inform managers on how to build resilience to future climate change, in order to prevent or mitigate potentially catastrophic shifts to alternative (often less productive) ecosystem states. Under a changing climate there are no historical analogs, and hence forward-looking strategies that are pre-tested against a broad range of plausible future outcomes are needed. MSE can be used to compare the performance of alternative future strategies, whilst taking into account the considerable uncertainty both in future climate variables, and their impacts. An example is presented of the use of MSE to integrate across biological and climate uncertainties, and test the performance and risks (biological, multispecies, economic) of alternative management strategies applied to the Torres Strait bêche-de-mer (sea cucumber) fishery. Spatial management approaches based on adaptive feedback performed best and substantially reduced risks under future changing climate and biological uncertainty, compared with *status quo* management. Finally, we describe recent advancements in modeling capability to extend considerations beyond the biophysical domain as part of a broader socio-ecological framework. Models are the only approach that can provide such insight in a rigorous, repeatable and transparent fashion.

Keywords: *Climate change, adaptive management, ecosystem shifts, resilience, socio-ecological*

Australian Potential for PRO-Assisted Desalination

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Abstract: Seawater desalination is an energy intensive process. In Australia, the desalination industry heavily relies on the energy from fossil fuel combustion, and as such, the industry is deemed to significantly contribute to climate change. Incorporating forms of renewable energy in seawater desalination to combat increasing CO_2 emissions and to help plants achieve better energy efficiency is becoming a necessary condition, but more research is needed, particularly on what sources of renewable energy would best suit desalination in terms of technical and economic aspects.

This study investigates a form of reducing the excessive consumption of energy in seawater desalination based on the utilization of the energy harnessed from the mixture of brine (the main seawater desalination by-product) and seawater. When seawater is mixed with brine, a great amount of energy is released from the salinity gradient between these two solutions. The power generated from salinity gradients is referred to as 'osmotic power' and is completely renewable and greenhouse gas emission free. Pressure-Retarded Osmosis (PRO) is a technology used to generate osmotic power. In this study, we suggest the use of PRO to generate power for the desalination process.

Two major Australian desalination plants are used as case studies – the Perth Seawater Desalination Plant and the Southern Seawater Desalination Plant. Calculating the energy released from the salinity gradient between brine and seawater, estimating the quantity of energy that could be potentially harnessed using the PRO technology and calculating the energy offset in the desalination process, were the main objectives of this study.

The maximum energy extractable during the mixing of solutions with concentrations similar to brine and sweater in a PRO system is approximately 1.1 MW per m^3 s^{-1} of seawater (Helfer and Lemckert, 2015). In this current study, a plant efficiency of 70% was adopted (Loeb, 2001), making the extractable energy 0.77 MW per m^3 s^{-1} of seawater.

For Perth Seawater Desalination Plant and the Southern Seawater Desalination Plant, which produce about 60 GL and 140 GL of brine per year, respectively, the combined amount of osmotic power that could be generated is 43 GWh. This would correspond to approximately 7% of the requirements of energy for the seawater desalination process. The preliminary results showed in this study are promising, but an investigation to estimate the costs involved in building a PRO plant is required in order to determine the financial viability of PRO-assisted desalination.

In a future study, a different scheme will be investigated, using Australian desalination plants operating in "stand-by mode" as case studies. It has been suggested that, for such plants, the membrane modules of the RO process could be used under PRO, rather than RO conditions, during times when the plant is not being required for freshwater production. Under this proposed configuration, the utilization rate of the desalination structure would be significantly augmented, as the plant would be generating energy instead of producing freshwater in periods of high water availability; conversely, it would be producing freshwater, instead of generating energy, in periods of severe water scarcity. Low plant utilization rates have been a common public concern in several coastal cities in Australia and discussions towards this issue has sparked debate of how to justify costs of constructing and maintaining desalination infrastructure. Designing these plants in such a way that they could be utilised for dual purpose (ie, PRO power and RO desalination) would be one way to justify these high investments. The results of this investigation will be reported in a future publication.

Keywords: *Desalination, renewable energy, osmotic power, salinity*

A spatially-explicit integrated source-fate-effects model for sedimentary metals in Sydney estuary and catchment (Australia)

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Abstract: Sediments in Sydney estuary (Australia) and soils of the catchment are highly enriched in heavy metals such as copper (Cu), lead (Pb) and zinc (Zn). This has coincided with observed elevated heavy metal concentrations in the soft-tissue of local bivalve filter-feeders. Assessing the risk and mitigating the effects of heavy metals in the Sydney estuary requires an understanding of the processes linking source, fate and effects of metals. This includes comprehending both the spatial and temporal evolution of heavy metal dynamics.

Here, we present the development and testing of a 14-compartment box model for the Sydney estuary that acts as a framework for coalescing previous 'component' modelling into a single integrated spatially-explicit model. The process-based (kinetic) box model is coupled directly to an ion-equilibrium speciation model to enable temporal changes in the speciation patterns of Cu, Pb and Zn to be simulated. Specifically, a critically-compiled database of stability constants were used to estimate the complexation of these metals to dissolved inorganic (OH^-, CO_3^{-2}, SO_4^{-2}, Cl^-, F^-), dissolved organic (single ligand model), particulate inorganic (as hydrous ferric oxides; HFO) and particulate organic ligands at a daily time step. Furthermore, an oyster biokinetic model is also integrated into the box model, enabling metal-specific bioaccumulation potential to be assessed for each box. Parameters used in the integrated model were sourced from a combination of existing models (e.g. atmospheric, stormwater, hydrodynamic), monitoring data, literature and model calibration. To account for uncertainty in many of the parameters (e.g. metal stability constants), the model was run as Monte Carlo.

Preliminary results from the integrated box model indicate that the increase in dissolved and particulate organic ligands associated with a stormwater event entering the system appears, in some scenarios, unable to compensate for the concomitant increase in aqueous metals and that the excess may be associated with dissolved inorganic ligands after the organic complexation sites have been exhausted. This highlights the importance of being able to dynamically calculate the chemical speciation patterns of the metals involved rather than relying on more 'static' approaches such as partition coefficients. Spatially, the distribution of metals shows their slow migration away from contamination 'hot spots', facilitated by the magnitude and duration of stormwater inputted into the estuary.

Overall, a key challenge for this model was addressing the high level of parameter uncertainty in the coupled model. The speciation model alone uses 78 stability constants whilst the kinetic model is comprised of over 300 parameters representing physiological (e.g. oyster clearance and egestion rates, metal assimilation efficiencies) and physical (e.g. sediment resuspension and settling rates, residual flow mixing coefficients, stormwater loading) processes across the spatial domain. This challenge was addressed by using a Monte Carlo modelling approach, where the model was repeatedly re-run (n=1000), select parameters (settling and resuspension rates for each box; mixing coefficients between each box; DOM concentration; POM binding site concentration) were represented as probability density functions (pdfs) and random draws were made on these during each of the model runs. The parameters assigned to a pdf were selected by sensitivity analysis (i.e. the most sensitive parameters were used). Parameters assigned pdfs included the oyster physiological feeding rates (clearance rate, metal assimilation efficiency and efflux rates), concentrations of dissolved organic material (i.e. the dissolved organic ligand), the binding site density for particulate organic and inorganic (HFO) ligands, and the residual flow mixing coefficients between the 14 compartments comprising the box model and the catchment loading rates. Finally, parameter sensitivity and the associated large variation in predicted outcomes the Monte Carlo modeling indicated the importance of explicitly accounting for parameter uncertainty during model development and testing.

Keywords: *Metals, Sydney estuary, atmospheric deposition, fluvial loading, hydrodynamic*

A modelling framework for assessing water conservation potentials through demand-based tariff structures from societal and economic perspectives

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Abstract: The water resources conditions influenced by population growth, coupled with declining water availability and changes in climatic conditions underline the need for sustainable and responsive water management instruments. Supply augmentation and demand management including pricing are two main policy mechanisms generally utilised by water utilities. However, the question of pricing to change water use behaviour (demand) is a challenging process as they bring additional social and political issues into the already complex management of water resources. The complexity is characterised by many interdependent components and requires the participation of stakeholders in developing management strategies. The key factor of pricing is to calculate a price that reflects the full cost of water consumption and provide incentives for efficient water-use behaviour, and thereby contributing to the long-term sustainable water resources management. Therefore, stakeholder involvement is crucial to determining the successes and failures of implementing pricing strategies. In the light of the above discussion, this paper presents a participatory framework for achieving greater water conservation potentials through demand-based tariff structures from societal and economic perspectives. The framework provides an appropriate modelling platform for assessing this water tariff (price)-demand-revenue nexus as it explicitly accounts for the feedbacks, interdependencies, and non-linear relations that inherently characterise such systems. Thus, in this research, a participatory System Dynamics modelling (SDM) approach was employed to explore the water demand fluctuations and revenue outcomes by introducing an inclining block tariff (IBT) to residential customers on the Gold Coast. To build the model, we have worked with a range of stakeholders from academia, experts from the water utility and a number of agencies (e.g.: Queensland Council of Social Services, Queensland Competition Authority, Gold Coast Chamber of Commerce), in order to produce a logical simulation model. The SDM tariff modelling incorporates three distinct modules to achieve the specific objectives of the study; these modules considered revenue forecasting; differentiating high and low water users; and demand feedback. The SDM results show that: a) the IBT, where the highest users pay more for using more, is an effective method for incentivising high water use customers to reduce water use through pricing rather than restrictions across the board; b) revenue neutrality can be achieved using an IBT by determining the feedback of customers to the higher cost; c) the IBT represents a successful water demand management and water conservation strategy whereby reducing household costs are an incentive for water efficiency; d) there is also an opportunity for the water utility to vary the proportion of customers that are charged the second block tariff during wet seasons (high water availability) or dry seasons (low water availability).

Keywords: *Water conservation, demand-based tariff modelling, integrated modelling, system dynamics modelling, stakeholder engagement*

A comparative analysis of engineering options for adaptation to sea-level rise: a case study for a vulnerable beach in Shoalhaven NSW

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Abstract: Mollymook, Collingwood and Callala beaches and the communities living near them were identified as especially vulnerable to sea level rise by the Shoalhaven City Council. A number of possible engineering and management solutions have been identified for mitigating or eliminating the effects of expected flooding and erosion (e.g., sea wall, groyne, beach nourishment), based on guidelines developed by Engineers Australia. However, the question remains as to how to assess and compare the benefits (and not just the costs) of each option. While the cost of designing and implementing these options are reasonably easy to estimate, other environmental and aesthetic costs are more difficult to valuate. Even more challenging is quantifying in monetary terms the benefits of each option. Methods are available in the economic literature for estimating some of these parameters, however, their application requires data and resources that are not always available to local government.

In this study, we propose a pragmatic approach (relatively simple yet detailed) which combines a monetary-based probabilistic flood-damage estimation technique with an estimate of non-monetary consequences of an adaptation option using local knowledge and stakeholder consultation. These two types of information (monetary and non-monetary) are combined using multi-criteria decision analysis (MCDA) methods in order to generate a ranking of engineering adaptation options and assist in decision-making. We illustrate the method by applying to Callala beach in Shoalhaven. First, we calculate respective cost-benefit ratios of each option by simulating the likely effects of a flood event (with multiple probabilities of occurrence or return period) with and without proposed adaptation options, for different scenarios of sea level rise. Specifically, a flood model of Callala is developed using high resolution LiDAR Digital Elevation Model (DEM) data and tested for impacts under different sea level rise scenarios (using IPCC AR5 projections) and their corresponding exceedance probabilities (using Canute sea level rise calculator). Second, we estimate the potential damage to properties and infrastructures (cumulative over time) through flood damage function curves (quantifying the relationship between flood depth and potential damage cost of private properties and public infrastructure). Third, we estimate the non-monetary benefits of each option using a simplified approach, based on stakeholder consultation. Finally, we use two different multi-criteria decision analysis (MCDA) approaches (simple additive weight and outranking methods) for comparison of a number of engineering adaptation options (both hard and soft measures). Results show that, in general, a combination of beach nourishment & groynes is the most preferred option for Callala beach, across all decision analysis methods. Our analyses also show that hard measures such as sea walls tend to perform better in cost-benefit analyses where non-monetary factors such as community preferences, aesthetics and environmental factors are omitted. On the other hand, including these factors through MCDA methods seems to push sea walls down the rank.

Keywords: *Coastal, climate change adaptation, local government, engineering*

Assessing the role of electricity networks in bushfire ignitions: estimation of current and prospective performance

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Abstract: Subsequent to the Black Saturday fires in 2009, the Victorian government created the Powerline Bushfire Safety Program (PBSP), which, among other things, is focused on the identification and prevention of faults and ignitions caused by electricity distribution networks as a way to reduce bushfire risk on high fire days. Successfully achieving this goal first involves obtaining or creating a dataset capable of evaluating the current fault and ignition situation in Victorian power networks. Subsequently, this information on power network fault/ignition performance provides a basis for predicting future fault/ignition performance on the network. Over time new network assets are created; are moved; or are modified to apply new fire preventative measures as required by new regulatory requirements. A positive side-effect of the development of this network performance data and predicted performance capability is the ability to attribute changes in bushfire events to policy and equipment changes on the distribution network.

The data needed to assess current (and historic) performance of electricity distribution systems includes information on pole locations; line locations; technology status; electric fault location and time data; conversion from fault to ignition under different meteorologic conditions; meteorological conditions at the time and location of recorded faults; and so on. Collection of this data had to be coordinated between multiple agencies including electrical distribution companies, and state and federal government agencies. Such data was then processed to allow an estimation of fault/ignition rates for different equipment under different meteorologic conditions so that the expected role of the electrical network in bushfires losses is estimable. Due to stratification along meteorologic variables when considering network performance, we can predict how network changes will interact with climate change in terms of expected bushfire rates caused by electricity. Our calculations and modelling form an important part of the work discussed. Additionally, we also consider lessons learned about compiling data from different sources entities. We believe there is a fundamental need to develop relationships and synergies with multiple organizations if we are to attribute changes in natural hazards to various causes.

Keywords: *Bushfires, electricity systems, quantitative risk modelling*

Statistical modelling of extreme ocean climate with incorporation of storm clustering

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Abstract: Knowledge of the extreme ocean climate is essential for the accurate assessment of coastal hazards to facilitate risk informed decision making in coastal planning and management. Clustered storm events, where two or more storms occur within a relatively short space of time, may induce disproportionately large coastal erosion compared to non-clustered storm events. Therefore this study aims to develop a statistical approach to modelling the frequency and intensity of storm events on the eastern and southern coast of Australia, with a focus on examining storm clustering. This paper presents the preliminary analysis of the recently developed methods and results when they are applied to a study site on the central coast of New South Wales, Australia. This study is a key component of the Bushfire and Natural Hazards CRC Project "Resilience to clustered disaster events on the coast – storm surge" that aims to develop a new method to quantify the impact of coincident and clustered disaster events on the coast.

Extreme storm events at a given site can be described using multivariate summary statistics, including the events' maximum significant wave height (H_{sig}), median wave period, median wave direction, duration, peak storm surge, and time of occurrence. This requires a definition of individual storm events, so the current methodology firstly involves the extraction of storm events from a 30-year timeseries of observations. Events are initially defined using a peaks-over-threshold approach based on the significant wave height with the 95% exceedance quantile (2.93 m) adopted as the threshold. Subsequently, these events are manually checked against sea-level pressure data to examine if closely spaced events are generated by the same meteorological system, and if so the events are combined. This means that the final event set is more likely to consist of meteorologically independent storm events.

Various statistical techniques are applied to model the magnitude and frequency of the extracted storm events. A number of variations on the non-homogenous Poisson process model are developed to estimate the event occurrence rate, duration and spacing. The models account for the sub-annual variations in the occurrence rate, temporal dependency between successive events, and the finite duration of events. The results indicate that in the current dataset, closely spaced events are more temporally spread out than would be expected if the event timings are independent, which we term anti-clustering. A particular marginal distribution is fitted to each variable, i.e. a Generalised Pareto (GP) distribution for H_{sig}, and Pearson type 3 (PE3) distributions for duration and tidal residual. Empirical marginal distributions are employed for wave period and direction. The joint cumulative distribution function of all storm magnitude statistics is modelled by constructing the dependency structure using Copula functions. Two methods are tested: a t-copula and a combination of a Gumbel and Gaussian copulas. Comparison of modelled and observed scatterplots shows similar patterns. Goodness-of-fit tests such as Komologorov-Smirnov (K-S) tests, Chi-square tests and AIC and BIC are used to quantitatively evaluate the fitting qualities and to assess model parsimony, along with graphical visualisations, e.g. QQ plots.

Based on this approach, a long-term synthetic time-series of storm events (10^6 years) is generated using the event magnitude and timing simulated with the fitted models. These long-term synthetic events can be used to derive exceedance probabilities and to construct designed storm events to be applied to beach erosion modelling.

Keywords: *Storm clustering, non-homogenous Poisson process, marginal distribution, Copulas, synthetic events*

Past and future trends in Australian floods: what are the causes?

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Abstract: The possibility of changing flood hazards due to climate change is an issue of concern for engineers, governments and emergency services. However it is not yet clear how flood hazard will change and how these changes may vary across Australia. Here we approach these questions by considering the complex interactions between flood-causing variables. This is achieved by synthesizing existing research on the trends and likely changes in the causes of floods. These causes include the possible changes to meteorological variables, in particular extreme rainfalls, as well as impacts of changing catchment conditions including catchment wetness and land use modifications due to vegetation changes and/or urbanization.

There has been research into trends in daily rainfall extremes around the world and for Australia but less work on sub-daily rainfall. Australian daily rainfall extremes show limited evidence of trends when the annual maximum series is considered although there is significant variability in these time series and changes in seasonality are not accounted for in this type of analysis. Sub daily rainfalls show clearer evidence of generally increasing trends. The interaction between these generally increasing trends and changes to catchment wetness which are more likely to be linked to annual rainfall and evaporation trends is a question of particular interest.

An issue of concern is how to separate trends from other cycles of variability introduced through large scale climate drivers. Improved statistical methods are required to separate these interactions both in rainfall and more importantly in the flood hazards. Promising work from detection and attribution studies on the likelihood of individual extreme events needs to be translated into methods that can assess the likelihood of trends and the possibility of detecting these trends.

Here the focus is on how the trends in each of these aspects can be combined together to better understand the observed changes in flood risk. Using this improved knowledge, projections of changes in flood-producing mechanisms can be combined to establish likely future flood risk. Open research questions have been identified that could be addressed by the Australian research community over the next 5 to 10 years include:

- The need for robust future projections of extreme precipitation over daily and longer durations from a large ensemble of climate projections at resolutions (~3 – 10km) that can capture important phenomena such as east coast lows, orographic effects, bands on thunderstorms etc.
- Work in extending the findings from convection-permitting climate models to inform engineering practices that depend on sub-hourly and sub-daily extremes.
- Common frameworks for undertaking catchment scale assessments of future flood risk to allow findings to be translated and regionalized.

Keywords: *Climate change, trends, flood risk, flood-producing mechanisms*

Detecting and attributing changes to Australian drought over the past 2000 years

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Abstract: Detecting and attributing changes to the frequency, duration, magnitude and location of drought is challenging. This is especially true for Australia, where spatial and temporal hydroclimatic variability is large and instrumental records are relatively short and sparse. Recent work conducted at the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC) used trace chemistry records from Law Dome (East Antarctica) that vary with multidecadal components of the Southern Hemisphere ocean-atmospheric circulation were exploited to produce a 1000 year proxy record for annual rainfall in eastern Australia. Here we show how this annual rainfall proxy, combined with emerging local hydroclimate proxies (lake, cave and sediment records) can be extended and recalibrated to provide catchment-scale, seasonal rainfall reconstructions for the last 2000 years. It is then shown how this information can be used to better understand interannual to multidecadal hydroclimatic variability which in turn leads to improved detection and attribution of drought and other hydroclimatic extremes. This work reveals that the instrumental hydroclimatic records (which cover only 100 years at best for most parts of Australia) do not capture the full range of drought (or flooding) that is possible in Australia. Therefore, work is urgently required to establish the true risk of low probability, high impact droughts and also to determine how water resource managers and other decision makers might robustly and efficiently deal with the vulnerabilities exposed by these findings

Keywords: *Pre-instrumental drought, drought risk, natural variability, flood*

Understanding and managing drought in Australia – What do we know? What do we need to know?

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Abstract: Our ability to monitor, model, forecast and manage drought in Australia, and to differentiate between and understand the causes and impacts of the different types of droughts (e.g. meteorological, hydrological, agricultural, socioeconomic) is exposed as insufficient every time a drought occurs. This paper reviews the existing literature on i) defining, monitoring and forecasting drought, (ii) drought causes and impacts, (iii) instrumental and pre-instrumental insights into Australia's drought history and (iii) observed variability in, and expected future changes to, the frequency, magnitude, duration, location and spatial extent of drought in Australia.

Open questions that may guide future research endeavours are also identified in the paper. These include:

- How best to use emerging information sources (e.g. satellite data, GIS tools, reanalysis data, soil moisture data etc.) to better understand and deal with drought in Australia?
- What are the effects of antecedent catchment conditions and land use changes such as vegetation, urbanisation and regulation on drought risk?
- Is drought risk in Australia changing and if so where and when and how and why?
- Is the instrumental record a reliable indicator of the true risk of drought in Australia (now and into the future)?
- What is the relationship between atmospheric temperature and the different types of drought?
- What is the relationship between anthropogenic climate change and drought in Australia and is it possible to distinguish this from influences associate with natural variability (if so, how?)?
- How can insights into the climatic causes of drought be exploited and turned into practically-useful information that is meaningful for decisions makers and water resource managers responsible for ensuring water security?

Keywords: *Climate change, trends, drought risk, natural variability*

Natural hazards in Australia: heatwaves

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Abstract: Heatwaves have disastrous impacts on many different systems, including human health, infrastructure, and natural ecosystems. Australia is no stranger to these impacts, with over 370 fatalities attributed to the 2009 Victorian heatwave, and 3500 flying foxes killed when temperatures soared to 42ºC over New South Wales in 2002. Marine heatwaves (prolonged periods of anomalously warm oceans) also have significant impacts. The infamous "Ningaloo-Niño" in 2011 led to a "tropicalization" of fish communities and severely damaged the distribution of temperate seaweeds and fish, which may never fully recover.

Recent research efforts have concentrated on furthering our understanding of both terrestrial and marine heatwaves. However, a comprehensive understanding of these events also requires a comprehensive understanding of the underpinning physical mechanisms and their interactions. This presentation reviews the current state of the scientific knowledge of marine and terrestrial heatwaves, with particular emphasis for the Australian region. Based on this knowledge, recommendations are given for the concentration of future research, both short and long term, and how the Australian science community, as well as the global science community, will benefit from this. The supporting paper for this presentation is part of the OZewex special edition on Australian hazards.

Specifically, the review finds that while unified metrics for measuring terrestrial heatwaves is yet to be determined, increases in intensity, frequency and duration are detectable since at least the 1950s. Moreover, projections from the Coupled Model Intercomparison Project phase 5 (CMIP5) global climate model ensemble and the dynamically-downscaled NSW/ACT Regional Climate Modelling (NARCliM) simulations project larger increases of all heatwave characteristics in the future. While there are spatial similarities between the two types of simulations, future changes in heatwave projections by NARCliM are generally of smaller magnitude. A similarly comprehensive analysis on future projections of marine heatwaves is yet to be constructed.

Moreover, an extensive research effort has been undertaken in understanding how the land surface and atmosphere couples together in priming local terrestrial heatwave conditions, as well as their interactions and feedbacks during particular events. For a similar analysis to be undertaken over Australia, various atmospheric modeling simulations at high spatial resolution are imperative. Such experiments may be run, for example, with a range of prescribed soil moisture levels to investigate how dry it must be for a heatwave to occur, persist and intensify. Another recommendation of this review includes the employment of coupled climate model simulations that are run both with and without greenhouse gas forcings in order to ascertain the human signal behind observed trends in Australian terrestrial heatwaves. This method, called formal optimal fingerprinting, has been successfully applied regional trends in other extremes, and can be readily applied to numerous models part of the CMIP5 archive.

Keywords: *Heatwaves, hazard, OZewex, projections, climate*

A framework for the development and use of Decision Support Systems for multi-hazard mitigation

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Abstract: Social and economic losses from natural disasters are potentially staggering. To reduce losses, the immediate and post-crisis response to disasters is important. However, mitigation activities before natural disasters occur can be even more effective in reducing losses. Nevertheless, developing and implementing long term mitigation schemes is often difficult for various reasons: decision makers tend to invest in works with clearer short-term benefits, risk attributed to disasters is prone to inaccuracy as disasters are relatively infrequent, the people influencing mitigation activities may have little personal experience to guide their evaluation, and mitigation budgets are always limited. Therefore, selecting the optimal trade-off of mitigation options can be very difficult.

Decision support systems (DSSs) can be advantageous in helping to overcome these obstacles, because of their analytical capabilities to combine various sources of information and support trade-off analysis. However, DSSs for natural disaster mitigation have so far tended to focus on disaster preparedness and the immediate and post-crisis response to emergencies.

Consequently, a framework for the development and use of multi-hazard mitigation DSSs is being developed. The generic DSS developed through this framework optimizes the choice of mitigation options in a multicriteria sense, through assessing the performance of various policy options in the long term. An integrated simulation model incorporating a cellular automata model for land use and change together with risk models for e.g. earthquakes, flood, bush fire and coastal surges, allows the impact of various mitigation options on a range of indicators to be assessed. These include the reduction in hazard risk and associated benefits and costs, but also the wider implications of the mitigation options on the social, natural and built environment. The model includes a set of external drivers (socio-economic and climatic) to assess the robustness of mitigation portfolios under various scenarios. An optimization routine is then applied to sift through combinations of mitigation options in order to come to near to optimal sets of mitigation portfolios that rank well on the selected criteria under a range of plausible futures.

Throughout the life cycle of the DSS, development and use are separate processes, although they are closely interconnected and interdependent. During the development phase the DSS software framework is designed and implemented, while in the use phase the DSS software framework is applied to a specific case study, by including case study specific (hazard) models, data and parameters and the resulting DSS is used for specific scenario and impact assessment studies. In the early stages of the DSS life cycle, more effort goes into the development of the system, while in later stages focus lies on the use.

To test the approach in different contexts, it is being applied to three case studies in Australia: Greater Adelaide, Greater Melbourne and Tasmania. This paper introduces the framework for the development and use of the Decision Support System and exemplifies both processes and their interrelation through the Greater Adelaide case study.

Keywords: *Policy impact assessment, exploratory scenarios, social learning, integrated modelling, natural hazard mitigation*

Large-scale modelling of environments favourable for dry lightning occurrence

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Abstract: Lightning that occurs with relatively little accompanying rainfall, known as dry lightning, is one of the main ignition sources for wildfires throughout the world. A method for indicating large-scale environments favourable to the occurrence of dry lightning is examined here. The method is designed to be of coarse spatial and temporal scales, for potential application to global climate models. It is developed based on atmospheric conditions obtained from reanalyses, in conjunction with lightning observations from a ground-based network of sensors during the period from 2002 to 2013. The method is applied to global climate model simulations to examine the influence of increasing atmospheric greenhouse gas concentrations on the projected frequency of occurrence of dry lightning activity in Australia. The results indicate considerable seasonal and spatial variability of the projected changes in environments favorable to dry lightning occurrence. Given the importance of dry lightning to the area burnt by fires, long-term changes in dry lightning activity could potentially have a range of significant impacts, including in relation to fire regimes, ecology, fire emissions and emergency management.

Keywords: *Lightning, thunderstorms, convection, climate change, bushfire, storms*

NARCliM model performance including teleconnections with climate modes

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Abstract: NARCliM (NSW/ACT Regional Climate Modelling project) is a regional climate modelling project for the Australian area. It provides a dynamically downscaled climate dataset for the CORDEX-AustralAsia region at 50km, and South-East Australia at a resolution of 10km. NARCliM data is being used by the NSW and ACT governments to design their climate change adaptation plans. Data is available through the AdaptNSW website (http://climatechange.environment.nsw.gov.au/).

NARCliM uses version 3.3 of the Weather Research and Forecasting (WRF) regional climate model (RCM) to perform an ensemble of simulations for the present and the projected future climate. WRF is run in three different model configurations (different combinations of physical parametrizations) that have been shown to perform well in the South-East Australia and were chosen based on performance and independence. These three RCMs are used to simulate three different periods: 1990-2009, 2020-2039 and 2060-2079. Four different Global Climate Models (GCMs: MIROC-medres 3.2, ECHAM5, CCCMA 3.1 and CSIRO mk3.0) from CMIP3 are used as initial and boundary conditions for the WRF simulations. These GCMs were chosen through a process that considered model performance, independence and projected future changes. Thus a RCM ensemble of 12 simulations for each period is obtained. Additionally to the GCM-driven simulations, 3 control run simulations driven by the NCEP/NCAR reanalysis for the entire period of 1950-2009 are also performed in order to evaluate the RCMs performance in the area.

The NARCliM ensemble is found to have a consistent cold bias throughout the year with many areas showing the ensemble members significantly agreeing on the bias. This bias is significant over most of southeast Australia in winter and summer. The ensemble also displays a consistent wet bias with most of southeast Australia showing significant agreement amongst ensemble members on this bias in summer and autumn. A dry bias is present on the southeast coast in winter

The regional models are found to do a reasonably good job at capturing the teleconnections with large scale climate modes such as El Niño – Southern Oscillation (ENSO), when compared to the driving global data. Each regional model displays differing strengths and weaknesses in this respect.

Keywords: *Regional Climate Model, Future Climate Projections, south-east Australia, precipitation, temperature, WRF*

Status and directions for the CORDEX Initiative

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Abstract: The COordinated Regional climate Downscaling EXperiment (CORDEX) is backed by the World Climate Research Programme (WCRP). The goal of the initiative is to provide regionally downscaled climate projections for most land regions of the globe, as a compliment to the global climate model projections performed within the fifth Coupled Model Intercomparison Project (CMIP5). It is anticipated that the CORDEX dataset will provide a link to the impacts and adaptation community through its finer resolution than global climate models (GCMs) and regional focus. Participation in CORDEX is open and any researchers performing climate downscaling are encouraged to engage with the initiative.

The model evaluation framework consists of dynamical and statistical downscaling performed using the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim re-analysis as “perfect boundary conditions”. The climate projection framework within CORDEX is based on CMIP5. CORDEX focuses on the GCM experiments using emission scenarios known as RCP4.5 and RCP8.5 which represent a moderate and a high-level emission pathways.

Progress towards an adequate regional ensemble varies between regions, with simulations for Africa (the original focus) and Europe the most advanced. A number of groups have performed simulations for the CORDEX-AustralAsia domain. While these groups continue to perform and evaluate their simulations, the next step is to make the data available through the Earth System Grid Federation Node at the National Computational Facility in Canberra which will be done through 2015.

The next phase of CORDEX is currently being planned and will include a similar downscaling experiment for CMIP6 GCMs, as well as a focus around five key regional challenges: Added value, Human elements, Coordination of Regional Coupled Modelling, Precipitation and Local Wind systems. In addition to the key challenges, four cross-cutting themes have been identified: Water resources and Hydrological cycle, Development of process based metrics, the Water-Energy Nexus and Extremes. Flagship Pilot Studies are one proposed mechanism through which CORDEX will attempt to address these issues.

Keywords: *CORDEX, regional climate downscaling, Australasia*

Projected change in Frequency, Intensity and Duration of Atmospheric Temperature Inversions for Southeast Australia

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Abstract: Temperature inversions occur when temperature increases with altitude in the lower atmosphere. An inversion can lead to pollution events such as smog being trapped close to the ground, with possible adverse effects on health, and may result in violent thunderstorm and freezing rain in the cold season. The effect of temperature inversions means that any trends in their frequency, intensity (temperature gradient within the inversion layer), and duration under global warming have implications for sectors such as air pollution management or agriculture.

In this study, we used outputs of 12 historical and future Regional Climate Model (RCM) simulations (each covering three time periods: 1990-2009, 2020-2039, and 2060-2079) from the NSW/ACT Regional Climate Modelling (NARCliM) project to investigate changes in low level temperature inversions. For each 10km by 10km grid cell within the NARCliM domain, temperature inversions were identified by checking the vertical temperature profile in 3-hourly data. Characteristics of the inversions such as height, temperature at the top and bottom of the inversion layer were recorded. Temperature inversions for the two future periods (2020-2039 and 2060-2079) are compared to the historic period (1990-2009) to investigate the changes in frequency, intensity, and duration of inversions for each of the 12 simulations.

The results show that there is a substantial increase in the frequency and duration of temperature inversions and a decrease in the intensity of the temperature inversion for most simulations for southeast Australia. The largest differences between simulations were associated with the driving GCMs, suggesting that the large scale circulation plays a dominant role in forming and sustaining low level temperature inversions.

Keywords: *Temperature inversion, NARCliM, ensemble mean*

A New Quantile Projection Method for Producing Representative Future Daily Climate based on Mixed Effect State-Space Model and Observations

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Abstract: Agriculture is particularly sensitive to climate variability and change. In Australia, agricultural production spans the tropics, sub-tropics, Mediterranean and temperate climatic zones, and operates under conditions of high climatic variability compared with other countries (Stokes & Howden, 2010). In response to operating under these conditions good risk managers have been actively using climate variability information to support operational management decisions. Increasingly these producers are now considering the longer term implications of anthropogenic climate change in their strategic farm planning (Meinke & Stone, 2005). To meet these longer term requirements, the Queensland Government through its Queensland Climate Change Centre of Excellence (QCCCE, now the Department of Science, Information Technology and Innovation (DSITI)), started delivering climate change projection data in 2010 via the Consistent Climate Scenarios (CCS) data portal (Burgess *et al.*, 2012). Since mid-2012, CCS projections data have been more widely available via the CCS web-portal on DSITI's Long Paddock website, providing representative point-referenced *daily* data for periods centred on 2030 and 2050. Currently, registered users can access projected daily climate data free of charge as patched-point data (for any of the 4,759 SILO weather stations), or as individual points from a 0.05 degree grid across Australia. The future projections are based in part on observed trends as well as from Global Climate Models (GCM) and emission scenarios from the Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (AR4). CCS data are available in formats suitable for most biophysical models, enabling various stakeholders to undertake climate change adaptation studies for various primary industries across Australia, in particular within the grazing, cropping and horticultural sectors. To generate plausible and weather-like point-referenced future daily data from coarse-scale GCM outputs (typically monthly values on a 100-200km spatial grid), two downscaling approaches were developed, change factors and quantile matching. The quantile matching employs regression on monthly quantiles from daily observations to project future quantiles; and spatial pattern scaling to adjust quantile means based on GCM outputs. Quantile matching is used to simulate future daily climate based on historical observations, which incorporates quantile forecast bias correction, auto-correlation and cross-variable correlations.

The CCS system has recently been refined to incorporate new GCM outputs from the IPCC Fifth Assessment Report (AR5), as outcome from a DSITI and CSIRO collaboration. Improvements on the quantile projection method are described in this paper. We use a multivariate Linear Mixed Effect State Space (LMESS) model for all the possible historical data to replace simple linear regression on data from each single month (Kokic *et al.*, 2011). We model 12 months of data and three quantiles together to handle missing data issues in the historical observations. We select the same set of covariates from time and seasonality terms in order to maintain the consistent cross-variable correlations among the climate elements. We allow time-varying coefficients for some covariates. The model parameters are estimated via an Expectation-Maximisation algorithm. It is implemented in the statistical computing language R, and is called by the CCS from Python via the package rpy2. The model was tested and validated on dozens of representative SILO stations across the Australian continent. The hindcast results show that LMESS improves the hindcast accuracy and maintains the quantile spread, over the monthly regression used in the CCS system, linear regression (LR) and multivariate LR. Whilst the improvements are not statistically significant, the results are sizeable enough to support a move to this revised modelling approach.

Keywords: *Bootstrapping, climate change projections, consistent climate scenarios, LMESS, quantile matching*

Comparison of the seasonal cycle of tropical and subtropical precipitation over East Asian monsoon area

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Abstract: The East Asian monsoon includes the tropical monsoon and subtropical monsoon. They are different systems, and the formation mechanisms and major weather systems are not similar, and thus, the structures and characteristics of the associated tropical and subtropical monsoon rainfall and precipitation differ. The properties of precipitation can indicate thermodynamic and dynamic structures and cloud microphysics, and can reflect many characteristics associated with the onset and variation of monsoon, so is the focus of this paper.

Four regions (one for tropical monsoon, three for subtropical monsoon) are selected. The components of precipitation (i.e., convective and stratiform rain) are studied by using 10-year (1998–2007) Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) rain products (2A25). The results show that the convective rain contribution in the tropical monsoon region (10°–20°N) is much higher than that in the subtropical monsoon regions (20°–35°N). Time series of rainfall, rain probability and rain ratios over each region are analyzed to study the seasonal variability of tropical and subtropical monsoon. Results show that after East Asian summer monsoon onset, rapid increases in convective, stratiform and total rainfall occur in all the four regions. The percentage of convective rain increases significantly in the three subtropical monsoon regions after monsoon onset, but decreases in the tropical monsoon region. TRMM PR observations show that there is no striking difference in the temporal variability in either the rain amount or probability between the East Asian tropical and subtropical monsoon; however, the associated convective rain contribution is significantly different, and East Asian tropical and subtropical monsoon precipitations can thus be separated according to the ratios of convective and stratiform precipitation.

Intergovernmental Panel on Climate Change (IPCC) Coupled Model Inter-comparison Project phase 3 (CMIP3) general circulation model (GCM) rainfall simulation results (1980-1999) are evaluated against 10-year TRMM observations. The results show that the GCMs have a better simulation of the subtropical monsoon regions (20°N–35°N) than the tropical region, with a consistent variability of convective rain relative to the TRMM observations, during the convective rainfall surge after the monsoon onset, with about 10% deviation. But the GCM simulated convective rain fraction is generally overestimated in East Asia. The largest precipitation biases are found in the tropical monsoon region (0°–20°N), where there is more than 30% deviation for convective rain relative to TRMM observations. The TRMM rain measurements indicate that the contribution of convection precipitation in the tropical monsoon region falls considerably after onset of the East Asian monsoon. However, the CMIP3 GCMs show the opposite. Results from TRMM PR observations demonstrate that convective precipitation and stratiform precipitation have similar spatial–temporal distribution patterns and are closely correlated in both subtropical and tropical regions, but the GCMs simulate a small coefficient and even a negative correlation over tropical region. Current GCMs significantly underestimate stratiform rainfall over South China Sea, resulting in poor simulations of total rainfall and latent heat profiles; suggesting that some weather and climate phenomenon are not accurately simulated, and thus there is low confidence in GCM projections of East Asian monsoon. The results suggest that a better GCM parameterization scheme for convective and stratiform rain is needed for improving model simulation of the monsoons.

Keywords: *Tropical monsoon, subtropical monsoon, convective precipitation, stratiform precipitation*

EXTENDED ABSTRACT ONLY

Climate modelling projections to price climate derivatives

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Abstract: Climate adaptation requires large investments that can be provided by governments, but could also be sourced from financial markets with climate derivatives. Such instruments would allow two parties with different expectations about climate risks to transact for their mutual benefit and, in so doing, allow exposed parties to finance climate adaptation. Here we provide an example of how climate derivatives could be used and calculate derivative prices for sale to investors.

Using auto-regressive moving average (ARMA) models fitted to down-scaled climate model forecasts of average annual sea surface temperature (SST) in Tasmania Australia, we calculate the price of a European put option, and show how, with an 18°C 'strike' value, this derivative could assist Tasmanian salmon companies adapt their production systems to higher SST, generate a quantifiable risk indicator for planning purposes, and give investors a market assessment of climate change.

Keywords: *Climate risk management, GCM*

Comparison of northern hemispheric anthropogenic black carbon emissions from global datasets

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Abstract: There is a large interest in the impact of short-lived climate pollutants (SLCPs) for the Arctic climate but the performance of emission inventories that serve as input to climate models remains unknown especially in high latitudes. To assess emissions that are expected to have a more direct impact on the Arctic, a comparison of available SLCP emission inventories was conducted utilizing spatially-distributed global emission datasets downloaded from the ECCAD-GEIA website (http://eccad.sedoo.fr). In this paper, the comparison was done for black carbon emissions. Differences in both emissions and their locations were addressed.

There remains large variation between the emission inventories in northern latitudes. Relatively speaking the variability is larger than at the global level. Total emissions at high latitudes tend to be lower which makes them more sensitive to uncertainties in regionally important source sectors than at the global level. Variations within the sector emission estimates arise most likely from uncertainties in key parameters, i.e. activities and emission factors. The accuracy of the parameters needs further development. However, the differences were unsystematic, so this was not enough to explain the variation. Some of the variation is due to differences in inclusion of relevant source sectors and spatial distributions of the emission data. Notably flaring was included to the full extent only in some inventories, although the emissions are significant in the Arctic region. Another sector omitted in some inventories was international maritime transport. Inclusion of relevant emission sectors is a common improvement suggestion for all models.

Another aspect affecting the quality of emission inventories is the location of the emissions. The spatial aspect is especially important in the case of black carbon, since its life-time is relatively short and, therefore, the concentration around the sources is higher. This is highlighted in the Arctic area in particular, since black carbon reduces albedo and thus enhances melting when deposited on snow or ice.

There were significant differences between the spatial distributions of the black carbon emissions in the inventories, often with no spatial agreement at all. The differences also varied between source sectors, being sometimes mostly systematic, unsystematic or both. Uncertainty in the spatial distribution of the emissions potentially increases the uncertainty of impact modelling. The differences indicated that the inventories use different spatial proxies for the emissions. One way to develop the quality of the spatial distribution would be to incorporate more data from national or regional emission inventories or models into the global inventories, provided their quality is sufficient.

Keywords: *Short-lived climate pollutants, black carbon, Arctic, emission modelling, spatial agreement*

Multi-model ensemble projections of future extreme temperature change using a statistical downscaling method in eastern Australia

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Abstract: Projections of changes in temperature extremes are critical to assess the potential impacts of climate change on agricultural and ecological systems. Statistical downscaling can be used to efficiently downscale output from a large number of general circulation models (GCMs) to a fine temporal and spatial scale, which now provides the opportunity for future projections of extreme temperature events. This paper presents an analysis of extreme temperature in data downscaled from ensembles of 13 selected GCMs, out of 28 GCMs, contributing to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5) under two Representative Concentration Pathways (RCP4.5 and RCP8.5) in eastern Australia. The statistical downscaling procedure begins with spatial interpolation of the monthly gridded data to specific locations of interest using an inverse distance-weighted method, followed by a bias correction towards historical observed climate. Daily climate data for each location are then generated by a modified version of the WGEN stochastic weather generator. The extremes of temperature are described by eleven indices, namely, the annual maximum daily Tmax (TXx), the annual maximum daily Tmin (TNx), the annual minimum daily Tmax (TXn), the annual minimum daily Tmin (TNn), the number of hot days (HD) and frost days (FD), warm days (TX90p) and nights (TN90p), cold days (TX10p) and nights (TN10p) and extreme temperature range (ETR). The results show that downscaled data from most of the GCMs reproduced the correct sign of recent trends in all the extreme temperature indices (except TN10p) although there was much more variation between the individual model runs. An independence weighted mean method was used to calculate uncertainty estimates, which verified that multi-model ensemble projections produced a good consensus compared to the observations in magnitude of the trend in $\mathrm{TXx}, \mathrm{TN90p}, \mathrm{HD}, \mathrm{TNn}, \mathrm{ETR}$ for the period 1961-2000 when averaged across eastern Australia. In the 21st century the frost days, cold days and nights decrease while more frequent warm days and nights and hot days are projected in the New South Wales (NSW) wheat belt. The changes in temperature extremes under RCP8.5 are more pronounced than that under RCP4.5. Greater warming occurs in the east and northeast of the NSW wheat belt by the end of the 21st century and increases the risk of exposure to hot days around wheat flowering date, which results in farmers needing to reconsider wheat varieties suited to maintain yield. This analysis provides a first overview of projected changes in climate extremes from the ensemble of 13 CMIP5 models with statistical downscaling data in eastern Australia, and supplies important information to mitigate the adverse effects of climate extremes on NSW wheat belt and improve the regional strategy for agricultural systems.

Keywords: *Warm indices, cold indices, GCMs, observations, independence weighted mean*

ACCESS model simulation of ENSO, IPO and rainfall variability in eastern Australia

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Abstract: Rainfall variability shapes the Australian climate, economy and society. Despite its significance, our knowledge of Australian rainfall variability is incomplete. Australia experiences higher levels of rainfall variability than other locations with similar climates, driven by interactions between different processes; of all inter-driver interactions, those between climate oscillations (such as the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO)) impact rainfall variability the most. However, the influence of multiple interacting rainfall drivers on variability has not been as well studied as the influence of single drivers. In particular, our understanding of how well global climate models (GCMs) capture the influence of inter-oscillation interactions on rainfall variability is limited. This is a considerable gap in existing knowledge, particularly as the information that can be derived from GCM output is especially useful for informing policy and decision making in sectors impacted by rainfall variations, such as agriculture and natural resource management. Improved understanding of the uncertainties in representations of rainfall variability drivers in GCMs will contribute to better informed decision making.

This study focuses on eastern Australia, as findings are of particular relevance in this area from both societal and scientific standpoints. Eastern Australia houses the majority of the Australian population, and contains the agriculturally significant Murray-Darling Basin. Additionally, ENSO—the climate oscillation which has the greatest influence on Australian rainfall—affects this region strongly. Interactions between ENSO and the IPO are known to significantly modulate eastern Australian rainfall; this relationship is ideal for study.

The degree to which the Australian Community Climate and Earth-System Simulator model (ACCESS1.3, historical experiment) simulates observed twentieth century rainfall variability attributed to the interaction between ENSO and the IPO is analysed. Model output is compared with observational rainfall data from the Australian Water Availability Project (AWAP, run 26j), for the years 1900–2005. The annual ENSO–IPO relationship, measured by correlating the Niño 3.4 and TPI indices, is similar in observations (AWAP: r = 0.29) and model runs (ACCESS, three runs: r = 0.26–0.31). However, seasonal and monthly correlation coefficients are weaker in the ACCESS model runs than in observations. Composite analysis in which rainfall data are stratified according to ENSO and IPO phases reveals that the observed relationship between the negative IPO phase and enhanced influence of ENSO on rainfall is not reflected in the ACCESS model runs. The strongest observed relationship between ENSO, the IPO and rainfall is observed in eastern Australia; however, this is not reflected in the ACCESS model runs, which produce different spatial patterns of rainfall, over-estimate rainfall extremes, and simulate the strongest relationship between ENSO and the IPO in the austral spring (the strongest observed relationship occurs in austral summer). Observed rainfall anomalies in eastern Australia are greatest when ENSO is in its neutral phase, allowing the IPO to influence rainfall strongly; this is not reflected in the ACCESS model. This research deepens our understanding of interactions between ENSO and the IPO. It is the first study to assess how well a GCM captures the interaction between ENSO and the IPO and their joint influence on Australian rainfall variability.

Keywords: *ACCESS1.3, El Niño Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO), Pacific Decadal Oscillation (PDO), historical rainfall variability*

Climate change impacts on rainfall erosivity and hillslope erosion in NSW

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Abstract: There are considerable seasonal and inter-annual changes in rainfall amount and intensity in South-East Australia (SEA), particularly in coastal New South Wales (NSW). Consequently, soil erosion rates may be expected to change in response to changes in the erosive power of rainfall or rainfall erosivity. Recently, the downscaled 10 km rainfall projections from New South Wales (NSW) and Australian Capital Territory (ACT) Regional Climate Modelling (NARCliM) project have become available for the SEA region for the baseline (1990-2009), near future (2020-2039) and far future (2060-2079) periods. The aim of this study was to model and assess the impacts of climate (rainfall) change on rainfall erosivity and hillslope erosion risk in SEA based on the NARCliM projections from all the 12 model member ensembles. Outcomes from this study are to assist the long-term climate change adaptation and regional planning such as NSW state planning regions (SPR).

A daily rainfall erosivity model has been specifically developed and applied to calculate monthly and annual rainfall erosivity values from the NARCliM projected daily rainfall data for the baseline and future periods. Monthly and annual hillslope erosion risks for the same periods were estimated using the Revised Universal Soil Loss Equation (RUSLE). Finer scale (100 m) surfaces of rainfall erosivity and hillslope erosion have been produced using spatial interpolation techniques. Automated scripts in a geographic information system (GIS) have been developed to calculate the time-series rainfall erosivity and hillslope erosion so that the processes of large quantity NARCliM data are realistic, repeatable and portable.

Adequate random sampling points (4991) were used to sample and assess the accuracy of the modelled rainfall erosivity from the NARCliM projections. The GIS modelled mean annual rainfall erosivity values from the NARCliM projected daily rainfall were compared with those calculated using the gridded daily rainfall data from Bureau of Meteorology for the baseline period (1990-2009). The overall coefficient of efficiency (E_c) is 0.9753 (R^2 = 0.9762), and RMSE 13.2% or 143 ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$) indicating the relative size of the error bars from the 1:1 line.

The modelled baseline rainfall erosivity in NSW varies from less than 300 on parts of western NSW to over 15,000 on parts of the North Coast, with a mean of 1112 ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$). Both rainfall erosivity and hillslope erosion risk are predicted to increase about 7% in the near future, and about 19% increase in the far future compared with the baseline period. The change is highly uneven in space and time, with the highest increase occurring in the Far-west SPR in autumn, with an increase about 22% in the near future and about 29% in the far future. The rainfall erosivity is generally higher in summer and lower in winter, with about 10 times difference between February (highest) and July (lowest).

Overall, the risk of soil erosion on NSW agricultural and plantation lands is expected to be steady, largely due to the flat topographic factor. The lands with "Intensive uses" will have high erosion risk due to the combined effect of terrain and rainfall erosivity. These 'hot-spot' erosion risk areas have been identified and mapped to assist decision makers to develop the best management practices.

Keywords: *Rainfall erosivity, hillslope erosion, climate change, impact assessment, NARCliM*

Modelling hydrological changes in New South Wales under future climate change

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Abstract: Within New South Wales, the Office of Environment and Heritage (OEH) supports climate-change adaptation by working with communities, agencies and other stakeholders to identify and understand regional vulnerabilities. Scientific impact assessments for bushfires, biodiversity, sea level and coasts, floods, soil, human health and water resources have been undertaken.

In this study, impacts of climate change on the water cycle and hydrology is investigated. Assessing the impacts of climate change on hydrology is important because changes to the water cycle influence water security, water quality, salinity and groundwater availability.

We use the NARCliM (**N**SW / **A**CT **R**egional **Cli**mate **M**odelling) ensemble of climate projections for south-east Australia. This ensemble is designed to provide robust projections that span the range of likely near and future changes in climate *(Evans et. al. 2014).*The water balance was simulated using the PERFECT model *(Littleboy et al. 1992)* which is a daily time-step model that predicts surface runoff, infiltration, soil evaporation, transpiration, profile drainage and recharge. PERFECT was applied at a 10km resolution across NSW to predict surface flows and groundwater recharge.

Maps and graphs from this modelling form part of the NSW Climate Impact Profile which provides an assessment of projected biophysical changes across the State. Maps presented show central estimates or arithmetic means of future projections. Bar graphs are used to present projections as ranges of plausible change, illustrating the projections from the twelve individual simulations as well as the central estimate.

In the near future, less recharge is predicted across much of NSW, especially in the south east of the State. Considerably less recharge is likely in alpine areas. Some areas of western NSW do show a slight increase in recharge but these increases are considered relatively small. In the far future, recharge is expected to increase across many parts of NSW. Some areas along the Great Dividing Range are likely to experience less recharge to groundwater. The largest impact is the dramatic reduction in recharge in alpine areas.

Across much of NSW, surface runoff is projected to increase in both the near and far future. Largest increases are evident in the central west through to the northern tablelands. Largest reductions in surface runoff are projected in both the near and far future for alpine areas in the south of the State.

More complex analyses at a resolution on 100m are underway for the ACT and coast catchments of NSW. This analysis will permit allow spatial variability in land use and soils to be taken into consideration in the climate impact assessments. This is not represented in this paper.

***Keywords**:* *Climate change, hydrology, soil water balance, PERFECT model, NARCliM*

Drought assessment in the Pampanga River basin, the Philippines – Part 1: Characterizing a role of dams in historical droughts with standardized indices

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Abstract: Droughts are frequent disasters in the Philippines with the most severe 1998 drought, which caused food shortages nationwide and major losses of rice production in the Pampanga River basin. For the Pampanga River basin, irrigated rice agriculture contributes about 30% of the rice production in the Philippines and relies on the complex water infrastructure system consisting of barrages, irrigation canals, Pantabangan and Angat multi-purpose dams, and trans-basin tunnels to increase inflows into these two dams. Both Pantabangan and Angat dams supply irrigation water for both wet and dry season rice production, which did not exist prior to the construction of these two dams, while the Angat dam supplies water to the Metro Manila City with population of about 12 million people.

We conducted drought assessment with standardized indices in the Pampanga River basin by characterizing historical droughts (Part 1), introducing a comparative approach of standardized indices for climate change quantification (Part 2), and evaluating climate change impacts (Part 3). In Part 1, we computed standardized indices with collected field data (i.e., precipitation, reservoir inflows and water volumes, and dam discharges) to identify natural and socio-economic droughts at the Pantabangan and Angat dams. We utilized the standardized precipitation index (SPI) to characterize meteorological droughts and developed a standardized inflow index (SII) from reservoir inflows for hydrological drought assessment. To characterize socio-economic droughts, we developed a standardized reservoir storage index (SRSI), which was computed with reservoir inflow and water volume data, and compared SRSI values with standardized discharge index (SDI) values, which were estimated from dam discharges that were released to meet irrigation and municipal water demands.

From the results of our drought assessment, we identified several meteorological, hydrological and socio-economic droughts between 1980 and 2012 with standardized indices. The use of several standardized indices allows us to identify the most extreme conditions based on the combined meteorological, hydrological and socio-economic droughts. The newly developed SII and SRSI indices match historical natural and socio-economic droughts in the Pampanga river basin and reflect increased inflows in the Pantabangan dam after the construction of trans-basin tunnel. As a result, the full-set of standardized indices represents the existing dam infrastructure and operation and could also be utilized for drought forecasting in the Pampanga river basin.

Keywords: *Pantabangan dam, Angat dam, natural drought, socio-economic drought, standardized inflow index (SII)*

Drought assessment using tritium river water measurements for existing dam infrastructure in the Ishikari River basin, Japan

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Abstract: Understanding of groundwater transit times is needed to answer practical questions of water quantity and quality as well as provide information for numerical model simulations. The groundwater storages, which have complex groundwater dynamics and provide much of the river water during droughts, are often difficult to include in rainfall-runoff models due to the absence of available subsurface information at the river basin scale. For example, the distributed hydrologic model BTOP, which has been applied in several river basins for flood and drought hazard quantification, utilizes groundwater travel distance to simulate the baseflow component of river flow. Therefore, we need a robust tool that can help to answer the practical water management questions such as what are the groundwater volumes and travel times, by illuminating the groundwater catchment dynamics.

A proposed methodology of assessment of groundwater volume that can maintain drought river baseflow is based on estimating groundwater volumes from tritium river water measurements in the Ishikari River basin of Hokkaido Island, Japan. In our drought assessment, we characterize available groundwater storage that can be used for the water supply during prolonged droughts. To estimate groundwater storage, we used tritium measurements obtained during baseflows to determine water mean transit times (MTTs). Tritium is ideally suited for characterization of the catchment's responses as it can reveal MTTs up to 200 years. It is a component of meteoric water, decays with a half-life of 12.32 years, and is inert in the subsurface. The radioactive decay allows us to quantify water lag time in the subsurface even at the natural tritium concentrations in precipitation that currently prevail. However, this requires the most sensitive equipment to detect the small changes of tritium concentrations in water, similar to the requirements in the Southern Hemisphere.

In Hokkaido, river samples were collected in June, July and October 2014 at selected river gauging stations operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan. These stations record hourly water levels, have catchment areas between 45 and 377 km2 and are located upstream of MLIT dams at altitudes between 36 m and 860 m MSL. The measured tritium ranged between 4.065 TU (±0.07) and 5.290 TU (±0.09) with both lowest and highest tritium values analysed in June river samples at Tougeshita and Okukatsura stations, respectively. For the MTT estimation, we selected the exponential(80%)-piston(20%) Lumped Parameter Model (LPM) with a reconstructed tritium record in Hokkaido precipitation and obtained a non-unique fit of young (1-11 years) and old (16-98 years) groundwater MTTs. This result indicates that bomb-peak tritium is still present in Japanese groundwater and may take several years to flush out. From the MTTs and baseflows, the calculated groundwater volumes range between 13 MCM and 17436 MCM and indicate potentially available groundwater storage during prolonged droughts in the Hokkaido headwater catchments. As a result, the adopted approach may be a cost-effective method of characterizing groundwater in river basins for their potentially available water supply during droughts. In future studies, the accuracy of the estimated groundwater volume can be improved by conducting another tritium sampling round at baseflow in 3 years' time. Having tritium-series measurements with 3 year intervals will enable us to choose either the young or old MTT value and therefore to reduce the ambiguity of the LPM mixing parameters. Eventually, tritium in groundwater will reach natural levels and one tritium river water sample will be sufficient to estimate a robust groundwater storage volume.

Keywords: *Drought assessment, Mean Transit Time (MTT), groundwater storage*

A comparative SPI approach for qualifying historical and on-going droughts in the Pampanga River basin, the Philippines

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Abstract: In the Pampanga River basin, Pantabangan dam constructed in 1979 to drain 937 km^2 and Angat dam, which was constructed in 1967 to drain 546 km^2, are located in the headwaters of the Pampanga basin and have limited historical rain gauge data. The two dams have experienced severe droughts in the past affecting downstream agricultural water users that contribute to about 30% of the rice production in the Philippines. For example, the most severe 1997-1998 drought affected 16,106 ha of irrigated rice paddies in the Pampanga River basin due to limited water releases from these dams. Therefore, the quantification of historical and on-going drought hazards is an important task in the Philippines especially for the Pampanga River basin.

In the Philippines, the Philippines Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) conducts meteorological drought assessment and issues a bulletin with drought affected provinces. The PAGASA defines drought as 3-consecutive month rainfall with 60% reduction from average rainfall and does not utilize the standardized precipitation index (SPI). The SPI was developed as a versatile tool to characterize meteorological droughts on multiple timescales and is used by national meteorological and hydrological services world-wide. However, the use of SPI for an operational drought monitoring drought requires recalculation of the long-term observation when the newest precipitation is added and modifies the distribution basis of the SPI every time.

To address this issue, the comparative SPI (cSPI) approach is applied for analyzing the precipitation characteristics of historical climates to select a reference data set for the on-going drought investigation. The strength of the cSPI is to adjust the combination of target and reference datasets without recalculation through the whole period when the newest precipitation is added. When a certain period of ongoing long-term observation is treated as a reference, we can estimate the meteorological drought on the fixed basis of the historical reference. In addition, the window of the reference period can be shifted within the entire period of available data allowing us to analyze the effect of multi-decadal variability and climate change by the ongoing long-term observations. For the historical data, the latest version of the gridded daily rain gauges dataset in Asia, APHRODITE V1101, was released in 2012, over the Monsoon Asia, Middle East, and Russian regions for 57-year record from 1951 to 2007. This dataset is commonly analyzed to supplement a coarse rain gauge observation network in data-poor regions as well as to analyze the performance of climate models' simulations and satellite observations. As the result, we compare the traditional SPI and cSPI with moving reference window of 30-year period to produce operational drought assessment in the Pantabangan and Angat dams in the Pampanga river basin, the Philippines.

Keywords: *Standardized precipitation index (SPI), comparative SPI (cSPI), meteorological drought*

Quantifying and managing the risk of hydrological extremes on seasonal to multi-decadal timescales

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Abstract: Managing hydrological extremes (i.e. flood and drought) requires consideration of impacts and management options across a variety of timescales. For example, short-term drought (i.e. lasting for less than 2 years) can usually be well-managed via introduction of restrictions or water transfers, whereas medium-term droughts (i.e. lasting 5-10 years) might require new infrastructure (e.g. new dams or desalination plants) and multidecadal epochs where drought is persistent and/or frequent might require totally new adaptation policies to ensure water security. Accordingly, the information requirements when seeking to model and manage hydrological extremes also differs depending on whether the focus is short-, medium- or long-term. Accurate understanding and quantification of the risk of hydrological extremes across all timescales is critical for the development of secure, robust and efficient water, food, energy, health, transport and communications infrastructure and management systems. In places like Australia, where the historical impacts of natural climate variability are significant and the projected impacts of anthropogenic climate change are expected to amplify existing vulnerabilities, accounting for the non-stationarity of hydroclimatic risk is also crucial. Overlooking this need can be, at best, uneconomic due to production of stranded assets and, at worst, dangerous in the sense of making the system seriously vulnerable to drought.

This study demonstrates, for case studies in the Murray-Darling Basin and South Australia, two different approaches for quantifying the risk of hydrological extremes – one focused on short-term (i.e. seasonal to interannual) risks and the other focused on long-term (i.e. decadal to multidecadal) risks.

The first method utilises a novel method for quantifying the inherently non-linear nature of the links between large-scale climate ocean-atmospheric phenomena (e.g. El Niño/Southern Oscillation (ENSO)) and hydroclimatic variability in Australia. The method objectively identifies the key combinations of ocean-atmospheric drivers that explain the most seasonal-interannual hydroclimatic variability and therefore can best inform short- to medium-term hydrological risk quantification and management activities.

The second method uses recently produced paleoclimate proxies to reconstruct pre-instrumental hydroclimatic variability for the last 2,750 years. This involved the development of novel methodology to provide reconstructions in locations that currently lack in situ paleoclimate proxies. These pre-instrumental reconstructions are then utilized to improve the accuracy and realism of instrumental-based hydrological extreme risk estimates. Droughts were found to persist over multiple decades in the reconstructions, and in some centuries were also much more frequent than the droughts observed within the instrumental record. In addition, the persistence of wet epochs comparable to the flood dominated period experienced between 1945 and 1978 across eastern Australia, were found to be approximately 25% longer during the 16th century. This suggests that hydroclimatic risk assessments based on the instrumental record likely underestimate, or at least misinterpret, the frequency, magnitude and duration of hydrological extremes and that new approaches such as those presented here need to be implemented and further developed..

Keywords: *Water resource management, uncertainty, climate scenarios, flood, drought*

Specifying design rainfall extremes in locations with limited observational records

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Abstract: The prospect of climatic change and its impacts have brought spatial statistics of extreme events into sharper focus. The so-called "water bombs" or "explosive cyclones" are predicted to become more frequent in the extra-tropical regions, and, actually, they raise serious concerns in some regions of the Mediterranean area. However, quantitative statistical methods to properly account for the probability of occurrence of these super-extreme events in formerly untouched areas are still lacking. This is due to their rare occurrence and to the limited spatial scale at which these events occur.

In order to overcome the lack of data, different studies concerning flood frequency analysis underline the importance of combining local flood data with additional types of information, to improve the quality of the estimation of the exceedance probability for a given discharge. We propose to apply such a kind of approach in extreme rainfall frequency analysis, with the adoption of a Bayesian framework, aimed at combining local gauge information, discontinuous in space and time, with climatic regional information. The identification of this type of hierarchic relationship can complement local information, conditioning the exceedance probability to the large and meso-scale characteristics of the system, allowing the simulation of design rainfall extremes in sites where historical evidence of that hazard is lacking. The Bayesian approach allows us also to keep track of all the uncertainties involved in the prediction process, producing a measure of uncertainty associated to the estimates.

The case study refers to a database of daily rainfall measurements extracted from the NOAA GHCN-Daily dataset, recorded during the 20th century by 700 rain gauges distributed in the Mediterranean basin.

First, to identify the conditional variables, we analyse the large-scale environment associated with the different intense precipitation systems in the Mediterranean area, exploiting the reanalysis of the European Centre for Medium-Range Weather Forecasts (ERA-20). With the aim to define the hierarchical relationships between the events and their type, we relate the daily precipitation with different parameters both atmospherical and local. Despite the high variability, different climatic configurations that combined with the local morphology and the seasonal condition of the Mediterranean Sea can trigger very intense precipitation events are identified.

Once defined the hierarchical relationships, the parameters are calibrated and the methodology is tested on a subset of daily series provided by local authorities, evenly distributed on the whole domain.

The results, compared with those obtained with the classic techniques of frequency analysis and spatial interpolation, demonstrate an increased knowledge coming from climate and local factors, ensuring more reliable and accurate spatial assessment of extreme thunderstorm probability.

Keywords: *Mediterranean storm, rainfall extremes, Bayesian, super-extreme*

River discharge simulation of a distributed hydrological model on global scale for the hazard quantification

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Abstract: We introduce a global river discharge simulation system based on the BTOP models for individual river basins (Global BTOP) and apply Global BTOP to quantify flood and drought hazards globally. The BTOP model utilizes a modified topographic index and simulates runoff processes including snowmelt, overland flow, soil moisture in the root and unsaturated zones, sub-surface flow, and river discharge. The Global BTOP is constructed from available river network data on the 10-arcmin (about 20-km) grid in the current version. The BTOP model topographical features are obtained using river network upscaling algorithm that preserves 3-arcsec (about 90-m) HydroSHEDS and 30-arcsec (about 1-km) Hydro1K characteristics in order to reduce the impact of upscaled dataset to the discharge simulation. In the Global BTOP, the International Geosphere-Biosphere Programme (IGBP) land cover and the Food and Agriculture Organization of the United Nations (FAO) soil digital maps of the world are used for the root zone depth and soil properties, respectively. The long-term seasonal potential evapotranspiration are estimated by the Shuttleworth-Wallace model using climate forcing data CRU TS3.1 and a fortnightly Normalized Difference Vegetation Index (NDVI). The Global BTOP is run with globally available daily precipitation datasets and calibrated to the observed global and local river discharge data. From these preliminary calibration results, the Global BTOP has demonstrated good performance in selected river basins and can be utilized for many useful applications.

For the hazard quantification, we utilized simulated daily river discharges of the Global BTOP to estimate flood peak discharges of the selected return periods for the past, present and future climates. In each 10-arcmin BTOP grid, the flood peak discharges of 10-, 25-, 50-, 100- and 200-year return periods were obtained using the Gumbel distribution with L-moments. We also utilized simulated runoff of the Global BTOP to estimate standardized runoff index (SRI) for quantifying hydrologic droughts. The climate change impact assessment is conducted using GCM outputs of MRI-AGCM3.2S after applying bias correction and evaluated using flood peak discharges. For the dynamic applications of present climate, the Global BTOP is run with JAXA GSMaP-NRT precipitation to simulate daily river discharges, which are utilized in a prototype near-real time discharge simulation system (GFAS-Streamflow). The GFAS-Streamflow is designed to issue flood hazard alerts globally using estimated flood peak discharges via web-interface and may also be used as a combined flood and drought hazard monitor. This may be particularly useful to close the gap between local and global scale hazard assessments under the International Flood Initiative (IFI) Flagship Project, which aims to support benchmarking flood risk reduction at global, national and local levels.

Keywords: *River discharge, hazard assessment, flood, drought, SRI*

Agricultural flood and drought risk reduction by a proposed multi-purpose dam: A case study of the Malwathoya River Basin, Sri Lanka

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Abstract: In this study, we investigate the role of a proposed multi-purpose dam for flood and drought risk reduction in the Malwathoya River Basin, Sri Lanka. The Malwathoya River Basin is the second largest basin in Sri Lanka with an area of 3,246 km^2 located in the dry zone of northern Sri Lanka. The river basin has an average annual rainfall of 1200 mm with two distinct dry and wet seasons and has an elevation range between 350 above mean sea level (AMSL) in the mountainous areas and 0 AMSL near the sea shore. For the lower part of the river basin, the dry season rice production of 170 km^2 area cannot be fully utilized due to annual precipitation of less than 750 mm and lack of irrigation water, which is diverted from the Malwathu River at the Thekkam diversion weir to large water storage tanks via a cascaded irrigation scheme. In the wet season, the rice paddies are frequently flooded due to intense rainfall from the North East monsoon between October and January as well as the inter monsoon during April causing severe economic losses during 2012 and 2014 floods. As a result, a multi-purpose dam with the capacity of 210 million cubic meters (MCM) was proposed in the middle of the Malwathoya River Basin to reduce flood peak discharges during wet season and to supply irrigation water for the Thekkam diversion weir during dry season.

In our methodology, a holistic approach of combined drought and flood assessment is adopted for the multi-purpose dam operation. From this point of view, opposite actions are required for the risk reductions: the full reservoir storage should be maintained before the start of the dry season and the low levels are necessary for the flood peak reduction during flood season. For the hazard severity assessment, the long-term precipitation record has been investigated with the use of Standardized Precipitation Index (SPI) as well of Standardized Precipitation Evapotranspiration Index (SPEI) to select the most severe dry and wet seasons. In addition, past agricultural damages caused by 2012-2014 floods and droughts were correlated using the Normalized Difference Vegetation Index (NDVI) and Land Surface Water Index (LSWI) with field data at several locations. For the dam operation simulation, the 30-arcsec (about 1-km) grid distributed hydrological model BTOP was constructed from the global data sets and included reservoirs and medium water storage tanks with total capacity of 540 MCM located upstream of the Thekkam diversion weir. The BTOP model simulation with the ground-based precipitation was calibrated with observed river discharge data at the diversion weir and had a satisfactory statistical performance. Then, the calibrated BTOP model was used to simulate multi-purpose dam operation with the short- and long-term precipitation. From the BTOP model results, the proposed dam allowed us to establish an optimum operation for the flood and drought risk reduction and indicated a decrease in water related hazards. In addition, we estimated a standardized inflow index (SII) and a standardized reservoir storage index (SRSI) from the BTOP simulated reservoir inflows and water storage to demonstrate long-term dam performance on the same scale with SPI and SPEI values. As a result, this study demonstrates a combined flood and drought risk assessment from the water resources infrastructure point of view and allows us to reduce farmers' vulnerability in the northern region of Sri Lanka.

Keywords: *BTOP model, flood discharge, agricultural drought, SPI, SPEI*

Flood and drought assessment with dam infrastructure: A case study of the Ba River basin, Fiji

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Abstract: In Fiji, frequent flood and drought events require implementation of preventive infrastructure and planning measures to reduce potential damages that may be caused by these events. The Ba River basin, which is located in the Western part of the main island, Viti Levu, has experienced severe floods and droughts. The flood record of the Ba River extends from 1871 to 2009 and reports flooding of about 127 times with the most disastrous floods in 1931, 1956, 1993, 1999 and 2009 (McGree et al., 2010). For example, the 1993 flood damages amounted to about 8 million USD. For the past droughts, the rain fed sugar cane agriculture is affected by shortages of precipitation with the most severe drought in 1998. In the Ba River basin, the sugar cane agriculture recorded a loss of 21.80 km^2 at the Rarawai Mill during the 1998 drought. For the flood hazard reduction, a dry dam infrastructure is proposed upstream of the Ba Town allowing for natural river flows while only reducing flood peaks. In addition, two multipurpose dams are proposed for the water supply during droughts as well as flood reduction.

In our approach, we utilize numerical models to investigate the effectiveness of dam infrastructure for flood control and water supply, and standardized indices to characterize historical droughts. For the standardized indices, the precipitation record of the Ba River basin has been investigated with the use of Standardized Precipitation Index (SPI) from 1960 to 2009 and the Standardized Precipitation Evapotranspiration Index (SPEI) was obtained from global datasets. The 3-arcsecond (about 90-m) grid block-wise TOP (BTOP) and 15-arcsecond (about 450-m) grid rainfall-runoff-inundation (RRI) models were constructed for the Ba river basin of 957 km^2 to simulate flood river flows and inundation. For the BTOP model, monthly potential evapotranspiration and Normalized Difference Vegetation Index (NDVI) were obtained using climate forcing data CRU TS3.1. Both BTOP and RRI models with short- and long-term local precipitation data were calibrated and validated with the local available data at two river gauging stations. Using the simulated discharges of the calibrated BTOP model, we estimated flood discharges of the selected return periods with flood frequency analysis and conducted flood inundation simulations with Flood Inundation Model (FID) model. The estimated flood inundation area and flood exposure with and without infrastructure are utilized for the flood risk estimation. For flood risk, we estimated the number of flood affected people and agriculture and found a satisfactory comparison with the record of the 1993 flood. For the historical drought assessment, both SPI and SPEI demonstrated the most extreme drought conditions of the 1998 drought and are consistent with the affected agriculture record during the 1998 drought. These preliminary results indicate the usefulness of our approach and suggest it could be used for selecting effective counter-measures for flood and drought risk reduction in Ba River basin.

Keywords: *BTOP model, RRI model, flood inundation, standardized indices*

Flood and drought hazard reduction by proposed dams and a retarding basin: A case study of the Upper Ewaso Ngiro North River basin, Kenya

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Abstract: The Ewaso Ngiro North River Basin, which is the largest river basin in Kenya, has been experiencing alternate incidents of flood and drought hazards that cause fatalities and economic losses. In the upper reaches of the Ewaso Ngiro North basin, heavy rains contribute to flood river flows and inundation in the downstream areas whereas the lower part of the basin is semi-arid drought prone area. These climatic variety and frequent hazards make the river basin management difficult and have caused a series of water conflicts between the upstream and downstream water users. In the previous river basin studies, the increase of water storage and adaptation of water allocation plans are selected as a viable option. From previous studies, four possible sites of proposed multi-purpose dams were identified in the headwaters of the Ewaso Ngiro North river basin for three main purposes: to maintain minimum river flows during droughts, to provide municipal, livestock and minor irrigation water supply and to decrease flood peak discharges at the tourist lodges in Samburu and residential areas around Archers post town located in the downstream part of the river basin. In addition, flood retardation basin nearby the Isiolo town can be used for storage of flood peak discharges during wet season and release of the stored water during dry season. However, a comprehensive approach of the flood and drought risks as well as the effectiveness of the proposed structures has not been investigated. Therefore, this study quantifies the extreme effects of the usefulness of the proposed water infrastructure to mitigate water related disasters with the use of a distributed hydrological BTOP model.

In our study, a holistic approach of combined drought and flood assessment is adopted for the multi-purpose dam operation to maintain full storage before the start of dry season and to keep flood capacity for the flood peak reduction during flood season. For the hazard severity assessment, the long-term precipitation record has been investigated with the use of Standardized Precipitation Index (SPI) as well as Standardized Precipitation Evapotranspiration Index (SPEI). To evaluate water infrastructure effectiveness, we utilized existing 600-arcsec (about 18-km) grid BTOP model, which was developed for the entire Ewaso Ngiro North river basin as a part of the global BTOP modelling system, and focused on the catchment area located upstream of the Archers post. The 600-arcsecond BTOP model preserves small scale topographical features and utilized global datasets of land cover and soil properties due to unavailability of locally data. The long term seasonal potential evapotranspiration within BTOP model was estimated by the Shuttleworth-Wallace model using climate forcing data CRU TS3.1 and a fortnightly Normalized Difference Vegetation Index (NDVI). The 600-arcsec (about 18-km) grid BTOP model was run with short- and long-term local precipitation data and calibrated with river discharge data of the Archers post river gauging station. The calibrated BTOP model demonstrated a satisfactory statistical performance and represented peak and low flows of the Ewaso Ngiro River. From the calibrated BTOP model, the proposed dams and retention basin were simulated to find an optimum dam location for water supply and flood control. From the results of our study, the possible location and capacities of flow control structures (dams/retarding basin) enable as to plan on a combined flood and drought risk reduction.

Keywords: *BTOP model, water storage, flood peak discharge, water scarcity*

A stochastic modeling framework for the Invitational Drought Tournament

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Abstract: Droughts are better defined as socio-hydrologic phenomena. On one hand, hydroclimatic extremes dictate the frequency and severity of droughts. On the other hand, management decisions alter associated impacts of droughts on coupled human-natural systems. Although hydrological aspects of drought have been explored in the past, the social dimension of drought management has received less attention. Drought management exhibits a complicated decision making process and is normally performed through a pluralistic decision making context, which involves a wide range of social groups with potential for competing interests. In order to explore and understand social relations within drought management, theoretical and modelling frameworks are required. Such a framework should be able to describe and model the human dimension of drought management. We argue that Cultural Theory, an existing conceptual framework to explain societal conflict over risk, can frame the social aspects within drought management practice. We introduce a dataset from an Invitational Drought Tournament event and demonstrate how Cultural Theory and stochastic modelling of participant's preferences explains the social relations empirically. We find that competition is an important social behavior within a drought management. The Invitational Drought Tournament captures important social relations that result in new and innovative management strategies to tackle drought risks by reducing probability/frequency and impact severity. The strategies put forward to manage the drought depend on the stage of drought, participants' insights and different ways of organizing. We show empirically that an autonomous regulatory framework is required to guide individual and institutional conflicts while allowing for pluralism in drought management practices.

Key points:

- We suggest more effort is needed to model the human dimensions of drought
- Cultural Theory is proposed as a useful lens to support analysis
- The Invitational Drought Tournament is outlined as a behavioural observatory
- Choices of participants in the game are used to create Empirical Cumulative Distribution Functions (ECDFs)
- ECDFs are used to simulate the game to fit the referee's scores

Keywords: *Socio-hydrology, drought management practice, pluralistic decision making, cultural theory, Invitational Drought Tournament*

Constructing damages functions for paddy field hit by water-related disasters based on MODIS FPAR and a distributed hydrological model in data sparse context: the example of Solo river basin, Indonesia

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Abstract: In the current scenari of climate change, changes are foreseen in spatiotemporal patterns as well as variability of precipitation. Moreover, the impact on Asia and the Pacific region water spatiotemporal availability is believed to be particularly severe. Also among the ten biggest producer of rice, nine are from the Asia Pacific region and paddy is the typical farming system supporting most of the population in the region. Therefore, it is very important to understand where and how damages to paddy occurred during past water extreme events. This will allow putting in place informed flood and drought mitigation measures to tend to both food and water security. However, a part from some exceptional cases, damages records from water related disasters reports are usually spatially and temporarily aggregated and insufficiently detailed to allow the construction of damages functions even though their undeniable importance. Hence, this paper reports a simple methodology based on MODerate resolution Imaging Spectroradiometer (MODIS) data fraction of Photosynthetically Active Radiation (FPAR) MCD15A2 analysis and reported damages linked with hydrological modeling in order to re-distribute the reported spatiotemporally aggregated damage data and finally construct damage functions for paddy during water extreme events. The steps followed to construct the damage functions for paddy were : 1) extract and analyze MCD15A2 data from 2003 to 2009 for paddy field in Solo river basin, 2) extract patterns for MCD15A2 for paddy grids with fast Fourier transform for combined annual (45weeks) and paddy cultivation duration (17-19weeks) periods. This pattern is considered as the non-damage pattern, 3) identify paddy grids with negative difference between 8-days individual MCD15A2 paddy data and corresponding non-damage pattern as damaged areas and reconcile with damage aggregated reports data, 4) link between damaged grids and hydrological variable such as flood water depth using Rainfall-Runoff-Inundation (RRI) model.

Once these damage functions are available, it allows the assessment of expected damages for hazard of given return periods and at last the risk assessment of a given river basin. This methodology is tested on Solo river basin on Java Island, Indonesia, suffering both from flood and droughts in the past years with significant impact on local economies.

Keywords: *MODIS FPAR, distributed hydrological model, fast Fourier transform, Solo river basin, Indonesia*

Integrated Approach of Inundation Analysis using Hydrological Observation and Hydraulic Analysis in Data Sparse Basins

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Abstract: Recently, water-related disasters have become frequent in many parts of the globe; In 2011, a large flood occurred in the Chao Phraya River basin of Thailand, causing considerable damage. To prevent such a catastrophe from recurring, risk reduction strategies need to be developed with comprehensive risk assessment, which is constructed based on an appropriate estimation of flood extent, for example. For this purpose, mainly in data sparse basins, the authors understand that the numerical simulation of inundation processes, including river flow, is one important tool and should be numerically simulated with the following procedures: 1) construction of initial conditions, 2) construction of boundary conditions, 3) modeling of sediment hydraulics, and 4) verification with remote-sensing techniques and field observation, and 5) tuning up the numerical simulation based on the verification results. To implement those procedures for inundation simulation, the authors propose a set of techniques as explained in the following paragraph.

The first technique is the implementation of Digital Surface Models (DSM), for example, from the Shuttle Radar Topography Mission (SRTM) with modification by means of bathymetric information and hydraulic structures in a expected given? inundation area, such as embankment roads. Regarding bathymetric information, the authors propose field observation by acoustic instrumentations as well as 1-D water/sediment governing equation to interpolate the bathymetry between observed sections to minimize the load of field observations. The second one is the construction of a stage-discharge relationship with the help of the knowledge of sediment hydraulics. This method most likely enables to create the stage-discharge relationship with a few or no discharge-measurements using water gauge and cross section. Though the accuracy of estimation depends on the number of measurements, still it is beneficial to have tools requiring no discharge measurements. The authors introduce a boat-mounted acoustic Doppler current profiler (aDcp) to construct the relationship as well as check the accuracy of estimation. The third one is the modeling of the sediment hydraulics to appropriately incorporate the channel-conveyance capacity of river flow into simulation. The fourth one is the understanding of the actual phenomena by remote-sensing techniques and field observation. Regarding remote-sensing techniques, the authors use the Modified Land Surface Water Index (MLSWI) with the MODerate resolution Imaging Spectroradiometer (MODIS) data. The fifth technique is the tuning up of numerical simulation results, compared with those obtained by the fourth one.

The authors describe the first, second and third techniques, which were actually implemented in the Lower Mekong River basin in Cambodia.

Keywords: *Inundation simulation, discharge and riverbed measurements, data sparse basin*

The potential impact of pain on health outcomes among patients with chronic obstructive pulmonary disease

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Abstract:

Background

Pain among COPD patients is under-recognized and has not received in depth exploration. Our objective was to examine the relationship between patient-reported levels of pain with other characteristics to examine the associations with psychological distress, functional performance, and health care utilization.

Methods

This was a cross sectional analysis of baseline data from a randomized trial of physical activity self-management. Pain was assessed using the Bodily Pain domain of the SF-12. Psychological distress was assessed with the SF-12 Mental composite score (MCS). Both SF-12 Scores range from 0 to 100; lower scores are suggestive of greater pain and greater psychological distress. Functional performance was assessed by 6 minute walk distance (6MW), Chronic Respiratory Questionnaire Dyspnea (CRQ). Healthcare utilization was based on self-reports for the 6 months prior to enrollment. Other patient characteristics included socio-demographics, body mass index (BMI) and spirometry. The distribution of pain was assessed and categorized into quartiles, we assessed for trends across pain quartiles using the Cochran-Armitage trend test for categorical variables and linear contrasts for continuous variables.

Results

Among the 325 patients with baseline data, we observed that the highest pain quartile was associated with younger age (P-trend=0.0003), higher BMI (P-trend=0.002), greater psychological distress (P-trend<0.0001), and less severe spirometric impairment (P-trend=0.0004). In addition to this, we observed a large and clinically significant negative impact on CRQ dyspnea, 6MW distance, and health care utilization (P-trend <0.01). Those who reported being in the high pain quartile more often reported hospitalizations and use of urgent care for lung and non-lung disease in the previous 6 months, as well as utilization of home health services.

Conclusions

Our findings suggest that pain has a large, clinically significant impact on psychological distress, functional performance and health care utilization. In order to improve the health outcomes of COPD patients reporting pain, effective interventions which enhance the recognition and management of pain are needed.

Keywords: *Chronic obstructive pulmonary disease, health outcomes, quartile, pain*

Using the Bayesian Logistic Regression Model to Determine the Relationship of Demographics and Hyperaldosteronism

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Abstract: Aldosterone excess (Hyperaldosteronism) has been reported to be a common cause of resistant hypertension. High aldosterone is also linked to sleep apnea. Investigators have reported that primary aldosteronism (PA) has a prevalence of approximately 20% in patients with resistant hypertension. These studies have been based largely on office blood pressure (BP) measurements. Thus, the degree to which hyperaldosteronism contributes to resistance of 24-h blood pressure control is not known. Thus, an ambulatory investigation appeared to be in order.

Two hundred fifty-one patients were referred to the University of Alabama at Birmingham (UAB) Hypertension Clinic for resistant hypertension and were enrolled over a 46-month period. Resistant hypertension was defined as uncontrolled hypertension (>140/90 mm Hg) as determined at 2 or more clinic visits, in spite of use of 3 or more antihypertensive medications at pharmacologically effective doses. Secondary causes of hypertension other than aldosteronism, such as renovascular hypertension, pheochromocytoma or Cushing's syndrome, had been excluded by laboratory analysis and/or radiological imaging as clinically indicated. Subjects with a history of congestive heart failure or chronic kidney disease (creatinine clearance <60 ml/min) were excluded from study participation. In the reporting of the results the investigators noted that there was no difference in mean office BP between aldosterone excess (H-Aldo) subjects and normal aldosterone status (N-Aldo) patients. Daytime, night-time, and 24-h systolic and diastolic BP were significantly higher in H-Aldo compared to N-Aldo males. Daytime, night-time, and 24-h systolic BP were significantly higher in H-Aldo compared to N-Aldo females. Multivariate analysis indicated a significant interaction between age and aldosterone status such that the effects of aldosterone on ambulatory BP levels were more pronounced with increasing age.

The purpose of the present research is to pursue the secondary finding of demographics and its relationship to aldosterone excess using a Bayesian logistic model. Applying a Monte Carlo Markov Chain approach, the authors focused on both age and gender as possible correlates of hyperaldosteronism. Using normal priors for the age and gender parameters we note that both younger age (posterior OR=1.04) and males (posterior OR= 4.33) are more likely to experience aldosterone excess. The 95% posterior credible intervals did not contain unity. Posterior density profiles also indicated marked departure from posterior expected unit odds ratios.

We demonstrate how the model performs under relevant clinical conditions. The conditions are all tested using a Bayesian statistical approach allowing for the robust testing of the model parameters under various stress conditions which we introduce into the model. The convergence of the parameters to stable values are seen in trace plots which follow the convergence patterns This allows for precise estimation for determining clinical conditions under which the logistic pattern will change. We give further numerical and graphical examples of our results.

Keywords: *Aldosterone, Bayesian, demographics, logistic, hypertension quality*

Using Time Series Analysis to forecast future RACGP OSCE capacity

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Abstract:

Problem:

The Australian government increased the number of first year general practice (GP) trainee places from 600 in 2010 to 1,200 in 2014 and again to 1,500 in 2015. No extra funding was provided to assess the clinical competency of the trainees to ensure they meet unsupervised Australian General Practice standards, that is, for trainees to be workforce ready.

Objective:

To forecast the timing and number of GP trainees requiring clinical assessment. The focus is the Objective Structured Clinical Examination (OSCE) at the Royal Australian College of General Practitioners (RACGP). This research will encourage a proactive approach to capacity planning and reduce potential GP workforce delays.

Participants/Data:

Historical aggregate RACGP and General Practice Education and Training (GPET) data were linked for the first time to produce time-series forecasts. Ethics approval was not required. Individuals could not be identified as only aggregate data was used.

Results:

The best forecast model from over 30 models was adjusted using GPET data. Based on two OSCEs a year, figures suggest a potential steady increase of candidates from 2014 semester 2 (2014.2) to 2016.2, with figures expected to reach about 900 and 1,100 respectively. In 2018.2, candidates are expected to peak to approximately 1,200 per semester.

For perspective, to assess 600 candidates, around 1,000 FRACGP GPs are required as examiners in a day. Current capacity is stretched to assess 800 candidates. More needs to be done to meet future expected candidates.

Conclusion:

The forecasts show how many candidates are expected to present for future OSCEs and their respective timing. This forecast can enhance current and future education and training capacity planning by planning additional exams, updating policies and continuing collaboration between organisations. Benefits of this research extend beyond the RACGP, medical workforce planning and continual professional development bodies. These forecasts could be applied in other health areas other than education. For example modelling patients, hospital resources required costs of services over time, etc.

Keywords: *Forecasting, time series analysis, general practice, workforce planning*

Hospital Event Simulation Model: Arrivals to Discharge

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Abstract: Many Australian public hospitals operate under strict resource constraints. Arguably, this is manifested in higher incidence of ambulance ramping and patient flow congestion episodes, which has led to an increase in public complaints and, possibly, sub-optimal health outcomes for patients. Consequently, there is a well accepted need to make best use of all available information and domain knowledge to ensure that hospital resources and expertise are utilised more efficiently, for the benefit of patients.

The latter is not a simple task since hospital operations involve complex interactions among many groups of health professionals utilising limited physical facilities and equipment. This is further complicated by the inherent variability of patient responses to treatments. Indeed, the stochastic nature of the demand process, as well as uncertainty in durations of medical treatments and patient recovery, lead to probabilistically distributed bed availability. Fortunately, in Australia, hospitals are "data rich" in the sense that reliable records of patient journeys have been kept for many years. While older data may reflect procedures and priorities that are no longer in place, data from recent years may be regarded as quite robust, especially in cities that have not experienced major demographic changes. Thus there is an opportunity to apply modern tools of mathematical, statistical and simulation modelling to enhance our understanding of key processes that influence a hospital's operations. The understanding so obtained can then be used to assist hospital staff in devising operational procedures that are likely to minimise disruption without adversely impacting the public service provided to the patient population.

In this paper we outline the Hospital Event Simulation Model: Arrivals to Discharge (HESMAD) to describe the patterns of patient flows within the Flinders Medical Centre, an urban teaching hospital. The logical design of HESMAD was developed through extensive consultation with colleagues from the hospital. In particular, patients within HESMAD are not modelled as identical entities, rather, they are assigned different attribute values such as mode of arrival, triage category and division to reflect the typical profile of all patients. Patients go through a set of physical units and process modules that model various physical areas, processes, interactions and behaviours within the hospital to replicate a wide spectrum of patient journeys. Hospital and patient data from 2012 to 2013 were used to fit various probability distributions, for instance the waiting times for treatment or discharges. The model allows for a realistic representation of patient flows, at a level of resolution that was deemed appropriate by the hospitals data management experts. The model has been validated against historical data and through consultation with health care and hospital experts.

Within space limitation we provide an outline and a brief discussion of HESMAD's structure, features, capabilities, design decisions and development. In addition, we provide a brief case study demonstrating the potential applicability of HESMAD for 'what if' analyses of hospital interventions. While all discussions are specific to the Flinders Medical Centre, the methodology used within HESMAD is generic enough to apply to other public hospitals in Australia.

Keywords: *Hospital operation, discrete event simulation, Poisson processes, simulation, modelling*

Optimization of patient scheduling in a hospital department

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Abstract: The efficient allocation of resources in medical organizations remains a pressing problem given the limited budgets often bestowed upon healthcare providers by governing bodies. Both the quality and efficiency of medical services delivered to patients are greatly affected by the level of coordination and organization achieved in these facilities, whose overall functioning is heavily dependent on the optimized scheduling of medical procedures, patient appointments and available facility resources. These appointment schedules can be constructed using various quantitative approaches. This study is conducted based on the analytical approach to scheduling, aiming to develop appointment schedules that reduce the idle time of departmental infrastructure. The study is aimed at developing an algorithm to assist scheduling in the Image Guided Therapy (IGT) Department, Hospital of Sick Children, Toronto, Canada. Data to test the algorithm were collected during a three week period of clinical sessions, running from 8:30 a.m. through 4:30 p.m. on weekdays. Emergency cases treated after clinic hours were not taken into account. 193 individual medical procedure cases were recorded and the obtained data were deemed sufficient to investigate a quantitative algorithm for schedule optimization. The IGT department works with three types of patients: outpatients, inpatients and emergencies; no walk-in patients were observed or expected. With the exception of extraordinary emergency cases, all patient arrivals are pre-scheduled in advance, allowing both inpatients and outpatients to be classified in the same way. Should an inpatient require an urgent procedure, they are re-classified as an emergency case, thus reducing the classification of patients to scheduled and emergency patients, respectfully. The department is equipped with four procedure rooms, but is only staffed to run a maximum of three simultaneously. Two rooms are fully equipped to implement any departmental procedures, while two others are limited in the types of procedures that can be performed. As a result, the availability of both a room appropriately suited to a given procedure, and a team of specialists to perform the procedure are aggregated into the concept of ‘a server’. Under this assumption, departmental operations can be considered a multi-server environment with different types of servers, namely, two servers implementing the full range of departmental procedures, and a single server limited in its scope. The difference in servers leads to variations in the multitude of cases treated during a clinical session. Patients are given an expected arrival time, and there is no preference for a given medical team incorporated into scheduling. A patient is, therefore, called from the queue when a suitable server becomes available. To formalize the queueing process, each clinical session is divided into 15-mintue time slots. Each appointment may last for the entirety of the allocated time slots. Any necessary room turnover time is added to the appointment time, resulting a minimum appointment duration of two time slots. The scheduling algorithm has been developed as an extension of the Generalized Bailey-Welch (GBW) rule, which was formulated for an environment with two functionally identical servers to minimize patient waiting time. The proposed algorithm starts from a schedule constructed in accordance with the GBW rule, extended to the case of three servers. The schedule is further modified to ensure server suitability for each case and to minimize the total idle time of all three servers. An efficient daily schedule, therefore, can be obtained as a solution of a series of static assignment problems, minimizing the goal function and reflecting time-based performance measures. In the first step of the study, emphasis is placed on developing deterministic schedules which do not incorporate extraneous factors of varying nature that affect schedules and their successful implementations. Such factors may include untimely patient arrival, patient health conditions and any complications sustained during procedures. These factors are stochastic and will be added to the model in the next steps of the study. The scheduling algorithm was programmed in MATLAB. The paper presents the comparison of proposed schedules with schedules used in the department and developed based on heuristic methods.

Keywords: *Generalized Bailey-Welch rule, time-based performance measure, multi-server environment, static assignment*

Determining the Optimal Number of Beds in the Subacute Section of a Large Hospital

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Abstract: Austin Health (AH) currently operates inpatient Continuing Care services across two satellite campuses, and faces the problem of calculating the optimal number of beds needed in its subacute wards. It is inefficient if a patient needs to wait in an acute ward for a bed in a subacute ward, just as is operating too many beds in the subacute ward to always meet demand. In recent years the demand for acute beds has increased, creating pressure for faster patient movements and more admissions at times of high demand, with the consequent need to determine best-performing bed configurations. Additional constraints, related mostly to availability of medical resources, were of concern to AH staff and were considered when developing the model. The subacute bed allocation problem is significant because it cannot be formulated in closed form using simple probability distributions, but demands the use of actual variable data on admissions and separations to ensure a reliable result. The solution approach we used to tackle the problem is based on the combined use of the cross-entropy method for optimisation. It uses the simulation of subacute ward occupation and demand using a parametric bootstrap to generate data to solve this problem. We used a simulation model to represent the six wards under study and the dynamic relationships that describe this system. To obtain the optimal bed configurations, we use the cross-entropy method for optimisation. This is a modern optimisation method whose working principle is based on the fact that cross-entropy divergence can be used as a measure of closeness between two sampling distributions. Optimisation by cross-entropy estimates a sequence of parametric sampling distributions that converges to a distribution with probability mass concentrated in a region of near-optimal solutions. We used a parametric bootstrapping approach to generate the admission data that is used as an input to the optimiser. The expected result is a slight increase in the number of existing beds. We justify the effectiveness of the proposed approach for determining the optimal number of beds on the grounds that the actual results and the general behaviour of the optimisation software in its current version match the intuition of hospital staff on the behaviour of the system.

Keywords: *e-Health, subacute bed allocation, cross-entropy optimisation, parametric bootstrap, hospital capacity planning*

Developing an eBoard for resource management in the Image Guided Therapy Department

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Abstract: The health care sphere presently faces a number of challenges. There is a steady necessity to improve the quality of services and to reduce their cost. Information technologies are an important factor in responding to these challenges. Health information systems are aimed to capture, store, manage and communicate information related to health at individual and population levels or the activities of organizations working within the health sector. The unique features of the e-health systems are rooted in the inherent confidentiality issues and diversity of the stakeholders involved in both development and utilization of the systems comprising of patients, doctors, nurses, administrators, scientists, payers, and regulators. Because of this diversity, health informatics is a multi-disciplinary field combining information science, computer science, economics, social science, epidemiology, behavioral science, public health and medicine.

Operations of the Image Guided Therapy (IGT) Department of the Hospital for Sick Children ("SickKids"), Toronto, Canada have been investigated in the study. IGT provides valuable diagnostic and therapeutic data using procedures that involve different forms of anesthesia or sedation administered to the patients. Procedures done at the IGT can be divided into three major groups: (1) general anesthetic (GA) cases, which require complete anesthesia of the patient; (2) registered nurse (RN)-sedation or non-GA cases, which do not require complete anesthesia; and (3) local cases done under local anesthesia. The department works with three main groups of patients: inpatients, outpatients and emergency cases. There are also different types of imaging produced: ultrasound, fluoroscopy/digital subtraction angiography and computerized axial tomography (CT/CAT scan).

The coordination of departmental resources and scheduling procedures is a necessary step in improving the efficiency of the department's operation. At present, IGT utilizes a manual version of the operation board to facilitate communications and coordination of all the resources, including radiologists and fellows, anaesthesiologists, technologists and nurses as well as operation, observation and consultation rooms, *etc*.

A computer-based application called "eBoard" implementing board functions is suggested. It can be considered as a transaction processing system which stores and updates necessary data and delivers them in an organized form on request. The application does not require complex computational algorithms for data processing. The data manipulation operations include capturing and entering the data stored in a database, retrieving the data and organizing them in a predefined format. For such types of data processing activities, the utilization of CASE tools is warranted and can be very beneficial. Given that this system should be integrated with other departmental and hospital information systems, the principles of modularity and extensibility of software components become essential.

The object-oriented approach (OOA) in combination with the Unified Modeling Language (UML) have been applied in the development of the eBoard information system for the IGT department. An obvious advantage of the UML is the availability of multiple commercial and free code-generating and round-trip engineering CASE-tools. As a comprehensive design, modeling and development CASE tool supporting the OOA and integrated with the UML, IBM® Rational® Software Architect was selected.

Although many IT projects in health care do utilize the UML, it is possible to conclude that a common methodology or standardized framework to do so is still lacking. This issue needs a further elaboration and will be addressed in the presentation. The paper is intended to inspire and shape the discussion within the session on "Health Information Systems: Challenges and Solutions".

Keywords: *Health information system, Unified Modeling Language (UML), actor, use case*

Simulation modelling: A systems approach to support the use of evidence to inform decision making in gestational diabetes care

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Abstract: This project will apply and evaluate a simulation modelling approach to understand the factors associated with gestational diabetes and its treatment. It will examine participatory group model building as a tool to support evidence synthesis, knowledge exchange, and consensus building on the relative merits of prevention policy options.

Simulation modelling offers a unique tool for synthesizing and leveraging existing evidence, data, and expert local knowledge to examine in a robust, low-risk and low cost way the likely impact of alternative policy and service provision scenarios for the management of gestational diabetes. Gestational diabetes (GDM) has been chosen as a case study as pregnancy has been identified to be a point in the life cycle where individuals have increased motivation to commit to health improving behaviours such as smoking cessation. A diagnosis of GDM (or even a Glucose Tolerance Test result that approaches the diagnostic cut-off) may provide a leverage point for multidisciplinary health interventions promoting lifestyle change to reduce the risk of developing diabetes later in life.

Policy, clinical practice and research experts will work collaboratively to develop, test and validate a simulation model of gestational diabetes in the ACT. The model will be applied to support evidence-informed 'policy dialogues' with diverse stakeholders to build consensus on an efficient, effective, equitable and acceptable course of action for the management of gestational diabetes in the ACT.

The case study methodology allows for illustration of the strengths and weaknesses and evaluation of simulation modelling as a mechanism to inform policy and program decision making and develop consensus on policy and program actions. The key evaluation questions include those relating to engagement of experts in the process; perceived commitment, influence and confidence of stakeholders in implementing policy and program decisions identified in the modelling process; and measuring the impact of the process in terms of policy and program change.

Evaluation methods to determine the effectiveness and impact of simulation modelling will include:

- observations and/or recordings of the group model building process
- pre- and post- surveys with participants to measure change in perceptions regarding comparative impact of risk factors, screening times and methods, interventions and individual maternal characteristics on prevalence of gestational diabetes and resulting outcomes.
- semi-structured interviews with participants regarding their engagement with the process and their confidence in the resulting model
- environment scan to determine the policies and program decisions that were informed by the modelling process and the model outputs.

The study will generate empirical evidence on the feasibility and potential value of simulation modelling to support knowledge exchange and consensus building in health settings.

***Keywords**:* *Health systems, participatory modelling, gestational diabetes*

Modelling change in multivariate depression symptoms adjusting for gender and baseline temperament and character traits: a Latent Transition approach

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Abstract: Personality is linked to mental illness. Data on 9 symptoms of psychological distress items of the Symptom Checklist (SCLs) (Derogatis, 1983) and 7 temperament and character traits (TCIs) of Cloninger (2008) were analysed from patients measured pre and post treatment from the NZ Christchurch Psychotherapy of Depression Study (Joyce et al. 2002; Turner, Hudson et al., 2003). Latent transition analysis (LTA) was used to investigate: How do depressive symptom *patterns* change over time pre and post treatment; is this change different across gender and how is it impacted by baseline temperament and character traits (TCIs).

The LTA model found 4 latent classes based on the multivariate symptom response profiles of 9 SCLs. The 4 patient classes represent different levels of symptom risk whose interpretation varies across gender. Latent class 1 (C1), a high risk group was characterised by high probabilities of elevated scores on all 9 SCL items. Class 2 (C2) a low risk group was characterised by a low risk of high scores on all SCLs. In fact the likelihood of scoring above the median for depression, phobic anxiety and anxiety was zero for both sexes in C2. Class 4 males were characterised by very high depression, interpersonal sensitivity (IS), psychoticism (P) and OC, intermediate anxiety (A), phobic anxiety (PA) and paranoid ideation (PI) but low scores on somatisation (S). In contrast C4 females had a high risk of elevated anxiety and P, intermediate OC, depression and S, but low scores on IS, anger hostility (AH), PI and PA. Class 3 females exhibited very high IS, high P, intermediate AH, PI and depression risk, and low scores of (phobic) anxiety. Class 3 males had very high P and intermediate S risk, and like C3 females low scores on IS, AH and PA. Anxiety differentiated females across C3 and C4. Apart from the high risk class, C1, only C4 females had increased anxiety risk. The latent classes seem to represent a scale of distress risk, suggesting a continuum of low to high risk, as opposed to qualitatively different groups.

LTA transition probabilities pre to post treatment showed the males had a higher chance of remaining in the high risk class than females. For both sexes at high risk pre-treatment, 0% transitioned from C1 to C4 post-treatment. For females at high risk pre-treatment, 37% moved to low risk, but only 20% males moved from high to low risk. Neither gender transitioned from C4 to C3. Three times more males in C3 remained in C3 (very high P, intermediate somatisation, low scores on IS, AH and PA) compared to females. The proportion of males remaining in C4 (high depression, IS, psychoticism and OC, and intermediate A, PA and PI) was over twice the C4 female rate (high anxiety and P, intermediate OC and depression). No males starting in the low risk class transitioned to the high risk class, compared to 6% of females, whereas of females starting in the low risk group a quarter transitioned to C4. Three times more males starting in C3 transitioned to the high risk class than for C3 females, and more than twice as many males moved from C3 to C4. A quarter of females starting in C4 transitioned to the high risk class, but no C4 males moved to the high risk class C1 post-treatment.

Two character traits, self-directedness (SD) and self-transcendence (ST) were highly significant predictors of latent class status. In general higher ST was associated with higher distress and higher SD with lower distress. The impact of ST and SD varied across gender in class 4 and to a lesser extent in the low risk class. There was an enhanced benefit of increased SD for both sexes, especially for females in C4 characterised by a high risk of anxiety and P, intermediate OC, depression and S, but low scores on IS, AH, PI and PA, and for males in the low risk class. Increasing SD did not benefit the C4 males characterised by very high depression, IS, OC, and P, intermediate phobic/anxiety and PI, but low somatisation. Similar for both sexes, high ST was associated with higher odds of distress, except for males in C4. Low risk females were less likely to be in the low risk class (*vs* high) for a one unit increase in ST, and C2 males had a slightly less reduced odds of low risk *vs* 'high' risk status. This work extends Leigh et al. (2012) and shows that 4 discernible classes differed across gender, and transitions between classes pre to post treatment differed across gender (after baseline TCI adjustment). This study adds credence to the need for gender-specific scores of psychological distress risk to be developed.

Keywords: *Latent transition analysis, psychological distress, temperament and character traits, gender*

EXTENDED ABSTRACT ONLY

Do Working Hours Matter in Maintaining Cognitive Ability among Middle-Aged and Older Adults?

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Abstract: Using panel data from the Household Income and Labour Dynamics in Australia (HILDA) Survey, we examine the impact of working hours on the cognitive ability of Australians aged 40 and older. An aging population is a serious issue for many developed countries, and Australia is no exception. An aging population raises concerns of a potential shortage of labour supply. An obvious policy solution to this potential labour shortage is to delay the age at which individuals retire. Previous studies suggest that following retirement, cognitive performance declines because retired individuals do not use their cognitive skills as much as when they are working. This suggests that working in old age is potentially important for maintaining cognitive ability. However, long working hours can cause fatigue which potentially damages cognitive functions (Virtanen et al., 2008). Thus, the relationship between working hours and cognitive ability is not clear. In particular, whether part-time or full-time work is more important for maintaining cognitive ability in old age has not been determined.

There are three measures of cognitive ability in the HILDA Survey. The first measure is the Backward Digit Span (BDS); the second is the Symbol Digits Modalities (SDM); and the third is a 25-item version of the National Adult Reading Test (NART25). BDS is a test of working memory span and is used in many traditional intelligence tests. SDM is a general test for divided attention, visual scanning, and motor speed. NART25 is a reading test for providing a measure of mainly crystallized intelligence. We use a respondent's BDS, SDM and MART25 scores as measures of the respondent's cognitive ability.

In order to capture the potential non-linear dependence of cognitive ability on working hours, the model for cognitive ability includes working hours and its square. We deal with the potential endogeneity of the decision of how many hours to work by using the instrumental variable estimation technique. From estimates of a model for working hours, the fitted values of working values and the square of the fitted value of working hours are obtained and used as instruments when estimating the model of cognitive ability. One potential problem in using working hours as the variable of interest is that working hours are left censored, that is, for individuals who are retired or unemployed, working hours are treated as zero. In order to take account of these zero values in the working hours, we apply the Tobit estimation technique when estimating the model for working hours.

Our findings show that there is non-linearity in the effect of working hours on cognitive functioning. For working hours up to around 25 hours a week, an increase in working hours has a positive impact on cognitive functioning. However, when working hours exceed 25 hours per week, an increase in working hours has a negative impact on cognition. These results suggest that people in old age could maintain their cognitive ability by working in a part-time job such as 20–30 working hours per week.

Keywords: *Cognitive ability, retirement, working hours*

Modelling risk profiles of depression symptoms using Cloninger's temperament and character traits: a non-iterative approach to assess linear-by-linear association within ordered contingency tables

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Abstract: Personality is linked to mental illness. The relationship between the seven temperament and character traits (TCIs), (Novelty seeking (NS), Harm Avoidance (HA), Reward Dependence (RD), Persistence (P), Self-directedness (S), Cooperativeness (C) and Self Transcendence (ST)), of Cloninger (1994) and three symptoms of psychological distress, or SCLs (Depression (D), Anxiety (A) and Psychoticism (Psy)) is investigated across gender and shown to have significantly different symptom profiles post treatment. The data used in this study was earlier analysed by Turner, et al. (2003) and comes from patients measured pre and post-treatment from the NZ Christchurch Psychotherapy of Depression Study (Joyce, et al. 2002). In this study we have used the newly developed direct estimation approach (Beh and Davy, 2004 and Zafar et al., 2015) to estimate the linear-by-linear association in two-way tables, within the framework of ordinal log-linear models (OLLMs), with the aim of analysing associations between the TCIs and SCLs. Two non-iterative estimators were considered for this study – the Beh-Davy non-iterative estimator (BDNI) (Beh and Davy, 2004) and the Log non-iterative estimator (LogNI) (Beh and Farver, 2009). The BDNI and LogNI estimation methods provide closed-form estimators which do not require iteration to estimate the linear-by-linear association parameter of OLLMs, unlike their conventional and iterative counter parts, such as the Newton-Raphson and the iterative proportional fitting methods.

The estimates obtained from the BDNI and LogNI estimation methods are reported, for pairwise relationships between TCIs and symptoms, along with the standard errors and p-values for males and females for pre and post treatment. Both estimators, BDNI and LogNI, provide estimates which are close to each other. We found significant changing relationships between the seven TCIs and psychological distress symptoms across gender for NS and P post treatment; with both TCIs and SCLs dichotomised by the median. We found statistically significant differences between the BDNI and LogNI estimates for males and females, post-treatment; establishing that higher levels of NS are associated with less D and Psy in males as compared to females. Higher HA is shown to be associated with higher D, A and Psy in males and females, pre and post-treatment. S is found to be negatively related to D, A and Psy for males and in females, pre and post-treatment. P is demonstrated as gender-specific only in the case of D; with less D associated with higher levels of P in males comparison with females post treatment. In addition, we demonstrate the linear-by-linear association between pre-treatment TCI's and change in depression, anxiety and psychoticism (ΔD, ΔA and ΔPsy), where the change is defined as categorised by the median scores of the (post – pre-treatment) levels. We show that pairwise association between three TCI's (HA, P and C) and two of our three symptoms of psychological distress, ΔD and ΔPsy, are gender-specific. These results reported agree, in part, with preliminary univariate Generalised Additive Model for Location, Scale and Shape (GAMLSS) models based on the combined pre and post treatment data (Hudson et al., 2015a), which allow for non-linearity between TCIs and symptoms, and for interactions between TCI with gender and time.

Keywords: *Ordinal log-linear model, non-iterative estimation, linear-by-linear association, temperament and character traits inventory (TCI), symptom checklist (SCL)*

Can we use the approaches of ecological inference to learn about the potential for dependence bias in dual-system estimation?

An application to cancer registration data

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Abstract: The dual-system estimator, or estimators with a similar underlying set of assumptions and structure, is a widely used approach to estimate the unknown size of a population. Within official statistics its use is linked with population census, while in health applications it is often used to estimate true levels of incidence from imperfect reporting systems; the classic example being work by Sekar and Deming exploring the estimation of births in India in the 1940s. Critical to the implementation of dual-system estimation are the assumptions that the probability of being counted in a source is homogeneous and that the event of being counted in each source is independent. When either of these assumptions fails, the two by two table will have an odds ratio different to one and the dual-system estimator will be biased.

Inferential frameworks such as the aggregate association index (AAI) have been developed to allow the researcher to assess the plausibility of independence between two variables in a two by two table, when only the margins are observed. Given any appropriate measure of relationship, this strategy relies on determining the AAI, which provides an indication of the likely association structure between the variables given only the marginal information. Further advances of the AAI have also been established including its link with the odds ratio and its relationship with the size of the study being undertaken. Determining the population size from a two by two table given limited information is an alternative variation of the framework on which the AAI is built. Therefore the underlying theoretical properties of the two by two table are identical in both scenarios – it is only the nature of the unknown information that differs.

In this paper we make the first steps to exploring the use of an AAI type framework (and its relatives) to assess the plausibility of an independence assumption in applications of population size estimation. We use alternative data set-ups based on real data relating to historical cancer registration (with three sources of registration) to demonstrate that the chi-square statistic behaves differently over a range of values for the missing data for differing true relationships between the two variables. We then apply the approach to the cancer registration from two of the registration systems to show that we can see evidence of potential dependence from the observed but incomplete data.

The first results in this paper demonstrate the possibility of exploring the independence assumption when estimating the unknown population size from two lists. As with the AAI framework, the aim is not to directly estimate the level of the association but rather alert the analyst to the potential for an association and its direction allowing them to assess the likelihood of a biased estimate for the population size. This has important implications within a health setting where it is potentially useful to understand if the true population size, of say cancer patients, is likely to be higher or lower than the estimate constructed assuming independence. Within the official statistics setting, it can alert us to situations where it is advantageous to explore whether external data exist that would allow an adjustment for dependence in our two lists.

Keywords: *Aggregate association index, dual-system estimation, dependence, ecological inference, measures of association*

On the quantification of statistical significance of the extent of association projected on the margins of 2x2 tables, when only the aggregate data is available: A pseudo p-value approach – applied to leukaemia relapse data

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Abstract: Aggregate data arises in situations where survey research or other means of collecting individual-level data are either infeasible or inefficient. The recent increasing use of aggregate data in the statistical and allied fields – including epidemiology, education and social sciences – has arisen due to number of reasons. These include the questionable reliability of estimates when sensitive information is required, the imposition of strict confidentiality policies on data by government and other organisational bodies and in some contexts it is impossible to collect the information that is needed. In this paper we present a novel approach to quantify the statistical significance of the extent of association that exists between two dichotomous variables when only the aggregate data is available. This is achieved by examining a newly developed index, called the *aggregate association index* (or the AAI), developed by Beh (2008 and 2010) which enumerates the overall extent of association about individuals that may exist at the aggregate level when individual level data is not available.

The applicability of the technique is demonstrated by using leukaemia relapse data of Cave et al. (1998). This data is presented in the form of a contingency table that cross-classifies the follow up status of leukaemia relapse by whether cancer traces were found (or not) on the basis of polymerase child reaction (PCR) – a modern method used to detect cancerous cells in the body assumed superior than conventional for that period, microscopic identification.

Assuming that the joint cell frequencies of this table are not available, and that the only available information is contained in the aggregate data, we first quantify the extent of association that exists between both variables by calculating the AAI. This index shows that the likelihood of association is high. As the AAI has been developed by exploiting Pearson's chi-squared statistics, the AAI inherently suffers from the well-known large sample size effect that can overshadow the true nature of the association shown in the aggregate data of a given table.

However, in this paper we show that the impact of sample size can be isolated by generating a pseudo population of 2x2 tables under the given sample size. Therefore, the focus of this paper is to present an approach to help answer the question "*is this high AAI value statistically significant or not?*" by using aggregate data only. The answer to this question lies we believe, in the calculation of the p-value of the nominated index. We shall present a new method of numerically quantifying the p-value of the AAI thereby gaining new insights into the statistical significance of the association between two dichotomous variables when only aggregate level information is available. The pseudo p-value approach suggested in this paper enhances the applicability of the AAI and thus can be considered a valuable addition to the literature of aggregate data analysis.

Keywords: *Aggregate data, Aggregate Association Index, pseudo p values, Ecological inference, sample size*

Inference and Simulation for Dynamic Network Models from Egocentrically Sampled Data

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Abstract: In epidemiological modelling of sexual partnership networks, it is often of interest to model and simulate not just the presence of relationships of interest but their timing. Yet, the data available are often limited: rather than observing a network in the conventional sense—as a set of relations among the actors of interest—only an *egocentric* view is available: a subset of individuals (egos) in the network is surveyed, and only information about their partners (alters) is observed, and often only their demographics and not identities. Furthermore, most of such surveys only provide a snapshot at a single point in time, albeit with additional information about duration of extant and recent ties.

One practical approach to fitting dynamic network models to these data is to find what network evolution parameters had to have been in order to induce, in the long run, the network with properties implied by the egocentric data. That is, suppose that function $\boldsymbol{t}(\boldsymbol{y}^{\text{obs}})$ of the network evaluates features of interest that can be inferred from such data (e.g., numbers of partners actors have, covariate, and assortative (by age and ethnicity) and disassortative (by sex) mixing, and average duration of ties), and suppose that the model for network evolution $p_{\boldsymbol{\theta}}(\boldsymbol{y}^t|\boldsymbol{y}^{t-1})$, parametrised by $\boldsymbol{\theta}$ (such as the exponential-family random graph model (ERGM)-based separable framework) is ergodic, so that a unique equilibrium distribution $p_{\boldsymbol{\theta}}(\boldsymbol{y}^t)$ exists. An equilibrium generalised method of moments estimator (EGMME) is then

$$\tilde{\boldsymbol{\theta}} \equiv \arg\min_{\boldsymbol{\theta}}\{\boldsymbol{\mu}(\boldsymbol{\theta}) - \tilde{\boldsymbol{t}}(\boldsymbol{y}^{\text{obs}})\}^\top \boldsymbol{V}(\boldsymbol{\theta})^{-1}\{\boldsymbol{\mu}(\boldsymbol{\theta}) - \tilde{\boldsymbol{t}}(\boldsymbol{y}^{\text{obs}})\},$$

for $\boldsymbol{\mu}(\boldsymbol{\theta}) \equiv \mathrm{E}_{\boldsymbol{\theta}}\{\boldsymbol{t}(\boldsymbol{y}^t)\}$, $\boldsymbol{V}(\boldsymbol{\theta}) \equiv \mathrm{Var}_{\boldsymbol{\theta}}\{\boldsymbol{t}(\boldsymbol{y}^t)\}$, and $\tilde{\boldsymbol{t}}(\boldsymbol{y}^{\text{obs}})$ being the estimated value of $\boldsymbol{t}(\boldsymbol{y}^{\text{obs}})$. Then, simulating from the fit reproduces network series from which the data could have plausibly come. This approach has yielded promising results, and has been used to study the effects of concurrent sexual partnerships (as opposed to serially monogamous ones) on the spread of STIs like HIV.

In this work, we consider the two major sources of uncertainty in $\tilde{\boldsymbol{\theta}}$: loosely, *when* the egocentric sample was taken (in that the state of the network could have been different at a different time, resulting in a different $\boldsymbol{y}^{\text{obs}}$) and *who* was in the egocentric sample (in that had different individuals been surveyed, a different $\tilde{\boldsymbol{t}}(\boldsymbol{y}^{\text{obs}})$ would have been inferred), and quantify and combine the uncertainty from these two sources, showing that under repeated egocentric sampling, the variance of $\tilde{\boldsymbol{\theta}}$ is approximately

$$\mathrm{Var}(\tilde{\boldsymbol{\theta}}) \approx \boldsymbol{D}(\tilde{\boldsymbol{\theta}}) + [\boldsymbol{D}(\tilde{\boldsymbol{\theta}})\boldsymbol{G}(\tilde{\boldsymbol{\theta}})^\top \boldsymbol{V}(\tilde{\boldsymbol{\theta}})^{-1}\widetilde{\mathrm{Var}}\{\tilde{\boldsymbol{t}}(\boldsymbol{y}^{\text{obs}})|\boldsymbol{y}^{\text{obs}}\}\boldsymbol{V}(\tilde{\boldsymbol{\theta}})^{-1}\boldsymbol{G}(\tilde{\boldsymbol{\theta}})\boldsymbol{D}(\tilde{\boldsymbol{\theta}})],$$

where $\boldsymbol{G}(\boldsymbol{\theta}) \equiv \partial\boldsymbol{\mu}(\boldsymbol{\theta})/\partial\boldsymbol{\theta}$, so that $\boldsymbol{D}(\boldsymbol{\theta}) \equiv \{\boldsymbol{G}(\boldsymbol{\theta})^\top \boldsymbol{V}(\boldsymbol{\theta})\boldsymbol{G}(\boldsymbol{\theta})\}^{-1}$ is the estimated variance in $\tilde{\boldsymbol{\theta}}$ due to *when* the sample was taken, and $\widetilde{\mathrm{Var}}\{\tilde{\boldsymbol{t}}(\boldsymbol{y}^{\text{obs}})|\boldsymbol{y}^{\text{obs}}\}$ is the estimated variance of $\tilde{\boldsymbol{t}}(\boldsymbol{y}^{\text{obs}})$ for a given $\boldsymbol{y}^{\text{obs}}$ due to *who* was sampled.

We apply this to egocentrically sampled sexual partnership network data. This technique, while it depends strongly on the assumption that the network process modelled is in equilibrium for inference, can also be used to obtain the full range of predictions for evolution of the network that are consistent with the observed data, as opposed to just the predictions based on the point estimate $\tilde{\boldsymbol{\theta}}$.

Keywords: *Dynamic network, separable temporal exponential-family random graph model, STERGM, ERGM, generalised method of moments estimation*

Prediction of shear strength of concrete structures based on ANFIS

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Abstract: Shear failure of concrete structures is a complex phenomenon, which may be triggered by various different failure mechanisms. The complexity of the shear problem is also attributed to the ambiguity of modeling parameters (e.g. concrete cracking strength) and the difficulty in precise measurement of parameters (e.g. cracking angle); this precise measurement of parameters cannot be captured by the classical empirical approaches used in the existing design codes. Therefore, a more robust modeling technique is needed which can account for the dependence of shear strength on a number of interacting variables and the inherent uncertainty (randomness, vagueness, and ambiguity) in shear modeling and definitions. In the present study, an alternative design method using fuzzy set theory was developed to predict the shear strength of slender concrete beams.

The fuzzy sets defined by the degree of membership could represent non-random uncertainty due to fuzziness, vagueness, and/or ambiguity, and the bell-shape membership function was adopted in the present study, using three parameters representing the center, top width, and shape of the membership function.

To evaluate the shear strength of slender beams with/without shear reinforcement, adaptive neuro-fuzzy techniques were used by combining neural network and fuzzy inference system. In addition, the adaptive network-based fuzzy inference system (ANFIS) was used to optimize design parameters for Sugeno systems. These techniques are in order to implement the human learning ability and the human decision making skills.

Analytical techniques using Bayesian modeling with the aid of Markov Chain Monte Carlo Methods could be used to examine the significance of all possible parameters affecting the phenomenon. In the current analysis based on Bayesian modeling techniques, the significance of various possible parameters were examined, including concrete compressive strength, effective depth, span length, shear span to depth ratio, beam size, compression and tension reinforcement ratios, and shear reinforcement ratio.

In addition, the second step in ANFIS is the fuzzification process in which the type and number of the membership function for each input parameter are determined. The third step in ANFIS is to establish the fuzzy rule-base which describes the output (shear strength) defined for each fuzzy set. The exemplar in the fuzzy rule-base is defined using the ‘if-then’ rule. Then, the shear strength of slender concrete beams can be computed as weighted predicted strength the fuzzy rule-base. The learning process was aimed at defining the unknown parameters for the fuzzy-based model, and was performed iteratively to obtain the optimal premise parameters and the consequence coefficients until the root mean square prediction error becomes a target root mean square prediction.

For training and testing the fuzzy-based model, 636 test datasets that were reported to have failed in shear (no flexural failure) were used. In the comparison, it is found that the fuzzy-based model predicts the shear strength with a consistent accuracy according to various design parameters: concrete compressive strength, reinforcement ratio, and effective depth while the existing design methods do not accurately evaluate the shear strength of concrete beams.

As conclusions, a rational shear design method of slender concrete beams was developed based on fuzzy learning from examples. The proposed method is applicable to simply supported slender concrete beams with and without shear reinforcement and yields acceptable accuracy in the prediction of shear strength. The fuzzy-based model shows better accuracy in strength prediction than current design codes such as ACI 318-11 and EC2, which indicates that the proposed model is able to address uncertainty and interactions between modeling parameters.

Keywords: *AI, fuzzy theory, ANFIS, concrete structures, strength prediction*

Lattice gas model for company profit: cooperative relation between contractors and subcontractors

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Abstract: In Japan, there are many long-lived companies which survive more than 200 years. Such companies typically use a cooperative strategy: win-win interactions with other companies. It is very rare for them to dismiss subcontractors. In the present article, we apply ecological theories of population dynamics to illustrate how cooperative management promotes sustainability. We assume three contractors compete in a single market. The scenario examined illustrates that the dismissal of subcontractors is optimal for very short periods, but not optimal in relatively long periods. Hence, the long-term dynamics and perspectives are necessary to know the superiority of cooperative management.

Keywords: *Company management, cooperation, long-lived companies, contractor and subcontractor, long-term optimality*

Estimating hitting probabilities of an interacting particle system on a graph

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Abstract: We consider the problem of estimating hitting probabilities related to a class of interacting particle systems. These systems, in which two types of particles — 'electrons' and 'holes' — move on a graph, are simplified versions of models describing charge transport in disordered materials. The probability of interest is the probability that an electron reaches a certain region of the graph before colliding with a hole. We provide a detailed description of our model and explain how it can be simulated. Next, we give a brief introduction to importance sampling, which we use to improve the efficiency of our estimators. To our knowledge, importance sampling has not yet been used to estimate probabilities related to interacting particle systems. We describe how importance sampling can be used to improve the efficiency of estimators of hitting time probabilities involving discrete time Markov chains. We then use importance sampling to estimate the probability that we are interested in. In doing so, we observe that there are a number of complexities that arise when working with interacting particle systems. We describe some simple heuristics for implementing importance sampling. These heuristics make minimal changes to the probability measure under which the original system evolves. We consider a specific example of our problem and investigate the effectiveness of the importance sampling approach. We show that our estimators outperform standard Monte Carlo estimators. Finally, we describe possible future work, which includes a more sophisticated importance sampling approach that uses 'locally optimal' changes of measure.

Keywords: *Importance sampling, Monte Carlo, interacting particle systems, hitting time, rare event simulation, Markov chains*

Fisher Information, stochastic processes and generating functions

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Abstract: Continuous-Time Markovian Population Models (CTMPM) continue to gain in popularity for modelling a range of phenomena, including evolutionary, ecological and epidemiological processes. The reason is their ability to reflect the discrete, interacting and random nature of these processes while retaining numerical efficiencies. Inherent in the application of CTMPMs is the ability to estimate the parameters of these models. The Fisher Information (FI) arises in such situations of inference and optimal experimental design. Thus, the evaluation of the FI for CTMPMs is important.

In 1983, Becker and Kersting considered the use of experimental design theory to determine the optimal times at which to observe a population governed by a CTMPM, the so-called simple birth process. Although Becker and Kersting were able to derive an explicit expression for the FI for the simple birth process as a finite series, contributions to the evaluation of the FI for CTMPMs were rather minimal until recently.

We consider another extension increasing yet further the applicability of the simple birth process. This is the evaluation of the FI for the simple birth process in the situation where each observation is a Binomial random variable of the true population size (with fixed probability of observation for all time). We name this CTMPM with binomial observations the Partially-Observable CTMPM (POCTMPM). For example, in biological invasions, the species, or each individual of the species, may only be detected with a certain probability upon each survey. This may be due to practical restrictions such as time and budget constraints which limits the ability to survey comprehensively, or might be an implicit component of the data collection process. This extension is extremely realistic in ecological and epidemiological applications and also substantially increases the complexity of the analysis.

I, in collaboration with Bean, Elliott and Ross, showed that POCTMPM is not a Markovian process and accordingly finding the FI for a POCTMPM, in general, appears intractable. Nevertheless, I, in collaboration with Bean and Ross, exploited probabilistic properties of the POCTMPM and derived an approximation for the FI. We showed, both theoretically and numerically, that the approximation acquired a good level of precision. However, this approximation is limited to only two observation times which is not large enough. Recently Salavy and I, exploited the concepts and techniques of generating functions from the area of Experimental Mathematics to develop a novel approximation for the FI. Our preliminary results revealed that this new approach surprisingly could reduce the run-time of the computation of the FI by a factor of at least 32,000!

These promising analytical and numerical results are the motivation of establishing the following research directions in future: (i) Developing an efficient approximation for the FI for higher number observation times; (ii) Considering the fixed probability of observation as unknown parameters and attempting to find the FI of the observations in the POCTMPM by considering this assumption. Clearly, in this case, the FI is a matrix and one is commonly interested in finding the determinant of this matrix; (iii) Developing all these results for a more general and, perhaps, practical POCTMPM, the so-called a birth-and-death process.

Keywords: *Simple birth process, Fisher Information, binomial observations, generating functions*

Mean Shift Detection for State Space Models

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Abstract: In this paper we develop and validate a procedure for testing against a shift in mean in the observa-tions and hidden state sequence of state space models with Gaussian noise. State space models are popular for modelling stochastic networks as they allow to take into account that observations of the true state of a sys-tem may be corrupted by measurement noise (usually, a Gaussian noise process is assumed). Although state space models are very general, they are still relatively tractable in that the true system state can be estimated efficiently by a recursive procedure known as Kalman filtering.

State space models can be regarded as a special type of hidden Markov model. As such, they are a flexible modelling tool that has been found useful, for example, for modelling road networks (Stathopoulos and Karlaftis, 2003) to account for uncertainty in the measurement of travel times. For instance, we may assume that travel times have to be estimated from flow and occupancy data. An increase in the unobserved mean travel time can be caused by traffic congestion; a shift in the mean value of the observations on the other hand could indicate a bias of the sensors. State space models can also be used to model communication networks: Suppose that the current *state* of a channel (e.g. measured by the probability of packet loss) is not observed directly, but has to be inferred from the received package flow. A change in the mean value of the hidden state sequence, or a change in the mean value of the received package flow can deteriorate the performance of the network if it remains unrecognised.

This motivates us to investigate procedures for testing against a shift in mean in the observations and hidden state sequence of state space models. The objective is to detect a change as quickly as possible while keeping the ratio of false alarms at a pre-specified low level.

Since the observations are generally not independent, in (Basseville and Nikiforov, 1993) a cumulative sum (CUSUM) procedure is applied to the (independent) sequence of innovations, which is obtained as a by-product from Kalman filter estimation of the hidden states. That is, a log-likelihood ratio (LLR) test statistic is used and an alarm is raised as soon as this test statistic exceeds a certain threshold that is assumed to be given. Change point detection for state space models has also been considered in (Lai and Shan, 1999) for the case where the size of the mean shift is unknown, in which case a generalized LLR test can be applied.

In this paper we tackle the question of how the threshold of the sequential LLR test can be chosen when the shift size is assumed to be known. In practice, the latter assumption can be dealt with by realizing that typically there will be a minimum change size that is of interest from an engineering perspective, and that can thus be used as input for the model. Based on this assumption we can identify the appropriate level of the threshold based on approximations of the false alarm probability – essentially the probability that a random walk process exceeds a given threshold on an interval.

A persistent change in the mean value of the observations results in a dynamic change in the mean value of the innovations, which are therefore not identically distributed after the change point. However, it follows from the stability properties of the Kalman filter that under weak conditions the magnitude of the shift converges to a constant. This allows for large-deviations (LD) approximations as well as approximations motivated by a functional central limit theorem (CLT). LD approximations to the false alarm probability have been considered in (Bucklew, 1985; Ellens et al., 2013; Kuhn et al., 2014) for testing i.i.d. and vector autoregressive moving average (VARMA) models. CLT approximations were motivated, for example, in Siegmund (1985). We compare the numerical performance of the tests under both types of limiting regimes with respect to the false alarm probability and the detection delay.

Keywords: *Change point detection, threshold approximation, state space models, Gaussian processes*

A Simulation Algorithm for Queueing Network Stability Identification

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Abstract: One of the first considerations in the design of a queueing system is ensuring stability. This is a guarantee that the capacity of the system is sufficient to meet demand in the long run. Due to this, the stability of queueing systems has long been an area of intense research by the applied probability community. The aim of this research has been to determine the set of parameters, such as arrival or service rates, for which the number of customers in a given queueing system will remain finite over time. For us this means that the drift of the system's size is expected to remain sublinear. We call the set of parameters satisfying this condition the stability region, and develop a method to efficiently find it using simulation.

Since determining the stability region of a given queueing network is often a highly non-trivial task, results are primarily only available for specific, relatively simple, systems. There does not currently exist a unified framework with which to determine the stability region of a general queueing network. Moreover, for many systems a closed form expression for the stability region is not mathematically tractable. In this case a sensible approach is to use an approximation method that provides a reasonable guarantee of determining the stability region.

It is common to use simulation to establish stability for a given choice of parameters. If a particular parameter choice appears to result in the simulated queue size becoming unbounded over a long time frame, then this is often taken as an indication that the parameter choice is unstable. To determine the stability region more generally requires a sequence of simulations, and it is sometimes possible to perform an exhaustive search (up to a chosen granularity) of the parameter set to identify which choices appear to produce unstable behaviour. In other cases, however, such a search may be computationally infeasible. It is therefore sensible to develop methods of ensuring that available computational effort is allocated in the search of the parameter space in an efficient manner.

In this talk we will discuss an approach to searching the parameter space which is based on the well known simulated annealing optimisation algorithm. Our principle result shows that the stability of a set of parameters for a given system can be summarised using a single Markov chain that randomly searches the parameter space for an element that is 'most likely' to induce instability.

Our algorithm is given informally as follows. Consider a set of Markov chains $(X_\lambda : \lambda \in \mathcal{L})$, each with state space $\mathcal{X}$, where $\mathcal{L} \subset \mathbb{R}^n$ parameterises different configurations of the chain. For instance, $\lambda \in \mathcal{L}$ could parameterise the arrival rates of a queueing network. The Markov chain generated by the algorithm has state $(x, \lambda) \in \mathcal{X} \times \mathcal{L}$, where x is the current state of the queueing system and λ is the parameterisation last considered by the algorithm. Given this configuration, our algorithm then samples randomly from $\mathcal{L}$ a new candidate parameter μ. After running the chain for τ time units from initial state x, it then samples $X_\mu(\tau) = y$. Here τ is chosen to be proportional to $|x|$. The next state of the Markov chain is chosen by comparing the new candidate solution (y, μ) and the old state (x, λ) according to the following rule

$$(x', \lambda') = \begin{cases} (y, \mu) & \text{with probability} \quad \exp\big(\min\{0, |y| - |x|\}\big), \\ (x, \lambda) & \text{otherwise.} \end{cases}$$

We will show how to construct a Markov chain that has greater expected drift than any chain produced by the algorithm that has no measurable subset of parameters which is unstable. Using this chain we are able to derive a criterion for rigorously testing (statistically) the hypothesis that the set of parameters is stable. In the talk we will also apply the algorithm to some example networks.

This is joint work with Neil Walton and Michel Mandjes.

Keywords: *Queueing network, stability, simulation*

Does extra information harm or hinder? Probabilistic and state-dependent routing in networks with selfish routing

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Abstract: The performance of congested road or communication networks can be severely affected by selfish routing. This term describes regimes where users choose routes (on roads or in cyberspace) without allowing for the effect of their choice on other users. Paradoxically, adding capacity to a network operating under selfish routing does not always lead an improvement in performance, and may even make if worse. However, when users are provided with more information about the state of a network before joining it, the selfish routing effect may be mitigated and performance improved.

We will examine probabilistic (less information) and state-dependent (more information) selfish routing schemes in two kinds of network. One consists of a mix of first in first out single server queues, and batch service queues, a model which is sometimes used as a simple representation of private vs. public transport. The second network has a collection of processor sharing queues. For this second network, interesting questions also arise of existence of one or more equilibria, and then also convergence to those equilibria, under state-dependent routing. We will also discuss methods for identifying equilibria under state-dependent routing.

This is joint work with Heti Afimeimounga, Lisa Chen, Wiremu Solomon, Mark Holmes and, more recently, Niffe Hermansson and Alex Wang.

Keywords: *Selfish routing, queueing networks, stochastic networks*

Neighbour Hospitals Collaboration in Blood Supply Enhancement

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Abstract: The aim of the blood supply chain is supplying adequate safe blood to hospitals. It is very important that blood is available at hospitals for transfusion purposes since a shortage may risk the life of patients. In the blood supply chain, replenishment in the blood bank is not fully in control of the decision makers, since replenishment occurs by blood donations. This important property discriminates the blood supply chain from other well-studied supply chains with perishability. The blood supply chain can be modelled as a two-echelon inventory system where the items arrive at the first echelon (the blood bank) stochastically and stochastic demand is realized at the second echelon (the hospitals).

The hospitals place orders at the blood bank and there is a lead time for fulfilling the orders. In case of emergencies, the orders are fulfilled immediately with almost zero lead time. Outdates and shortages can happen at the first or second locations. There are recent studies that show transfusion of younger red blood cells may lead to better results in some groups of patients. This means not only that a blood supply chain should minimize outdates and shortages, but it also needs to reduce (minimize) the age of transfused items. Therefore, the performance of a blood supply chain can be quantified by the outdate rates, shortage rates and the average age of issued items. One way to improve supply chain performance is to reshuffle the structure of the supply chain by centralization of hospitals in the second echelon as much as possible. For example, assume there are four hospitals H^1, H^2, H^3 and H^4 at the second location of the supply chain (i.e. there are four inventory locations in the second echelon). All of them receive items from the blood bank.

We show that if H^1 can receive items from H^2 within a negligible amount of time and H^3 can receive items from H^4 within a negligible amount of time, keeping inventories only in H^2 and H^4 (having two inventory locations in the second echelon) will significantly improve the supply chain performance. The numerical study showed that reducing the inventory locations from 5 to 2 can reduce the total cost by 21%. It was interesting to see that in most of the cases centralization also improved the average age of issued items to the end users while fewer items are outdated in total. This is an important finding since some patient types achieve better clinical outcomes with the transfusion of fresher red blood cells. Studying the transshipment policies and its impact on the blood supply chain and considering multiple blood banks in the system are recommended for future research.

Keywords: *Blood supply chain, perishable inventory management, two echelon supply chain*

The Many-Visits-Few-Cities Travelling Salesman Problem on Threshold Graphs

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Abstract: For a given undirected graph with weights on each edge, the Travelling Salesman Problem (TSP) consists of finding a minimum-weight cycle that visits each vertex exactly once. With a few exceptions, such as Halin graphs and Hamiltonian circulant digraphs, the TSP has so far typically been studied on complete graphs, i. e. on graphs where each node is adjacent to each other node. In this talk we will address the TSP on a particular type of graph known as "threshold graph".

A threshold graph is a graph with a "threshold" α in which each vertex is assigned an integer number and two vertices are adjacent if and only if the sum of the integer numbers assigned to the vertices is greater than or equal to α. As the complete graph is a special case of a threshold graph, the TSP is NP-hard on threshold graphs.

In this talk we look at a TSP with a specific structure, called the Many-Visits-Few-Cities TSP. The Many-Visits-Few-Cities TSP arises when the salesman has to visit only a small number of different cities, but these cities have to be visited several times. For this special case there exists an algorithm by Cosmadakis and Papdimitrou that exhibits polynomial-time behavior.

The algorithm exploits the fact that any solution to the Many-Visits-Few-Cities TSP can be represented as the union of a minimal Eulerian multi-digraph and a balanced multi-digraph. The algorithm proceeds in four steps. First, all minimal Eulerian multi-digraphs are constructed for the given set of vertices. This is achieved on the basis of the fact that the number of 1's in the indegree sequences of all minimal Eulerian multi-digraphs is greater than or equal to the maximum degree in the sequence. Second, for each feasible degree sequence the algorithm determines, by using the classical Held-Karp dynamic programming approach for the Travelling Salesman Problem, the minimum-weight digraph among all minimal Eulerian digraphs constructed in the first step. Third, a transportation problem is solved to find minimum-weight balanced multi-digraphs that, when superimposed on the digraphs that result from the second step, provide a feasible solution of the Many-Visits-Few-Cities TSP. Finally, among all constructed feasible solutions the minimum-weight digraph is chosen.

The most-time consuming step in this approach is the solution of the dynamic programming problem in the second step. This means that the algorithm will need less computational time if the number of graphs constructed in the first step can be reduced. In our talk we draw on the structure of threshold graphs to improve Cosmadakis and Papadimitrou's algorithm significantly for the case of threshold graphs. In particular, we provide further criteria that the indegree sequences of minimal Eulerian multi-digraphs have to satisfy to comply with the structure of threshold graphs. Additionally, by providing an upper bound on the number of minimal Eulerian multi-digraphs that the first step of our version of the algorithm constructs, we can prove that our approach reduces computational time by several orders of magnitude.

Keywords: *Travelling Salesman Problem, Many-Visits-Few-Cities, threshold graph*

Discrete flow pooling problems in coal supply chains

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Abstract: The pooling problem is a nonconvex nonlinear programming problem (NLP) with applications in the refining and petrochemical industries, but also the coal mining industry. The problem can be stated as follows: given a set of raw material suppliers (inputs) and qualities of the supplies, find a cost-minimising way of blending these raw materials in intermediate pools and outputs so as to satisfy requirements on the output qualities. The blending in two stages (in pools and outputs) introduces bilinear constraints. The pooling problem can alternatively be described as a minimum cost network flow problem with additional bilinear constraints to capture the blending of raw materials.

In this paper we study a variation of the pooling problem that arises naturally in the coal mining industry and is sometimes referred to as *grade targeting*. Coal is made-to-order according to customers' desired product qualities. Deviations from these target qualities result in contractually agreed bonuses and penalties. In the pooling problem variation we study, costs are associated with these bonuses and penalties instead of network flows. While in the original pooling problem we have hard bounds on the qualities and unmet demand is penalised in the objective function, in our coal mining variation we have hard demand constraints and deviations from target qualities are penalised. This makes finding a feasible solution easy, while in the pooling problem finding a nontrivial feasible solution that satisfies the quality requirements is already hard. An implication of this is that we are able to solve larger problem instances than those typically studied in the pooling problem literature.

To model the coal blending process accurately, we define a time-expanded network where the intermediate pools represent coal stockpiles over time. Since coal is transported in large quantities, we study the trade-off between continuous and discretized flows in coal blending, i.e., solving a continuous flow problem where arbitrarily small flows are allowed versus solving a discretized flow problem where flows must be in multiples of some basic unit, e.g. trainloads. We also study two exact mixed-integer linear programming (MILP) linearizations of these mixed-integer nonlinear programs (MINLPs), which can be derived from unary and binary expansions of the flow integrality constraint. Such discretizations are typically studied as approximations to an originally continuous problem, however, in our application, a discretized formulation describes the original problem more accurately than a continuous formulation.

The paper is organized as follows. In Section 1.1, we introduce the pooling problem and present a variant of the well-known PQ-formulation. In Section 1.2, we extend the pooling problem to model a simplified coal supply chain. After a short literature review on coal supply chains, we present four different problems: the continuous flow problem (a MINLP), in which arbitrarily small flows are allowed, and three discretized flow problems (a MINLP and two MILPs), in which flows must be in multiples of trainloads. The discretization can be achieved by adding integrality constraints for the flow variables. We then show how to overcome the nonlinearity which is inherent in the pooling problem with the use of unary and binary expansions of the integer flow variables, which yields exact MILP reformulations of the discretized MINLP. We conclude the paper with Section 2 where we provide computational results for the four different problems which we solve for a real-life industry setting.

Keywords: *Coal blending, pooling problem, mixed-integer nonlinear programming, mixed-integer linear programming*

A Whole of Coal Chain Strategic Planning Model for the Hunter Valley

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Abstract: The Australian coal export industry is the second largest in the world making up almost 13% of Australia's total export earnings. The Hunter Valley coal export supply chain is the primary source of thermal coal exports in Australia, exporting around 159 million tonnes in 2014 which generated in excess of $13 billion in annual export income for Australia.

The Hunter Valley Coal Chain Coordinator Limited (HVCCC), whose stakeholders include mining companies, rail track owners, above rail operators, and terminal operators, is the primary planning organisation responsible for the export of coal through the Port of Newcastle. The HVCCC is tasked with coordinating the activities of all the corresponding parts of the coal chain so as to maximise the system efficiency. They also have a forward looking planning role in which strategic capacity planning is a core activity: the demand for coal is expected to double in the next decade due to an increasing need for coal for power generation in emerging and expanding economies.

We present an inventory focused, whole of coal chain, strategic planning model for the Hunter Valley coal chain that has been developed in conjunction with the HVCCC. The model captures the inventories of clean coal stockpiled at the mines, the export cargo product stockpiled at the terminals, and the movement of clean coal from the mines to the terminals via the connecting rail infrastructure. Each stockpile of export cargo product consists of clean coal blended to a specific recipe that is to be loaded aboard one or more vessels that will berth at the corresponding terminal. The model is driven by a shipping stem, that is a stream of vessels arriving at each terminal and their requisite cargoes, that represents the possible demand for export cargo product over the planning horizon.

The primary purpose of the model is to provide insights into the relationships between supply, demand, and inventory, and to give quantitative analysis in support of potential new inventory management and demand management strategies. Due to the limited amount of stockyard space available at each terminal, inventory management largely focusses on whether stockpiles of export cargo product should be either long-term dedicated stockpiles that will supply multiple vessels, or whether they should be cargo assembly stockpiles, built to order for a specific vessel, in which case the timing of when to build these stockpiles is important. Complementary to the management of inventory is the management of demand, the timing of which can be influenced by either expediting or delaying the arrival of specific vessels in the shipping stem. Other features captured in the model include rail and terminal maintenance, above rail fleet capacity, and tide constrained vessels.

Keywords: *Supply chain, strategic planning, mixed integer programming*

A route integration approach to determine marginal costs in road freight transport

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Abstract: Most road freight transport industry operators calculate costs based on distance, goods specification and urgency of the request; negotiations and discounts also play an important role. This approach results in specific transport fares per kilometre and disregards occurring economies of scale and scope. This paper presents an alternative model that determines the marginal costs for integrating a forwarding request into an existing route set. It makes use of all existing transport-related request information at that particular time. The knowledge about the actual occurring costs gives companies a competitive advantage as they can (if necessary) offer cheaper prices, acquire more transport jobs and increase their productivity due to better use of capacity.

The model is designed as a vehicle routing problem with time windows and pickup and delivery (VRPTWPD) and discriminates costs of incoming requests. It is applied in a dynamic decision environment with incoming requests considered throughout the whole planning process. For the costs calculation, an insertion algorithm is used that executes two vehicle routing optimisations, before and after inserting the incoming transport request. The model then determines the marginal costs as differences. The VRPTWPD model and a tabu search heuristic for solving the problem was implemented in Java code. Thirty test cases were simulated. Each test case consists of a central depot and randomly distributed customer locations in a 100 km^2 area (14-24 customers depending on the test case). Shipping requests are randomly generated in each test case. Then, for each instance, 10 experiments with additional incoming requests are performed. A number of 300 experiments are executed in total, testing the sensitivity to busyness (number of existing and incoming requests), location of customers, and time windows.

Preliminary results indicate a significant saving of between 7% and 31% for the marginal costs compared to the costs for the corresponding roundtrip (depot – request origin – request destination – depot), considered as a benchmark. Given this information, the scheduler is able to be much more accurate in establishing the transport prices. He is not only able to determine a price that corresponds to the associated costs, but also to offer discounts without generating a negative profit margin. Besides, the insertion algorithm enables the scheduler to investigate whether incoming requests can be served considering customer service time windows, available capacity and the existing demand set. The best suitable or most profitable requests can be accepted, depending on the objective of the company. Additionally, the integration in an executable computer program and the degree of standardisation by using standard pallets allows a connection of the system to online freight exchange databases. This enables automatic request evaluation which, compared to manual planning, is expected to result in faster and more accurate processing in vehicle routing, scheduling and capacity utilisation. While the companies using the system improve their efficiency, customers benefit from lower transport prices, as a result of the competition. Decreasing numbers of trucks on the road are expected to lead to reductions in air and noise pollution, with positive effects for environment and urban systems.

Keywords: *Vehicle routing, cost determination, capacity control, road freight transport, less-than-truckload*

Adaptive Process of Schedule Recovery for Airline Operations

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Abstract: Operating a flight is the result of a long planning process: flight scheduling, fleet assignment, aircraft routing, crew planning, maintenance planning. However, during the day of operations, disruptions, like bad weather or strikes, can perturb the schedule, and requires fast reaction to restore the planning. Major disruptions can have significant impacts on the financial results of the airlines. Currently those situations are generally managed manually by the operations controllers. The main challenge of the problem is to have a model relevant enough to consider all aspects impacted by modifications of the schedule, but keeping a model with a reasonable size. Because it is based on live and changing data, the optimiser must quickly return a solution to repair the schedule, before it becomes outdated.

Airline schedule recovery consists in minimizing the impact of disruptions for the schedule and in returning as quickly as possible to the planned operations. The other impacted stakeholders are the passengers, the crew, the maintenance planning and the airport resources. The available actions for repairing the schedule depend on the closeness to the operations. A few days before, we only consider equipment changes or flight cancellations; the day before, we can also delay flights, change the aircraft type or create ferry flights.

Our model considers the partial integration of all stakeholders and their most critical requirements to anticipate infeasible situations. For example, we are integrating the crew duty limitations by banning long sequences of flights for the same aircraft with tight turnaround times that would avoid crew replacement. The optimisation also takes into consideration the role of the Operations Controllers and their possible interaction with the solutions for validating critical decisions like flight cancellations.

Our solution to repair the schedule is based on a sequence of algorithms that is adaptable depending on the available actions. The core algorithm is a MIP-based local search solving a problem of minimum cost multi-commodity flow in a pruned network using business rules. We illustrate the behaviour of the optimisation on real life data sets issued from international airlines.

Keywords: *Airline disruption, integrated model, optimisation algorithms*

Rail Simulation for Complex Yard Operations

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Abstract: Rail yards are large and complex pieces of infrastructure that are capital intensive and often difficult to extend or modify as their usage changes or traffic volume grows. It is therefore critical that rail yard designs along with their operating plans are fit-for-purpose, particularly given that rail-yards are often bottleneck facilities in national or regional freight transport networks. The long-term on-going operation of a rail yard is challenging because the traffic volume and usage patterns evolve over time, often in ways that weren't anticipated when the rail-yard was originally designed. As operations become increasingly awkward and the freight volumes exceed the yard's capacity, the operators and owners must determine how they can modify operations or add infrastructure to relieve the bottleneck that the rail-yard has become.

The question that must be answered is whether a new rail-yard design, or modification of an existing rail-yard will be fit-for-purpose in terms of projected freight volumes, residence times and required turnaround times. This question is difficult to answer because large rail-yards involve a variety of activities occurring in parallel, competing for resources (e.g. shunt engines) and track. In some cases a good spreadsheet model may be capable of determining whether the yard has sufficient capacity to satisfy freight volumes and stowage requirements. However, in more complex yards there are often conflicts between parallel activities leading to delays, which puts upward pressure on turnaround times, resource utilisation and track utilisation. There is significant risk in relying on spreadsheet models which cannot capture these realities and may overestimate rail-yard capacity.

Dynamic or discrete-event simulation provides a means to estimate rail-yard capacity and performance whilst capturing delays resulting from conflicts. There are several readily available off-the-shelf rail operations simulation packages used widely in the industry, such as OpenTrack and RailSys. These packages are most suited for modelling mainline traffic, but do not have sufficient functionality to model rail-yards with complex sequences of shunting and rule-based operation rather than every single movement being strictly timetabled. For this reason, Aurecon has developed RailNetSL, which is a fully customisable rail simulation library implemented in SLX (Wolverine Software).

As input, RailNetSL takes in a scale representation of the track network to be modelled. This is typically read directly from a CAD file drawing of the network. A database of properties is configured as an overlay to the network, providing information that is used by the train movement and operations logic modules. This includes information such as location tags, speed limits and routing guides. Other inputs to RailNetSL describe the physical and performance characteristics of the rolling-stock. A model built in RailNetSL includes the trunk library covering reusable aspects of rail simulation such as route-finding, dynamic speed profiles (with acceleration and deceleration) and control logic (signalling, switches, priorities, etc). Project specific logic is implemented as a plug-in to the RailNetSL trunk. The plug-in includes scripts defining the sequences of movements and resource usage required for the variety of tasks performed in the yard. RailNetSL produces a vast array of log-files and performance statistics for detailed analysis of the simulated rail-yard operation. It also produces 3D animation to visually play out the simulation and provide live on-the-fly data. This has proved invaluable for clients to validate the simulation model, and to secure buy-in from all levels of their organisation. RailNetSL has been applied successfully on a number of projects for clients such as KiwiRail and several operators in the Australian resources sector.

Keywords: *Discrete-event simulation, networks, rail*

Optimal Design of Inventory Management Systems for Micro-Warehousing in the Healthcare Industry

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Abstract: Reverse logistics' research has focused on how to improve current operations to recover some value from supply chains that distribute and sell products that end up with a customer. For high-value, low-volume supply chains, particularly those operating on a contract-loan basis such as specialized medical goods, reverse logistics has a different value proposition. As with most unidirectional supply chains, these have developed over time out of necessity and without a plan or design to operate efficiently. As health care has become widespread and universal, they have grown organically into systems that are far from optimal.

In contrast to traditional supply chains, chains working on loan contracts are inherently closed, as products must be returned for re-fitting and conditioning before the next loan, and thus any inefficiencies in reverse logistics will directly impact the business. Moreover, at the consumer end of the health care sector (that is, the hospitals), efficiency for the supplier is not necessarily seen as a priority. In this paper, we investigate two important logistic questions that distributors of goods for the health industry face today. First, what are the efficiency gains if the medical good distributor assumes the lead role in centralising some operations (e.g., in sterilisation policies) which are currently distributed and owned by health staff? Second, can new sensors and the Internet of Things (IoT) assist reverse logistics of medical material in improving services, lead times and bottom lines of hospitals and distributors, without impacting patient care? We introduce an optimisation model to calculate an optimal distribution schedule to address these questions.

Keywords: *Inventory management, health care, logistics for the health industry, optimisation, mixed-integer linear programming*

Assessing direct economic impacts of disruptions in transport networks

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Abstract: The increasing rates of natural disasters such as bushfires, floods, cyclones or hurricanes in the last few decades and their enormous economic impacts have forced us to think about the potential costs of a major disruption to our infrastructure systems. Such disruptions can affect a region's economy and extend to other regions via export-import relationships with serious economic consequences. To prepare for such disruptions, we need to implement better risk management strategies. To this end, we need to estimate the potential costs of any disruptions to the regional economy.

This paper presents a method to estimate the direct economic impacts from a major disruption in transport networks within a national and regional context. The method accounts for the interactions among different industrial sectors using economic input-output relationships. However, a major difficulty of using input-output relationships, at a finer resolution (e.g., at regional levels), is that such information is typically available at a national level. Our method solves this problem by integrating a regional input-output model with a network equilibrium model. The model determines the increasing length of shipments due to a disruption giving their direct economic impacts.

The analytical methods employed are twofold: a multi-regional input-output model and a regional commodity flow model. In particular, we formulate a mathematical programming model minimising the sum of the total costs in the system, which is obtained by summing the network assignment costs, intraregional travel costs and interregional flow distribution costs. The commodity flows in links and routes and between origin-destination pairs for each industrial sector are then estimated by distributing flows among subregions and selecting minimum cost travel routes. We use material balance constraints incorporating the input-output relationships and production constraints so that there is a limit up to which a region can produce a commodity matching the real world data.

As a solution method, Lagrangian analysis is performed to find the optimality conditions:

- all selected transport alternatives have equal travel cost, and
- no unselected transport alternatives has a cost lower than a selected alternative.

We use a combination of Evan's algorithm and Wilson's iterative balancing method to solve the combined distribution and assignment problem.

We conduct a case study on the potential impacts of a disruption in the Australian national highway network. The data consists of major highway network and national input-output relationships provided by the Australian Bureau of Statistics. Using the analytical framework, we first estimate the base-case commodity flow and link costs under a normal situation. We then estimate the increased costs of shipment due to a hypothetical disruption scenario in the network.

The model developed in this work can be used for state, regional or national level strategic planning purposes to assess the risk exposure of transport infrastructures in a better way and to prioritize among alternative future investment options. The model can also be used as a strategic management tool for planning recovery and reconstruction efforts after a major disaster event.

Keywords: *Input-output modelling, commodity flow, freight demand, highway disruptions, natural hazards*

Integer Programming Formulations for the Uncapacitated Vehicle Routing p-Hub Center Problem

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Abstract: Hub facilities are used in many-to-many transportation networks such as passenger airlines, parcel delivery, and telecommunication system networks. In these networks, the flow that is interchanged between the demand centers is routed via the hubs to provide discounted transport. Many parcel delivery firms serve on a hub based system where the flows from different demand nodes are concentrated, sorted and disseminated at the hub centers in order to transfer them to the destinations points. The main purpose of hub location problem is to decide the location of hub facilities and to allocate demand nodes to the hubs. In hub based systems, as an alternative way of serving each origin destination node directly, the flow is accumulated at the hub facilities in order to exploit the substantial economies of scale.

Hub location problems can be categorized in terms of the objective function of the mathematical models. In the literature, hub location problems with total transportation cost objectives (median), min-max type objectives (center) and covering type objectives are well studied.

In the hub location problem literature, it is assumed that only one vehicle serves between each demand center and hub. The vehicles are not permitted to visit more than one city. The need to design a network of combined hub locations and vehicle routes arises in various applications. For example, in cargo delivery systems, sending separate vehicles between each demand center and hub is rather costly in terms of investment on the total number of vehicles. Instead, if the vehicles are allowed to follow a route by visiting different demand nodes in each stop, the total investment cost may decrease considerably. In airline companies, similarly, if a separate aircraft and separate air staff are assigned for each destination, they incur high investment and operating costs. Also, traffic congestion occurs at airports and in air networks.

In the light of above-mentioned real life considerations, the vehicle routing hub location problem has been receiving increased attention from researchers. This problem is to decide the location of hubs, the allocation demand centers to the hubs and the associated routing structure with multiple stopovers and allowing vehicles to make a tour so as to minimize total transportation cost.

In addition to the cost, parallel to the increase of the competition in the market, companies tend to promise to the customers 'next day delivery' or 'delivery within 24 h' guarantees. However, the hub location and vehicle routing problem, which consider both the flows and distances, may sometimes lead to delays from non-simultaneous arrivals at hubs, when worst-case route lengths for vehicles are excessively large. Although classical hub location problems provide one option when origin-destination distances are huge, they become less appropriate when vehicle routing is required and delivery time is a major concern.

In this study, we introduce the uncapacitated vehicle routing $p-$hub center problem to the literature. The aim of our model is to find the location of the hubs, assign demand centers to the hubs and determine the routes of vehicles for each hub such that the maximum distance or travel time between origin-destination pairs is minimized. We propose mathematical programming formulations for this problem with O (n^2) and O (n^4) variables. The formulations trade off tightness against formulation size. The computational results on standard data sets from the literature allow this trade off to be evaluated empirically and provide an indication of the challenge of solving these combined vehicle routing hub location problems.

Keywords: *p-hub center problems, hub location, hub location and routing problem, p-hub center and routing problems*

Exploring the effects of mixed request schemes for demand-responsive feeder services

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Abstract: Modern day communications mean travellers can request transport options, such as taxis and seats on demand-responsive vehicles, on the fly without having to plan ahead. However, last minute requests for transport could be inefficient for the operator. This paper explores the effects of mixed book-ahead/immediate request schemes in the context of a feeder service.

Demand responsive transportation (DRT) combines aspects of both buses and taxis: passengers travel together, but not necessarily to or from the same locations. A simple form of demand-responsive service is that of a feeder bus, permitting passengers to connect to a mass transit service such as a train.

A DRT service can run by getting passengers to book ahead or by allowing requests to arrive at the last minute, however the performance of the system may differ under different mixes of these requests. The ratio of the immediate (last minute) requests to total requests is known as the degree of dynamism. The impact of the degree of dynamism is measured by the total vehicle kilometres travelled (VKTs), the success rate (the ratio of requests that actually got served) and the waiting time for customers.

This paper simulates a DRT service using an event-based model where requests arrive during a simulated day for booking of both book-ahead and immediate requests. A booking system assigns the request to an appropriate time slot if possible and then an optimiser finds efficient routes to pickup and drop-off the customers at the required locations. Finally a dispatching system notifies and updates the driver of the vehicle with the current route.

To optimise the route, the customer demands are modelled as a series of vehicle routing problems that optimise the total distance travelled, with the current solution used as the starting point for the next iteration. A solution method using adaptive large neighbourhood search attempts to fit the new customer request into the existing routes while still allowing the feeder service to meet the scheduled train.

Three scenarios are tested using multiple vehicles. Instances with realistic demand and 250 customers are generated using realistic distributions derived from the Victorian Integrated Survey of Activities and Travel.

The first scenario varies the degree of dynamism across different instances. A second scenario varies the degree of dynamism with a spatial distribution of immediate requests reflecting distance to the train station. We also investigate the impact of train frequencies on the feeder service by altering the headway between trains. More frequent trains leaves less scope for optimisation and the longer headway has a higher success rate as the vehicle has time to pick everyone up. Overall we find that the most inefficient service occurs around 80% degree of dynamism.

Keywords: *Demand-responsive transportation, optimisation, degree of dynamism*

A near Optimal Cane Rail Scheduler under Limited and Unlimited Capacity Constraints

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Abstract: Australia is the world's third largest exporter of raw sugar after Brazil and Thailand, with around \$2.0 billion in export earnings. Transport systems play a vital role in the raw sugar production process by transporting the sugarcane crop between farms and mills. In 2013, 87 per cent of sugarcane was transported to mills by cane railway. The total cost of sugarcane transport operations is very high. Over 35% of the total cost of sugarcane production in Australia is incurred in cane transport.

A cane railway network mainly involves single track sections and multiple track sections used as passing loops or sidings. The cane railway system performs two main tasks: delivering empty bins from the mill to the sidings for filling by harvesters; and collecting the full bins of cane from the sidings and transporting them to the mill. A typical locomotive run involves an empty train (locomotive and empty bins) departing from the mill, traversing some track sections and delivering bins at specified sidings. The locomotive then, returns to the mill, traversing the same track sections in reverse order, collecting full bins along the way. In practice, a single track section can be occupied by only one train at a time, while more than one train can use a passing loop (parallel sections) at a time.

The sugarcane transport system is a complex system that includes a large number of variables and elements. These elements work together to achieve the main system objectives of satisfying both mill and harvester requirements and improving the efficiency of the system in terms of low overall costs. These costs include delay, congestion, operating and maintenance costs.

An effective cane rail scheduler will assist the traffic officers at the mill to keep a continuous supply of empty bins to harvesters and full bins to the mill with a minimum cost. This paper addresses the cane rail scheduling problem under rail siding capacity constraints where limited and unlimited siding capacities were investigated with different numbers of trains and different train speeds. The total operating time as a function of the number of trains, train shifts and a limited number of cane bins have been calculated for the different siding capacity constraints.

A mathematical programming approach has been used to develop a new scheduler for the cane rail transport system under limited and unlimited constraints. The new scheduler aims to reduce the total costs associated with the cane rail transport system that are a function of the number of bins and total operating costs. The proposed metaheuristic techniques have been used to find near optimal solutions of the cane rail scheduling problem and provide different possible solutions to avoid being stuck in local optima. A numerical investigation and sensitivity analysis study is presented to demonstrate that high quality solutions for large scale cane rail scheduling problems are obtainable in a reasonable time.

Keywords: *Cane railway, mathematical programming, capacity, metaheuristics*

Routing Field Service Officers with SIMULINK

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Abstract: City West Water (CWW) operates water and sewerage networks and associated infrastructure in the central business district and inner and western suburbs of Melbourne, Australia. At times these assets fail requiring an immediate response ('responsive maintenance') prioritised by assessed urgency. As part of this response, an initial assessment is made by a Field Service Officer (FSO). The FSO determines the resources required to repair the failure and informs the Dispatcher who allocates a field crew to perform the repair. The company's responsive maintenance performance is recorded for each job and reported in CWW's Key Performance Indicator (KPI) reports for the CWW Board of Directors and the Essential Services Commission.

CWW has set itself the goal of keeping its process at or below current levels while continuing to provide a consistent level of service. This is driving CWW to look for cost efficiencies. Two such efficiencies that CWW has considered are risk based job priority zoning and more efficient FSO job assignment and routing. In order to test the impact of these initiatives a simulation model was constructed using MathWorks' SIMULINK™ software. The model uses data from CWW internal systems including priority, time and location for each job, as well as the assigned FSO. Travel times between jobs are approximated using centroids of Melways map grids. The model processes the job queue and makes FSO assignment decisions for the Dispatcher, allowing the effects of various job priority zoning rules to be measured and compared.

The first version of the model simulated the current FSO job assignment and rules showed similar or slightly better average response times when compared to historical data. The model was modified further to test the Risk Zone prioritisation of jobs with different response time rules. The results showed blending job urgency and risk prioritisation achieved desirable response times. This paper describes the approach used to develop risk based job priority zones and how SIMULINK™ block diagrams were used to build a simulation of the current routing process and test some alternative approaches to job prioritisation.

Keywords: *SIMULINK™, MATLAB™, routing, simulation*

Markov Decision Process Model for Optimisation of Patient Flow

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Abstract: Australian hospitals are facing the challenge of increased demand in ED and inpatient services. Congestion and poor quality of care for some patients may occur as a consequence of such challenging situations. Modelling patient flow is a way to capture a small number of salient characteristics of a hospital operation permitting us to investigate the causes and effects of congestion, and identify optimal improvement policies.

The data used in this project are drawn from an extensive Patient Journey Database of a major South Australia hospital, Flinders Medical Centre (FMC). This database tracks journeys of patients through the hospital system, from arrival to discharge. This allows for very detailed analysis and modelling of these journeys.

Analysis of historial bed occupancy data indicates that there are remarkably regular patterns in patient occupancy, on both daily and weekly time scales. Based on this observation, we develop a Markov decision process (MDP) model over a weekly time horizon to analyse FMC's bed occupancy patterns with a goal of proposing policies that lead to reduced incidence of congestion.

A simple, four state, approach is used in categorising the occupancy level, and daily and weekly probability transition matrices are derived from midnight census data over a three year period. We then introduce a reward function that attempts to balance the benefit of maintaining sufficient buffer in the occupancy of wards versus the cost of diverting patients elsewhere. An optimal policy from the MDP model was found using the dynamic programming approach.

Employing an MDP approach in these problems will also, potentially, allow hospital staff the ability to forecast possible onset of very high occupancy levels, based on the hospital's current situation. Such a "warning signal" may enable hospital managers to be proactive in their strategies to reduce the magnitude and impacts of congestion episodes. Although, to managers, the underlying mathematics may appear relatively complex, it is possible to embed an MDP model inside a software package so that the model is available in a more user-friendly form, allowing it to be easily run on-the-fly so that staff can react to changes in the hospital in real time.

The issue of validation of "optimal" policies suggested by an MDP model is addressed in three, separate, ways. Firstly, the steady state probabilities resulting from such policies are examined to see if they reduce the long-run frequency of highest occupancy levels. Secondly, consultation with FMC experts, an integral part of this study, has provided a degree of qualitative validation. Thirdly, synthetic data generated by a discrete event simulation system developed in another component of the larger project is used to provide surrogate statistical testing environment for the performance of MDP's policies. Simulated experiments also serve the purpose of convincing hospital's management before piloting policies in real setting.

Future work includes refinement of both the MDP and the simulation model and establishment of a formal framework for cross-validating MDP and simulation modelling results.

Keywords: *Markov decision process, hospital patient flow, process optimisation*

Group Assessment of Interview Ready Model Reliability

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Abstract: Developing decision-aiding models to support national security decision making is challenging due to constrained access to high profile subject matter experts (SME). In such cases the necessary model building interviews with SMEs are rare and time critical. Interview ready models (IRM), that is, preliminary models that convey an initial view of the problem, provide a powerful means to extract the maximum benefit from these interviews. However there are risks associated with this strategy. Of greatest concern is that an unreliable model could lead, constrain or distract the interviewee, thereby negating its benefits and undermining the validity of the resulting decision-aiding model. Consequently, there is a need to extend the concept of model validity to the construction of the IRM. In the case of interview ready causal models, possible causal associations between concepts (model nodes) may need to be identified via textual sources using a subjective coding scheme such as content analysis. The reliability of the coding scheme essentially governs the logical validity of the resulting IRM. The process of assessing coding reliability is further complicated when a single analyst/model builder conducts the coding and analysis used to construct the IRM. This paper examines the argument for employing an IRM, reviews the literature regarding model reliability for such models, proposes an approach to assess the reliability of an IRM constructed using content analysis that balances adequacy and feasibility and applies this approach to a case study.

Keywords: *Interview ready model, decision-aiding models, model validity, content analysis*

Using optimisation to suggest alternative supply chains in the context of industrial symbiosis

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Abstract: The concept of firms exchanging materials, energy, water, and/or by-products in a collective approach to competitive advantage is called Industrial Symbiosis (IS). It was first described by Frosch and Gallopoulos in 1989, and in the same year, scientists uncovered an extensively intertwined network of companies from different industries in Kalundborg, Denmark that was a realisation of Frosch and Gallopoulos' ideas. In IS, an unresolved research question relates to whether IS can be designed "ground up" into an industrial system (such as via planned eco-parks), or whether it can only occur "organically" through more serendipitous business interactions.

Given data on a defined set of businesses, quantified amounts of input and raw materials, and material transformation opportunities, our interest is on the use of computation and optimisation techniques in order uncover the potential for IS amongst firms, and to suggest for a single business which potential partners the business should target in order to build a network that could realise this potential. The transformation opportunities are modelled as processes in which a business, consortium, or external agent (such as a local authority) could invest, to enable materials to be transformed from lower to higher value. Examples might include (re-)manufacturing processes, a shared space for materials aggregation, or compressing and baling machinery that could increase waste density and so reduce storage and transportation costs for a material.

To formulate the problem, we consider the potential material flows between businesses and processes, using a linear distance model to describe transportation costs; market values to describe materials that are desirable inputs, and additional sourcing and sinking costs to obtain materials from outside of the network or dispose of surplus materials to landfill. The model is for a single time span, and as such we need to ensure that process investments do not lead to an amplification effect from the total investment cost not being amortized in the considered period.

Results are then presented for each participating business in terms of the origins, destinations and investments that describe the subgraph of material flows that maximises their financial return. For the proposed overall network to be commercially viable, each participant must show a positive return; as such we can demonstrate the difference between the set of local optima and the potential global optimal decisions, thereby uncovering the ideal opportunities for social or government investment.

Keywords: *Industrial ecology, supply chain optimisation, operations research*

Optimisation Technology for Operating Theatres Management

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Abstract: Operating theatres are a crucial type of resource and play critical role in hospital performance. While they are sources of the largest revenue, they also cost a lot to run. Managing theatres is very complicated, due to multiple resource requirements, conflicting priorities and multiple stakeholders' preferences. Operating theatre management has been largely studied in the last 60 years by mathematicians and statisticians.

In this talk, we describe a mixed integer programming approach to simultaneously allocate operating theatre time to surgery units, and select patients to be treated from waiting lists in order to optimize the KPIs of the hospital.

Patients on the elective waiting list are assigned to surgery departments and three different urgency categories in Australia. Category I patients are expected to be operated on in no more than one month, category II within three months and category III within one year. The hospital performance also depends on what percentages of treated patients are on time which consequently will (perhaps indirectly) influence their funding from the government.

To schedule operating theatres, we need to decide how many 4-hour block, or "sessions" should be allocated to each surgery department and which patients should be scheduled to sessions across the time horizon. We take into account multiple objectives, in a linear combination of different objectives with different weights. Our objectives are to minimize the waiting list, minimize the number of overdue patients, maximize the performance points of the hospital and maximize the estimated funding at the end of time horizon. The constraints to consider are limited resources and staff for surgeries including operating theatres, ward beds, beds in Intensive Care Units, surgeons and maximum funded sessions from the government. We have estimated duration of surgeries, length of stay, probability of using ICU beds and funding for each patient in the waiting list by using clustering and classification techniques from machine learning.

This work has been done for a public hospital in Melbourne based on their three years historical data. To the best knowledge of the authors, no work has been done to address the following aspects of operating theatre planning:

- Simultaneous allocation of treatment sessions to each medical unit and patient selection. Previous work on operating theatre management does not consider patient selection.
- Modification of the base plan or Master Surgical Schedule according to the circumstances. Related work either builds the base plan, which is an entirely different problem or uses it without changes.
- Considering multiple objectives, and taking into account regulatory constraints. Related work does not consider all of this at the same time.

Computational experiments on IBM Decision Optimization on Cloud (DOcloud), which launched publicly recently, will be presented.

Keywords: *Operation research, operating theatre, healthcare, mixed integer programming, planning*

A class allocation policy decision support tool for schools

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Abstract: The end of year administrative task of determining the class lists for students in their new grade in junior school can be time-consuming considering many schools have an explicit policy that seeks to construct classes balanced across a diverse range of criteria while simultaneously attempting to place friends with friends. Such policy reflects the principles that better learning occurs in heterogeneous groups and that friendships promote both the social and academic well-being of students.

While this task has some of the characteristics of the mathematical timetabling problem, the objective of maximising class-friends leads to a quadratic formulation. At ASOR2013 the author presented a new mixed-integer linear-programming model to solve such problems and the results of a pilot study with a local junior school based around the use of the Network-Enabled Optimization System (NEOS) web-portal. Feedback from delegates included the suggestion of using the more user-friendly OpenSolver package for Excel (opensolver.org) developed by Andrew Mason at the University of Auckland. A follow-on study was therefore conducted using the OpenSolver model to assist with the class allocation process for the 2014-2015 transition. This expanded study covered 697 students across 24 classes over 6 grades at two schools, and included 200 individual side-constraints.

Whilst the Excel-based nature of the OpenSolver model did afford significantly increased familiarity for the teachers, and the quick run-times allowed interactive 'what-if' analyses – by varying the minimum number of friends to guarantee, or the relative weighting afforded to best-friends, or the minimum fraction of class-mixing to ensure, or by including side-constraints not thought of until proposed class lists were visible – ultimately, both schools mostly reverted to their manual process to complete the allocations.

Table 1 presents key summary statistics of the model (optimal) solutions vs. the school implemented solutions. The model results are lower than that achieved in the previous year's transition (85% and 75%) but this is largely due to the more than doubling of the number of side-constraints elicited.

Table 1. Comparison of model solution vs. school implementation aggregated over all six grades.

	Best-Friend Satisfaction Rate		All-Friends Satisfaction Rate		
School	**Model Solution**	**School Δ**	**Model Solution**	**School Δ**	**No. Swaps**
A	78.3%	-5.8%	61.8%	-3.7%	5.8
B	75.6%	-4.6%	64.8%	-1.8%	2.2

Encouragingly, both schools did use the model solution for one grade's transition, but, as noted above, otherwise only used the solution as a start-point for their own manual perturbation (indicated by the average number of 'swaps' per grade). School A performed the most manual adjustments and subsequently resulted in a greater degree of sub-optimality (for one grade, the model solution wasn't consulted at all, leading to a 14% and 5% reduction in the best-friend and all-friends satisfaction rates, respectively).

More concerning however, is that in all but one case the school solutions violated a number of balance requirements, side-constraints (up to five in one grade), and/or did not ensure that all students have at least one friend in their class (also up to five in one grade) – all aspects that are explicitly mentioned in most of the class allocation policy documents proffered by schools.

Feedback from the schools as to the reasoning behind this mixed (but technically sub-optimal) strategy was centered on the commonly held conception of 'teacher judgement' or a 'sixth sense' as to what is best for students. It therefore remains a challenge – perhaps more cognitive than technical – in order to yield the maximum potential of such a mathematically-based class allocation decision support tool for schools.

Keywords: *Decision Support System (DSS), integer programming, education, friendship*

Polyhedral results for the Cardinality Constrained Multi-cycle Problem (CCMcP) and the Cardinality Constrained Cycles and Chains Problem (CCCCP)

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Abstract: In recent years, there has been studies on the cardinality constrained multi-cycle problems on directed graphs, some of which considered chains co-existing on the same digraph whilst others did not. These studies were inspired by the optimal matching of kidneys known as the Kidney Exchange Problem (KEP). In a KEP, a vertex on the digraph represents a donor-patient pair who are related, though the kidney of the donor is incompatible to the patient. When there are multiple such incompatible pairs in the kidney exchange pool, the kidney of the donor of one incompatible pair may in fact be compatible to the patient of another incompatible pair. If Donor A's kidney is suitable for Patient B, and vice versa, then there will be arcs in both directions between Vertex A to Vertex B. Such exchanges form a 2-cycle. There may also be cycles involving 3 or more vertices. As all exchanges in a kidney exchange cycle must take place simultaneously, (otherwise a donor can drop out from the program once his/her partner has received a kidney from another donor), due to logistic and human resource reasons, only a limited number of kidney exchanges can occur simultaneously, hence the cardinality of these cycles are constrained. In recent years, kidney exchange programs around the world have altruistic donors in the pool. A sequence of exchanges that starts from an altruistic donor forms a chain instead of a cycle. We therefore have two underlying combinatorial optimization problems: Cardinality Constrained Multi-cycle Problem (CCMcP) and the Cardinality Constrained Cycles and Chains Problem (CCCCP). The objective of the KEP is either to maximize the number of kidney matches, or to maximize a certain weighted function of kidney matches.

In a CCMcP, a vertex can be in at most one cycle whereas in a CCCCP, a vertex can be part of (but in no more than) a cycle or a chain. The cardinality of the cycles are constrained in all studies. The cardinality of the chains, however, are considered unconstrained in some studies, constrained but larger than that of cycles, or the same as that of cycles in others. Although the CCMcP has some similarities to the ATSP- and VRP-family of problems, there is a major difference: strong subtour elimination constraints are mostly invalid for the CCMcP, as we do allow smaller subtours as long as they do not exceed the size limit. The CCCCP has its distinctive feature that allows chains as well as cycles on the same directed graph. Hence, both the CCMcP and the CCCCP are interesting and challenging combinatorial optimization problems in their own rights.

Most existing studies focused on solution methodologies, and as far as we aware, there is no polyhedral studies so far. In this paper, we will study the polyhedral structure of the natural arc-based integer programming models of the CCMcP and the CCCCP, both containing exponentially many constraints. We do so to pave the way for studying strong valid cuts we have found that can be applied in a Lagrangean relaxation-based branch-and-bound framework where at each node of the branch-and-bound tree, we may be able to obtain a relaxation that can be solved in polynomial time, with strong valid cuts dualized into the objective function and the dual multipliers optimised by subgradient optimisation.

Keywords: *Integer programming, combinatorial optimization, cardinality constrained cycle problems, kidney exchange, clearing barter exchange*

On The Kidney Exchange Problem: Cardinality Constrained Cycle and Chain Problems on Directed Graphs–Integer Programming Approaches

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Abstract: The Kidney Exchange Problem (KEP) is a combinatorial optimization problem with a number of variations, and has attracted the attention of the community of integer programming/combinatorial optimisation in the past few years. Defined on a directed graph, the KEP has two variations: one concerns cycles only, and the other, cycles as well as chains on the same graph. A vertex on the digraph represents a donor-patient pair who are related but with incompatible kidneys due ABO blood type incompatibility or positive serological cross match. A kidney exchange pool contains multiple such incompatible pairs. In some cases, the donor of one pair can donate his/her kidney to the patient of another pair should the kidney be compatible. If Donor As kidney is suitable for Patient B, and vice versa, then there will be arcs in both directions between Vertex A to Vertex B. Such exchanges form a 2-cycle. There may also be cycles involving 3 or more vertices. As all exchanges in a kidney exchange cycle must take place simultaneously (so as to avoid donors dropping out from the program when his/her partner has obtained a kidney from another donor), due to logistic and human resource reasons, only a limited number of kidney exchanges can occur at the same time, hence the cardinality of these cycles are constrained. In recent years, kidney exchange programs around the world have altruistic donors in the pool. A sequence of exchanges that starts from an altruistic donor forms a chain instead of a cycle. We call the cycles-only KEP a Cardinality Constrained Multi-cycle Problem (CCMcP) and the cycles-and-chains KEP a Cardinality Constrained Cycles and Chains Problem (CCCCP). The cardinality for cycles is restricted in both CCMcP and CCCCP. The cardinality for chains, on the other hand, is considered to be restricted in some studies and unrestricted in others.

The CCMcP can be viewed as an Asymmetric Travelling Salesman Problem that *does* allow subtours, however these subtours are constrained by cardinality, and are not required to cover all vertices. In existing literature of the KEP, the cardinality constraint for cycles is usually considered to be small (not more than six in most existing work). In a CCCCP, on the other hand, each vertex on the directed graph can be part of at most one cycle or one chain, but not both. The CCMcP and the CCCCP are interesting and challenging combinatorial optimization problems in their own rights, particularly due to their similarities to some travelling salesman- and vehicle routing-family of problems. In existing literature of ILP models for the CCMcP, the three major classes of formulation are arc-based (with exponentially many constraints), cycle/chain based (with exponentially many variables), and polynomial size formulations that involve cloning the directed graph into multiple copies. As for the CCCCP, existing formulations are mostly cycle/chain based, but some contain an exponential number of both variables and constraints.

In this presentation, we will first review the existing literature in terms of formulations, problem reduction schemes, symmetry elimination of the IP models, and solution methodologies for both the CCMcP and the CCCCP. We will also propose a polynomial-size and an exponential-size mixed-integer linear programming model for the CCCCP, discuss a number of strong constraints for cardinality-infeasible-cycle elimination, present some preliminary numerical results for the strengths of these strong constraints, and the impact of changes in cycle- or chain-cardinality on solution time. We will also discuss the various objectives considered in the past, and possible strategies to deal with the multi-criteria nature of these optimization problems.

Keywords: *Integer programming, combinatorial optimization, cardinality constrained cycle problems, kidney exchange, clearing barter exchange*

Heuristic Approaches for Multi-Criteria Optimisation in Kidney Exchange Programs

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Abstract: The Kidney Exchange Problem (KEP) is an optimisation problem that was first discussed in Rapaport (1986) but has only more recently been the subject of much work by combinatorial optimisation researchers. This has been in parallel with its increased prevalence in the medical community.

In the basic formulation of a KEP, each instance of the problem features a directed graph $D = (V, A)$. Each node $i \in V$ represents an incompatible pair wherein the patient needs to trade kidneys with the patient of another incompatible pair. The goal is to find an optimal set of cycles such that as many patients as possible receive a transplant. The problem is further complicated by the imposition of a cycle-size constraint, usually considered to be 3 or 4. Kidney exchange programs around the world implement different algorithms to solve the allocation problem by matching up kidneys from potential donors to patients. In some systems all transplants are considered equally desirable, whereas in others, ranking criteria such as the age of the patient or distance they will need to travel are applied, hence the multi-criteria nature of the KEP.

To address the multi-criteria aspect of the KEP, in this paper we propose a two-stage approach for the kidney exchange optimisation problem. In the first stage the goal is to find the optimal number of exchanges, and in the second stage the goal is to maximise the weighted sum of the kidney matches, subject to the added constraint that the number of exchanges must remain optimal. The idea can potentially be extended to multiple-objectives, by repeating the process in multiple runs.

In our preliminary numerical experiments, we first find the maximum number of kidney matches by using an existing open source exact algorithm of Anderson et al. (2015). The solution will then be used as an initial solution for the stage two optimisation problem, wherein two heuristic methods, steepest ascent and random ascent, are implemented in obtaining good quality solutions to the objective of maximizing total weight of exchanges. The neighbourhood is obtained by two-swaps. It is our intention in the future to implement a varying neighbourhood scheme within the same two heuristic framework, or within other meta-heuristic framework.

Keywords: *Kidney exchange, multicriteria optimisation, population generation*

ASPIRE to uncover the value in SME waste streams

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Abstract: Municipal Solid Waste (MSW) is a well-understood resource, with existing collection processes and well-modelled quantity and value. The wastes from small to medium enterprises (SMEs) are not nearly so well understood, even in aggregate, and as such their potential value is often lost. Moreover, it's estimated that 50% of SME waste goes to landfill. In the ASPIRE (Advisory System for Processing, Innovation and Resource Exchange) project, we engage with SMEs to uncover information around wastes and by-products, to enable supply chain methodologies to be used to suggest the best destination for waste resources, thereby jointly maximizing resource productivity for the economy and minimizing environmental pollution for society.

A simple but plausible model to suggest alternate supply chains, would consider the kinds and quantities of material available from and required by each SME, the market value of these materials, handling and transportation costs, and the current cost of disposal, and use these to build a network-flow model. This would follow conventional freight modelling approaches, where a solvable implementation using suitable proxies could be created. However, such modelling starts with the available data. With SMEs, we first need to find it.

Each SME has its own existing supply chain, in which they order their required inputs, and distribute and sell their products. The manufacturing sector SMEs we target are relatively sophisticated in their understanding of these flows. However, circular economy thinking, where one identifies a recycled or repurposed material as an input, is not often a priority unless the resource required becomes scare or expensive. Instead, they have tight quality standards on what they're willing to accept. Accordingly, the primary destinations for wastes are landfill, recycling, and remanufacturing – in that order. The ideal circular economy behaviour is remanufacturing, but this creates two problems for optimization modelling – firstly, an ill-conditioned maximization model may increase waste production to get a higher return from remanufacturing; secondly the remanufacturer's products as well as wastes must be considered.

Unlike input resources, only the cost of disposal is well-understood for wastes. For an SME to provide data about the quantity, type and frequency of their wastes, an initial audit may be required – and then, the SME may need to put into place a basic segregation strategy to begin to be able to describe and quantify their materials, which has an opportunity cost. There are standards for waste audits, and grants available for SMEs to implement resource efficiency measures – but the quantification of wastes is likely to remain at the 'X bins per week' level, rather than the mass and density required for unified modelling. To uncover the value of the wastes, we ask remanufacturers to provide estimates of what they may pay under various scenarios, and SMEs to indicate disposal costs. It is unlikely this information will be accurate for competitive reasons, but by holding this information confidential we can iterate to an appropriate proxy.

A qualitative description of materials is also required, with sufficient detail to avoid time-wasting suggestions, but simple enough to allow an SME to rapidly classify their wastes. Environmental reporting classifications are not sufficiently detailed. We have developed a classification with a 3-layer hierarchy, which allows detailed information to be given while maximizing the potential for matching by allowing matching at multiple levels. We have also developed a system of attributes to describe the desired state (e.g. clean, contaminated) and form-factor (e.g. pellet, sheet) of the resource, based on natural-language descriptions by potential users.

One outcome is that this model of advising individual SMEs can't work, until a sufficiently large number have followed these steps to provide the necessary information. As such, our key innovation is in our methodology to collect this information – by partnering with local business networks, and providing them with a tool for engagement that allows input/output data to be collected. Instead, ASPIRE suggests potential matches on the basis of common resources, where a desired input matches another SMEs output *and* provides tailored information on resource efficiency and the benefits of engaging with circular economy principles.

Keywords: *Industrial ecology, sustainability, alternative supply chains, small to medium enterprises*

A Hybrid Simulation Model for Preparedness

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Abstract: Defence allocates considerable resources to maintain preparedness. Preparedness is the capacity of defence to sustainably provide forces that are able to accomplish government-directed tasks. Defence Preparedness Requirements plans are produced every year and agreed upon by the chiefs of services. Each service commits to deliver Defence Elements to perform specific military roles in certain numbers and at certain readiness notices. In light of this, the question arises: how well do these preparedness plans perform in reality? That is to say, how well prepared are we to perform disaster relief operations, military conflicts, and other operations, within reasonable warning times? In order to address this question, a non-linear dynamic probabilistic model of preparedness called DyPSim, has been developed and implemented in Java. DyPSim is a hybrid simulation model that quantitatively determines Defence Element availability for a given force structure subject to the demands of a series of military operations. We have employed the concept of supply and demand to model the preparation of Defence Elements for deployment, and their subsequent deployment on military operations. DyPSim combines continuous processes described by differential equations (the supply model) with stochastic discrete events (the demand model). We present the results of running an unclassified dataset through the model for verification purposes.

The system performance metric has been defined as the ratio of successful events divided by failed events to the total number of events during the simulation period. Events are judged to be successful or failed on the basis of their level of resourcing and the timeliness of the resourcing. System success as a percentage was measured by the number of successful events during 30 years of simulation time compared to the total number of events over this period and averaged out over 30 simulation runs. The system failure rate was measured in an equivalent manner. A tipping point can be seen in Figure A1 above which the number of failed events will exceed the number of successful events. Lack of resources in the appropriate time frames due to the spread of resources across different events will cause more failures than successes. We now have two ways to assess the performance of a force structure: we can monitor the success or failure of key events, and we can monitor the system failure to success ratio. Figure A2 shows the success and failure trend as a function of the number of concurrent events. The obtained results demonstrate force structure suitability as a function of the concurrent event profile in the context of preparedness requirements.

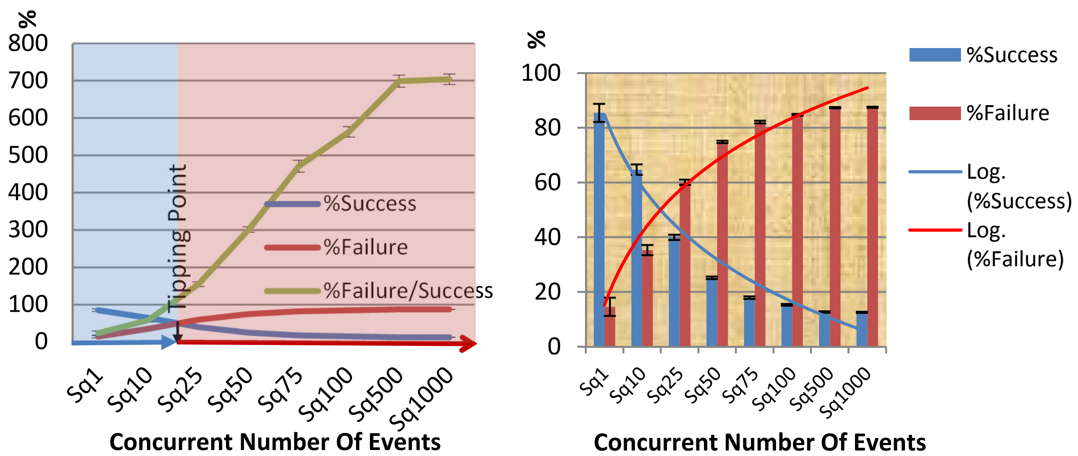

Figure A1 (left) & Figure A2 (right)

Keywords: *Simulation, hybrid modelling, readiness, operations analysis*

Catchy catchments: estimating outflow of the Iponan watershed using Anylogic

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Abstract: The increasing frequency and intensity of storms that hit the Philippines and the destructive floods that follow has made the prediction of outflow behaviour for catchment basins during high precipitation events essential in preparing riverside communities to manage disaster scenarios. This paper reports on the development of an agent-based simulation tool for modeling runoff within the Iponan watershed using a Java-based simulation software called AnyLogic. This tool provides a structured, transparent and interactive approach to helping communities understand the relationship between rainfall, flooding and disaster management. The model, called the Iponan Watershed Simulation System or IWSS, will use agents to encapsulate the properties and interactions of the watershed components, starting with the major subbasins, junctions and reaches, then followed by potential flood-affected areas and the populations and infrastructure within. IWSS uses forecast data from defined rainfall scenarios to simulate extreme storm conditions for which outflow values from the different components of the watershed will be calculated for specified points in time. The tool is envisaged to consist of three interacting modules that will model the behaviour of the watershed through the stages of precipitation and runoff, flooding and intervention, and population impact. The three modules contain components, such as rivers, vegetation, populated areas, and infrastructure that will interact with water and with each other to produce emergency conditions and represent policy implementation scenarios. To facilitate this interaction between components, an agent-based modeling and simulation (ABMS) approach was applied to construct the modules using the Anylogic simulation platform. For each module, agents were created to represent the major physical and social components operating within the watershed. The agents were assigned attributes and behaviour that approximated the behaviour of the physical counterpart under defined precipitation scenarios. To achieve this, each module needs to: (1) replicate a validated model of the natural system while (2) simultaneously allowing its agents to interact with agents from other modules. This paper details the attributes and actions of the agents in the rainfall-runoff module, first module to be completed. The rainfall-runoff module applies three hydrometeorological techniques for runoff computations namely, Soil Conservation Service - Curve Number (SCS-CN) for rainfall excess, Clark Unit Hydrograph (Clark UH) for direct runoff and Muskingum-Cunge for channel routing. The model outputs are compared with results from the widely-used HEC-HMS model for validation and accuracy assessment purposes. Further work has commenced on the development of the agents for the flood and intervention module.

Keywords: *Simulation modeling, watershed modeling, disaster management*

EXTENDED ABSTRACT ONLY

Support to Armed Reconnaissance Helicopter Tactics development using Constructive Simulation

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Abstract: In the complex world of defence systems and processes, the need for highly responsive Operations Research (OR) to support decision-making in active military operations is becoming increasingly important. Joint and Operations Analysis Division (JOAD) of Defence Science and Technology Group (DST Group) uses OR to enhance the Australian Defence Force's (ADF) acquisition, upgrade and tactical deployment of aircraft systems. As an example, the DST Group has supported the transition to service of the Australian Armed Reconnaissance Helicopter (ARH), also known as the Eurocopter Tiger, by providing advice on the evaluation and development of Tactics, Techniques and Procedures (TTPs). OR methods, ranging from simple analytical calculations to a complex constructive simulation framework have been developed for this purpose.

CHOPPA (Combined Helicopter OPerational and Performance Analysis) is a DST Group developed constructive simulation framework built using the Matlab/Simulink[1] environment. It is used to support Monte-Carlo simulation and analysis of complex mission scenarios. CHOPPA contains a number of mathematical models to replicate various military scenarios. Among them are aircraft platform, vulnerability, and human crew behaviours. The aircraft platform model consists of a six degree-of-freedom linearised aerodynamic flight model, while the aircraft vulnerability model consists of a fault-tree model developed by DST Group's Weapons and Combat Systems Division (WCSD), adapted for judicious OR use. The scalable and flexible architecture of CHOPPA permits rapid model prototyping and integration allowing for timely OR response to ADF research requests. The paper focuses on the OR methodology employed in CHOPPA supported studies and demonstrates the framework's effectiveness for timely results.

The constructive simulation process begins with a research request from the client, such as determining optimal tactical decisions or evaluating the benefit of a new capability. This question is then formulated into a scenario which is implemented in CHOPPA. Modelling of complex elements of the scenario, such as human behaviour, is achieved through knowledge elicitation from tactical, sensor and gun operators. Parallel processing of orthogonally designed experiments are then conducted and the consequent multivariate statistical analysis is condensed into graphical representation to facilitate communication with the client. Two previous ARH TTP assessment studies are presented as examples. The first example study determines ARH defensive manoeuvres to maximise survivability whilst the second compares a number of current ARH attack profiles to determine the most appropriate for different mission objectives.

By using CHOPPA to examine operational issues for the ARH, the DST Group is directly contributing to improving operational effectiveness, enhancing Australia's military capability and ensuring value for money for the ADF.

[1] Matlab and Simulink are registered trademarks of Mathworks.

Keywords: *Constructive simulation, tactics, Simulink, Armed Reconnaissance Helicopter (ARH), DST Group*

Using process simulation to demystify scheduling software – a case study

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Abstract: A case study will be presented where a Tram Depot Simulation Tool has been developed using discrete event technology to demystify schedules produced by route schedule optimisation software. The case study is of schedules for tram services that are provided by a pool of tram resources that are stabled at a single tram depot. A particular tram can service any of two routes that are timetabled and it is possible for one tram to do multiple runs on one day (with stabling at the tram's depot in between runs). Route schedules for different service patterns had been produced using optimisation software that optimises tram routing and scheduling with objectives to meet service patterns and resource utilisation, and depot capacity constraints. However, the schedules produced do not take into consideration variability arising from factors such as operational delays due to congestion at the depot and traffic variability. Additionally, the optimized schedules don't account for requirements that trams remaining in the depot and trams returning from service undergo a variety of processes as required, such as servicing, washing, maintenance and sanding. Whilst a route schedule may meet all of the constraints against which it has been optimised, it is unknown whether the schedule is flexible to cope with variability, and whether a schedule can recover from a range of localized perturbations. The concepts introduce the notion of a 'robust' schedule, defined as a degree of insensitivity to localized process perturbations, and measured in this case by lateness for tram run-out and stabling times. To test the robustness of schedules and to ensure the tram depot has the capacity to meet the stabling, servicing and maintenance requirements inherent in the schedule, a process model was developed that included all the key processes relevant to the tram operations. The process model simulates the operations of up to 75 trams, plus maintenance trams from other depots. Both the high frequency activities in the southern half of the depot (stabling, sanding, servicing, sand test, wash) and the lower frequency maintenance activities in the northern half were incorporated in the model. The user is able to apply variability to travel times for routes, and depot operations as required, to test the robustness of tram schedules. Key Performance Indicators customised for the model included stabling and service road utilization at the depot, waiting times and run in and out times during peak operations. Some insights into the usefulness of using discrete event process simulation models to test the robustness of optimised route schedules will be presented.

Keywords: *Optimised, schedule, process simulation*

Understanding the impact of removing a fence between two game ranches with different management objectives

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Abstract: When two adjacent properties have opposing management strategies for the same resource, problems arise regarding equitable benefits. This raises questions relating to the equitable distribution of economic benefits of such resources. The issues relate to the conflicting management objectives of these resources such as consumption versus non-consumption. In this study, we consider these problems in the context of potential commercial harvesting and environmental conservation of African wildlife.

To obtain a better understanding of the implications of these problems, we investigated a scenario where two neighbouring properties were engaged in a co-operative and non-coopertive enterprise respectively. This paper describes modeling the movement of animals in an African environment on neighbouring properties with and without a common fence, which implies cooperative and non-cooperative regimes. This analysis was based on the assumption that the species distribute themselves according to the Ideal Free Distribution (IFD).

We found that when the fence is removed, the returns from the non-consumptive tourism enterprise is decreased due to the animal migration to the neighbouring property, which has a lower density of animals because of removal from hunting. Ths model provided insight into the effect of migration on the profits for both landowners.

Using a model to explore these factors we find that there is an optimal solution to the problem of the equitable distribution of returns for both landowners.

Keywords: *Resource modeling, conservancy, merging game ranches, wildlife tourism, wildlife harvesting*

Where does Oxygen Extinction Occur in a Soil Profile?

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Abstract: The problem of where and under what circumstances oxygen extinction (concentration in gas phase, C =0) in a soil profile is of increasing interest, due to the effect of nitrous oxide and methane fluxes on atmospheric chemistry (Ravishankara et al., 2009) climate change (Forster et al., 2007). The oxygen concentration profile is also of importance as the biogeochemical processes in soils are mainly mediated by oxidation/reduction reactions.

In soil there are two main sinks for oxygen (O_2), microbes and plant roots. Cook and Knight (2003) developed an analytical model for the steady-state transport of oxygen into a uniform soil by use of transformations of the independent variables, the concentration (C) and spatial dimension (z). The transformed concentration is $C' = C - C_r / \alpha$; C_r is the critical concentration in the water phase at the root surface and α is the Bunsen coefficient. The spatial transform is $X = 2Z_r \exp(-z/2Z_r)\sqrt{g}$ with $g = 2\pi\alpha D_l L_0 / \left[D_a \ln(R/a)\right]$, Z_r the scaling depth for an exponentially decreasing root length density with z, D_l is the diffusion of O_2 in soil water, D_a is the diffusion of O_2 in soil air, R is the radius of the root plus saturated soil around the root, a is the root radius and L_0 is the root length density at z = 0. This model could not calculate the depth at which either C or C' went to extinction. A subsequent extension was able to calculate the depth (X_1) when $C' = 0$ and the air-filled porosity (θ) was less than a critical value (θ_c) but with the restriction that $dC'/dX\big|_{X_1} = 0$. Here we remove this restriction and by coupling with model of Cook (1995) where the only O_2 sink is microbes are able to determine the depth (Z_0) at which C = 0. This requires solving a set of five boundary condition equations and a recursive method is presented.

The extension to $dC'/dX\big|_{X_1} < 0$ results in essentially the same critical air-filled porosity (θ_c) below which $C' = 0$ at a finite depth. When θ < θ_c the recursive method can be used to determine X_1 and from this Z_1. Coupling this with the Cook (1995) solution so that $C = C_r/\alpha$ at Z_1 the remainder of the O_2 profile can be obtained. When θ is less than a further critical value (θ_{z0}) then C = 0 at a finite depth and Z_0 can be determined. An example of a typical result for a silt loam soil is shown in figure 1. This shows the rapid increase in Z_1 and Z_0 that occurs as θ approaches the critical value. The model of Cook and Knight (2013) where $dC'/dX\big|_{X_1} = 0$ (solid circles) overestimates the depth of Z_1 compared to the new model given here which removes this restriction. There is not a perfect match in Z_1 around θ_{z0}, this is likely due to difficulties with computational limitations. This suggests that nitrous oxide generation in particular is likely to occur close to the soil surface in accord with measurements (Clough et al. 2004).

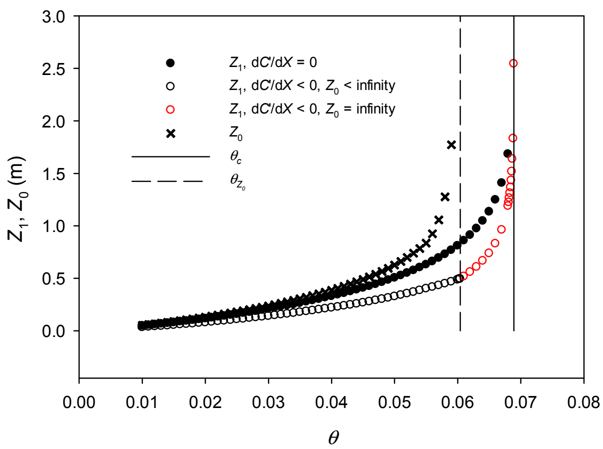

Figure 1. The depth at which Z_1 or Z_0 occurs as a function of θ for different models for clay soil (Table 1). The critical values of θ are shown.

Keywords: *Oxygen transport, soil aeration, nitrous oxide, methane*

Modelling Fire Crew Requirements for Bushfire Scenarios

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Abstract: Resource planning for bushfire response is a major challenge in Australia due to massive personnel and equipment requirements during several large scale incidents and extensive experience required to manage larger fires. During February 2009, when the black Saturday bushfires occurred, nearly 300,000 personnel shifts were deployed in Victoria at a cost of $589 million. This motivated the need for a planning tool to forecast personnel and equipment required under future fire danger scenarios. To develop a model for forecasting resource requirements, a dataset was created from past recorded fire events (2004 to 2012) and resource deployments and historical maximum daily Forest Fire Danger Index (FFDI) information across Victorian weather stations. Using multiple polynomial regression, several models of different variables were tested. The chosen model was a function of the following variables, average monthly FFDI, number of fire events, and number of days in a given month in the FFDI categories of High, Very High, Severe, Extreme, and Code Red. A separate model was produced for personnel and equipment deployed to Level 1, 2 and the more severe Level 3 fires in each month. Each multiple polynomial regression model was build using 3600 data points (40 fire districts by 90 months of records).

We validated the model using the bushfire season from December 2013 to April 2014. It was an ideal case study due to the large scale bushfire events in January/February 2014 that burnt more than 460,000 hectares and destroyed 80 residences across Victoria and required a very large deployment of crews and machinery. The forecasted personnel deployed to Level 2 and 3 fires were 38% higher than actual overall, though the trends at a district level were consistent with the actuals. This over-estimation was due to the number of recorded fire events versus deployments being higher for the 2013/2014 season than the average in the data (2004-2012) used to build the model. For the equipment deployed to Level 1 fires the forecasts were about a 25% under estimation of actuals during the 2013/2014 season. The validation helped identify reasons contributing to differences between the model forecasts and actual deployments, and allowed model calibration for future applications.

The fitted model was used to test the sensitivity of climate change scenarios of Lucas et al. (2007) on fire response personnel requirements. High and low scenarios of the CSIRO climate simulations named CCAM Mark 3 for 2020 and 2050 were used in representative locations of Victoria contained in Lucas et al. (2007). There was a substantial increase in resource requirements for the high and low climate change scenarios at 2020 and 2050 compared to a 2008 baseline. Under the high climate change scenarios there would be up to 22% increase in personnel required for a severe fire season in 2020 and up to 285% additional personnel across Victoria in 2050. The long-term resource projections are extremely important as they could potentially drive the recruitment and personnel development needs. For example because of a long lead times to develop the Incident Management Team capabilities, for personnel to be ready for the challenges in year 2050, they will need to be recruited around 2025 and then developed in the targeted, concentred effort.

Keywords: *Climate change, fire crews, forecasting*

Wavelet characterisation of eucalypt flowering and the influence of climate and budding

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Abstract: In this study we examine the influence of climate (temperature and rainfall) on both flowering and budding, of *E. leucoxylon* and *E. tricarpa* from Victorian Forest Commission records and the field diaries of the Forest Overseer from Maryborough, Victoria between 1940 and 1962. Observations on the timing, quantity and distribution of flowering and budding of these species were collected on a monthly basis and placed into categories which had been pre-determined by the Commission. Flowering and budding intensity of both species were quantified by assigning a rank value producing a categorical time series (Table 1).

Table 1. Terms for budding and flowering intensity and assigned value.

Observation parameter	Symbol	Description	Value	
			Buds	Flowers
Quantity	X	No buds/No flowering	0	0
		Very scattered or isolated*	0.5	0.5
	L	Light Crop/Flowering	1	1
	M	Medium Crop/Flowering	2	2
	H	Heavy Crop/Flowering	3	3
Bud size	1	Small (recently formed)	1	N/A
	2	Medium	2	N/A
	3	Mature (ready to flower)	3	N/A
Distribution		Isolated*	0.5	0.5
	S	Scattered	1	1
		Fairly General*	1.5	1.5

Eucalyptus leucoxylon and *E. tricarpa* both had significant negative relationships at 2 and 4 months with all temperature variants (minimum, maximum and mean temperature). *Eucalyptus tricarpa* was the only species for which rainfall had a significant, positive relationship with flowering at the 4 month scale. For *E. leucoxylon* the highest absolute value of wavelet correlation occurred between flowering and minimum temperature and for *E. tricarpa* with maximum temperature - significant at the 4 month scale. Level 4 profiles indicate a two year cycle in bud and flowering production.

Significant wavelet cross-correlational (WCCORRs) relationships ($P \leq 0.0001$) were found only between flowering and budding for rainfall at 4 months (wavelet scale, level 3) and at 2, 4 and 8 months (levels 2, 3 and 4) for the temperature variants. WCCORRs reveal seasonal dynamics and lead/lag relationships of climate on both flowering and on budding. For *E. leucoxylon* peak budding based on imputed values aligns with the start month of flowering and occurs 3 to 4 months prior to peak flowering. For *E. tricarpa* budding reaches a peak the month prior to the commencement of flowering and 3 months prior to peak flowering. Wavelet cross-correlations (WCCORRs) established the cyclical influence of climate on both peak flowering and budding; and of budding on flowering.

For each species there are on average 6 months of the annual cycle in which minimum temperature and rainfall positively influence flowering and budding intensity and also 6 months of negative influence. The WCCORRs demonstrate that for both species temperature and rainfall do not act in concert on flowering nor on budding. Our results indicate temperature may be influencing bud development, not so rainfall, where temperature in turn influences flowering; also impacted by rain. This complex interplay between climate and budding on flowering needs further work with the examination of additional species, but, given that flowering is dependent on budding, our postulate makes sense.

Keywords: *Wavelets, Eucalypt flowering, budding, phenophases, Wavelet (cross) correlations*

A mixed integer programming model to optimize environmental water releases in river systems

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Abstract: Every river system is home to a large number of species, such as fish and vegetation, and has assets, including multiple river reaches or wetlands, that are significant for the ecosystem. Environmental Managers may have an allocated volume of water - environmental water - that they can actively manage by releasing water from different storage facilities, over a given time horizon, into the river to maintain the health of these species and assets. With the growing increase in the demand of water for irrigation and consumptive purposes, in most river systems, the volume of allocated environmental water is not sufficient to meet the demands of all environmentally significant species in each reach of the river. In addition to this, different species within a river system may have conflicting flow demands at a given point of time. For example, a constant low flow may be required to provide habitat for macro-invertebrates, whereas high flows may be needed to stimulate spawning of a fish species. Hence important decisions on the volume and timing of water releases need to be made in order to achieve maximum environmental benefit. In this presentation we model the problem as a mixed integer linear program that schedules environmental releases on a daily time step over a planning horizon of one year with the objective of maximizing the total benefit to the environmentally significant assets in a river.

This problem poses a number of key modelling challenges, one of which is around the representation of ecological benefit/score of the species in the river system. The ecological outcome of a species may depend on a number of components of the flow regime in conjunction to each other, leading to a non-linear interaction between them. For example, the overall recruitment of a fish species may depend on the constancy of low flows in summer (for habitat provision) and the frequency and volume of high flow pulses in winter spring (for spawning). In order to represent the ecological outcomes linearly, we demonstrate the use of conditional probabilities based network models for each species/asset. In such a network, the nodes represent the different flow components required by the species and the links represent the conditional dependence between two nodes. Conditional probabilities are used to infer the overall ecological score of the species under a given water release decision.

Another key challenge that we address is about the selection of an appropriate objective function in the mixed integer programming model, i.e., how the scores of different species must be combined linearly such that the resulting combination represents the overall ecological benefit to the river system.

The Yarra river system in Victoria, Australia is used as a case study and an extensive computational study is done to demonstrate the efficiency of the proposed strategy.

Keywords: *Environmental water management, optimisation, mixed integer programming, scheduling*

A Network-Based Approach to Bushfire Fuel Management

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Abstract: Bushfires are part of the Australian landscape. They have been around for an estimated 60 million years and they are part of a regular cycle in Australian climate. Each year, such fires impact extensive areas presenting a real and continuing problem that can have a major impact on people, wildlife and the environment. The largest recorded bushfire known as the Black Thursday dates back to the 6th of February 1851 when approximately 5 million hectares in Victoria where affected with the loss of about 12 human lives, 1 million sheep and thousands of cattle (the records are imprecise). Over the last decade there were 24 significant bushfires with the combined area of more than 3 million hectares.

On one hand, bushfires can cause property damage and loss of human life. On the other hand, certain native flora in Australia have evolved to rely on bushfires as a means of reproduction, and fire events are an interwoven and an essential part of the ecology of the continent. For thousands of years, Indigenous Australians have burned the country for various purposes, including hunting, communication, horticulture, ease of travel and ceremonies. The effect was a system of opportunistic burning techniques, which controlled the buildup of fuel, thereby reducing the incidence of large, intense fires. Traditional burning practices resulted in a greater frequency of fires, which left a mosaic of different post-fire states. The amount of fuel available to carry fires was broken up into patches and, in occupied areas fires could be contained.

Since eliminating bushfires completely is not an option, we would like to reduce the severity of their effect building on the traditional practices and experience of Indigenous Australians. This can be achieved through fuel management, which usually consists of mechanical thinning and prescribed burning of the landscape. We propose a general methodology to address the problem of optimal resource allocation for bushfire fuel management subject to landscape connectivity and stochastic fuel regeneration. In this work we draw inspiration from the literature on robust optimisation, network interdiction and critical element detection in graphs. We develop a number of mixed integer programming formulations that are based on various landscape connectivity metrics. We then extend the formulations using robust optimisation to incorporate stochastic fuel regeneration in discrete time. The proposed approach takes into account the uncertainty of the fuel regeneration without assuming a specific distribution, while remaining highly tractable and providing insight into the corresponding optimal policy. It also allows adjustment of the level of conservativeness of the solution to trade off performance and protection against uncertainty. The attractiveness of the proposed approach is two-fold. First, the use of various connectivity metrics in the objective function adds to the modelling flexibility. Second, the robust problem is of the same difficulty as the nominal problem, i.e., it requires the same amount of computational effort. We also show that for some objective functions, the optimal policy obtained in the robust approach is identical to the optimal policy obtained in the nominal case for a modified and explicitly computable budget. We present extensive computational experiments that reveal interesting insights and demonstrate advantages and limitations of the proposed framework.

Keywords: *Bushfire, fuel management, network, mathematical programming, robust optimisation*

Using spatial fishing data and DEA to inform spatial fisheries management

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Abstract: Estimates of fishing capacity and capacity utilisation provide valuable information to fisheries managers, particularly in relation to potential excess capacity in the fleet, which has implications to both biological and economic sustainability. Data envelopment analysis (DEA) is the preferred method for estimating fishing capacity, and applications of the approach in fisheries are widespread. In most studies, DEA estimates of capacity are undertaken based on individual vessel data. Increased interest in spatial fisheries management, and in particular closure of certain areas for either conservation (e.g. marine parks) or dedicated recreational fishing, requires a more spatially oriented estimate of fishing capacity.

In this study, we use DEA to estimate fishing capacity utilisation for the net component of the Queensland inshore finfish fishery using fishing area data as the DMU. Several areas of the fishery are potentially subject to closure to enhance recreational fishing. The DEA analysis can provide an indication of which areas are the most "efficient" and have high capacity utilisation, indicating the importance of these areas to the commercial fishing sector. Assuming profit maximizing behavior, and the ability of fishers to move between areas, areas with low capacity utilization in a spatial context most likely reflect either low productivity, higher access costs than other areas, or high seasonality such that they are only preferred as a fishing location at certain times of the year for short periods.

The results of the analysis identify several areas with high capacity utilization. Of the three proposed net closures, only one corresponds to an area with high (>0.9) capacity utilization, with the other two corresponding to areas with medium (around 0.65) capacity utilization on average. However, in all cases, adjacent cells have lower capacity utilization, suggesting that transferring effort into these areas will be at either a higher cost or result in a reduction in productivity.

Keywords: *DEA, fishing capacity, spatial analysis*

Managing invasive species under structural uncertainty using partially observable Markov decision processes

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Abstract: *Aedes albopictus* is a worldwide invasive mosquito that vectors debilitating diseases to humans. It has invaded the Torres Straits Islands, an Australian archipelago situated between Papua New Guinea and mainland Australia. These islands are potential sources of dispersal to mainland Australia via numerous human-mediated pathways including local boats, airplanes and ferries. The problem consists in preventing the mosquito from colonising mainland Australia under a limited budget. At each time step and on each island, managers can choose among three actions.

In our talk, this sequential decision problem will be modelled, in a first step, as a Markov decision process (MDP). The states depict the invasion status of each island and the transition function captures the efficiencies of actions and the dispersal of the mosquitoes.

However, the transition function is not known perfectly (structural uncertainty) and will be assumed to be one of a finite number of possible functions. It will be demonstrated that solving the MDP for these different transition functions leads to significantly different optimal policies resulting in earlier or later infection of mainland Australia. However, it is possible to learn about the transition function over time by analysing the evolution of the system. Further, such learning can be actively provoked by selecting certain actions, referred to as informative decisions. A good policy should trade off rewarding decisions on the short-term (i.e. that effectively delay the infection of mainland Australia) against informative decisions (that mainly improve our knowledge and hence the rewards on a longer term).

In a second step, we model the problem as a partially observable MDP (POMDP), where states are not perfectly observable anymore. Each POMDP state is the combination of a system state and a model state, where the model state represents our current and imperfect knowledge of the transition function. This POMDP can be solved by readily available solvers; the resulting policy achieves an optimal trade-off between informative and rewarding decisions to delay infestation of Australia as much as possible.

First computational results recommend managing the highly populated Thursday Island as a priority. This general approach can be replicated to find the optimal decisions on problems with structural uncertainty.

Keywords: *Sequential decision making, partially observable Markov decision processes, structural uncertainty, invasive species*

Minimizing Discontinuities in Electricity Tariffs

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Abstract: Electricity retailers typically offer a set of different electricity tariffs to their customers. The individual tariffs that make up the tariff structure of an electricity retailer are often characterized by different price components, i.e. the total price to be paid by a customer can depend on several variables, such as the peak energy demand or the total energy consumption over a period of time, and there may be different prices for different time periods during a day (time-of-use tariff).

To determine a particular customer's tariff within the tariff structure offered, electricity retailers may use certain thresholds regarding the customer's peak demand or energy consumption, i.e. a customer may be forced into a different tariff when its demand or consumption exceeds, or remains under, a relevant threshold. This can lead to a situation in which small changes in the energy demand or consumption of a customer may lead to a large difference in the electricity price that the customer has to pay. A customer friendly approach therefore would be to design the tariff structure such that discontinuities between tariffs are minimized.

Our paper presents a linearized optimization model with stochastic components to address this problem for a case in the Australian electricity market. More precisely, the objective function of our model minimizes the discontinuities between tariffs, weighted according to the percentage of customers who are potentially affected by a transition between a certain pair of tariffs within a certain energy demand or consumption interval. The constraints of our model represent the tariff rules imposed by the regulator and additional restrictions on tariffs that may be requested by the electricity retailer, such as criteria that ensure a consistent tariff system, for example.

Moreover, our model takes into account the probabilistic nature of the problem and models customer numbers, demand and consumption as random variables within the framework of a single-stage stochastic program. Additionally, the model includes variance constraints (approximated by piecewise-linear functions), that ensure, in line with the demands by the regulator, that the annual revenue exceeds certain thresholds only with pre-given probabilities.

Detailed sensitivity analyses for several parameters of the model demonstrate that the model achieves a reliable approximation of the underlying real-life problem.

Keywords: *Electricity tariffs, discontinuities, mixed-integer programming, stochastic programming*

Optimal control of electrical and thermal energy storage to minimise time-of-use electricity costs

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Abstract: The advent of new electricity metering technologies means that consumers can now be billed for electricity using prices that vary with time-of-use. At the same time, new electrical energy storage systems and thermal energy storage systems give consumers an opportunity to control when they import electricity from the grid.

In this paper we construct a power flow model of a system with both electrical and thermal energy storage, and use Pontryagin's principle to derive necessary conditions for a control strategy that minimises the cost of energy from the grid. The optimal control has just three control modes for each storage system: charge, off, and discharge. Which mode should be used at any instant for each of the storage system depends on the price of electricity relative to two critical prices for each of the storage systems. We use a realistic example to illustrate how the critical prices for each subsystem can be determined, and to determine the ideal capacity of each storage system.

Keywords: *Electrical energy storage, thermal energy storage, optimal control, time-of-use tariff*

Modelling of household electricity demand when using home batteries

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Abstract: Until 2009 electricity consumption in Australia had increased consistently on an annual basis for more than a century. Since 2009 the net electricity used from the grid has declined, again consistently on an annual basis – from year to year. For example for the last five financial years the total electricity used from the grid in the National Electricity Market (NEM) that covers all Eastern and South-Eastern States has decreased by 8%. This decline has been attributed to several factors, including rapid uptake of solar photovoltaic (PV) arrays supported by government policies, energy efficiency programs and other government policies related to climate change and renewable generation, structural change of the economy away from electricity intensive industries and the response of residential consumers to higher electricity prices. The uptake of solar PV panels by residential customers in Queensland for example approaches 30%. This creates opportunity for the customers not only to buy but also to sell electricity to the grid.

In April 2015 Tesla announced mass production in USA of two new, affordable lithium-ion batteries for residential use – 7 kWh and 10 kWh. These batteries were priced significantly lower than the previously mass produced similar batteries, which created a lot of excitement and the home batteries are now considered a new disruptive technology for households. It is expected that home batteries will change significantly the way residential customers buy and sell electricity. This is confirmed in the Emerging Technologies Information Paper published by Australian Energy Market Operator (AEMO) in June 2015. According to this paper, it is estimated that the installed battery capacity in the regions of the NEM will grow to 3.4 GWh in 10 years, even without considering retrofitting of existing solar PV with battery storage.

This paper examines household electricity demand and consumption scenarios with solar PV panels, home batteries and different electricity price tariffs. When modelling these scenarios a set of battery charging and discharging rules need to be considered based on different customer's circumstances, including price tariffs. It is assumed that households will use their battery to maximise income generated from electricity exported to the grid and reduce import from the grid due to self-consumption and load shifting from peak periods. Use of the battery will also heavily depend on which solar PV feed-in-tariff (FiT) the household is on. In general, households on high FiT will use the battery to maximise electricity exported from their PV panels, whilst those on low FiT will do the opposite (minimise the import/use from grid and storing the excess from solar PV generation for later use).

The annual cost of electricity for each of the modelled tariffs, for several dwelling types, occupancy patterns and different configurations are calculated and analysed.

Keywords: *Home battery, household electricity demand, solar PV, residential electricity consumption*

Impacts of Feed-in Tariff and Metering Types on Electricity Consumption Efficiency in Australia

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Abstract: Small scale renewable energy technology mainly includes rooftop solar photovoltaic (PV) panels for electricity generation at household level. Solar feed-in tariff (FiT) is meant to encourage households to alleviate import from electricity grid especially during peak demand, via investment on on-site generation. We investigate the impact of FiT, net and gross metering types on household energy consumption, in Australia.

A macro level model is developed for New South Wales (NSW) using a recent Australian household energy consumption dataset. The results indicate that net metering is more effective than gross metering, in terms of curtailing electricity consumption. Additional micro level analysis is conducted for Queensland (QLD) and other states which also verify similar effects.

In the last four years the cost of production of solar panels has declined by 80 percent, which alongside high FiT would increase the number of prosumers. An immediate response is that most states have already reduced FiT to one third or less. However, further decline in technology cost and the advent of new technology are expected to lead to massive uptake. Today, more than 10 percent of Australians use solar power. The 8,000 rooftop solar systems in 2007 have increased to 1 million in 2013, a number first expected for 2030 (ABC, 2013). On the other hand, since the intermittent PV electricity is not fully reliable, the stable grid electricity has become more pricy. In Australia, average annual electricity price is now rising at 8% (ABS, 2013). Accordingly, households opt to either invest more on renewable technologies or adapt to lowered consumption.

Statistics show average annual electricity consumption decline by 5.8% since 2009 (AER, 2014). This reduction is at both households with or without renewable electricity technology (ABS, 2014b). An implication is that non-generating households now have to suffer from high price of grid electricity, while generating households have less difficulty. In fact high FiT would even make profit. The situation signifies the need for a minimal FiT that could still encourage sustainable uptake of the renewables.

In this article, we analyse and evaluate solar FiT in Australia since its introduction in 2008. Our focus goes on investigating the impacts of metering types (gross and net) with low and high FiTs on electricity efficiency behaviours in Australia, however regardless of Renewable Energy Target (RET) incentives and possible retail price-tariff structures. In gross metering (GM), imported electric energy (E_{in} kWh) and exported energy (E_{out} kWh) are metered separately and respectively equal to total consumption and solar generation, while in net metering (NM), the offset values are equal, i.e., E_{out}-E_{in} = generation minus consumption. Dwellings with no onsite electricity generation use non-generating meters (ngM). The notations, GM, NM, ngM, are used frequently in this article.

This study indicates that high FiT only encourages higher consumption and does not effectively alleviate demand from grid. This in particular applies to GM where FiT profit is more visible. In comparison, under high FiT, GM households tend to consume more electricity than NM households, while in general all generating households (whether GM or NM) consume more electricity than non-generating households. This could be further discussed with regards to the rebound effect. Another implication of this study is in line with maintaining low FiT. For example Victoria has reduced FiT per kWh from 60c to 25c and to 8c, from 2009 to 2014. The FiT currently offers minimum premium of 8c per kWh for excess electricity exported to the grid. Some electricity retailers may offer higher rates although not obligated to do so. The Essential Services Commission (ESC) has released a decision to adopt a minimum FiT of 6.2c per kWh from 2015 (FiT, 2014a). Other states have reduced FiT, capped generation capacity, or cut premiums.

Keywords: *Solar feed-in tariff, net metering, solar panel uptake*

Minimizing bushfire risk through optimal powerline assets replacement and improvement

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Abstract: Fires initiated by powerline faults disproportionately are associated with a majority of bushfire fatalities in South-Eastern Australia. Over 150 deaths have occurred since 1977 in South-Eastern Australia. A response from governments and utilities has been to embark on electricity asset improvement and replacement programs where the definition of improvement is tied to an aim of reducing powerline sparked ignitions under the most dangerous meteorological conditions for fire. This paper introduces an optimization model which provides a strategy for adding technologies to powerline distribution assets such that there are improvements in terms fire risk being lowered. The goal of the model is to minimize financial outlay while the risk of electricity sparked bushfire incidence is a solid constraint in the model, set to mimic potential bushfire risk reduction target scenarios. Currently, strategies for targeting investment in improvement of the electrical distribution system have not used such a mathematically based optimization approach. Instead they are based on expert interpretation of risk maps which visualize risk of fault of asset technologies with the consequence of fire starts at the same locations. Application of an optimization model by government and utilities when investing in powerline improvements could lead to reduced bushfire impacts within given funding frameworks relative to current practice. Estimated fault and fire ignition behavior of current and proposed electrical asset technology are a basis for our model. Fire mitigating treatments can range from the installation of new electrical fault detection systems at zone sub-stations; burying individual sections of powerline; installation of automatic circuit reclosers (ACRs); adjusting the settings on existing ACRs; insulating bare lines; etc. The work here represents a natural extension of bushfire risk-modelling work being undertaken by the authors in collaboration with the Victorian Government's Powerline Bushfire Safety Program (PBSP).

Keywords: *Bushfire risk, mixed-integer programming, powerline safety, combinatorial optimization*

Sensitivity analysis of gas supply models for South-Eastern Australia

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Abstract: The security of gas supply is a crucially important question for the economy of any country. South-Eastern Australia has a sophisticated network of gas pipelines which connect the production sites in the ocean shelf and in the inner part of the continent with major consumers which are the state capital cities (Adelaide, Melbourne, Hobart, Sydney and Brisbane) and the regional industrial town of Gladstone. Two optimisation models were developed in order to test the security of the gas supply system to the possible global impacts which affect the demand for natural gas. The modeling research in the present work was focused on the simulation of delivery when demands reach their peak values. The first model minimizes shortfalls in major supply nodes. As major constraints the models used the production levels, supply capacities and the mass balance in pipe junctions. The second model minimizes the total cost of gas delivery, which is a sum of production and transportation costs, whereas the constraints stay the same. Both models were run for a series of the plausible economic scenarios which generated the future values of demands. The potential "bottle necks" in the system components were identified. It was found that the first constraint which became scarce is the pipe providing gas to the port of Gladstone. The capacity of this pipe should be increased in order to meet growing demand. Gladstone is also the site of the liquefied natural gas export industry on the east coast. An increase in pipeline capacity will facilitate the increase of export from Gladstone, but will reduce supply to other consumption nodes.

The Sensitivity Analysis (SA) was implemented for both formulations of the model. It was examined how the key indicators of system security and pipelines' flow were impacted by the changes (increase and decrease) in peak demands. For this analysis the predicted annual scenarios for peak demand increase for four states (ACT was treated as part of NSW in the present work) were used. For the analysis of the decrease of demands the equal proportional changes in demand were used for all demand nodes. It can be concluded that under current infrastructure the most vulnerable components of the system are industrial gas users in Gladstone and Mt. Isa, whereas amongst the domestic consumers it is Brisbane. This conclusion can be utilized in further decision on pipeline infrastructure upgrades.

SA was also implemented in order to indicate how sensitive production levels are to the changes in cost of production. This analysis was performed for two production sites in Longford, which is a largest producer with lowest cost and who is a major supplier of gas to the domestic consumers in Melbourne and Sydney, and in Moomba, which is an important supplier of gas to the industrial users. This analysis indicated the critical values of production costs which cause the stepwise reductions in the production levels.

Keywords: *Network optimisation, gas supply, sensitivity analysis*

A Hybrid Cross-Entropy and Progressive Hedging Matheuristic with application to a RAPS System

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Abstract: In many applications the design of a system needs to be optimised but the effectiveness of the design choices can only be evaluated by considering the behaviour of the system over a longer time period or multiple scenarios. Here we develop a general hybrid matheuristic method that can be used in such situations and apply it to a particular problem that arises in the design of a Remote Area Power Supply (RAPS) system in the presence of storage.

The major elements of our RAPS system include the load (demand for power), solar energy from photovoltaic (PV) panels, a diesel generator and a battery based storage facility. The aim is to find a fixed strategy is for using the diesel generator and battery storage facility to efficiently meet demand. Similar types of problems arise in a range of other design applications such as expansion planning of electricity transmission networks; selection and sizing of power generation facilities in a RAPS or electricity grid; or supply chain design (sizing warehouse storage and transport infrastructure). All of these applications can be formulated as large MIP models with have a similar structure: high level design variables relating to infrastructure or policy, and additional variables for evaluating the effectiveness of these decisions in a number of scenarios.

In this paper we consider how to deal with such problems by combining ideas from progressive hedging, a Lagrangian decomposition based method, with the cross-entropy optimisation meta-heuristic. We describe the general structure of mixed integer programming (MIP) problems to which this applies, show how our application can be formulated in this structure and then describe the new hybrid matheuristic. Indicative computational results are provided comparing the new method against the CPLEX integer programming solver, progressive hedging and cross-entropy optimisation.

Keywords: *Matheuristics, progressive hedging, cross-entropy optimisation, remote area power supply*

A Multi-level Approach to Planning and Scheduling Resources for Aviation Training

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Abstract: This paper describes a multi-level system dynamics (SD) / discrete event simulation (DES) approach for assessing planning and scheduling problems within an aviation training continuum. The aviation training continuum is a complex system, consisting of multiple aviation schools interacting through inter-school student and instructor flows that are affected by external triggers such as resource availability and the weather.

SD was used to model the overall training continuum at a macro level to ascertain relationships between system entities. SD also assisted in developing a shared understanding of the training continuum, which involves constructing the definitions of the training requirements, resources and policy objectives. An end-to-end model of the continuum is easy to relate to, while dynamic visualisation of system behaviour provides a method for exploration of the model.

DES was used for micro level exploration of an individual school within the training continuum to capture the physical aspects of the system including resource capacity requirements, bottlenecks and student waiting times. It was also used to model stochastic events such as weather and student availability. DES has the advantage of being able to represent system variability and accurately reflect the limitations imposed on a system by resource constraints.

Through sharing results between the models, we demonstrate a multi-level approach to the analysis of the overall continuum. The SD model provides the school's targeted demand to the DES model. The detailed DES model is able to assess schedules in the presence of resource constraints and variability and provide the expected capacity of a school to the high level SD model, subjected to constraints such as instructor availability or budgeted number of training systems. The SD model allows stakeholders to assess how policy and planning affect the continuum, both in the short and the long term.

The development of this approach permits moving the analysis of the continuum between SD and DES models as appropriate for given system entities, scales and tasks. The resultant model outcomes are propagated between the continuum and the detailed DES model, iteratively generating an assessment of the entire set of plans and schedule across the continuum. Combining data and information between SD and DES models and techniques assures relevance to the stakeholder needs and effective problem scoping and scaling that can also evolve with dynamic architecture and policy requirements.

An example case study shows the combined use of the two models and how they are used to evaluate a typical scenario where increased demand is placed on the training continuum. The multi-level approach provides a high level indication of training requirements to the model of the new training school, where the detailed model indicates the resources required to achieve those particular student levels.

Keywords: *System dynamics, discrete event simulation, training continuum*

An Efficient Modified Greedy Algorithm for the *P*-Median Problem

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Abstract: The fundamental objectives of locating facilities can be summarized into three categories. The first category refers to those designed to cover demand within a specified time or distance. This objective gives rise to location problems which are known as the Location Set Covering Problem (LSCP) and the Maximal Covering Location Problem (MCLP). The LSCP seeks to locate the minimum number of facilities required to 'cover' all demand or population in an area. The MCLP is to locate a predetermined number of facilities to maximize the demand or population that is covered. The second category refers to those designed to minimize maximum distance. This results in a location problem known as the *p*-center problem which addresses the difficulty of minimizing the maximum distance that a demand or population is from its closet facility given that *p* facilities are to be located. The third category refers to those designed to minimize the average weighted distance or time. This objective leads to a location problem known as the *p*-median problem. The *p*-median problem finds the location of *p* facilities to minimize the demand weighted average or total distance between demand or population and their closest facility. The *p*-median problem is a typical combinatorial optimization problem with many practical applications such as location of warehouses, schools, health centers, shops etc.

Greedy algorithms are the simplest algorithms to design however it is not easy to understand its capability and limitations. A greedy algorithm solves a global optimization problem by making a sequence of locally optimal decisions. That is a greedy algorithm always chooses the next step of an algorithm that is locally optimal. For example for Facility Location Problem we will consider the facilities for which decisions regarding locally optimal locations will be made. The decisions that are made regarding where to locate successive facilities by a greedy method are permanent. That is the greedy algorithms make permanent decisions about the construction of a solution, based on the restricted consideration such as choosing a location that gives a minimum cost. Greedy algorithms for facility location problems are constructive in principle. They are designed to give solutions of fairly good quality without using much time that is needed to compute better quality solutions by other algorithms. The most natural and simple heuristic for the *p*-median problem is the greedy algorithm. For the *p*-median problem to locate facilities, this algorithm picks a most 'cost-effective' facility until every required number of facilities *p* is located.

We propose a modified form of the myopic (greedy) algorithm for the *p*-median problem. The new algorithm is simple and it gives relatively quality solutions. We demonstrated the importance of the removal of extreme values from a distance matrix before locating the first facility. The modification of the algorithm involves the removal of the extreme or large values from each column of the distance matrix. We then determine the first facility (1-median) after the removal of the extreme values. We revert to the original distance matrix after the first facility (1-median) is located. We then determine the additional facilities using the original distance matrix. We compare the results obtained by the original Myopic algorithm with the modified version using the 400 random problems. The results demonstrate the efficiency and superiority of our new method.

Keywords: *Facilities, p-median, greedy algorithm, modified*

Social Media Monitoring for Health Indicators

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Abstract: Social media has been recognised as a new source of information from the general public to help achieve positive social outcomes. Some examples are detecting earthquakes, monitoring ongoing disaster events, tracking public opinion, marketing, human behaviour research and public health issues. Given the large volume of information available on numerous social media platforms currently in use, a significant challenge is to extract meaningful and relevant information for these different purposes.

In the area of health research, social media has been investigated to provide health information to the community for the purposes of early warning or intervention, preparedness and targeted health advice. Crowd source content has also been used for disease mapping, see for example Google flu trends, https://www.google.org/flutrends/au/#AU, while information published on social media has been identified as an indicator for public health issues, such as detecting influenza epidemics (Aramaki et al. 2011). The importance of early detection of large-scale contagious disease outbreaks and the ability to understand how a population is reacting to such events, whether naturally occurring or as a result of bioterrorism, is of interest to governments world-wide.

Health monitors and decision makers need credible early signals of disease outbreaks. Although this is difficult due to the variability of health monitoring capabilities, early warnings combined with available key data could be used for a number of improved population health outcomes such as estimating the spatio-temporal spread of diseases, severity of disease outbreaks, projected peak time and duration of disease outbreaks, the use and effect of early mitigation measures and the targeted deployment of limited medical resources. This has the potential to augment and complement existing information to reduce the cost of information gathering and analysis to increase the productivity, responsiveness and planning for health agencies to achieve a new perspective on population health for government agencies and health professionals.

In Australia, CSIRO have been investigating these techniques using statistical data mining methods and natural language processing procedures, such as text classification and unsupervised clustering, applied to messages published on Twitter to identify content of relevance to emergency managers. A large collection of tweets from Australia and New Zealand have been processed since late 2011 to identify unexpected emergency incidents and to monitor ongoing disaster events (Yin et al. 2012; Power et al. 2014).

This previous work has been adapted to develop an investigative tool using content published on Twitter to provide indicators of population health and well being. The aim was to conduct a preliminary feasibility study to better understand the potential for detecting and alerting on medical symptoms in on-line communities using social media postings. The following two key questions were investigated:

1. Is it feasible and valuable to detect and alert on unusual variations in medical symptoms within online Australian communities monitored through social media?

2. Can social media monitoring, equipped with novel statistical and online data mining algorithms, provide reliable early evidence of disease outbreak?

This paper reports on our experience to date which includes preliminary positive results indicating that health issues such as colds, influenza and fever expressed by the general public can be identified from tweets originating from Australia. These results need to consider the issue of selection bias inherit in the Twitter data source before population inferences can be made.

Keywords: *Health monitoring, social media, syndromic surveillance, Twitter*

Using Microblogging Messages to Detect Emergency Events in China

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Abstract: Microblogging services have successfully been used as a new source of crowd sourced content describing emergency events. For example, information published on Twitter by the public has been used to detect earthquakes and as a source of intelligence about fire and flood events in progress. While Twitter is not available in China, Chinese specific microblogging platforms are popular such as Sina Weibo. We have applied some of the text processing techniques shown to be useful on Twitter to messages published on the Sina Weibo platform. We have found that these techniques can successfully be applied to detect disaster events such as earthquakes, fires and floods and also to identify messages describing disaster events underway.

We describe our results to date including successfully identifying disaster events and being able to determine when a message is a report of someone experiencing a disaster event. A number of issues have had to be resolved to achieve these results. Accessing the Sina Weibo messages from the public timeline has at times been difficult due to service outages. Also, applying Natural Language Processing techniques to Chinese text has been more difficult than other languages, partly due to dialects, the use of traditional and simplified Chinese, segmentation difficulties (lack of whitespace between words) and identifying stop words.

Our long term aim is to develop a general emergency notification and monitoring system for various disaster event types in China reported by the public on Sina Weibo. To support this goal, we have developed a preliminary web site to demonstrate our system: https://swim.csiro.au/, referred to as the Sina Weibo Incident Monitor (SWIM). Access requires a username and password which can be obtained by contacting the first author. Our hope is that this can be used by the appropriate emergency services in China as a source of improved situational awareness during disasters and crisis situations.

In summary, the Sina Weibo Incident Monitor is a multi-disaster detector based on near-real-time microblog messages from China. The system filters keywords related to disaster events of earthquake, flood, fire, typhoon and storm (heavy rain) published as Sina Weibo messages on the public timeline. These messages are then processed by Support Vector Machine (SVM) classifiers to determine if the messages containing the target keywords correspond to the people experiencing a disaster, or are using these words for a different meaning. Ten-fold cross-validation of the SVM classifiers for each event type resulted in accuracies ranging from 84% to 93%.

The web site is an interactive map based user interface consisting of four elements: a map of China, disaster related keyword search filters, message count graph and message display. The map interface supports standard map navigation features such as zooming and panning to a location of interest. The messages displayed can be for the whole of China, or for a particular province or city of interest. The messages can also be searched to identify those that contain keywords of interest relating to one of the target disaster categories. The messages determined to be positive examples by the classifiers are also highlighted. A timeline graph shows the distribution of messages.

Examples of using the SWIM interface will be presented showing how disaster events can be detected as well as example messages from people experiencing known events.

Keywords: *Text mining, disaster detection, microblogs, Sina Weibo, SVM*

On the Feasibility of Answer Suggestion for Advice-seeking Community Questions about Government Services

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Abstract: Government departments are increasingly using social media and web resources to deliver information about services available to the citizenry. Part of this delivery includes online responses to community questions that are posted on social computing platforms such as Facebook, Twitter and forum sites. With the growth in the number of questions posted on such sites and the expectation that such questions are answered promptly, government customer service staff are faced with new challenges in terms of responding in a timely, accurate and complete manner.

In this work, we study a set of online engagements in which government customer service staff have answered community questions posted in public forums such as Twitter and Facebook pages. We examine the feasibility of automatically suggesting content for inclusion in the response, based on previous engagements. Ultimately, auto-suggestion of content may facilitate timely responses and help improve the consistency of answers.

We describe preliminary feasibility tests examining word overlap between question-answer pairs in our data set. Our results indicate that there is some degree of content overlap between question-answer engagements in our data set, suggesting that automatic suggestions for responses is possible.

Keywords: *Community question-answering, Gov 2.0, improving government services*

Tracking biosecurity events on Twitter: Challenges and lessons learned

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Abstract: Twitter is being increasingly used as a data source to derive information on disasters (e.g. earthquakes), global events (e.g. FIFA World Cup) and human disease spread (e.g flu). It has been suggested that biosecurity surveillance could make use of this stream of information. In contrast to applications that trigger massive information streams, like earthquakes, the data input for biosecurity events is expected to be more sparse and less frequent. Data mining techniques that are typically applied to detect large-scale events will not apply. In order to use Twitter for the detection of small-scale events, we propose a three-step process: (1) verify if the information of interest is present in the tweets, (2) check if the information of interest can be extracted from the tweets, and (3) relate the extracted information to an independent data source for validation.

First, we confirmed that there are tweets reporting sightings of two migratory species, the Bogong moth (*Agrotis infusa*) and the Common Koel (*Eudynamys scolopaceus*). Both species share similar seasonal movements, but are different in terms of familiarity to the public.

Second, we verified if we could extract the relevant tweets for these species. We developed three query types: (1) a taxonomic query (e.g. *Agrotis infusa*), (2) a common name query (e.g. Bogong moth), and (3) a symptomatic query using keywords that are frequently used to describe the species (e.g. moth, first, invasion, plague, season). For the Bogong moth this resulted in 2, 98, and 333 hits, respectively, with signal-to-noise ratios around 50%, 90% and 55%. For the Koel, 0, 22, 480 tweets were retrieved, respectively, with signal-to-noise ratios of 100% for the common name query and 13% for the symptomatic query. The results clearly indicate that the taxonomic query delivers only a very few or no tweets, while the symptomatic query resulted in a large number, however, with significantly lower signal-to-noise ratios. It seems that the common name query provides a reasonable balance between number of hits and signal-to-noise ratio.

Third, we related the Tweets to ground truth data to validate our results. The ground truth data for the Bogong moth are the result of frequent planned surveys of the top of Mount Gingera, ACT. The Koel ground truth data were obtained from the Canberra Ornithologists Group, who have been running the Garden Bird Survey since 3 July 1981. In general, the common name queries were best related to the ground truth data, while the symptomatic queries did not provide usable results.

Finally, the level of familiarity with the species plays a major role. For the Bogong moth the results were more stable and reliable than for the Common Koel. Therefore, we conclude that tracking biosecurity events on Twitter could be possible for those species that the general public is highly familiar with. However, it is hard to imagine this being the case for exotic species unless the public is sufficiently exposed to biosecurity awareness campaigns.

Keywords: *Twitter mining, biosecurity risk, crowdsourcing*

Usability principles for the design of virtual tours

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Abstract: Museums are places of education, which are open and accessible to the general public. The diversity of the visitors puts museums in the role of a reference educational environment, where different methods and strategies can be developed and tested. The diversity of cultural and educational visitor backgrounds raises the challenge to adapt the museum tour guidance to specific interests and needs. New technologies are supporting an individually guided visit by mobile devices like tablets, smartphones or 3D glasses. However, along which lines could such an individually guided visit be designed?

This contribution provides a detailed definition of usability principles for virtual realities that are for instance designed as virtual tours or interactive educational environments. In two case studies, the developed design principles are applied to museums as specific reference environments, thus validating the applicability of the defined principles.

One main characteristic of the usability of a product is to be user-centered, giving an opportune response to user needs and requirements. The design of an interactive virtual tour should meet the requirements of a potential user, addressing aspects of interface, system functionality and interactivity, among others. This contribution elaborates usability principles for virtual tours, and validates them in two test scenarios.

Virtual tours in general are generated by software and presented on a screen or another display. According to guidelines applicable to general software products, they should be designed with the aim of allowing users to visit different sites and browse through them easily, allowing the users to find the information they need efficiently, when they need it and where they need it.

In this contribution, we understand by a virtual tour the predominantly audio-visual representation of a real site, its different aspects and the connections between them. As a feature, a virtual tour should allow individual interactions focusing on specific topics, in which a user is most interested. We assume that the virtual tour has the option to be coupled to a specific site in the sense that the virtual tour can be realized within this real site, thus coupling virtual and real experiences.

The perspective for further works is to apply the design principles in other contexts like guided tours of cities or through an archeological site. In a broader approach, the same principals also apply to any virtual reality environment, independent whether there is the option to connect the tour to a real location or not. The same design principles are also suited to be used to develop or improve interactive educational environments like virtual classrooms.

Keywords: *Usability, usability principles, virtual reality, virtual tours, virtual educational environments*

Sustainable living internet technical library

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Abstract: There are many reasons to live conservatively on renewables in low embedded energy homes e.g., personal, economic, freedom-creating, disaster-alleviating, and reduction in emissions. The author's 1986 $10,500 fire-proof flood-proof steel Island kit home on 0.1ha edible jungle (still available for about $20,000) - reportedly one of Australia's most sustainably integrated kit homes that operates via 150 essential job-creating budget devices: e.g., 12V solar appliances and transport, food plants and processes. Such currently topical, politically-focused, ingeniously simple and vitally interesting budget life-support systems – largely home-invented have supported the author for over 1/3 century. Sustainable home engineering provides a comfortable living style on less than a 5% pension at my age of 81 and wife's age of 65. It is arguable why with a total 4,152 inventions and discoveries; many of them providing global savings even though they don't produce a good financial return, have been modelled**.** However, we live frugally; we have no need of funds, so that inventions are freely available for *improving the planet* which is the main motive behind an internet technical library**.**

Internationally millions in the world are never ready. Since 1999 did anyone around the world affected by utility outages, floods, fire etc. Chicago, New Zealand, Sydney etc. - ever solve life-support problems via renewables?

Effortless *Sustainable Home Engineering* involves re-educating society's tastes. Adopting only token items – largely home-developed - of the 150 necessary is futile. Life-support designers often won't live with their hardware. Does an ineffective effort to match renewable energy to fossil needs - sound conservation? Yet, society tries e.g., 2 coffees + 1 paper per day ~=$3468/year.

This study reports on 31 of our largely lived-in innovations from this 1 GB sustainable internet library. Some of the items in the dynamic internet library include**:** power points, maths graphics and short videos**.**

Keywords: *Library, architecture, sustainability, economics, renewable-energy, renewable resources, maths library*

Whale tracking for everyone – using a smart phone application for citizen science

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Abstract: Citizen science and crowd sourcing is becoming popular with readily available and easy to use smart phone applications (apps). Apps have been used successfully in research and conservation for capture-mark-release biological studies, mapping of invasive species and capturing data on field sightings of marine mammals. A recently developed app "Whale Trails" allows the collection of whale data by whale watchers and enthusiast through a simple interface (Figure 1). The app was developed by the community organisation Humpbacks & High-rises in collaboration with Griffith University. The app was designed to gather information on behavior, location and movement for the worldwide most popular whale watching species, the humpback whale (*Megaptera novaeangliae*). Identifying the movement and behaviors of humpback whales can provide opportunities for conservation management and increase understanding of the species. Long-term scientific behaviour studies of marine mammals are costly and are limited due to funding constraints. Citizen science can therefore help to gather data and engage members of the public to participate in research. I have investigated the usage and performance of the app from a researchers point of view after its second year on the market. Over 100 data entries were collected by the app and ranged from the North Atlantic to the South Pacific. Results suggested that the app can be a useful tool when adjusted for user error and careful consideration of regional differences. "Whale Trails" provides the public with a useful tool to assist and contribute to research on humpback whales.

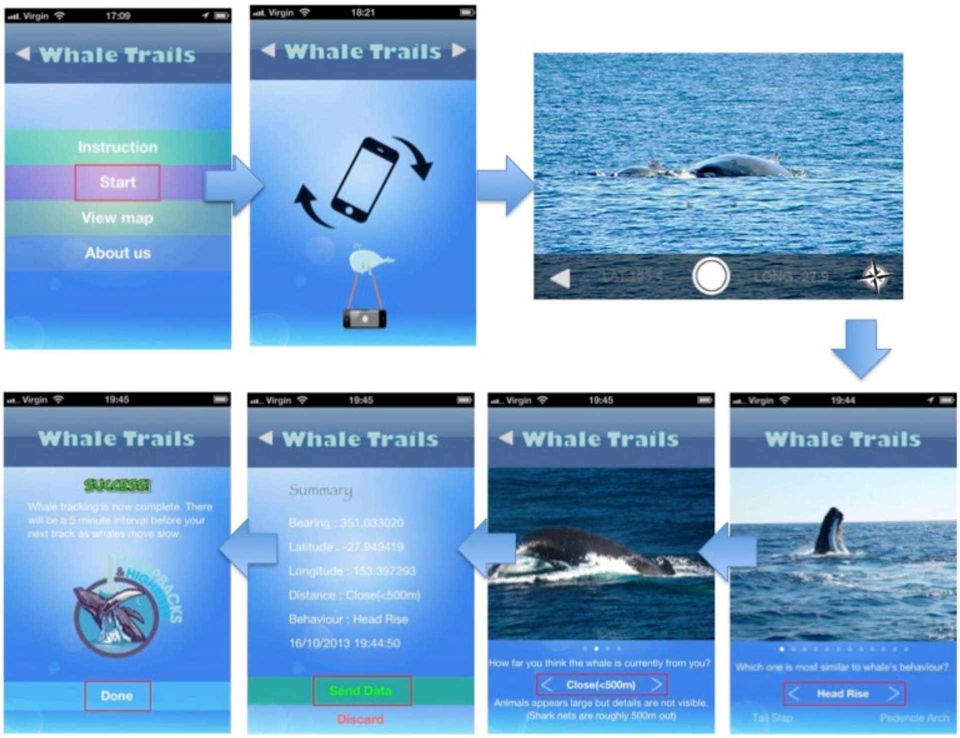

Figure 1. Screenshot samples of the GUI layout Whale Trails from an iPhone 5.

Keywords: *Apps, citizen science, whale watching, whale tracking, Australia*

Opening SESAMME: An iPad-based application for developing socio-ecological models

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Abstract: The CCRES (Capturing Coral Reef & Related Ecosystem Services) project is focused on enhancing livelihoods and food security, improving community health and wellbeing, and sustaining coastal ecosystems in two case study areas (El Nido, Philippines and Selayar, Indonesia). CCRES is funded by the Global Environment Facility, the World Bank and The University of Queensland.

A key activity of CCRES is to understand how communities currently use and interact with ecosystem services (e.g. provision of food, water quality treatment, climate change buffering), and how these interactions, along with external factors, have led to current problems such as resource degradation, resource use conflicts, failed or dwindling livelihoods or persistent poverty. We have developed an iPad application (SESAMME – Socio-Ecological Systems App for Mental Model Elicitation) to assist in addressing this key activity.

SESAMME provides a mechanism for eliciting the perceptions of local stakeholders (in Selayar and El Nido) framed around specific problems at specific geographical locations. In consultation with the in-country partners of the project (Palawan State University [PSU], Palawan Council for Sustainable Development [PCSD], El Nido Foundation [ENF]), the following four problems were identified; food insecurity (ENF), water quality decline (PSUa) fish catch decline (PSUb) and mangrove clearing (PCSD). Note that the problems for the Selayar site have yet to be finalized and therefore the focus of the remainder of this presentation is on the research being undertaken in El Nido.

SESAMME uses a 'drag and drop' icon approach that provides a graphical and interactive (participatory) means to mapping out socio-ecological systems. It is used in conjunction with a methodological script that enables the participants to be guided through this process in a consistent manner. This includes identifying the resources (e.g. fish), activities (e.g. fishing), pressures (e.g. climate change) and decisions (e.g. fishing ordinances) that characterise their 'system' and how they interlink with one another (causal mapping). SESAMME also allows a qualitative assessment to be made of the existing, current and future (expected and aspirational) changes in resource condition to be made. Furthermore, it is a spatially-explicit tool, utilising the Apple Map kit (similar to Google Maps) to locate the icons in a geographic location. Finally, socio-ecological maps constructed in the case study areas can be rapidly uploaded to the cloud (Parse), enabling data security and transfer from the case study areas to researchers in Australia.

The SESAMME app was recently (April – June 2015) used in over 60 focus group discussions (FGDs) in El Nido, Philippines. Each FGD was facilitated by one of PSU (PSUa or PSUb team), PCSD or ENF depending on the problem being discussed and each produced a rich picture map developed in SESAMME. Observations and feedback from these FGDs indicated that SESAMME was a good mechanism for engaging with the FGD participants and capturing their beliefs and perceptions in developing the rich pictures. Some issues with SESAMME were identified (bugs in the coding, usability of the app) during the FGDs with most resolved quickly because of clear communication with the in-country partners and the use of the internet to remotely update SESAMME.

Overall, we found the use of an interactive app to elicit the perceptions of stakeholders to develop rich picture maps to be effective and engaging. This was based on comments received from the in-country partners who facilitated the FGDs and the comments from many of the FGD participants. SESAMME is being developed for iPad and is only currently available through ad hoc distribution. However, it is planned to be available via iTunes after further refinement and testing has taken place.

Keywords: *SESAMME, iPad app, rich pictures, systems modeling, participatory workshops*

Simulating agricultural land-use adaptation decisions under changing climate using multi-agent system model in the Upper East Region of Ghana

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Abstract: This paper explores the application of the multi-agent system (MAS) models for understanding of agricultural adaptation to climate changes. To date, only very few studies empirically operationalise decision making on adaptation based on farmers' perception of climate variability in the MAS. The challenge particularly lies on how to isolate planned adaptation within a large traditional number of autonomous adaptation practices. This paper focuses on the implementation of a MAS approach for investigating the traditional adaptive strategies in the dryland areas in the Upper East Region of Ghana by considering farmers' perception of climate change and variability. In order to achieve this, Land Use Dynamic Simulator (LUDAS) approach was adapted and modified by integrating the two step-decision making sub-models. This modified version of LUDAS called SKY-LUDAS (referring to the communities where it was implemented: *Sirigu-Sumbrungu-Kandiga-Yuwa*) was constructed to capture the empirical heterogeneity of farm household agents and landscape agents (biophysical environment), and also to explicitly simulate interactions between these two agent types. From the results of the multivariate statistical methods, three farm household agent groups were identified. Also the factors explaining the decision of these three household agent groups on the choice of the six identified land-use types were analysed. Two sub-models were developed and calibrated for implementing the two-step decision making sub-models: Perception-of-Climate-Change and Adaptation Choice strategies. Simulation results of SKY-LUDAS suggested that the land-use behaviour in the study area reflects a tendency of subsistence farming. In terms of farm-households' livelihood strategy, especially the structure of the gross income, there was a growing contribution of rice and groundnut. Also the pattern of the gross income under the scenario of perception on climate change (PCC) showed explicitly the contribution of the adaptation options in the households' livelihood strategy. Accordingly, SKY-LUDAS has revealed a gradual shift among land-use types from traditional cereals farming to the cultivation of groundnuts, rice, maize and soybean. Based on the two-step decision mechanism implemented in SKY-LUDAS, groundnut in mono-cropping has emerged as coping measure. Therefore, this research has a merit of contributing to answer the critical question on whether some adaptation practices are stimulated by climate or other factors.

Keywords: *Heterogeneous farm households, perception on climate change, decision making, land-use adaptation*

Incorporating gender specific land-use decisions in agent-based land use models

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Abstract: Gender specificity in response to land-use options and agents offering new investment opportunities has received little attention to date. It may influence ecosystem services delivery especially to areas under conservation agreements (such as those targeting reduced emissions from deforestation and degradation). This study compares the land-use decisions of men and women, and assesses the implications of their decisions on provisioning of ecosystem services in the context of the Minangkabau ethnic group in central Sumatra, Indonesia. This is the largest matrilineal society in the world and men and women farmers have their own management decisions with regards to their land. In this paper, we explored how men and women differ in terms of land-use perspectives and ecosystem services' preferences and how these differences affect the land-use pattern and delivery ecosystem services. Due to its complexities, we combined sex-disaggregated surveys and role-playing games to parameterize the gender-specific agent decision making; and simulated the agent-based model (i.e., Land Use DynAmic Simulator or LUDAS) to explore the effect of the disparities between men and women in land-use decision making. In this paper, we present the key factors that make the two different based on the abovementioned methods. The simulations showed gender specific trends of land-use change; a majority of men preferred tree-based system (such as rubber agroforestry), whereas a majority of women preferred food and cash-based crops. Thus, women-dominated landscapes emitted more carbon than men-dominated landscapes. On the other hand, provision of ecosystem services is affected by gender specific roles, which often been misrepresented in many land-use change models.

Keywords: *Decision making, ecosystem services, heterogeneity, land-use preference, matrilineal society*

Using scenarios describing cross-over points to explore uncertainty in comparison of environmental management alternatives

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Abstract: Using scenarios can be a powerful way of addressing uncertainty. They provide self-consistent stories that the audience can evaluate, compare and respond to in light of their world view and the assumptions they are willing to make. Specifically, when comparing management alternatives, scenarios with different assumptions might differ as to which alternative is better, and hence also highlight vulnerabilities of the proposed management interventions. Scenarios can help prompt discussion of whether that vulnerability may occur and what measures can be taken to ensure it does not.

This paper specifically focusses on exploring the robustness of a decision by generating scenarios describing cross-over points, which are combinations of values where two alternatives are of equal value. There is a cross-over at these points between which of a pair of alternatives has greater value than the other. These points describe conditions under which an intervention may no longer be worthwhile. Interpreted as a scenario, the cross-over point provides a bridge between quantitative and qualitative techniques. The scenario itself is expressed in terms of values of variables within a quantitative model. However, those values are used to helps foster discussion on qualitative factors that might cause the scenario to occur, and the actions that can be taken to avoid the situation described.

The scenario generation method takes an iterative learning approach. We assume an initial model is available (e.g. a cost-benefit analysis), which has been used to compare management alternatives using variables that are directly meaningful to the user (e.g. an expert policy analyst or decision maker). We also assume that the expert user has the time and interest to interactively engage with the scenarios in order to improve them, potentially make modifications to the model, and prepare them for further discussion by other decision makers. Scenarios describing cross-over points are identified using computational techniques, varying first one, then two and finally many variables within the existing analysis. Crossover point scenarios are combinations of values of variables where cost-benefit or other trade-off analysis frameworks show two alternatives to be of equal value. The expert user is prompted to identify: 1) whether the scenario is sufficiently of concern that the initially preferred management alternative should be reconsidered; 2) whether it is expected that there would be a cross-over between management alternatives in that scenario; 3) whether further analysis might show the cross-over point is not of concern; and 4) whether action could be taken to avoid this scenario occurring. The resulting analysis is documented to allow further discussion with a large audience.

We demonstrate the utility of this approach with two illustrative case studies. The first is a cost-benefit analysis evaluating storage of water by managed aquifer recharge vs. farm dams. It demonstrates the applicability of the approach to the broad field of cost-benefit analyses, where net present value (NPV) provides a clear criterion for comparing management alternatives and a large number of factors may influence the results. The method can however be used with any indicator of performance of management alternatives, as shown by the second problem, which compares the water footprints of two alternative diets. This is a problem where the evaluation criterion and factors to be considered uncertain are not as obvious. We evaluate the effect of uncertainty in food product footprints on total blue and green water consumption, which prompts reflection on the factors influencing those food product footprints and the resulting uncertainty in diet recommendations.

Keywords: *Scenario analysis, deep uncertainty, decision aiding*

Using management scenarios and a participatory approach to encourage model adoption in managing invasive species

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Abstract: Engaging stakeholders and encouraging community engagement is fundamental for adoption of model results. Engagement benefits from starting from model development and continuing through to model completion and roll-out. This is especially the case when managing invasive species, where a coordinated management strategy between stakeholders works best. We use a participatory approach that combines expert knowledge and spatial data in a Bayesian network to develop risk maps of potential threats. Of particular relevance is the inclusion of management scenarios that can be manipulated to determine the effects of different strategies and combinations of coordinated strategies. Scenarios are built on expert opinion, guided from years of experience in research and management of the invasive species under field conditions. We capture their knowledge and understanding of the study system allowing us to independently validate how the model and scenarios replicate reality. Stakeholders are trained to run scenarios themselves at field days to encourage community engagement. Model results are presented as maps that visualise risk after applying different management scenarios. Maps facilitate interpretation of model results in a spatial context relevant to local communities. Capturing impacts of species invasions by running scenarios specific to targeted community groups, such as land managers, allow for increased adoption when economic incentives are introduced.

We demonstrate this with a case study using the European rabbit (*Oryctolagus cuniculus*), which is a serious agricultural pest in southern Queensland. We model the economic costs and effects of different rabbit management scenarios with the impacts of varying degrees of rabbit damage on different agricultural commodities. Our model allows end-users to choose the management strategies and the desired agricultural commodity, such as broccoli, spatially limited to the areas of suitable growth across the region. Model results show a distribution of costs for each modelled commodity scenario, giving end-users a range of costs unique to each agricultural region. Using ecological knowledge to understand the species' interaction within the environment and economic drivers to capture impact, our scenario modelling allows for immediate relevance to community users and ease of adoption with its participatory approach.

***Keywords**: Impact modelling, invasive species, pest management scenarios, relative costs, community engagement*

Applying an 'outcomes of interest' scenario framework to consider uncertainties impacting risk reduction policies

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Abstract: Decision-makers dealing with natural hazards face difficult decisions around resource allocation, scheduling and planning priorities to minimise hazard impacts. Along with day-to-day operational and short term management decisions, planners must face the complexities of long term change coupled with multiple actors and sources of ambiguity that create wicked problems for an integrated planning response to the changing threat of natural hazards. To counter this ever increasing uncertainty from natural, socio-economic and political drivers, planners must embrace advanced techniques to understand not only possible future developments but also the implications of intervening in these complex and volatile systems.

In support of decision makers and planners in the natural hazard field we propose the development and use of scenarios framed around key *outcomes of interest*, which in this study were elicited from a group of stakeholders. From these stakeholders, top down mitigation policies and resilience based approaches were seen as the two overarching approaches to the minimisation of risk. As such the effectiveness and outcomes of these interventions were highlighted as critical 'outcomes of interest' in effectively managing and minimising natural hazard risks. From these two highlighted outcomes, scenarios are placed within two axes, each one representing an increasing challenge to either top down mitigation or resilience allowing the robustness of risk reduction approaches to be tested. By selecting these axes, exploratory scenarios are developed that combine economic and demographic developments, technological advances, and social perceptions to test uncertainties that are critical to the effectiveness of mitigation and resilience based approaches to risk management. Construction of scenarios in such a manner ensures that the scenario spans the entire region of interest for policy makers, which in turn ensures solutions are more robust to a wider range of uncertainties than other scenario development techniques which can restrict scenarios to just two critical uncertainties, like the most common 2x2 approach.

The scenario development process consists of four stages, which are a combination of distinct stages of stakeholder engagement coupled with intermediate steps of quantitative analysis and complex systems modelling. The stages include participatory scoping of the problem and decision space, relationship and trend analysis of system drivers, participatory scenario narrative development, and scenario quantification. This allows for targeted exploratory scenario development to combine with simulation modelling, exploring these alternative futures, and assist decision making. The approach highlights the value of a small set of policy relevant scenarios to support decision makers and planners in the natural hazard field.

Following the four stages of development, four extreme and one central (or intermediate) futures exist and consist of both qualitative and quantitative information. These are then modelled using an integrated simulation model framework incorporating a land use model and various hazard risk models along with climate and socio-economic components, mitigation options and indicators. This modelling framework allows decision makers to consider the various futures and their associated risks, along with the ability to test the performance of a range of policies to minimise hazard likelihood and impact.

Keywords: *Exploratory scenarios, stakeholder engagement, integrated modelling, risk reduction, natural hazards*

Understanding the challenges of decision-analytic interventions in organizations – a practice-based approach

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Abstract: Decision Analysis has made remarkable and exciting progress in improving decision making in organizations, providing a sound prescriptive approach for the evaluation of decision alternatives. However, as decision analysts know from experience, applying the methods in real-life organizational interventions often turns out to be challenging. Some challenges reported in the literature are, for example:

1. Decision-makers may struggle to articulate a comprehensive list of objectives and alternatives. They tend to omit a large number of objectives that they themselves consider important and neglect alternatives that might be valuable.
2. Decision-makers may struggle with analytical methods or concepts used in DA.
3. Decision-makers may struggle with complex decision problems that are interwoven with a messy organizational context.

Our paper contends that these difficulties are the consequence of a gap between the prescriptive approach of Decision Analysis and the way in which unsupported decision-making is typically carried out in organizations. By discussing nine aspects of processes of decision-making, we argue that decision analyst tend to underestimate the width of this gap due to implicitly assuming that in praxis decision makers primarily decide under bounded rationality.

To shed light on the nature of this gap, we draw on a sociological strand of theorizing known as “theories of social practices”. This perspective on social phenomena proceeds from the assumption that human behavior is primarily routinized behavior (humans as “creatures of habits”). As a consequence, it analyses the activities of human actors by looking at the “social practices” that underlie their behavior. A social practice, such as reading a book, holding a meeting, carrying out a cost-benefit analysis, giving a presentation, or using a particular software package, is conceptualized as a bundle of patterns of routinized behavior that (a) consists of cognitive and normative schemes or patterns that provide actors with the know-how required to carry out the specific practice in question; that (b) is, due to the routinized nature of practices, embodied in the actors that carry out the practice and does not only have a mental, cognitive basis, and that (c) involves the use of object, artifacts or resource, i.e. practices also have a material component.

On the basis of this sociological strand of theorizing, we describe a new, alternative perspective on decision-making and contrast it with the concept of bounded rationality along the nine aspects of decision-making processes introduced earlier. We also illustrate our perspective by referring to an empirical study on unsupported decision-making that we conducted in two international companies. We then show how the three challenges of decision analytical interventions sketched above can be explained fruitfully by our practice-based perspective on decision making. This leads to nine guidelines that may help decision analysts to deal with the implementation challenges they encounter.

All in all, our paper provides a conceptual framework that provides a systematic explanation of the challenges decision analysts have to cope with. In this way the paper contributes to a deeper understanding of the behavioral aspects of decision analytic interventions and offers a means to reflect on the challenges frequently experienced by decision analysts, which may guide the further development of decision aiding methods.

Keywords: *Decision analysis, behavioural operations research, bounded rationality, social practices, DA interventions*

Using mathematical modelling to tackle a wicked problem: the energy poverty trap

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Abstract: Approximately 1.3 billion people lack access to electricity and 2.6 billion are without clean cooking facilities worldwide. Energy access, consumption and form of energy available to people has a known impact not just on greenhouse gas emissions, but on health, income and local environmental issues such as forest degradation. As we progress into the United Nations Decade for action on "Sustainable Energy for All", global efforts on energy poverty alleviation are gaining momentum. However changes to energy access alone will not necessarily lift people out of poverty. There are a multitude of other challenges faced by those in poverty, other than energy impoverishment. Furthermore, the success of energy-poverty alleviation initiatives will be strongly affected by local and regional issues. Every village, city and country is different, and approaches which are successful in one context might fail in another, for a range of hard-to-predict reasons.

This research uses a number of models to explore interactions between energy and other elements of poverty, based upon literature sourced narratives. We demonstrate how different approaches surrounding energy interventions have led to varying degrees of success, and a range of unexpected outcomes. The issue of energy poverty needs to be considered within the broader system of poverty and deprivation, where the energy impoverished are making decisions on the margins, with limited resources at their disposal, in order to survive. This is well supported in literature, where many sources recommend coupling energy projects with broader development goals, working to assist other elements of deprivation. Single-themed interventions which focus too much on one component of poverty may be less successful in creating positive and sustained benefits than interventions based on more holistic or whole-of-system approaches.

We demonstrate how using models to conceptualize the challenges of energy-poverty in different ways can help to expand our understanding of what will actually work to increase the wellbeing of the energy impoverished. There is a discrepancy between how energy related decision makers in powerful and well financed global institutions see this very complex problem, and the reality of it in the field. Financing of large-scaled, single themed development interventions continues, without recognition of mistakes made in the past, experienced by other sectors. Often approaches are ideologically driven, based on each individual's construction of the problem, rather than on evidence, and most involve quite linear thinking, rather than considering the broader poverty system. We use mathematical and conceptual models to illustrate these challenges, and as a tool for finding a way forward in addressing this wicked problem.

Keywords: *Energy, poverty, intervention, complexity, modelling*

Exploring Social Practices of Peer-Review in an Agent-Based Simulation: The COST Action PEERE

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Abstract: The peer-review process was designed to assure the validity and quality of science that seeks publication. As such, peer review is a cornerstone of science, confirming the "worth" of scientific studies and results. However, the peer-review process is increasingly seen as biased, opaque, slow and inconsistent. Its quality and efficiency depends on a complex, large-scale collaboration process, which is sensitive to motivations, incentives and institutional contexts.

PEERE (New Frontiers of Peer Review), a recent EU-funded action, aims to improve efficiency, transparency and accountability of peer review through a trans-disciplinary, cross-sectorial collaboration. In this paper, we report on the results of one of PEERE's activities, in which we explore, in a simulated environment, different approaches to peer reviewing. The objectives of this Action are: (i) to analyse peer review in different scientific areas by integrating quantitative and qualitative research and incorporating recent experimental and computational findings, (ii) to evaluate the implications of different models of peer review and to explore new incentive structures, rules and measures to improve collaboration in all stages of the peer review process; (iii) to involve science stakeholders in data sharing and testing initiatives, and, (iv) to collaboratively define a joint research agenda that points to an evidence-based peer review reform.

In order to understand the effect of different peer-review models on the behaviour of reviewers, an understanding of the context and culture of peer review is required. In this paper, we present a framework to analyse different peer-review formats, based on models of social aspects of human motivation. In order to analyse the effect of different peer-review models on the behaviour of reviewers, a deep understanding of the context and culture of peer review is required, which includes a rich model of agent's motives and behaviours. The theory of human motivation by McClelland distinguishes four motives (McClelland (1987)):

- **Achievement**: is about achieving goal states and drives people to try to achieve different things, thus, fostering explorative behaviour that satisfies the need for novelty.
- **Power**: is about trying to have an impact on the world, and includes both the need to control both its own and other's actions.
- **Affiliation**: drives people to seek the company of others and to establish and maintain positive interactions with others.
- **Avoidance**: leads to self preservation, seeking certainty, and emotional regulation, and fosters the categorization and simplification of behaviour so that it becomes more standardized (and thus predictable).

Moreover, our simulation framework supports the specification of different peer-review practices. These practices are then compared by letting agents with different social frames enact the different reviewing approaches.

The model considers motives and social practices as basis for deliberation. We show initial simulation results on two different peer-review processes.

Keywords: *Peer review, social practice theory, agent-based modelling and simulation*

Behavioural issues in environmental modelling – the missing perspective

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Abstract: The paper aims to demonstrate the importance of behavioural issues in environmental modelling. These issues can relate both to the modeler and to the modelling process including the social interaction in the modelling team. The origins of behavioural effects can be in the cognitive and motivational biases or in the social systems created as well as in the visual and verbal communication strategies used. The possible occurrence of these phenomena in the context of environmental modelling is discussed and suggestions for research topics are provided. Every environmental model embeds behavioural issues related to the modeler. Modelling is not about models only. It matters how we choose the models and how we work with the models. In a recent paper (Hämäläinen et al., 2013) we introduced the term Behavioural Operational Research (BOR). It refers to research which considers the human impact on the process of using operational research (OR) methods in problem solving and decision support as well as using OR methods to model human behavior. We pointed out the need to take into account effects caused by psychological factors such as mental models and cognitive biases as well as social systems created and communication effects.

The aim of this paper is to bring this idea and perspective into the discourse taking place in the environmental modelling community too. Because of the complexities of the problems in environmental management the focus is easily narrowed down to seeking the best model only. Listing different types of modelling approaches and their technical merits and weaknesses is not enough as it can leave us ignorant of the problems and risks related to the way the models are used and implemented. In today's world, models are being used to solve and to help understand complex environmental problems. Modelers with high ethical standards must be open to acknowledge the risks of behavioural effects. Some biases can be unintentional consequences of cognitive limitations others can be strategically motivated omissions or over or under emphazisations of aspects. Discussing and studying these behavioural risks and possibilities will help to improve trust in modelling.We can also use of modelling to understand and explain people's behaviour in environmental processes and settings and even develop people in the loop models.

The fact that we as modelers are subject to cognitive as well as motivational biases can at first be somewhat difficult to accept. We would like to see ourselves as sincere and bias free truth seekers. However, on the second thought we can still hold on to this image by acknowledging our cognitive challenges and trying to develop as bias free modeling approaches as possible. Setting up a research agenda in the behavioural issues of modelling will benefit the environmental modelling communities in getting increased approval for their work and better serve the environment and people. Understanding behavioural aspects from cognitive biases to communication styles is key in creating a fruitful participation process based on systems skills which also recognize the social and motivational factors in the process. How to do this in practice is also an open research theme.

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Keywords: *Behavioural effects, cognitive biases, best practice, modeler bias, systems intelligence*

Modeling the adoption of energy efficient retrofits by mid-tier commercial buildings

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Abstract: The low uptake of cost effective, energy efficient retrofits for commercial buildings suggests that economic considerations are not the sole determinant for their adoption. Socio-psychological surveys provide additional insights into consumption behaviour reflecting important lifestyle, attitudinal, risk, familiarity of technology, cultural and other forms of demographic preferences. There is a need for an evidence based tool that can forecast the effectiveness of intervention options for commercial buildings whilst removing the confounding effects of business-as-usual strategies. This paper describes a framework for evaluating the uptake of building retrofits under various government policy and behaviour program interventions aimed at reducing carbon emissions. The framework incorporates socio-psychological factors into an agent based model, applying diffusion and discrete choice modeling in evaluating the effectiveness of intervention programs, especially those involving direct subsidies (e.g. rebate to upfront costs, tax deductions) to facilitate the uptake of low carbon living practices. This framework is implemented in the ZEO Uptake Analysis Tool which allows planners, researchers and policy makers to assess the relative impact of assumptions about future technology and policy using a defined baseline (or "business as usual" scenario) for comparison. The Tool uses agent-based modeling and simulation (ABMS) to encapsulate the attributes and behaviour of various elements and entities in the building retrofit problem. The paper presents preliminary results from application of the agent-based model to the State of Victoria building stock, in a case study to understand the potential of the Energy Efficient Office Buildings Program in the uptake of energy efficient retrofits. The analysis indicates that the proposed policy options offered by EEOB have very little impact when we consider small building owners and limit the application to building tuning only. There is improvement in uptake when we expand the eligibility to all technologies (excluding lighting) and this is dominated by HVAC (Chiller) upgrades.

Keywords: *Agent-based modeling, simulation modeling, energy efficient retrofits, commercial buildings*

Why so slow?
Mathematical modelling demonstrates how implicit bias can perpetuate low workforce diversity

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Abstract: Increasing workforce diversity is a priority for many organizations, to enhance creativity and innovation, address important social justice issues and create stronger connections with the community and customers. However workforce diversity has been resistant to change in many sectors, typically for a range of reasons. For example, low retention and seniority of women in science, technology, engineering and mathematics (STEM) is variously attributed to implicit bias, competitive workplace, family responsibilities and lack of role models, among other things.

One of the challenges in shifting workforce composition is that the factors perpetuating dominance by one group are often interconnected. There is ample sociological and psychological research that being a "demographic misfit" can adversely affect perceived performance, networks, mentoring, satisfaction and engagement. In practice, this means that mean that people who contravene common stereotypes about given occupations and/or are present only in small minorities may be less likely to be appointed, and to have lower retention rates than others.

Here we use a simple mathematical model to investigate how subtle biases can affect long-term workplace demographics. Our model predicts that low workforce diversity can be perpetuated by preferential appointment and retention of individuals from the dominant group. Specifically, if appointment and departure bias increase non-linearly as workforce diversity declines, then multiple equilibria for employee diversity are possible. This can create hysteresis in how workforce composition changes in response to applicant diversity: the model predicts that under certain conditions an organisation can get "stuck" at low diversity, such that increasing applicant diversity may not necessarily change employee diversity.

Our results have a number of practical applications. Firstly, from the mathematical model, we derive three quantifiable "inclusion metrics" which can identify barriers and opportunities to change. Individuals find it very difficult to identify implicit bias in themselves or others, so objective, quantitative evidence is needed to verify the presence or absence of such biases, and assess how bias varies across different departments or organisations. Secondly, we introduce a new conceptual model to illustrate how factors at individual, workplace and societal scales interact to affect inclusion. There are many causes for appointment and departure bias and low applicant diversity: our conceptual model can help identify which factors are involved in any specific setting. Finally, we combine the quantitative inclusion indicators and the conceptual model in a practical framework for identifying barriers and opportunities to changing workforce composition. We illustrate our findings with examples from science, medicine and the mining industry.

Keywords: *Diversity, implicit bias, hysteresis, feedbacks, workforce*

A comparison of results between interactive and non-interactive forms of visualisation to improve learning.

A case study of Te Waihora/Lake Ellesmere, Canterbury, New Zealand

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Abstract: Computer-aided visualisation has been used in a number of natural resource management applications with the aim of enhancing people's understanding of issues, but little evaluation of the effectiveness of these tools has been undertaken. The purpose of this study was to investigate whether there are significant differences in knowledge acquisition depending on the form in which visualisation of environmental changes is presented, using a case study of Te Waihora/Lake Ellesmere, a broad, shallow lagoon in the South Island of New Zealand.

Te Waihora/Lake Ellesmere is separated from the Pacific Ocean by the long narrow sandy Kaitorete Spit. Its unique position allows for it to be opened to the sea periodically to provide drainage and prevent flooding of surrounding farmlands. There is a lack of agreement among the diverse stakeholders regarding the appropriate levels at which the lake level should be maintained throughout the year.

We describe an interactive visualisation tool (ElleVis) which shows the effects of different lake opening regimes on lake values at Te Waihora/Lake Ellesmere. The tool allows users to input different opening scenarios and visualise the resulting impact on water levels around the lake at various times. It incorporates historical rainfall data from New Zealand's National Institute of Water and Atmospheric Research to deliver a graphical map display, including a summary table with a 'traffic light' status for lake values - birds, fish, farming and other stakeholder interests at different locations around the lake. The interactive nature of the ElleVis tool allows the stakeholders to compare Te Waihora/Lake Ellesmere under different opening scenarios using one interactive tool. However, it is possible, for example, that providing information about changes in lake behaviour in a carefully and clearly presented non-interactive form may be as successful as providing it in an interactive form of ElleVis.

A true experimental design was adopted to measure the knowledge of forty participants (randomly assigned to two test groups) who have various interests at Te Waihora, before and after using their assigned interventions of either –interactive or non-interactive - form of visualisation.

Overall, the results of this study show that participants demonstrate a greater knowledge gain through the use of interactive visualisation (M =18.05), than through information provided non-interactively (M =12.45), t (40) =2.663, $p < .05$). More widely, we think that the findings from this study can stimulate meaningful discussions and dialogue about whether interactive visualisation tools might contribute to assessing understanding in environmental management in situations that involve contested resources or a multiplicity of interests.

Keywords: *Personal understanding, interactive visualisation, static visualisation, evaluation, visual simulation*

Identifying decision drivers to support the application of Management Strategy Evaluation in the coastal zone

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Abstract: Natural resources management (NRM) involves a collective decision-making process. It usually involves multiple individuals with varying perceptions and influences and often uses the adaptive management framework. It requires generating information for comparing objectives with actual management outcomes. Management strategy evaluation (MSE) models of the adaptive management process are a useful means of evaluating the trade-offs and uncertainties associated with different decisions.

We identified the following key categories of attributes affecting NRM decisions: (1) governance structures, (2) power and leadership, (3) psychological dimensions, and (4) cognitive issues. We propose a staged and formalized description of how MSE can be considered as a participatory decision-support approach. In particular, we consider how the approach allows managers to: (a) identify and deal with governance structures; (b) identify key values and management objectives held by stakeholders and how they impact the ranking of alternative performance measures; (c) develop methods which fully consider the available information; (d) recognize avenues for choice under uncertainty that limit the sources of individual biases; and (e) provide incentives to respond to perceived changes in performance. Our research indicates that improving the information base about the natural resource and its dynamics alone is necessary but will have limited effect on the way decisions are made and implemented.

NRM also requires approaches that influence human behavior, cognition and attitudes. Thus a formal participatory MSE approach supports NRM by combining modeling techniques with methods for understanding human behavior, and by promoting stakeholder engagement to facilitate social learning, which includes both learning about potential solutions to natural resource use problems, and learning to make commitments and to trust one another in joint efforts involving managers, scientists, communities and other interested parties. We suggest that NRM in general is influenced by similar categories as those that influence decision-making processes. This finding strongly supports the application of MSE to NRM towards the development of a shared understanding about management issues and possible solutions.

Keywords: *Adaptive management, cognition, decision-making, management strategy evaluation, multiple-use*

Sustainable groundwater management with tradable permits

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Abstract: This article studies the sustainability of market-based instrument such as tradable permits for the management of a renewable aquifer used for agriculture production. In a dynamic hydro-economic model, a manager aims to satisfy different constraints in terms of food security and individual profit within a tradable permit scheme. We identify analytically the viability kernel that defines the states of the resource yielding inter-temporal feasible paths able to satisfy the set of constraints over time.

Keywords: *Groundwater, agriculture, irrigation, food security, individual permits*

Informing ecosystem-based management of the range extending long-spined sea urchin using a structured decision making process

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Abstract: The poleward movement of species is a global signature of climate change, which can affect regional biodiversity, ecosystem structure and functioning and pose significant challenges for managers of marine resources. This is particularly the case where there are multiple stakeholders with different and often conflicting views on appropriate management action. A structured consultative decision making process can assist managers in identifying some disparity between objective and subjective elements that may underpin stakeholder disagreement.

Following rapid climate-driven changes in ocean currents, the long-spined sea urchin (*Centrostephanus rodgersii*) has extended its range from Australia's mainland to eastern Tasmania. Due to the depletion of large rock lobster (*Jasus edwardsii*), its main predator on Tasmanian reef, by fishing, *C. rodgersii* has demonstrated the ability to form and maintain extensive 'barrens', i.e. bare rocks following the destructive grazing of macroalgal cover. Relative to dense seaweed beds, sea urchin 'barrens' represent a dramatic loss of habitat, biodiversity and productivity for important commercial reef species such a southern rock lobster (*Jasus edwardsii*) and abalone (*Haliotis rubra*). A small-scale commercial harvesting operation for *C. rodgersii* has developped over the last five years. Thus, the range of ecological, social and economic consequences associated with the range extension of *C. rogersii* to eastern Tasmania generates conflicts between different stakeholder groups (commercial and recreational fishers, as well as conservation sectors) and poses complex challenges for the regional management of reef communities and fisheries.

In this paper, we applied a Structured Decision-Making framework to help managers and stakeholders with identifying cost-effective interventions that perform well against conflicting management objectives. We conducted a workshop and two succesive surveys involving 12 representatives from key stakeholder groups to elicit and rank a suite of performance objectives and management scenarios. We then estimated the consequences of alternative management scenarios using the TRITON model, which realistically captures the dynamics of Tasmanian reef communities. 10-year consequences of management interventions on reef state (i.e. algal cover and reef species biomass densities) and fisheries productivity were simulated with the model. Additionnally, we assessed the cost and feasibility of available management interventions. We directly and indirectly elicited stakeholders' preferences for different scenarios using the simulated consequences of alternative management strategies. Quantification of scenarios performances against stakeholders' preferences, as well as benefits, cost and feasibility of management interventions were then used independently and in linear combination to estimate alternative quantitative cost-effectiveness ranking metrics. The range of quantitative performance metrics allowed to rank scenarios overall performance, as well as how they benefit individual stakeholder groups. This model-informed structured decision making process contributed to overcome some of the initial conflicts and led to a larger agreement between the different interest groups about best management scenarios. Enforcement of a zonal cap on both recreational and commercial catches of rock lobster combined with either, sea urchin harvesting, or lobster biomass translocation ranked as most cost-effective management scenarios.

Keywords: *Decision-support tool, ecosystem modelling, consultative management, multi-criteria analysis, cost and benefits*

Multi-criteria decision analysis as a learning platform to support water resources management – experience/lessons from case studies of three countries

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Abstract: Decision-making to manage the use and quality of water resources is usually complex. Conflicting stakeholder interests in particular are often an important impediment to the successful implementation of management interventions. Multi criteria decision analysis is a technique for evaluating and comparing different management options based on stakeholders' preferences. Multi Attribute Value Theory (MAVT) is one of the commonly used approaches in multi criteria decision analysis. We applied MAVT in three case studies: the Rokua eskers in Finland, the Rift Valley in Ethiopia and the Heihe river basin in China. The three cases represent the diverse nature of water management problems and challenges. The application of MAVT focused on stakeholders' learning through the participation in the processes. The step-wise procedure can be summarized as follows:

- Establish the decision context.
- Identify the objectives and criteria
- Identify the alternatives/options
- Predict outcomes of each alternative – decision matrix
- Elicit and quantify stakeholder preferences for outcomes (scoring and weighting)
- Aggregate total value for each alternative/option
- Synthesize the results

In the case of the Rokua eskers, the MAVT was applied to assess land-use management alternatives in the esker aquifer area where conflicting land uses affect the groundwater body and dependent ecosystems. Computer-aided interviews were used to help the participants to see how their preferences affected the desirability and ranking of alternatives. In the Ethiopia case, the MAVT was applied to assess the stakeholders' preferences to different fluoride removal technologies. Criteria for technology comparison were selected and weighted with the participation of stakeholders from different interest groups. In the case of the Heihe river basin in an oasis region in China, the MAVT was applied to seek more broadly preferred water re-allocation alternatives among different economic sectors and between up and down stream regions, while halting the ecosystem deterioration in the basin.

Across the three case studies, it is found that stakeholders' understanding of the processes and assumptions of MAVT was key to the success of the decision support framework. Other findings from the applications include: MAVT clearly identified the preferences of individual stakeholders for certain options and pinpointed where the differences and conflicts occur. The stakeholder meetings and interactions provided a platform for negotiation and compromise to reach a certain degree of mutual understanding among stakeholders and therefore are conducive to conflict resolution. The MAVT process also provided a learning ground for stakeholders in terms of broadening their views on water resources management involving multi-objectives and multi-stakeholders. Last, but not least, carrying out the MAVT analysis integrates available scientific knowledge towards operational water resources management.

Keywords: *Water resources management, stakeholder participation, decision support*

Eco-viability for Ecosystem Based Fisheries Management

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Abstract: Reconciling food security, economic development and biodiversity conservation is a key challenge, especially in the face of the demographic transition characterizing most of the countries in the world. Fisheries and marine ecosystems constitute a difficult application of this bio-economic challenge. Many experts and scientists advocate an ecosystem approach to manage marine socioecosystems for their sustainability and resilience. However the way to operationalize ecosystem based fisheries management (EBFM) remains difficult.

In this talk, we propose a specific methodological framework - viability modeling - to do so. We show how viability modeling can be applied in four contrasted case studies: small-scale fisheries of French Guiana and the Solomon Islands, and larger-scale fisheries of the Bay of Biscay (Europe) and the Gulf of Carpenteria (Australia). The four fisheries are analyzed using the same modelling framework, applying a set of common methods, indicators and scenarios. The calibrated models used in this analysis are dynamic, multi-species and multi-fleet and account for various sources of uncertainty. A multi-criteria evaluation is used to assess scenarios over a long time horizon with different constraints based on ecological, social and economic reference points. Results show that the bio-economic and ecosystem risks associated with the adoption of status quo strategies are relatively high. In contrast, strategies called eco-viability or co-viability strategies that aim at satisfying the viability constraints reduce significantly these ecological and economic risks. The gains associated with the reduction of bio-economic and ecosystem risks, however, decrease with the intensity of regulations imposed on these fisheries.

Keywords: *Ecosystem approach, ecological economics, modeling, viability, biodiversity, fisheries*

Multiple management objectives within a mixed prawn fishery: which win-win-win situations?

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Abstract: Fisheries management must address multiple, often conflicting objectives in a highly uncertain context. In particular, while the bio-economic performance of trawl fisheries is subject to high levels of biological and economic uncertainty, the impact of trawling on broader biodiversity is also a major concern for their management. The purpose of this study is to propose a model-based framework which allows to formally assess the trade-offs associated with alternative management strategies in a mixed fishery, with specific emphasis on the consequences of pursuing biological, economic and non-targeted species conservation objectives. This framework is applied in the context of the Australian Northern Prawn Fishery (NPF), which is one of the most valuable federally managed commercial fisheries in Australia. The NPF, located off Australia's northern coast and established in the late 1960s, is a multi-species trawl fishery which harvests several high-value prawn species, each with different biological dynamics and levels of variability. The fishery derives its revenue from an unpredictable naturally fluctuating resource, the white banana prawn (*Penaeus merguiensis*), and a more predictable resource comprising two tiger prawn species (grooved tiger prawn, *Penaeus semisulcatus* and brown tiger prawn, *Penaeus esculentus*).

We develop a stochastic co-viability framework of analysis to a multi-species bio-economic and stochastic model of the NPF under multiple management objectives. The performance of the fishery under various management strategies is assessed via the estimation of the Net Present Value (NPV) of the entire fishery and its co-viability probability, which is a measure of the likelihood of respecting at each time some constraints. The constraints taken into account in our study are related to the preservation of targeted stocks, the maintenance of acceptable levels of annual profit and the reduction of the impacts of the fishery on non-targeted sea snakes.

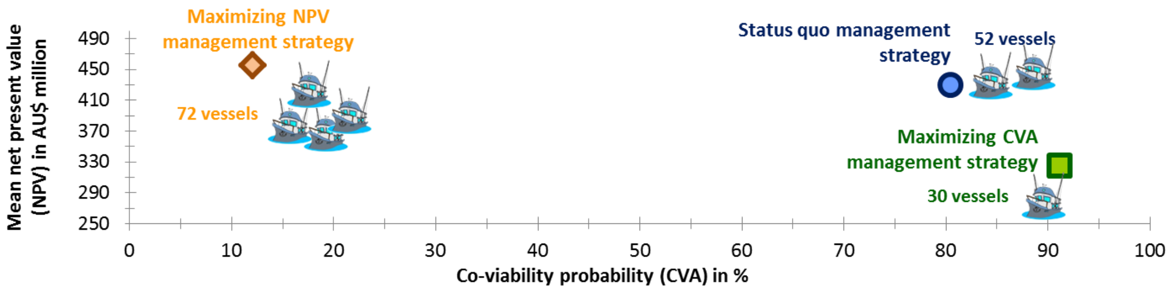

Fig.1. Performances, in terms of mean net present value (NPV) versus co-viability probability (CVA), and associated fleet sizes of three different management strategies.

Results (fig.1) highlight the trade-offs between respecting, at each time, biological, economic and non-targeted species conservation constraints with a high probability and maximizing the net present value of the fishery. More specifically, results show that, due to the variability in the interactions between the fishery and the ecosystem, current management strategies are characterized by biological and economic risks. Indeed, while the current management strategy appears to be constrained by the fleet size (which is more conservative than that which may maximise NPV), this smaller fleet size is not enough to meet the biological and economic interannual equity constraints. Higher co-viability probabilities can be achieved with management strategies aimed at maximizing the co-viability probability, but only at the cost of forgoing economic yield in the fishery. In particular, limiting biological and economic risks would require reductions in the fleet size compared to the status quo, which entails lost economic returns. While viability probabilities must be interpreted with caution due to sensitivity to the constraints and associated threshold values, comparisons between management strategies do not change qualitatively when multiple threshold values are tested. The proposed framework can assist fisheries managers and stakeholders in seeking consensus when assessing management strategies.

Keywords: *Bio-economic modeling, co-viability analyses, sustainability, multiple management objectives, uncertainty*

INFORMD: an environmental decision support tool for coastal salmon aquaculture in Tasmania, Australia

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Abstract: A range of human activities influence water quality and other marine environmental values. Given the multi-user nature of the marine environment, it is important to recognise the diverse needs and expectations of the broader community, when identifying values and evaluating trade-offs, in the system as a whole. We are developing a tool to support consultation, planning and management of aquaculture and other uses of southern Tasmanian coastal waters used for salmon aquaculture. INFORMD (the Inshore Network for Observation and Regional Management of the Derwent-Huon) relies on two important pillars: 1. Capturing a snapshot of the values stakeholders have towards the marine environment in southern Tasmania, and 2. A model to show how planning activities for salmon aquaculture farming affect those values.

In this talk we will report on the stakeholder values that were captured, and the decision support tool being developed. The decision support tool consists of a simple biogeochemical model emulator combined with a hydrodynamic model called CONNIE. The user-interface to the model is browser based and supported in the cloud. The emulator uses a BGC or similar ecosystem model to provide the background conditions from which the emulator projects water quality conditions spatially based on a simple empirically derived model.

Keywords: *Model emulator, Tasmania aquaculture*

Impacts of marine closures on catch rate standardizations – simulation testing

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Abstract: Spatial management measures such as marine protected areas (MPAs) in the form of marine closures have been in place in Australia's Southern and Eastern Scalefish and Shark Fishery (SEESF) for over a decade. These measures have implications on the way resource stocks are fished and corresponding catch-per-unit-effort (CPUE) statistics used to monitor resource abundance. In order to address the likely influence that MPAs have on CPUE statistics, an integrated resource-fisher operating model (RESFIM – **RES**ource-**F**isher **I**ntegrated **M**odel) has been developed to examine how adequately CPUE indexes resource abundance. The resource and fisher sub-models are integrated to form the basis of daily movements of a resource and harvesting activities of fishers, based on general fleet and species movement characteristics. The resource sub-model incorporates main characteristics of a fishery, such as spatial resource movement and recruitment. For each resource movement scenario, namely (a) random movements between locations; (b) habitat attraction; (c) habitat attraction + density dependence; and (d) environmental conditions, RESFIM generates daily resource dynamics and behaviour of fishers harvesting the resource, the latter using a Bayesian belief network (BBN) which determines where fishers will harvest. The decision on where to harvest is based on factors that include information sharing, use of acoustics and environmental conditions. This agent based model was employed to generate daily CPUE data of a SESSF like species under a number of resource and fisher behaviour scenarios with and without MPAs. The generated series for each scenario was standardized to examine the effect(s) of MPAs using statistical standardization methods commonly employed in fisheries studies such as generalized linear models and delta-GLMs. The resulting CPUE indices were then used to investigate how adequately standardized indices reflect resource abundance. Results depended on the interactions between resource movement and individual fisher behaviour, as well as the role a closure has on these two dynamics.

Keywords: *Agent based models, marine protected areas, generalized linear models, CPUE*

EXTENDED ABSTRACT ONLY

Modeling catch-quota management in a multi-species fishery

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Abstract: Individual transferable catch quotas (ITQs) are an increasingly popular tool used for fisheries management. By providing fishing operators with harvesting rights, individual quotas have the potential to reduce excess competition and foster economic efficiency. Implementing these management systems in multispecies fisheries however remains a challenge, given the existence of joint production problems, and discards of non-targeted species.

We propose a modeling framework that addresses some of the key management issues faced in ITQ regulated multispecies fisheries. The framework captures the main characteristics of a mixed fishery composed of multiple fleets with different species targeting patterns, and multiple species with different biological characteristics. The fishery is assumed to be regulated via TACs and individual quotas that can be traded on a lease market. The model is applied to a stylized representation of the Australian South-East Trawl Fishery with two fleets (Danish seiners and Trawlers), and three species (Flathead, Jackass Morwong and John Dory). We compare the outcomes of a fixed TAC policy schedule with or without a discard ban.

Results show that a ban on discards radically changes the outcomes of catch-quota management, in terms of quota prices, fleet profile and rent distribution across the two fleets. Given the catchability and abundance of Flathead, there is a strong incentive to catch this species, particularly for Danish seiners. The Flathead catch however entails a catch of Morwong which leads to an increase in the demand for quota of this species. With discards allowed, the fleet purchases Morwong quota up to a point where its price is equal to the market price for the species, but discards any catch beyond this level (with no obligation to hold quota for the discarded fish). The activity of both sub-fleets stabilizes at a slightly reduced effort level, and at comparable levels of rent. Significant discards of Morwong catch are observed. With discards banned, any increase in the catch of Morwong must be met with a purchase of quota on the lease market. This entails an increase in the quota price over and above the market price for this species, and a degraded economic performance of the trawlers that are less effective at catching Flathead, and have more difficulties avoiding Morwong. The fleet thus evolves towards a progressive eviction of the Trawl component, in favor of the Danish Seine. In this case, heterogeneity within the two fleets in terms of economic performance is also much greater than with discards.

The model thus enables the comparison of alternative approaches to setting TACs and managing for bycatch and discards in a mixed fishery. According to the results, the imposition of a discard ban on the fishery (provided it can effectively be implemented) entails significantly different fishery responses, with more variability in economic returns than without a ban. These results are of particular interest in the context of a move towards more comprehensive catch-quota management systems aimed at including the entire catch, rather than only its landed fraction, under the ecosystem approach to fisheries management. Further research with the model involves identifying TAC schedules across species that meet multiple sustainability criteria by which a fishery may be managed, and the inclusion of uncertainty in key economic and ecological processes.

Keywords: *Catch-quota management, mixed fishery, discard ban, bio-economic model*

Working with practitioners: how scientists can develop effective relationships that produce an enduring legacy

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Abstract: Protecting the environment requires scientists to work with a range of people including land managers, planners, policy makers and regulators. The literature abounds with the challenges of the different 'cultures' working together effectively so scientific results are translated into policy and practice. To address these challenges, we wanted to document factors that produce successful partnerships between scientists and practitioners from different cultures, and determine which factors were the most important in producing an enduring legacy.

We asked 12 environmental scientists from the New South Wales Office of Environment and Heritage (OEH) to nominate practitioners with whom they had developed a successful partnership that they believed delivered results for the environment. The scientists nominated land managers, park rangers, scientists, and planners from natural resource management agencies. The projects they were involved with ranged from: protection of threatened species and biodiversity; eradication of feral pests; environmental monitoring; land use planning and management; and planning for climate change.

The scientists each interviewed one of the 12 nominated practitioners (but not the person they nominated). At least one observer was present in all interviews. We used a structured set of questions and asked the practitioner to describe the work and its legacy. We also asked about the processes and systems which fostered or hindered the use of scientific input or expertise in the work; and how the approach and personal attributes of the scientist influenced the outcome. We recorded all interviews which were transcribed then analysed to identify common themes. We found the themes separated into those about the process of working together (nine common themes) and those related to the personal attributes of the scientist (nine common themes).

The common factors mentioned by practitioners about the process of working together were: a collaborative approach; a practical solution; rigorous process that could withstand scrutiny; regular communication; a team with diverse and complementary skills and experience; a shared purpose or vision; being involved from inception; debating how to solve the problem; and an innovative, new or bold approach.

Practitioners mentioned nine common personal attributes of the scientist: a committed, dedicated and passionate person; a leader or champion; a rigorous expert; well connected to universities or other organisations; a clear and effective communicator; who understood the practitioner's aims, needs and constraints; who was accessible and flexible; could function as a knowledge broker and translate complex and technical information into simple terms; and was pleasant, personable and "easy to get along with."

These factors created effective working relationships between scientists and practitioners, and helped bridge the gap between 'cultures.' Our preliminary results, if confirmed by future research, have implications for scientists as well as the organisations that employ them. We suggest ways to foster the common factors mentioned by practitioners so scientists can create more effective working relationships with them. Successful partnerships benefit the scientist and practitioner, as well as the environment.

Keywords: *Scientist, collaboration, practitioner, transdisciplinary*

Exploring the networks of government scientists using Social Network Analysis: a scoping study

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Abstract: Scientists working for the New South Wales (NSW) Office of Environment and Heritage (OEH) provide rigorous evidence and advice to support government priorities which include protecting the natural environment. They also collaborate with and attract non-government researchers to work on government priorities.

In this scoping study, we used Social Network Analysis (SNA) to visualise the ego networks of six government scientists from OEH who work on biodiversity conservation and landscape management. This allowed us to explore the potential reach of their advice and information within OEH and beyond; and examine gaps and redundancy in the stacked ego networks.

Each scientist exported contacts from Microsoft Outlook, and some also exported contacts from LinkedIn and ResearchGate. They added missing contacts from recall, then ranked contacts by frequency of contact in the previous year from: 0 times in the last year; ~1-2 times; ~3-6 times; ~7-12 times; or >12 times. Ego networks of each scientist were analysed separately then stacked to determine reach and overlap. Analyses and visualisations were run in UCINET and Netdraw.

We found the six government scientists have connections with 980 unique contacts from 27 categories of organisations in Australia and overseas. So, although our sample represents only 3% of staff from the Science Division in OEH, the potential reach of their information and advice to other organisations is large.

Most contacts of the six scientists (70%, n= 691) were from beyond OEH of which only 10% were shared (n=71). The majority of external contacts (34%) were from universities in Australia and overseas (n=235), and from research organisations (n=69) including CSIRO, Cooperative Research Centres and museums. Few of these contacts were shared. This reflects the diverse research interests of the scientists who collaborate with academics and researchers across Australia and overseas.

The scientists connect to a variety of organisations who influence land management in NSW, including Local Land Services (n=79) and councils (n=14). They also connect with many staff from National Parks & Wildlife Service (n=43). However, this represents only 2% of NPWS staff so may be a gap in the network of the scientists.

About one third of the contacts of the six egos (30%, n=289) were from OEH with many of these contacts shared (40% of OEH contacts shared, n=115). Most overlap of contacts was in Science Division (64% of Science Division contacts were shared, n=89). Shared contacts are likely to allow information to flow through the network and contribute to shared knowledge. However, there may also be some redundancy in the connections within Science Division.

The six egos had 10% of staff from Policy Division (n=7) in OEH and 13% of staff from Regional Operations (n=66) in their network. So their advice and information potentially flows into government policy, and informs management of environmental threats.

The ego networks ranged from 115 to 360 total contacts, and varied from 32% to 69% internal (OEH) contacts. The more contacts the scientist had, the higher percentage of external contacts in their network.

Our scoping study allowed scientists to visualise their networks for the first time, so they could reflect on potential gaps and duplication across the group's network. This stimulated discussion about the implications for the organisation. The analysis also raised many questions which we will seek to answer with future research. For example, we are yet to determine whether the total number and diversity of contacts enhance the scientist's skills and capacity, and the reach and impact of their work.

Keywords: *Social Network Analysis, scientists, government, knowledge*

Role of modelling and simulation in evidence-informed policy making: the case of impact assessment

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Abstract: The need for policies pursuing more sustainable futures is becoming more urgent with the growing threats of climate change and environmental degradation. The increasing interconnectedness of societal challenges makes the management of policy decision processes more complex and full with uncertainties concerning final decisions. Impact assessment (IA) as part of policy process is an ex-ante method and formalized procedure to understand likely impacts of decisions through an in-depth analysis of policy options. With its formalized procedure and stepwise approach IA offers great potential to include scientific knowledge for the ex-ante evaluation of policy options against sustainable development, where scientific models and data can be considered as a special branch of scientific knowledge. This presentation investigates the current use of models and data in Impact Assessment practices in a wide range of contexts and settings from the European Commission to EU member states and developing countries and international organizations. The presentation also reflects on the requirements for increasing the use of models and data by describing the roles of models and data in contextualization efforts focused on knowledge brokerage, contextualized description and strategic dialogue.

With the increased use of impact assessment (at the EU level, in individual developed and developing countries and at international organizations) as method, also the capacity of many institutions has increased in establishing formal procedures, support units, training courses and centralized units. The implementation of IA procedures at different institutions differs significantly with some introducing it as a legal requirement for all policy processes, while others only apply it for economic impacts and on a voluntary basis. There are also large differences in the independence of any impact assessment units or organization that implements the impact assessments. International organizations mostly apply impact assessment to evaluate the impacts of their programs.

Model use and use of scientific evidence was analyzed by an inventory of references to models and scientific evidence in IA reports of the European Commission in the time period 2003-2014, as this is one of the more advanced systems of IA. With respect to the references to scientific evidence, most used scientific evidence, and this was referred to as footnotes in 95% of the cases and 63 % used some formulation as part of an introductory section. However, only 25% included a section of references for the underlying materials and sources used in the impact assessment. Overall there is an increase in the use of references in the period 2003-2014.

The use of models increased gradually over the past decade providing a good opportunity for the inclusion of scientific knowledge in the development and application of such models. Mostly financial models (as the standard cost model) were used and some models were used for many impact assessments, often in the same thematic area. There is also a large tail to the distribution with many models being used only once for an impact assessment. In general, the diversity of use of models and the accounting of environmental and social impacts in model use is still low, while over the past decades a lot of research funding was invested in model developed indicating an underuse of the scientific reservoir.

Knowledge brokerage techniques can be used to increase the use of the knowledge reservoir by making models and data easier to find, which was studied in 5 case studies and which were different in their level of brokerage. Some were only informing, while others were truly collaborating across the science policy interface. All knowledge brokerage techniques worked to increase the awareness on both sides of policy and research what is available in terms of research and how this can be used. However, there is a lack of incentives at both sides of science and policy to do this in a structural way, and structural elements are missing to organize the interface in a substantial way. Realizing these efficacy and efficiency gains requires structural reform of the knowledge systems targeting sustainable development.

Keywords: *Knowledge brokerage, evidence, model use, environment, policy analysis*

Practicing and evaluating outcomes of working across the science policy interface

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Abstract: This paper reports on the practice and evaluation of co-constructed research conducted by researchers at the James Hutton Institute with a range of policy and other stakeholders. The research was undertaken to support a policy options appraisal for the reform of the Common Agricultural Policy (CAP) in Scotland, a major rural policy instrument that distributes 532M€ per annum (equivalent to over half of the total income from farming) and, by 2019, will redistribute approximately 280M € of funding. Over the course of ten years of science-policy interactions a variety of modes of working have been undertaken – the paper outlines the actors, the networks of interaction, the nature of the research undertaken and how this has evolved as the research team built credibility with policy makers and other stakeholders. The increasing degree of co-construction and even co-delivery of research through partnership between James Hutton Institute staff and analysts within government is assessed in terms of the mutual benefits, the potential pitfalls and institutional and career challenges for researchers working in this way. The research was also subject to formal evaluation of policy and other impacts by consultants employed by the research funder. The paper highlights the key findings from this evaluation for the CAP related research. A key finding from the evaluation was that instrumental change (in practice or policy) was more readily acknowledged by policymakers rather than research providing new knowledge or conceptual insights. This did not match the expectations of evaluators for whom the achievement of instrumental change was the greater challenge, and was dependant on conceptual change. The paper draws on the literatures of agricultural decision support and other literatures to ground these findings in a wider community of practice.

Keywords: *Co-construction, science-policy, evaluation, CAP, Scotland*

Building resilience in New Zealand farming communities through collaborative research

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Abstract: Zealand's economy is highly dependent upon its national agri-business system which in turn is dependent upon not only the natural environment, but also rural communities to supply necessary services, infrastructure, labour and skills. The challenges facing rural enterprises and communities in New Zealand create considerable and growing concern of expected decline. However, the implied adverse effects are not necessarily inevitable and may even be reversed though building resilience.

AgResearch, a New Zealand government research organisation, is collaboratively defining a 5-year research project with partners and participants to enhance the resilience and vibrancy of New Zealand rural communities and rural enterprises. It is doing this by co-creating and implementing locally contextualised, proactive resilience strategies and social innovations which help enable resilient, responsive, and entrepreneurial rural communities. This paper discusses the results of a series of workshops held to identify and co-define the research project.

The process consisted of three half-day workshops over three months. Representation was canvassed from a wide selection of relevant researchers and practitioners from several institutions. This ensured that the complex issue of research on rural resilience and capacity to adapt to changing circumstances was examined from multiple perspectives in order to gain a comprehensive system perspective of the issue. Participant organisations included research institutions: AgResearch, Lincoln University, Landcare Research, University of Melbourne, and GNS Research; central and regional government: Ministry of Primary Industries, Waikato Regional Council, Hawkes Bay Regional Council, and advocacy groups: Federated Farmers.

The first workshop aimed at jointly define the research context: identifying national internal and external challenges to rural socio-ecological resilience over the next thirty years, identifying drivers of pastoral sector and rural community change and the direction of change, and identifying current areas of strength and vulnerabilities in New Zealand rural communities. The second workshop aimed at ensuring alignment between the new research project and existing partners' initiatives, jointly define research themes and producing a social network map to identify the existing organisations, key network actors, and relationships important to rural resilience in New Zealand using social network analysis. The third workshop aimed at reaching agreement with participants on research priorities for the project: validating the implications of identified challenges and opportunities on communities and clarifying further involvement on project definition. A writing team was identified amongst participants to write the final research proposal.

Some brief results include three internal challenges to New Zealand rural resilience as identified by participants: social isolation, land use change and farm profitability. Three external challenges: climate change, decline of local services and infrastructure and global completion for agricultural products. Three drivers of pastoral sector and rural community change: increasing technology on farm, improved practices requiring more skilled workers and the increase of regulatory requirements, basic sustainable management. Three current areas of strength in rural communities: community and social capital, social energy and high levels of education and literacy. Three identified vulnerabilities: depopulation, lack of access to skilled labour and unknown and uncertain future. There were 15 current initiatives identified by participants to be taken into account for defining the new research project. Participants also generated a list of over 50 potential research questions. All of this information was taken into account to define the four broad challenges for the research project: 1) Policy upheaval, governance and new rural futures; 2) Technology, land use challenges and farm system transformation; 3) Diversification of rural economies and rural/farm business innovation; and 4) Anticipating and managing social change/needs and well-being in New Zealand's rural communities.

Keywords: *Resilience in rural communities, collaborative research, participatory methods*

Customer-focused science for environmental sustainability: a continuing case study from the NSW Government

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Abstract: This paper presents the progress of a new scientific branch in the New South Wales Government that aims to maximise customer service and optimise the management and sharing of knowledge**.** Summerell *et al.* (2013) presented the reasoning and design concepts used to establish the Ecosystem Management Science Branch (EMS) in the Science Division of the NSW Office of Environment and Heritage (OEH). EMS consists of new staff positions placed in cross-functional teams, in preference to discipline-based teams. Six teams were designed to collaboratively deliver research services and products to customers and colleagues who undertake environmental management, and develop and implement policy and programs. Two core objectives were adopted to underpin and progressively transform the work of EMS Branch. These were to:

(1) enhance knowledge management and customer engagement as a means of empowering community and government decision-making, and better achieving environmental sustainability;

(2) capitalise on our science leaders, and further develop them using the concept of 'scientist' social capital, which we define as benefits that arise from the science practitioner's reputation, status and relationships.

Traditionally, environmental science has struggled to embrace the social dimensions and implications of people in the landscape. This has reduced the incorporation of science into policy and regulation, and its use at all levels of decision making. This paper reports on the progress of these two core objectives over the last two years.

The EMS Branch has the challenge of integrating a wide range of highly diverse research areas to address issues of importance to the NSW Government. Six science leaders and one Director lead 65 staff who are located throughout NSW and undertake 134 projects throughout Australia. An early initiative of EMS Branch was to identify and map staff against projects. This improved transparency and accountability on how resources were being allocated. To provide strategic direction to EMS, the Director and Senior Team Leaders (STLs) developed a Program Logic to help consolidate, manage and communicate the purpose of our work.

Developing the EMS Branch Program Logic provided a shared clarity in direction and purpose of current activities and staff roles consistently with a long-term vision. It also demonstrated how EMS Branch research contributes to the goals of Science Division, OEH and the NSW Government. A bonus of the Branch Logic is that it enabled better communication and more capacity to influence and engage our customers and the organisation.

A case study is presented to demonstrate early benefits arising from pursuing the Branch's two core objectives. The project termed the Grazing Study seeks to provide comprehensive knowledge to inform evidence-based decision-making by the NSW Government for social, economic and ecological impacts for the continuation of livestock grazing in certain areas of parks and reserves managed by the New South Wales National Parks and Wildlife Service.

Examination of initial project results and outcomes suggest that the impact of our science is increased by using 'scientist' social capital, combined with a customer focus and collaboration with a range of partners. This approach produced an information exchange based on relationships and trust. A productive private-public sector partnership has increased the project's reach and delivery through greater awareness and shared understanding. Ultimately we expect our model, based on our two core objectives, to result in further impact of our science.

Keywords: *Environmental science impact, science sustainability, government science, knowledge management, matrix management*

An approach to consider the impact of co-designed science: Case study of Bayesian networks to set NRM targets

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Abstract: It is now often stated that the scientific community can gain greater impact from their work if they engage intended stakeholders in co-design, implementation and evaluation of projects. However, the evidence to substantiate these claims are rarely more than anecdotal and reflective comments from scientists. Previous evaluation methods for participatory work run the risk of being over simplistic, and therefore omit important impacts, or become too complex and not user-friendly. In this paper, we provide an intermediate option, combining the research of others (detailed in Table 1), to produce 5 key dimensions to consider when evaluating the impact of participatory projects. These dimensions are 1) an increase in knowledge and awareness, 2) a change in behavior or practice, 3) active dissemination of new knowledge, 4) change in policy or planning, or some level of government endorsement, and 5) physical system improvements or "on-ground" change. In addition, social learning, empowerment and new social norms are important, but due to complexity, they are not yet included in this method. Each dimension can be estimated for its breadth and depth of the impact by more detailed criteria (e.g. how many people have increased their knowledge? And how much more do they know (i.e. could they explain it to someone else?)). The breadth is more of a quantitative assessment, which is generally easier to measure, while the depth, particularly if self-assessed, is more likely to be qualitative and subject to bias. We provide a grid to plot the breadth and depth impacts, and the means to combine this impact into a single visual representation on a radar plot (Figure 1). Here multiple lines represent different people's views of the same project, but they could also show the impact of different projects, or both.

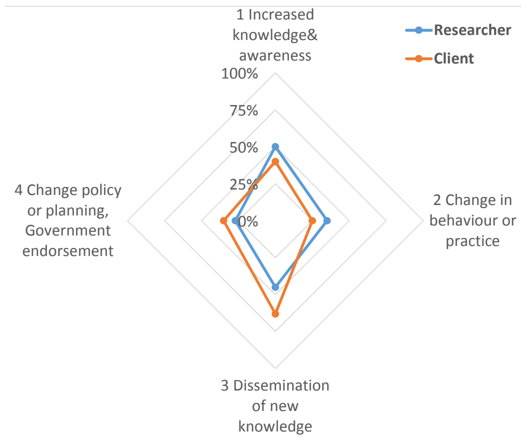

Figure 1. Application of impact assessment approach to case study of Bayesian network development during redevelopment of the Condamine catchment NRM Plan.

We applied the approach to a case study where the Condamine catchment Natural Resource Management (NRM) Plan was updated to better account for the interactions of management and outcomes across the people, water, land and wildlife themes, allowing for external influences such as climate change. A series of Bayesian networks (Bns) were co-developed with key staff from the Condamine Alliance (CA) and the plan's advisory team through a series of workshops emails and phone calls. The final Bns were used to set quantitative targets in the catchment plan for monitoring and evaluation. The Bns also underpin website interactive tools, used for communication and engagement with the wider community.

The impact assessment approach provided a useful structure to consider the impact of stakeholder engagement in science, but highlighted the difficulties in trying to measure impact retrospectively and without a large investment of resources. Ideally useful bounds to evaluate the impact of participatory science are discussed and decided upon prior to the commencement of a project, and if not, then the evaluation of its impact would require resourcing of its own.

Keywords: *Impact evaluation, Bayesian network, natural resource management targets*

Data licensing in the Bioregional Assessment Programme

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Abstract: The Bioregional Assessment Programme (the Programme) is an undertaking by the Australian Government in order to better understand the potential impacts of coal seam gas and large coal mining developments on water resources and water-related assets. The Programme is producing a series of products which are being published online and confidence in those products will be enhanced by supporting them with data that is visible to the community. While government policies to make public sector data available, under open access licensing, are progressing in all jurisdictions, the implementation of these policies is progressing more slowly at an agency level and industry data is frequently governed by restrictive use conditions. The Programme is therefore working with varying licences governing the legal conditions of use across a range of data.

The bioregional assessments are being delivered through a collaboration between the Department of the Environment, the Bureau of Meteorology (the Bureau), CSIRO and Geoscience Australia, with more than 100 scientists contributing from these agencies. While the data management practices implemented in the Programme build on the approach taken by previous large multi-disciplinary projects, such as the CSIRO Sustainable Yields projects, the complexity of issues in the Programme have required new innovations in order to meet the high levels of scrutiny and subsequent provenance chains that are required to meet the mandate of transparency and repeatability for all reported results.

All data used in producing bioregional assessments must be licensed for use and, where possible, publication. The preferred approach is to obtain data under an open access licence such as a Creative Commons Attribution 3.0 Australia (CC BY) licence which allows the Programme to freely use, publish and redistribute data.

There are some cases where data are provided with restrictions on use because of commercial sensitivity, privacy concerns, cultural sensitivity or biodiversity conservation concerns. Before these data can be used in a product, consideration is given to the potential impact on transparency and repeatability. Alternative data may be considered, or publishing the restricted data either in another format or after a specified time delay. When permission for the required use is denied, the data cannot be used and the bioregional assessment will include an analysis of data gaps.

The process of data licensing is critical to establishing the necessary legalities of the data provenance chain for all delivered products. The Bureau has taken the lead role in developing and managing the licensing process while CSIRO have provided the necessary software tools to support the process, such as a licence server and enhanced licence attribution tools. These tools sit within the programme Repository that contains all data used in bioregional assessments. Data may be acquired by programme staff if publicly available under a CC BY licence. All other data acquisition requests must be made through the Bureau to ensure that key contacts are established, the burden of data requests on data holders is minimized and information re-use is facilitated. The Bureau negotiates licences with data providers using standard templates to promote consistency while allowing specific conditions if required. The data licence service in the Repository is used to assign source datasets the appropriate licence type and any required attributions and conditions on use. This enables rules to be generated that can be applied to datasets derived from the source datasets, thus automatically assigning appropriate licensing and use conditions to each dataset stored in the Repository. The licence conditions of a dataset guide how the data may be used, and only datasets that meet specified rules are made publicly available.

The Programme, like many other large assessment projects, uses data from multiple data providers under a range of data licensing conditions. The commitment of the Programme to make all data and methods publicly available has been a key driver in creating a strong data management regime comprised of guidelines, processes, governance arrangements and tools, which support the process of data licensing and associated metadata attribution for all datasets used in the assessments. The result is that the scientific assessments of the regional cumulative impacts of coal seam gas and mining can be tested, verified, and will have a high level of confidence.

Keywords: *Data licensing, data management*

The death of documentation – the computer age

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Abstract: The development of scientific disciplines has been based on the use of inductive and deductive thinking with the use of empirical methods to test any new hypothesis. Without empirical testing science is merely assumption, possibly even faith or metaphysics. Empirical testing has therefore always required detailed and accurate documentation in order to provide evidence of the test methods and results, to support a hypothesis, as well as recording any particular phenomena that may provide ideas that lead to further hypothesis to be tested.

Since the advent of the computer age the use of digital technology has reduced, and nearly removed, the need to keep paper-based lab notebooks and journals, as large volumes of information can be recorded, stored, and archived within computer-based media. However, the reliance on computer algorithms has also taken the onus away from documentation as the computing software has become an 'authority' in itself with the components of evidence of testing assumed to be self evident, i.e. the computer model gave me the answer. Such reliance on digital media and the time now invested in building, running, and tuning models and simulations has changed the culture of scientific documentation to make methods less visible to an outside observer. It seems evident that there now exists a culture of laziness in documenting methods, compiling metadata and developing concise and accurate provenance chains. The aim of this work is to demonstrate the critical nature of scientific documentation, by way of example from some of the greatest scientific achievements by famous scientists such as Michael Faraday, Paul Erhlich, Sir Isaac Newton, and Albert Einstein, as well as highlighting how easily this can be achieved. It is hoped that this investigation will highlight the cultural barrier that has developed between having demonstrable integrity for all scientific results versus files filled with values that are assumed to be correct and of a certain level of accuracy and precision without having any real documentation to substantiate such a claim.

A change in the culture of data documentation is required in order to realign the quality of scientific documentation with the standards seen prior to computer-based technology. This is not a huge paradigm shift but simply requires some behavioral change by individuals in their approach to handling and managing data. When data is acquired it is received via download or sent on hard media, it is then stored, checked, and used. These behaviors occur at an individual level but need to follow common standards set by projects and/or organization-wide governance policies. The key component that is often missing is the authoring of appropriate metadata to provide a provenance chain for the data.

Metadata documentation is not only a critical aspect of the foundations of science but it is a relatively simple exercise with a relatively small time component that needs to be woven into the fabric of daily work, rather than being left as a mountainous accumulative set of tasks performed at the end of a project lifecycle when memory has faded and focus is changing to upcoming projects. The main components of metadata that require great effort involving free text entry are the Abstract and the History statement. The Abstract simply describes the dataset, and can also include a statement of Purpose (usually as a sub-field in a metadata catalogue). Just as this Abstract provides an outline to a conference presentation a metadata Abstract provides a user with the knowledge they require to understand what the dataset contains and how they can use it.

The metadata History field provides a description of how the dataset was derived including any methods, processing steps, decisions and logic applied, ingredients such as the input datasets used, any tools employed such as code and software, and other pertinent details that provide an understanding of how the dataset came to exist. As mentioned earlier, many famous scientists throughout history have provided great levels of detail in hand written journals (sometimes by candlelight!) in order to properly document their scientific methods.

The cataloguing tools exist for creating metadata and in some cases have been purpose-built for specific projects, e.g. the Great Artesian Basin Water Resource Assessment (GABWRA). It is time for scientists to plan for and provide documentation at a suitable granularity and to embrace the tools and technologies now available for developing and managing concise and accurate provenance chains in their science. It is also time to acknowledge that such tasks should be included in every scientific project plan.

Keywords: *Data Management, culture, documentation, provenance chains, models, software*

EXTENDED ABSTRACT ONLY

A Data Governance framework for the Bioregional Assessment Programme

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Abstract: The Bioregional Assessment Programme (BAP) is a transparent and accessible programme of baseline assessments that increase the available science for decision making associated with coal seam gas and large coal mines. A bioregional assessment is a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and large coal mining development on water resources. This Programme draws on the best available scientific information and knowledge from many sources, including government, industry and regional communities, to produce bioregional assessments that are independent, scientifically robust, and relevant and meaningful at a regional scale.

The BAP is also a multi-agency collaboration involving well over one hundred scientists and support staff across four different agencies, namely, the Bureau of Meteorology (BoM), CSIRO, Geoscience Australia (GA), and the Environmental Resource Information Network (ERIN). The BAP includes disciplines of geology, hydrogeology/groundwater, surface hydrology, ecology, risk and uncertainty, and information management, that all cut across five separate Project Bioregions, namely the Clarence-Moreton, Gippsland, Lake Eyre Basin, Northern Inland Catchments, and Sydney Basin. Having multiple agencies and disciplines collaborating poses many challenges in managing data and provenance chains for reported results. Therefore it is critical to have a well-structured data governance framework with clear roles and responsibilities, a stable and secure data management system (tools and storage infrastructure), a robust and clearly defined set of policies, protocols and processes, as well as a governing body which can apply consistent principles to make Programme-wide decisions on all aspects of the data governance framework.

The cross-agency issues are a complicating factor in that common computing infrastructures need to be shared while adherence to IT security protocols of each organization is also ensured. A stand-alone data repository has been developed to provide a secure interface for registering new data, a read-only cloud computing data register to securely store it, a metadata catalogue, with a web-based GUI accessible by all BAP partners, to document all data, an element conformance report (ECR) to check the provenance chains of all non-text elements (maps, tables, figures, charts, diagrams, photos) that appear in the report products, and an overarching data identification system that uniquely stamps each new dataset. The cloud-based data repository is not visible to BAP members. Instead, there is a visible shadow repository available in both CSIRO and GA so that BAP staff can access all datasets that have been registered.

The Information Management discipline consists of a team of Data Managers (one each in BOM, CSIRO, and GA), and individual Project Data Coordinators. The BoM have the lead role in the IM team as well as managing the data licensing process and the acquisition of source input datasets from various agencies. A team of software architects and engineers develop and administer the various computing infrastructure and tools that form the BAP Data Management System.

The BAP Data Oversight Group (DOG) includes representatives from all partner agencies, the client, i.e. Office of Water Science (OWS), and the three Data Managers. This group is responsible for overseeing all facets of the data governance framework as well as making key decisions on policy and process, which they report back to the Project Leadership Group (PLG) for ratification. A weekly Data Management 'scrum' is a short meeting of all Data Managers and Data Coordinators to raise and discuss current issues, to assign and report on actions, to raise technical issues, and to address any issue related to the overall data governance of any of the BAP projects.

The dual requirements of transparency and repeatability are addressed with strong and consistent provenance chains. The BAP data governance framework has provided a strong platform and, potentially, a powerful blueprint for future undertakings that require multi-agency and multi-discipline collaborations.

Keywords: *Data governance, data management, data repository, metadata catalogue*

EXTENDED ABSTRACT ONLY

Data management and publication at CSIRO

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Abstract: Over the past decade the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been restructured from many divisions with their own IT departments, to having a centralised Information Management and Technology (IM&T) service for all divisions. Prior to this, data management was handled within the divisions, and the legacy of this is various pockets of different data management practices and standards throughout the organisation. A common issue encountered by researchers is difficulty discovering and accessing the data assets held in other parts of the organisation.

Restructuring to one IM&T service presented the opportunity to create a central repository for data and metadata. In 2009 CSIRO received funding from the Australian National Data Service to develop the Data Access Portal. This development consisted of several stages, initially publishing some high profile data collections under the "Data Capture" project, eventually leading to the 2012 release of a publicly accessible data repository for the entire organisation to use. This web-based repository allows researchers to describe, archive and publish their data, with the option to set separate restrictions on metadata and data for internal or public use. This allows for general publication of data as well as restricting data and metadata descriptions to specific users who may be internal or external to CSIRO.

Beyond any technical requirements in hosting and serving the data, one of the main components informed by this process was the documentation and decision workflows for supporting researchers using the system. Licensing, intellectual property, sensitivity of data and quality assurance are only some of the issues encountered. Additionally, the systems need to support researchers working across a wide range of disciplines, e.g. intellectual property issues for applied research in a commercial setting like mining will be different from data obtained through the Australian Telescope National Facility. Widely applicable decision trees were developed by CSIRO's legal team, along with a low risk data licence for use when more commonly available licences are not suitable, reducing the need for specific legal advice on many projects. Guidance for the use of other licences was also developed. An approval process is built into the data publication workflow, with approvers from the various research groups able to assess data and the risk of publication according to the standards of the relevant discipline. Licences for software and code have been added, with supporting documentation and decision trees, also reducing the need for specific legal advice on many projects.

Now that a self-service system is in place, with scalable storage and a commitment to future development, CSIRO is in a position to develop organisation-wide policy on data management for projects. Research groups have been requesting policy for data management and publication, and this infrastructure supports compliance.

New development has begun, with various feature requests being worked on, including: Storing large volumes of data streaming from the Australian Square Kilometre Array Pathfinder; The expansion of data storage and access options, also linking metadata to data storage in other locations both internally and externally to CSIRO; Support for data services; Implementing standard keyword vocabularies; Providing support for provenance data; Semantic, linked-data interfaces; Object-level metadata to support image collections and the digitisation of the national biological collections; Integrated data management planning tools for use throughout a project.

Since the launch of the Data Access Portal, over 1600 data collections have been published, with over 1000 collections having publicly accessible data. The rate of new publications has been linear, as has the rate of uptake by first-time data publishers. The rate of downloads has roughly doubled each year, with over 180,000 downloads by September 2015. The volume of data stored is roughly doubling every six months, and is over 300TB in September 2015. With the forthcoming release of data from the Australian Square Kilometre Array Pathfinder this should quickly grow to several additional petabytes a year. All publicly available data can be found at https://data.csiro.au.

Keywords: *Data management, data repositories, policy, licensing*

An open data journal as a solution to the data curation and availability challenge in agricultural and environmental sciences

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Abstract: Recently there has been significant focus of the scientific community and political stakeholders to data starting with improved discoverability, data homogenization, and opening up of datasets (e.g. UN report on Data Revolution, open access in science publishing). Open data signifies open access to data through publicly accessible means under appropriate licensing conditions. Through changes in policies of many governments, international organizations and donors, open data is becoming more and more common, while the awareness of safeguarding valuable data for the future is increasing among government, private and research sectors. Political attention has turned to open data as a public good resource, as witnessed by open data initiatives (e.g. Global Open Data for Agriculture and Nutrition (www.godan.info), open data conferences and open data portals (e.g. data.gov, data.gov.co.uk, data.overheid.nl, data.fao.org)). Here it is assumed that increased data availability will lead to three major outcomes. First, with more government data available the transparency of government decision making increases. Second, increased data availability allows the business sector to develop new applications and potentially new income streams, thus leading to jobs and economic growth. Third, increased data availability can increase the possibilities for strategic assessment of decision options, either in business or government, and possibly through the engagement of citizens in citizen science.

For researchers open data translates into an opportunity to use much more data in analysis, which is publicly available, or available with fewer barriers to use. On the other hand it also creates the obligation to open up their data that is collected and analysed for research and new data sets created through analysis. Crucially, some research funders are incorporating requirements for open access and occasionally open data as part of their grant making. For example, the H2020 program of the European Commission requires a data management plan as part of every successfully funded project. This presentation discusses the establishment of the Open Data journal for Agricultural Research (www.odjar.org) as a new outlet for publishing valuable research data sets.

The ODjAR aims, first, to lower the publication barrier for researchers in the agricultural domain by providing a mechanism for citation and receiving credits for their investment in data management and sharing; second, to lower the annotation barrier of describing data in meta-data by adding the commonly required meta-data fields as part of the publication and upload process, and third, to lower the technical barrier by allowing easy upload in standard and proven data repository technology. ODjAR is based on strong institutional support from main agricultural research facilities (INRA from France, CGIAR as an international organization, and Wageningen UR from the Netherlands) to establish it as a publishing mechanism, and ties to global networks working on agriculture, food security and climate change (AgMIP, MACSUR, Yield Gap Atlas, ILSI CIMSANS) thereby reaching thousands of researchers across all continents. The first submissions are coming in and the awareness of researchers is increasing, in the various networks, for establishing data publication as an option in their daily research routines.

Ultimately publishing research data, as for other open data initiatives, requires a cultural change in research habits and an institutional change in professional management of research data. With ODjAR.org now established, there are indications that such a change is taking place, even if it is only leading to the lowest level of linked open data according to the 5 star model of Tim Berners Lee (see: http://www.w3.org/DesignIssues/LinkedData.html).

Keywords: *Data, cultural change, open access, research funding, data repository*

Demonstrating transparency: guidelines and processes to facilitate best-practice data citation

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Abstract: Researchers are increasingly required to not only provide high quality data, but also to provide access to the provenance of what they have created when generating their scientific information. This requires a robust data governance framework, where researchers record, store and use data and metadata by following agreed policies, and through the application of well-defined protocols and processes.

The Bioregional Assessment Programme provides scientific information for decision makers, industry, and the community to use when considering coal seam gas and coal mining developments and their potential impact on water resources (www.bioregionalassessments.gov.au). Over 200 researchers from four agencies are developing 150 reports, delivered both as PDF documents and also via an online information platform. A key requirement is transparency of the data creation process, which is met by including in-text data citations that use persistent uniform resource identifiers (URIs) that are linked to the metadata and (where possible) the data itself using unique global identifiers (GUIDs).

This is achieved through the close collaboration of three groups within the programme:

- *the information management team* developed a metadata catalogue, data licence service, automatic citation generator, and quality assure the metadata that has been entered by authors
- *authors* register datasets in the metadata catalogue, enter metadata, and cite datasets as they write reports
- *the products team* developed programme agreed guidelines and processes for data citations within written reports, and quality assure the data citations.

Stakeholders expressed a desire to easily distinguish between citations to data and to literature within the text. Therefore an in-text citation format for data is specified as, for example, 'CSIRO (Dataset 4)'. A dataset list follows each section, with metadata attributes and syntax as in this example:

> Dataset 4 CSIRO (2012) ASRIS Australian Soil Classification – Dominant Soil Order (250m raster). Bioregional Assessment Source Dataset. Viewed 28 May 2015, http://data.bioregionalassessments.gov.au/dataset/d6b0c5c7-37d0-4832-b5b1-53cb7eeb3cd7.

A dataset citation includes some metadata about the dataset. In determining which metadata fields to use in dataset citations, there was a need to find a balance between the information a reader might want to see, the information they might need to find the data for themselves, and the information that was readily available. The fields that were chosen were the organisation that created the dataset; the year created or published; the title; whether the dataset was sourced externally to the programme (source), or derived from within the programme (derived); the date that the URI was viewed; and the URI (which includes the GUID at the end of the link path). For source datasets, the year used in the citation is the year that the datasets were published as this was the year that was (i) most representative of the currency of the data and (ii) was available for most datasets. For derived datasets, the year created was used given that the datasets were not yet published at the time they were cited.

When citing datasets in text, authors follow the same principles as citing literature. When data is used in figures, key datasets are cited to enable a reader to understand the source of the pertinent information. Authors were given these guidelines, as well as two tools to facilitate citing datasets. The main tool used was the automated citation generator, which 'mined' the metadata catalogue for the information required in the citation. The other tool was a URI scraper, designed to list all URIs listed in a document. This was used by the information management team so that they could quality control (in the metadata catalogue) the fields required for the data citation. These tools ensured easy, accurate and consistent citations, and encouraged uptake by authors for this requirement of increased transparency.

Keywords: *Data citation, data management, quality assurance*

A National Environmental Information Infrastructure

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Abstract: Australia invests significant resources in environmental data acquisition, management and publication. Although data are abundant, users are typically hampered by an inability to discover, access and re-use the data. The National Environmental Information Infrastructure (NEII) activity will improve the effectiveness and efficiency of discovering, accessing and re-using environmental data beyond its primary purpose. The NEII is envisioned as a federation of environmental data nodes adopting common standards to create a data infrastructure with an initial focus on nationally significant environmental data. Its primary focus is on the discovery and re-use of national environmental data that is already well-managed, but that currently has limited application beyond its original business purpose. In common with spatial data infrastructures, the NEII encompasses common data models, exchange formats and standard network protocols along with centralised catalogues of uniform metadata descriptions. It also includes standardised models for describing environmental measurements, monitoring sites and methods used to observe the environment to address the unique requirements of environmental information. These architectural elements are more fully described in the NEII Reference Architecture (Bureau of Meteorology, 2014b, www.neii.gov.au).

The Bureau of Meteorology is leading the development of the NEII including provision of core coordination and integration infrastructure, as well as the governance and collaboration framework for its development and operation. However its ongoing success is dependent on establishing enduring partnerships with major national environmental information organisations. The NEII Programme is framed around five focus areas including (a) Communication, (b) Engagement, (c) Policies and frameworks, (d) Data management, and (e) ICT build. This paper provides a more detailed overview of one component of the Data Management area regarding the development of the NEII Conformance Framework.

Conformance means following established guidelines, specifications and standards or working towards them. A conformance framework is a structured set of guidelines that detail the levels at which a participant provides services that comply with the NEII architecture. The NEII Conformance Framework has been developed to (a) enable partners to set priorities against specific expectations that will jointly lead to developing a sustainable federated environmental information system; (b) enable users of the NEII to rapidly assess the suitability of data for their business needs; and (c) provide a common measurement system to monitor progress in the development of the NEII. The framework adopts a capability maturity model approach to describe the steady improvement required for NEII nodes to progress from a basic data release (experimental data service with limited operational support) to an enduring federated system providing environmental information. The design of the model is informed by other maturity-based approaches for open data such as the Open Data Institute's certification approach (Open Data Institute 2015). The paper also presents a worked example of the conformance framework against the Bureau of Meteorology's Australian Hydrologic Geospatial Fabric NEII data services.

The paper concludes with an overview of major learnings from the programme to-date. These relate primarily to reducing the cost of participation in NEII by data custodians given the challenge of delivering data using NEII standards; and developing approaches to better support users to use the portfolio of NEII data given some of the methods of data delivery may be new to non-technical users. The NEII programme has prioritised both these and developed work packages to achieve improvements.

Keywords: *NEII, federated information system, OGC, Open Data Institute, conformance, capability maturity model*

Modeling practice synthesis and key lessons learned across 20 years of model development: the ASRU experience

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Abstract: For many years, there has been an expectancy that a defensible and transparent set of fundamental modeling practices (in the form of broad-spectrum recommendations) should be utilized when applying models to ensure (among other things): 1) consistency between model applications; 2) better communication with and improved decision making by stakeholders; and 3) a high standard of model quality control and assurance, including quantification of uncertainty. Best-practice guidelines for modeling have been developed by numerous organizations to promote improved understanding of model development and application, facilitate evaluation of model robustness and provide a framework for documenting and communicating modeling activities among modelers and decision makers. Indeed, a literature search reveals at least 30+ manuscripts on best modeling practices in the environmental modeling domain alone over the past decade. During this time, the USDA-ARS Agricultural Systems Research Unit (ASRU) in Fort Collins, Colorado USA has developed various agroecosystem simulation models and decision support tools including the Great Plains Framework for Agricultural Resource Management (GPFARM), Root Zone Water Quality Model 2 (RZWQM2), and the AgroEcoSystem-Watershed (AgES-W) model among others. Throughout the course of development for the aforementioned models and decision support tools, we have created and maintained guidance documentation outlining a core set of general (and desirable) modeling practices for the environmental/agroecosystem modeling domain.

The purpose of this presentation is to share the guidelines and salient lessons learned (in the form of an "ASRU Good Modeling Practice Handbook" or AGMPF) in the hopes that they may be relevant and useful for the target audience of model practitioners. The AGMPF has have evolved over time (in response to improved software development tools, compilers, and computer hardware) and depends to a large degree on our interaction and collaboration with a wide range of customers and clientele including commodity groups, extension personnel, farmers/ranchers, scientists, academics, water managers, and conservation groups. A primary goal of the AGMPF is to improve the reproducibility and transferability of model application studies. The AGMPF is intended in particular to support the modeler. It deals with major steps in the modeling process and is therefore very suitable for use as a checklist (however, the AGMPF is explicitly not intended as an obligatory constraint or straitjacket for the modeler but rather as a technical advisory tool).

Keywords: *Model evaluation, good modeling practices, modeling guidelines, model reproducibility*

Communicating uncertainty: design patterns for framing model results in scientific publications

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Abstract: Uncertainty is a prominent issue in modelling. We learn early in our studies that "all models are wrong, but some are useful." We also learn accompanying techniques for quantifying performance, and methods for addressing uncertainty within our analyses. When it comes to publishing our results, communicating uncertainty appears to be part of the craft side of modelling, one that we learn best by experience. Sooner or later, we discover that reviewers (and the reader) are willing to accept limitations of our modelling if we use certain key phrases (e.g. "left to future work") or subtly change our wording (e.g. "seems to indicate" vs. "proves"). Our writing effectively frames the model results, implicitly conveying the author's judgement about model uncertainty, confidence about results and shaping the reader's expectations of how the model may be wrong and how it is still useful.

While it does not appear to have been broached in the literature on uncertainty in modelling, the framing of model results appears to be one of the primary means by which modellers have addressed uncertainty, and specifically communication of uncertainty, within scientific publications. It is one of the core practices that new modellers need to learn to ensure that their model-based analyses are considered to be credible and useful. Unfortunately, this practice cannot be easily distilled into an algorithm, method or recipe. As with other aspects of the 'art' of modelling, there does however appear to be some knowledge that should ideally be transferable.

This paper takes the approach of identifying 'design patterns' that are used for framing model results in order to communicate uncertainty. Design patterns are high-level concepts that describe widely applicable solutions to common problems. Design patterns are a communication technique for structuring and illuminating knowledge which might be tacit, subtle and hard to precisely pin-down. Patterns provide a more structured way to communicate research practices than case studies. One example of a common pattern in scientific publications is to 'Validate & Defend' the analysis. The author attempts to anticipate all criticism and convince the reader that their work is unequivocally correct. This is rarely realistic in environmental modelling, so other more common patterns include 'Step towards a goal' and 'Build the foundations' suggesting to the reader that while the current work respectively represents an incomplete or a solid base, future work is necessary before drawing firm conclusions. While a pattern does not tell the modeller what to write, it acts as a reminder of the type of language involved, and provides a shorthand for discussing alternative framing(s) they could be using. These patterns identified apply specifically for one-way written communication, as in the case of scientific publications, but may still be of use in other communication contexts.

This paper will identify and describe a preliminary set of these design patterns, providing examples and justifying their utility, with the aim of seeking feedback from the modelling community. While future work is necessary, initial results seem to indicate that communicating uncertainty by explicitly framing model results is a core modelling practice that will strongly benefit from being more formally described. It is hoped that in the future uncertainty communication will be more critically aware of which pattern/method is being addressed so that the client, be it researchers, commissioners of research or other interest groups, more clearly understands what has been achieved and what knowledge can be used.

Keywords: *Communicating uncertainty, scientific publishing, design patterns, core modelling practices*

EXTENDED ABSTRACT ONLY

Synthesising and evaluating the criteria of successful decision support models to support water resource assessment and management

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Abstract: Modelling projects that intend to aid aspects of water resource management typically require a large investment of time and resources from modellers, software developers, end users and other stakeholders. These projects are also prone to falling short in achieving expected outcomes. Several papers have been written that provide insight into why different models or Decision Support Systems (DSS) were adopted or not. Here, we report on a formal process designed to elicit and quantify researcher's viewpoint of the factors contributing to 'success' in decision support modelling projects (using 33 'success factors' from the literature) and to evaluate 15 projects against these factors.

We undertook a formal survey of the 11 authors who were involved in one or more of the projects. We were able to rank the variable importance in achieving success in research driven and client driven projects of 33 'success factors' synthesised from the literature (Figure 1). For both research driven and client driven projects, 'a good relationship and trust between the development team and end users' was key (SE2). Despite this commitment to stakeholder involvement, the respondents felt that research outcomes were more likely to be achieved than client outcomes.

SE2: good relationship and trust between developers and users; MD5: Well-structured modelling process; ME1: strong focus on model evaluation; MU1: time for reflection upon results; MU3: develop plausible scenarios; PA4: utilise local scientific knowledge

Figure 1. Radar plots showing the variable importance of 'success' factors in predicting the research and client outcomes of the surveyed projects. For brevity, not all factors are defined here.

The small sample size limits the statistical rigour of the analyses and the conclusions that can be drawn from the data. We were unable to explore how different people's opinions of a projects success could be influenced by their roles, values or expectations. Responses for some of the older projects may be affected by recollection error or moderated by the experience accumulated since that project finished. For client driven projects, project success is arguably better assessed by the clients rather than researchers. Despite these caveats, the methodological approach developed offers an advance from typically qualitative or case-study specific studies and has the potential to be adapted and used in a wider survey to the modelling community (and their clients) to gain further insights.

Keywords: *Decision support, evaluation, water resources*

Interdisciplinary teaching of Statistics

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Abstract: While the understanding of statistics is essential for model developers and users in a range of areas, the teaching of this content is not without its challenges. Teaching the next generation requires the employment of suitable core teaching practices to motivate and thus better support integrated resource management in terms of developing and using statistical models. Teaching statistics often involves teaching end users from multiple disciplines simultaneously.

There are often varying views among students undertaking statistics based courses of what statistics actually is and how it can be used in other courses of their degree and in the workplace such as in resource management. Feedback and attitudes of some students towards statistics subjects can be quite negative. The negative attitude could be due to a number of factors including the quality of previous exposure to statistics or mathematics or limited recognition of the role of statistics in other disciplines.

From an interdisciplinary perspective, there is an increased need to motivate students to want to learn statistics and hence a focus on developing methods to achieve positive outcomes in interdisciplinary statistics. This paper proposes four teaching strategies designed to motivate students, make content more relevant to them and thus improve their learning and teaching outcomes.

Clarifying the purpose of statistics to students both in society and for their specific disciplines is crucial and can be elaborated on in the first lecture in an attempt to capture engagement early. Creating an active learning environment to engage students' interest and extend on their understanding is also fundamental. Another principle to motivate students to learn is via the use of examples to which students can relate. These examples should include real world and current events to try to make links with students' interests and backgrounds. Employment examples should also be used for immediate relevance.

From an interdisciplinary perspective, the core practices described have been employed in the classroom environment in an attempt to improve students' statistical knowledge and to consequently be able to better develop and use models to support integrated resource management. The proposed strategies were implemented in first and second year interdisciplinary statistics courses and have been received favourably by students in terms of improving the relevance of interdisciplinary statistics courses as well as the students' overall satisfaction with the course, which are the initial steps required to consequently improve student learning outcomes among the next generation of learners.

Keywords: *Mathematics, statistics, student engagement, teaching*

Effects of climate indices on extreme rainfall in Queensland, Australia

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Abstract: Over the last 100 years, global surface temperature has increased approximately 0.75 ^{0}C. One of the main concerns regarding global warming is the increased frequency and magnitude of extreme weather events, e.g. extreme rainfall which has already been recorded in many regions of the world. During the last decades, losses in economy and society have increased due to extreme climatic events. In certain parts of the world, society and its natural resources are damaged by extreme rainfall causing loss of lives and destruction of infrastructures. Increased frequency and magnitude of extreme rainfall led to the failure of existing drainage system and risk of increased flooding. Therefore, it is necessary to obtain information on extreme rainfall events for designing hydrologic and hydraulic infrastructures, e.g. stormwater management, urban drainage systems, water sensitive urban design (WSUD).

The increased frequency and magnitude of extreme rainfall events throughout the world led to increase concerns amongst hydrologists and water resources engineers in estimating the design rainfall derived from extreme rainfall frequency analysis. Since design rainfalls are important input in water resources engineering, errors in the selection of design rainfall event will cause devastating consequences for water infrastructure projects and flood mitigations works.

Although several studies on extreme rainfall events have been conducted and ongoing, regional dependency of the phenomena hinder in drawing generic conclusion. This paper investigates the effects of climate indices on extreme rainfall and its prediction. The extreme rainfall analysis will be performed using data from a rainfall station in Queensland. The analysis focusing on extreme events is easily understandable and manageable on impact studies and design rainfall estimation for water infrastructures. Comparing the modelled extreme rainfall with the observed outputs, it was found good predictive capability of the developed MLR models. The findings of the study also have significant importance for other regions of the world where there is considerable hydroclimatic variability.

Keywords: *Climate indices, ENSO, IOD, multiple regression, rainfall forecasting*

Statistical correlations between rainfall and climate indices in Western Australia

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Abstract: As the concept of 'sustainable development' is increasing day by day, rainfall has become the most significant and investigated hydro-climate variable in Australia. Rainfall variability is considered as a major economic factor in Australia. It was observed that Australian rainfall is affected by several climate patterns and long-term prediction remains a challenge for many years. However, forecasting rainfall can be beneficial for the design, maintenance and management of water resources infrastructures. Nevertheless, rainfall is the product of complex global atmospheric phenomena. Strong correlations between rainfall and several climate indices have already been observed throughout the world. Any such correlation with climate indices and rainfall afterwards can be used in forecasting long-term rainfall. For the prediction of rainfall in advance, statistical and dynamic systems can be used in practice. However, dynamic systems are too complex and expensive to use in a wide range of situations. This paper focused on the investigation of statistical correlations between rainfall and several climate indices as potential predictor of long-term Western Australian rainfall. Since Australian rainfall is highly variable both in time and space, this analysis was performed on regional scale. Several multiple regression models were investigated using the climate indices as potential predictors of rainfall. The models which satisfied the limits of statistical significance were used to forecast Western Australia rainfall in advance. Historical rainfall data were obtained from Australian Bureau of Meteorology. The rainfall station Roebourne in Western Australia was chosen as a case study. The station was selected based on their long term recorded data having fewer missing values. The major aim was deterministic forecasting of long-term rainfall in terms of climate indices in regional scale. The analysis showed that DMI-ENSO based combined multiple regression models could be used for long-term rainfall forecasting of Western Australia except extreme rainfall.

Keywords: *Climate indices, ENSO, IOD, multiple regression, rainfall forecasting*

Demonstration of max-stable models for estimating catchment flood risk

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Abstract: Understanding extreme rainfall events is critical for estimating the risk of flooding, leading to better design of infrastructure and management of flood events. The majority of engineering design is based on estimates of extreme rainfall known as the Intensity-Frequency-Duration relationship (IFD). IFD curves are estimated at each rain gauge and are subsequently interpolated for application to ungauged locations. IFD curves are fundamentally a pointwise estimate, because the distribution of extreme rainfall is considered at each location independently. This leads to difficulties, especially at sub-daily timescales, due to the sparseness of sub-daily extreme rainfall data and relatively shorter records. As a result there is greater uncertainty and potential for bias when estimating sub-daily extreme rainfall. By using a model that incorporates dependence between spatial extremes as well as across multiple timescales, there is considerable potential to improve estimates of extreme rainfall.

The aim of this research is to develop max-stable models of extreme rainfall that have both spatial dependence as well as dependence across timescales. Max-stable processes are a direct extension of the univariate generalized extreme value (GEV) model into the spatial domain (de Haan, 1984). Max-stable processes provide a general framework for modelling multivariate extremes with spatial dependence for just a single duration extreme rainfall (Padoan et al., 2010). To achieve dependence across multiple timescales, Koutsoyiannis et al. (1998) proposed a mathematical framework which expresses the parameters as a function of timescale. This parameterization is important because it allows data to be incorporated from daily rainfall stations to improve estimates at sub-daily timescales. This approach therefore remedies the issue of sparseness for sub-daily stations by exploiting the denser network of daily stations.

A case study, the Hawkesbury-Nepean catchment near Sydney is used, having 82 daily gauges (>50 years) and 13 sub-daily gauges (>24 years) over a region of 300 km x 300 km width. The max-stable model incorporated spatial dependence by fitting parameters simultaneously, as well as considering covariates such as latitude, longitude and elevation. Models were fitted for the case of sub-daily gauges and daily gauges separately, and an additional model was fitted for the timescale dependent case. A comparison of the model results for the sub-daily case and the timescale dependent case shows significant improvement to the sub-daily estimates due to the density of the daily network. The improvement in sub-daily estimates comes despite the fact that the daily data are at a much longer duration, and is due to a better representation of the spatial structure of the location and scale parameters for the GEV distribution. Some important considerations with this approach are (i) numerical issues related to the number of model parameters and locations, (ii) how to represent differences in the spatial structure with duration (for example, shorter duration extremes are less spatially dependent than longer durations) and (iii) the fact that extreme events in the sub-daily record often come the same related events in the daily record (inferred from the timestamp). By adopting max-stable frameworks that explicitly incorporate spatial and temporal dependence it is possible to significantly improve the estimate of sub-daily extreme rainfall used in design situations.

Keywords: *Extreme rainfall, flood risk, max-stable process, sub-daily timescales, parameterization*

Impact of climate variability on rainwater savings: A case study for Sydney

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Abstract: With the growing population and ever-increasing water demand water authorities of many highly populated cities are struggling to maintain potable water supply for the residents. Without effective measure(s) the situation is expected to get worse day by day. To reduce the potable water demand, several methods/systems were proposed; rainwater harvesting, greywater reuse, recycled (treated) water supply and using water efficient appliances. Among all the water harvesting and recycling systems, Rain Water Harvesting System (RWHS) is considered to be the most effective, reliable and safe if used for non-potable purposes. Rainwater tank is the most common form among all the rainwater harvesting systems. For many remote communities rainwater tank is essential as they have to buy expensive bottle water for daily consumptions. In some urban areas due to lack of resources authorities are unable to provide continuous water supply. Even among urban communities where efficient urban water supply exist, rainwater tank is increasingly being used for non-potable purposes (i.e. garden irrigation, toilet flushing, cloth washing etc.) to reduce potable water consumptions. RWHS comprises with a rainwater collection surface (eg. roof), water storage (eg. water tank), pumping system for distribution and other accessories (eg. first flush diverter, overflow). However, optimisation of this system both in water savings and reliability is a challenge. Various studies and methods of analyses have been used in this regard. Among methods of analysing RWHS, a daily water balance method is most feasible and reasonably accurate. However, most of the relevant past studies using daily data used continuous simulations of historical daily rainfall for a long period, which provides single averaged outcomes (i.e. water savings, reliability, overflow etc.). Through such analysis of averaged variables, rainwater tank users do not get an adequate insight of the expected realistic situation(s) in regards to variability of outcomes. With the impacts of climate change, such ranges of realistic outcomes are expected to be widening further. This paper presents analyses from a recently developed daily water balance model (eTank), which calculates rainwater tank outcomes under three different climatic conditions (i.e. dry, average and wet years). To investigate the climatic variability fifteen representative years (five for each dry, average and wet conditions) were selected from historical rainfall data collected from a coastal site (Sydney Observatory Hill) of an Australian major city, Sydney. Calculated expected annual rainwater savings were compared with the calculated water savings generated by widely used tool, 'Raintank Analyser', which uses historical daily rainfall data for many years and presents an average of all the calculated years' cumulative water savings. It is found that 'Raintank Analyser' calculated water savings closely match with the eTank calculated water savings in average year, which is reasonable and ascertains eTank's accuracy. However, significant climatic variations in water savings are expected for the particular location as calculated by eTank. Also, eTank calculated water savings were compared with the published results from another continuous simulation type water balance model, CSWBM for the same rainfall station for large roofs. Calculations were performed considering same conditions in regard to daily rainwater demand, roof area, losses and tank volume. It is found that CSWBM produced water savings significantly vary with the eTank calculated water savings; for smaller tank sizes CSWBM calculated water savings are even lower than the eTank calculated water savings in dry year, whereas for larger tank sizes CSWBM calculated water savings are closer to the eTank calculated water savings in wet year. In reality, continuous simulation type water balance model results should be closer to the eTank calculated results in dry years. CSWBM calculated reliabilities were compared with the eTank calculated reliabilities in different climatic conditions. Again, it is found that CSWBM calculated reliabilities significantly vary with the eTank calculated reliabilities; for larger tank sizes CSWBM calculated reliabilities are much higher than the eTank calculated reliabilities even in wet year, which is not realistic. Presented comparisons reveals the fact that users should be cautious in using such computational tool(s) as some of these tools may produce erroneous results.

Keywords: *Rainwater tank; daily water balance, water savings, climatic conditions*

A comparison between single and combined climate predictors successes on predicting South Australian spring rainfall

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Abstract: The occurrence of rainfall over Australia is closely related with several key climate predictors, which are El Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM). Some researchers tried to explore the effects of these climate predictors in rainfall variability of different parts of Australia, particularly Western Australia, Queensland and Victoria. Nonetheless, clear association between separate or combined large-scale climate predictors and South Australian spring rainfall is yet to be established. Past studies showed that maximum rainfall predictability was only 20% with isolated/individual effects of ENSO and SAM predictors in this region. The present study further explored these hypotheses. For achieving better predictability of spring rainfall, this paper examined additional two important aspects; relationship between lagged individual climate predictors with spring rainfall as well as linked (multiple combinations of ENSO and SAM predictors) influence of these significant lagged climate indicators on spring rainfall prediction. Multiple regression (MR) modeling was used in this study. Two stations; Tarcoola and Mount Eba were chosen as case study of this region.

MR models with combine-lagged climate predictors (SOI-SAM based models) showed better generalization ability for both the model calibration (1957-2009) and model validation (2010-2013) periods for all the stations. Results also demonstrated that rainfall predictability significantly increased using combined climate predictors compared to predictability with individual effects of each predictor. The attained combined climate model predictabilities were 44% for Tarcoola and 40% for Mount Eba during calibration period. The predictabilities were significantly enhanced during model validation; the results are 94% for Tarcoola and 83% for Mount Eba. Whereas, the maximum rainfall predictabilities were limited to 33% and 30% respectively considering the effects of single climate predictors. Therefore, statistical analyses outlined the capabilities of SOI-SAM based combined climate predictors compared to their single/individual influences for predicting South Australian spring rainfall.

Keywords: *ENSO, SAM, multiple regression, correlation, rainfall prediction*

Comparative study between linear and non-linear modelling techniques in Rainfall Forecasting for South Australia

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Abstract: Australian rainfall is highly variable in nature and largely influenced by the several large scale remote climate drivers. Several past studies tried to establish the relationships between climate predictors (El Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM)) and rainfalls over Australia. However, the relationship between climate predictors and South Australian rainfall is still unclear. Most of the past studies in this region have been carried out based on the individual and concurrent relationship of climate drivers with rainfall. Moreover, the combined relationship considering lagged-time effects of multiple climate predictors has not previously been attempted in South Australia. This paper presents the application of linear Multiple Regression (MR) analysis and non-linear Artificial Neural Networks (ANN) modelling to forecast long-term seasonal rainfall in South Australia using the potential climate predictors. A rainfall station in South Australia was chosen as case study to broadly explore this present hypothesis. The use of combined lagged ENSO-IOD-SAM climate input sets for calibrating and validating the ANN and MR Models was proposed to investigate the effect of past values of these major climate modes on long-term spring rainfall. The ANN model was developed in the form of multilayer perceptron using Levenberg-Marquardt algorithm. Early stopping techniques were used to analyze the improvement in the network's generalization ability. Both the MR and ANN modelling were assessed statistically using root mean square error (RMSE), Pearson correlation (R) and Willmott index of agreement (d). Finally the superiority of rainfall predictability methods was established by comparing the both linear and non-linear techniques.

The developed MR and ANN models were tested on out-of-sample test sets; the MR models showed poor generalization ability than non-linear ANN models. This study found that predicting spring rainfall using combined lagged ENSO-DMI-SAM climate indices with ANN can achieve better correlation as compared to multiple regressions. The study discovered that lagged DMI-SAM combined climate model has more effect on spring rainfall predictability than other combinations of climate model. It was observed that ANN modelling is able to provide higher correlations using the lagged-indices to forecast spring rainfall in compared to linear methods. Using the combination of DMI-SAM dual climate indices in an ANN model increased the model correlation up to 87%, 76% and 37% for the three combined climate predictor's models in forecasting South Australian spring rainfall. Whereas, those rainfall predictability was 52%, 49% and 18% respectively in case of linear MR modelling. The errors of the testing sets for ANN models are generally lower compared to multiple regression models. The statistical analysis suggested the potentials of non-linear artificial intelligence techniques (ANN) over linear MR models for rainfall forecasting using large scale climate modes. This method can be used for other parts of the world where a relationship exists between rainfall and large scale climate modes which could not be established by linear methods.

Keywords: *MR model, ANN model, ENSO, IOD, SAM*

Building an Agro-Hydrologic Model of Europe: Model Calibration Issues

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Abstract: A combination of driving forces are increasing pressure on local, national, and regional water supplies needed for irrigation, energy production, industrial uses, domestic purposes, and the environment. In many parts of Europe groundwater quantity, and in particular quality, have come under sever degradation and water levels have decreased resulting in negative environmental impacts. Rapid improvements in the economy of the eastern European block of countries and uncertainties with regard to freshwater availability create challenges for water managers. At the same time, climate change adds a new level of uncertainty with regard to freshwater supplies. To address the above issues, a calibrated and reliable model of the region is of paramount importance. The Soil and Water Assessment Tool (SWAT) was used to build an agro-hydrological model of Europe. We simulated water resources as well as wheat, barley, and maize yields, and nitrate concentration of the surface and percolating water at the Hydrological Response Unit (HRU) level. The use of large-scale, high-resolution water resources models enables consistent and comprehensive examination of integrated system behavior through physically-based, data-driven simulation. However, calibration of large-scale models suffers from a number of conceptual and technical issues, which we believe require a more careful consideration by the scientific community.

The issues with large-scale model calibration include: 1) parameterization, 2) non-uniqueness, 3) objective function definition, 4) use of different optimization algorithms, 5) model conditionality, 6) inadequate definition of the base model, and 7) time constraints. A software for calibration of SWAT, SWAT-CUP was develop to enable the analysts to deal or to analyze some of these issues. In SWAT-CUP, i) detailed parameterization scheme is included to enable regionalization of parameters at the smallest SWAT unit (HRU); ii) Non-uniqueness is captured by including programs that address uncertainty issues; iii) 11 different objective functions are included to highlight the effect of using different objective functions; iv) 5 different optimization methods are included to highlight the effect of using different algorithms; and v) a Windows-based parallel processing scheme is includes to speed up the calibration procedure.

In light of the above issues, "conditionality" of the calibrated model becomes an important issue, which can partially be addressed by using different variables in the objective function. Finally, we emphasize the importance of performing pre-calibration processing of the hydrologic model and the use of an initially adequate model to be sued for calibration.

The SWAT agro-hydrological model developed for Europe was calibrated based on a large number of river discharge outlets and measured nitrate, mainly in the Danube Basin. Results of major river discharges and river nitrate concentration were quite well simulated all over Europe and in the Danube Basin, respectively. The results produced here could provide information support to the European Water Framework Directive and lay the basis for further assessment of the impact of climate change on water availability and quality. Many applications of this model could be foreseen such as: conducting policy and impact studies, calculating cross-boundary water transfers, calculating quantities of nitrogen loads being transferred from upstream to downstream of a river, and calculating nitrogen loads entering the seas and ocean. The approach and methods developed are general and can be applied to any large region around the world.

Keywords: *Water resources, nitrate load, SWAT, SWAT-CUP*

Soil Moisture and Runoff simulation Toolkit (SMART): A new framework for semi-distributed hydrologic modelling

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Abstract: Recently, a new approach of semi-distributed hydrologic modelling is developed to reduce the computational time/effort in distributed hydrologic modelling at large catchment scales. In this approach, equivalent cross sections (ECS) constitute the modelling elements and are formulated by weighting the topographic and physiographic properties of the part or entire first-order sub-basins. Model simulations are performed at equivalent cross sections scale using a 2-dimensional, Richards' equation based distributed hydrological model. Simulated fluxes from every cross section are weighted by the respective area from which the equivalent cross sections were formulated in a first-order sub-basin and then aggregated at catchment scale to obtain catchment scale fluxes. Simulations across a series of first order sub-basins using the ECS approach resulted in 3.7 to 22.8 times reduction in the number of computational units while reasonable accuracy in simulated fluxes are reached.

Despite the improvement in computational efficiency using the equivalent cross section approach, delineation of the equivalent cross sections at catchment or regional scales remains a challenge due to significant amount of terrain analysis techniques and spatial data processing involved. Here, we developed a MATLAB toolbox (SMART) to automate the pre- and post-processing steps for delineation and modelling of equivalent cross sections. SMART is a GIS-based hydrological modelling framework designed for semi-distributed hydrologic modelling. The basis of this modeling framework is on the delineation of contiguous and topologically connected Hydrologic Response Units (HRUs). The toolbox contains a series of scripts to automate the equivalent cross section delineation process, model simulations across multiple equivalent cross sections, and post-processing of model outputs to visualize the results. The automation steps include: i) delineation of first order sub-basins of a catchment using a digital elevation model, ii) hillslope delineation, iii) landform delineation in every first order sub-basin based on topographic and geomorphic properties of a group of sub-basins or entire catchment, iv) formulation of cross sections as well as equivalent cross sections and v) extraction of relevant biophysical parameters (vegetation and soils) using spatially distributed land cover and soil information for the 2-d distributed hydrological model. The post-processing tools generate streamflow at the outlet and spatially distributed evapotranspiration and soil moisture across the basin. The automation procedure improves the usability of the proposed approach and significantly reduces the model setup time for large catchment scale simulations.

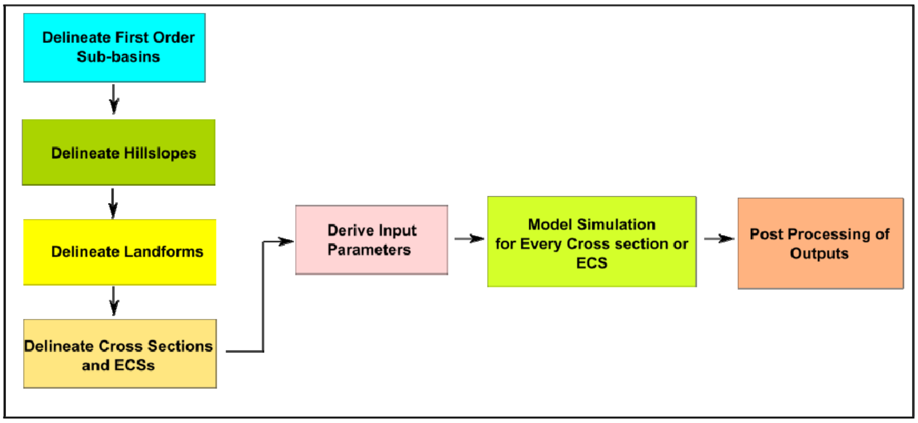

Figure 1. SMART workflow for semi-distributed hydrologic modelling

Keywords: *Equivalent cross section, distributed hydrologic modeling, soil moisture, computational time*

Streamflow assessment and uncertainty analysis for a midwest US watershed using the AgES-W model

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Abstract: AgroEcoSystem-Watershed (AgES-W) is a modular, Java-based spatially distributed model which implements hydrologic/water quality (H/WQ) simulation components under the Object Modeling System (OMS3) environmental modeling framework. AgES-W is implicitly scalable from field to regional scales, has a unique four-compartment surface-groundwater (vertical/lateral) routing scheme (Figure 1), and has recently been enhanced with various science components and tools for improved prediction of hydrologic and water quality response across large gauged and ungauged areas. Science component improvements include both new and enhanced modules for infiltration, water conveyance (e.g., ditches and diversions), conservation practice effects, and water table tracking. New modeling approaches and tools include: 1) coupling of AgES-W with the Model Optimization, Uncertainty, and SEnsitivity Analysis (MOUSE) software application, a newly developed Java-based toolbox of visual and numerical analysis components for the evaluation of environmental models; and 2) linkage of AgES-W to the Landuse and Agricultural Management Practices web-Service (LAMPS) tool which provides crop rotation and management information for user-specified areas within the 48 contiguous states of the USA using annual USDA-NASS Cropland Data Layers from the CropScape web service (http://nassgeodata.gmu.edu/CropScape) and the Land Management and Operation Database (LMOD) from the USDA-NRCS containing agricultural management practices.

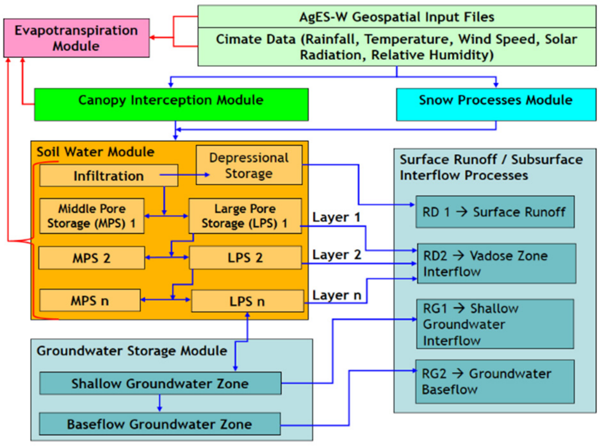

Figure 1. Core AgES-W soil water balance components.

Specific objectives of this research study include: 1) evaluating the accuracy and applicability of the enhanced AgES-W model for estimating (using several autocalibration approaches contained in MOUSE) streamflow for the South Fork Watershed (SFW) in central Iowa, USA; and 2) assessing and quantifying uncertainty (using GLUE and Bayesian model uncertainty analysis approaches housed in MOUSE) in AgES-W streamflow predictions for the SFW. In addition, the efficacy of the AgES-W and LAMPS linkage (including generated CropScape sequences of dominant land use for each simulation land unit and geospatially- and temporally-referenced LMOD crop rotation and management information input data) will be briefly demonstrated. AgES-W model performance for SFW streamflow was assessed using multiple statistical evaluation criteria including Nash-Sutcliffe efficiency (ENS), root mean square deviation (RMSD), and relative error (PBIAS) coefficients. Comparisons of simulated and observed daily and average monthly streamflow resulted in ENS, RMSD, and PBIAS values that were within the range (or better) of those reported in the literature for other hydrological models at a similar scale and time step. In general, study results indicate that AgES-W reasonably reproduced the hydrological dynamics of the SFW and should serve as a foundation upon which to better quantify additional water assessment and planning indicators at the regional scale. In particular, the topological routing scheme employed by AgES-W is potentially more robust than the quasi-distributed routing schemes used by other watershed-scale environmental models (e.g., SWAT). With a fully distributed routing concept, higher spatial resolution in combination with the lateral transfer of water and chemicals between land units and stream reaches should result in improved H/WQ modeling for mixed-use watersheds such as the SFW.

Keywords: *AgroEcoSystem-Watershed (AgES-W) model, hydrologic modeling, streamflow, flow routing, statistical evaluation*

Estimation of Natural Groundwater Recharge in Qatar Using GIS

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Abstract: Qatar is an arid country with limited water resources. With no surface water and an average annual rainfall of 80 mm per year, Qatar relies on desalination to meet the increasing water demand. As a result of groundwater overexploitation, the water table has dramatically dropped to unprecedented levels and salinity increased, in addition to other adverse environmental impacts.

In the light of Qatar's 2030 National Vision, three grand challenges facing the future of Qatar were identified. One of three main grand challenges is the artificial recharge of groundwater. To understand the water budget and to better manage the precious groundwater resources, it is important to estimate the natural groundwater recharge and its mechanism.

This study is based on historical groundwater level data in combination with topography data and hydraulic parameters to estimate the amount and spatial distribution of natural groundwater recharge. With the help of Geographical Information System (GIS), maps of topography and contour maps of groundwater level and rainfall were prepared. Watershed modelling was done to identify areas of surface water accumulation were recharge is likely to occur. A good match was found between watershed modelling results and historical groundwater data.

Results show groundwater recharge occurs in three areas: two in the northern part of the country and two in the south. In general, the majority of recharge area occurs in the northern part of the country.

Keywords: *Groundwater, GIS, recharge estimation*

Modelling delayed impact of historical land use change on stream flow and salinity in the south-eastern Australia

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Abstract: Clearing of native vegetation for dryland agriculture has increased aquifer recharge, resulting in rising groundwater levels in the south-eastern Australia. Rising groundwater levels have mobilised salt into stream networks contributing to water quality and stream degradation in the Murray River system. Despite the fact that large scale land clearing occurred decades ago, dryland salinity impacts on stream salinity have been gradually increasing over time due to the delayed arrival of salt from various landscapes into the river system. Goulburn Broken dryland region has been identified as one of main dryland salt contributors to the Murray River. This study linked the Catchment Analysis Tool (CAT) Framework, comprising a suite of farming system models, to the catchment scale CATNode model to investigate the magnitude and timing of the delayed impacts of historic land use change on stream flow and salinity in 34 catchments in the region.

The CAT modelling framework was applied to simulate daily soil/water/plant interactions and to estimate monthly time-series of evapotranspiration, runoff, subsurface lateral flow and deep drainage as inputs required by the CATNode model. The CATNode model is a lumped surface-groundwater model designed to model temporal surface and groundwater contributions of water and salt load to stream.

The models were calibrated on a monthly time-step from July 1974 and June 2000 for all gauged catchments in the region. The Nash-Sutcliffe model efficiency (E) and the bias (B) were used to evaluate the performance of the model calibration. Majority of the catchments achieved an E value greater than 0.7 and B value within ± 10% for both flow and salt load. To further assess the integrity of model calibration and sensibleness of the underlying fluxes, the correlation between the time-series of modelled groundwater storage and time-series of observed groundwater levels was also investigated. In general, the modelled groundwater storages reasonably correlated with the observed groundwater levels with R^2 values typically ranging from 0.7 to 0.8. To justify the appropriateness of the model assumption that the hillslope aquifer has an infinite salt store, the ratios of the modelled salt discharge to the modelled salt store in the catchments were examined over the calibration period. It was found that the annual salt discharges were generally very low relative to catchment salt storage (0.01-0.4% of the total catchment salt storage for the 34 catchments).

The calibrated models were run continuously for 200 years from 1900 to 2100 using historic land use up to 1988 and then 1988 land use for the rest of the simulation. Historic climate data was applied for the first 100 years of the simulation (from 1900 to 2000) and the climate data for the period from 1975 to 2000 (defined as MDBA BSMS Benchmark Period) was repeatedly used for each of the next four 25-year cycles (2000-2025, 2025-2050, 2050-2075 and 2075-2100). The modelling results showed that:

- Compared to the Benchmark Period (May 1975 to April 2000), stream flow from the majority of sub-catchments in the Goulburn-Broken upland decreased slightly (less 3%) for the period of 2000-2025 and then remained steady after 2025 until the end of the simulation period in 2100.
- The majority of the sub-catchments had their greatest increase in salt load and salinity for the 2000-2025 period and then continued to increase at gradually reduced rates for the next 75 years to 2100. The magnitudes of the increase in salt load varied significantly from one sub-catchment to another (ranging from less than 1% to approximately 65% over 100 years from 2000 to 2100).

These results suggest that the groundwater flow systems in the majority of the sub-catchments would have reached, or nearly reached, hydraulic equilibrium before 2025. That is, land use change that occurred before 1988 is unlikely to have a noticeable impact on stream flow beyond 2025. However, this historic land use change could have much greater and longer impact on salt load and stream salinity. These findings have significant implications for the development of salinity management strategies for the Murray Darling Basin and in particular the Goulburn Broken region.

Keywords: *Modelling, land use, stream flow, stream salinity, dryland salinity*

EXTENDED ABSTRACT ONLY

Performance of OpenCL implementation of AWRA

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Abstract: The continental calibration of the Australian Water Resource Assessment (AWRA) landscape model for Australian water accounts requires a computationally intensive parameter search. The accounts are based on semi-distributed conceptual models of Australian catchments. These models are populated with parameters that are generated by a metaheuristic approach (Shuffled Complex Evolution) using data from across the continent. The parameter-optimisation algorithms require running thousands of models around 100,000 times. The gridded calibration system uses significant resources of CSIRO supercomputer, Bragg, to conduct experiments. Each experiment can take approximately 10 days of processing on 20 nodes.

The aim of the analysis was to determine if an OpenCL implementation would improve calibration performance compared to the existing C# MPI implementation. The method for understanding the performance involved: 1) benchmarking a simple OpenCL model to assess model performance (in a custom test rig); 2) refactoring existing implementation to conform to OpenCL "structure of arrays" model; and 3) retesting performance in a larger system.

The result of the simple OpenCL benchmark model was up to a 2x speedup relative to the C#/MPI implementation. However, the performance speedup was not replicated when incorporated in the full MPI system. This was attributed to several factors including a) the embarrassingly parallel nature of the original model, which was reasonably well tuned; b) the use of OpenCL constrained the number of MPI worker processes that can be used on a compute node; c) C# array size limitations limited the number of grid cells that could be assigned to a single GPU device, leading to low occupancy; and d) the complexity and difficulty further tuning the OpenCL implementation. Although adoption of the OpenCL calibration was not recommended, future improvements to the infrastructure, or renewed effort improving the implementation may lead to a faster implementation.

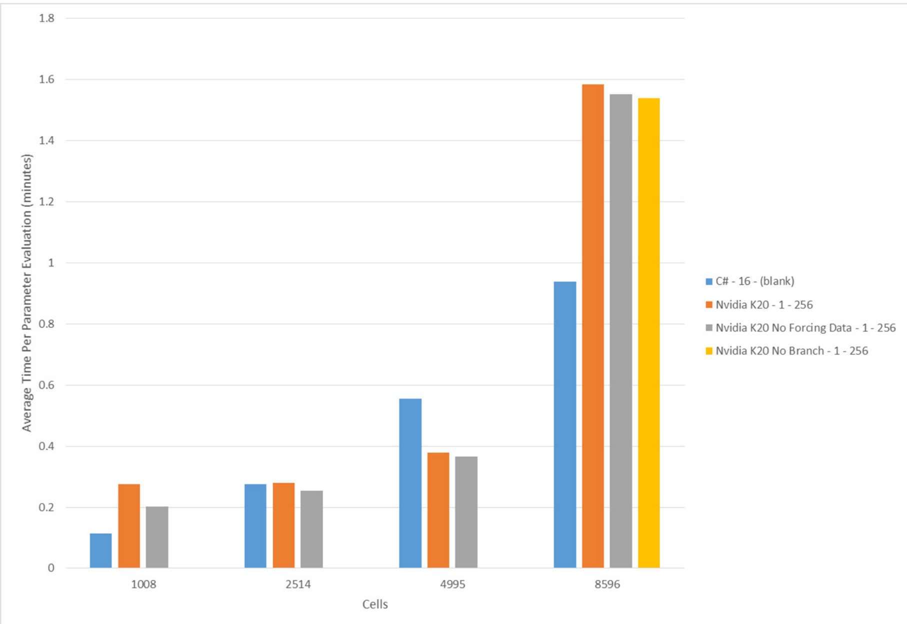

Figure 1. The performance of several OpenCL implementations of the AWRA-L model did not reduce the average time per parameter evaluation for large number of AWRA-L cells.

Keywords: *AWRA, OpenCL, high performance computing*

Blending field observations and AWRA outputs to estimate groundwater recharge in the Clarence-Moreton basin, eastern Australia

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Abstract: Groundwater recharge is one of the hardest components of the water balance to estimate, largely because it cannot be directly measured. The Landscape component of the Australian Water Resources Assessment model (AWRA-L), has been shown to have the capacity to reproduce the temporal trends of groundwater recharge when compared to time series of field data at a limited number of locations. However, it cannot reproduce the heterogeneity in long term average recharge at a local scale. Many of our field techniques for estimating recharge can only produce a long term average recharge rate and provide no information on temporal variations. Blending the long term average recharge estimates from field observations with the continuous daily output of the AWRA-L model allow us to create a time series of recharge that honours the long term average of field observations whilst imposing the modelled temporal patterns.

The Clarence-Morton Basin straddles the Qld-NSW border east of the Great Dividing Range and is one of the regions currently being studied as part of the Bioregional Assessments Programme. The majority of the basin has had limited investigations of its groundwater recharge processes with no knowledge of the long term average recharge rates and their inter-annual variabilities. Upon adoption of the chloride mass balance method for estimating recharge, 374 point estimates of recharge were obtained for this basin. These were subsequently used to create regression equations between the average annual recharge and the average annual rainfall for each of the surface geology types in the basin; this enabled those point estimates to be upscaled to the basin scale. The temporal pattern from AWRA-L was then imposed for each grid cell in the landscape to create a annual time series of recharge across the entire basin.

The results of this investigation showed that the Walloon Coal Measures had the lowest annual average recharge rate (for a given rainfall) and the tertiary volcanics had the highest. The temporal trends in recharge from AWRA-L were similar between surface geology types with wet years having above average recharge and dry years having below average recharge. These results form an essential input into the numerical groundwater model used to investigate the impact of coal seam gas extraction upon water dependent assets in the Richmond River catchment, NSW.

Keywords: *AWRA, recharge, WIRADA, bioregional assessments*

Water Accounting for sustainable water resources management – role of hydrological modelling

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Abstract: With increasing competition for finite and often scarce water resources, water information is critical for the water reform process. Water accounting, a systematic approach of organising and presenting water information relating to the physical volumes of water and how water resources are being used, provides a unique tool for integrated water resources management as well as for economic analysis of water issues. Due to limitation of available data and information at suitable spatial and temporal resolutions, it is difficult to produce water accounts in a consistent and systematic way in most of the river basins around the world. Hydrological models, if designed and implemented appropriately, can play a significant role in producing consistent and standardised water accounts complementing observed data and information. CSIRO and the Bureau of Meteorology of Australia have developed a hydrological river system model called "AWRA-R" for producing Australia's national water accounts. AWRA-R includes all the key hydrological processes and anthropogenic water utilisation that are required for producing different fluxes and stores for water accounting. The model is flexible enough to be able to use all available data sources (when modelling data rich and data limited regions) to provide nationally consistent and robust estimates. This paper describes the AWRA-R model and its calibration, validation, and application in the Murray-Darling Basin, Australia for producing various fluxes and stores required for water accounting in the basin.

Keywords: *AWRA, water resources assessment, landscape modelling, river system modelling, hydrological modelling*

Evaluation of AWRA-L: the Australian Water Resource Assessment model

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Abstract: The Australian Water Resource Assessment Modelling System (AWRAMS) provides nationally consistent water balance estimates at a national to regional scale for the past and present using observations where available, and modelling otherwise. The AWRA Landscape model, AWRA-L, is a 0.05° (~5km) gridded soil and groundwater balance model which provides credible estimates of landscape water yield (runoff and baseflow), evapotranspiration, soil moisture, and aquifer recharge across Australia, for retrospective Water Resource Assessment, National Water Account and soil moisture monitoring purposes. This paper evaluates and compares the hydrologic performance of various versions of the AWRA-L model with a national water balance model (WaterDyn) and a global biogeochemical land surface scheme (CABLE), applied regionally. The versions of AWRA-L evaluated are: (a) v4.5 nationally calibrated to streamflow, (b) v5.0 including updated soil drainage properties, nationally calibrated to streamflow *and* satellite evapotranspiration (CMRSET) and soil moisture (AMSR-E); and (c) v5.0 also calibrated according to eight separate regions to fit local conditions better. The models were compared against catchment streamflow, point estimates of flux tower derived evapotranspiration across Australia, and point estimates of 0-90cm profile soil moisture over the Murrumbidgee and Upper Hunter Catchments (see Figure 1). Satellite derived estimates of evapotranspiration (CMRSET, SLST) and soil moisture (AMSR-E, ASCAT) are also presented for comparison purposes.

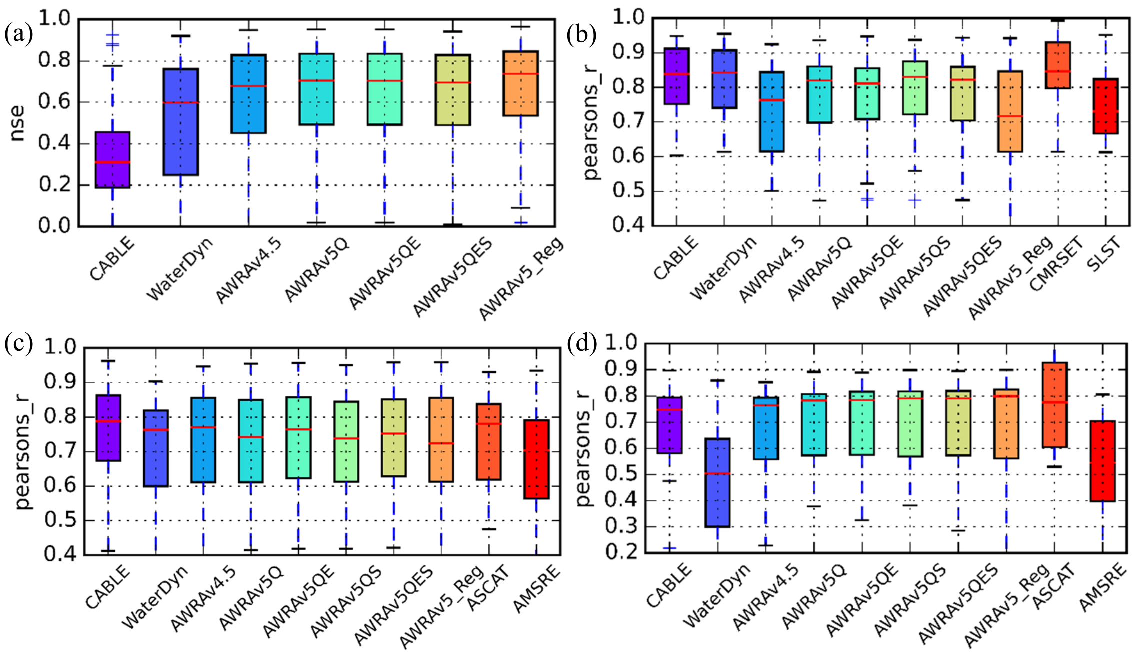

Figure 1. Comparison of CABLE, WaterDyn, AWRA-L (various versions) against monthly (a) streamflow (Nash-Sutcliffe efficiency over 291 catchments), (b) flux tower derived estimates of evapotranspiration (correlation), and 0-90cm profile soil moisture (correlation) from the (c) Murrumbidgee and (d) Upper Hunter.

AWRA-L reproduces streamflow relatively well over the 291 catchments reserved for validation. For ET, CABLE/WaterDyn are better than AWRA-L. AWRA-L/CABLE perform similarly for profile soil moisture, with WaterDyn worse. Regional AWRA-L calibration performs best for streamflow, but worse for soil moisture and ET. Performance of each of the models is explainable according to their design and data used in calibration. AWRA-L v5.0 (using streamflow, ET and soil moisture in calibration) is currently chosen for operational use in the Bureau of Meteorology due to its superior performance across the variables of interest.

Keywords: *Water resource assessment, soil moisture, runoff, evapotranspiration, validation*

Skill Assessment of a Suite of Catchment, Estuarine and Coastal Models of the Southeast Queensland Region

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Abstract: A suite of 8 catchment, three-dimensional hydrodynamic, and water quality models of Moreton Bay and associated estuaries were developed as decision-making tools for environmental managers in the South East Queensland region. The 8 distinct model domains are Moreton Bay, Pumicestone Passage, the estuaries of the Maroochy, Mooloolah, Caboolture, Pine, Brisbane and Logan (including Albert) rivers. The modelling framework utilised Source as the catchment model, TUFLOW FV as the hydrodynamic model and AED as the water quality model, which have all previously been used in applications of this type. The system was developed to allow all models to be run independently or to be dynamically linked in various configurations to provide larger models of particular areas of interest (e.g. to examine northern Moreton Bay a manager might link the Pumicestone Passage, Moreton Bay Pine & Caboolture models).

There are a large number of potential users within the region including local councils, state government, water utilities and community groups, and the models must demonstrate skill to be accepted as decision-making tools by the community. To this end, the models were subject to a comprehensive calibration process, which included comparisons against catchment hydrology, estuarine flow, water level and water quality observations. Following calibration, an independent panel of experts reviewed the results.

Environmental managers must have confidence that any decision-making tool developed on their behalf is fit for purpose, and must also understand any limitations the tool may have. While expert peer review is desirable in assessing a particular model, it may not be feasible or cost-effective. In these instances, an objective, statistical measure of model skill would assist managers in determining if their model is as skilful as comparable models within the scientific literature. In an attempt to provide such a benchmark, Arhonditsis & Brett (2004) provided a synthesis of reported r^2 and relative error statistics for a range of water quality variables from 153 papers comparing aquatic biogeochemical model results against observation. They found that the models were most skilful in predicting temperature and dissolved oxygen, nutrients and phytoplankton had intermediate predictability, while bacteria and zooplankton were poorly predicted. The authors note that modellers are unlikely to report unfavourable statistics so there may be a positive bias in these results. To address the positive bias, a number of marine biogeochemical modellers (Stow et al [2009]) described a list of 5 univariate statistics that should be reported with any hydrodynamic and water quality modelling paper subsequently published by the community: r^2, root mean square error, average absolute error, average error & modelling efficiency. The presentation will cover in detail the models developed, and presents this suite of statistics for temperature, salinity, total nitrogen, total phosphorus, chlorophyll *a* and dissolved oxygen, alongside commentary on the suitability or otherwise of the model for use by environmental managers.

Observations are provided by an ecosystem-health monitoring programme (EHMP), which has been operating within the region since 2001. The EHMP takes samples at a number of sites within a given estuary, which allows for both a time-series comparison at a given site and a spatial comparison of annual medians along the thalweg. Univariate measures comparing predictions and observations both spatially and temporally are presented for the period 1st July 2014 to 30th June 2015. Additionally, comparisons are presented of catchment model results against relevant flow gauges, and hydrodynamic model results against observed ADCP transects and water levels.

The models presented will continue to be developed, improved and provided with up-to-date forcing by the authors, and additional models within the region are under development. It is hoped that ongoing reporting of the same suite of statistics will assist environment managers in assessing the relative skill of any other hydrodynamic and water quality modelling tools they may use, and encourage other modellers to report the same to add to the body of literature.

Keywords: *Model skill, hydrodynamic modelling, water quality modelling, Southeast Queensland*

Whole of system calibration of river models: Weighting functions and their effect on individual gauge and system performance

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Abstract: A recently developed method for parameter optimisation in river system models has shown potential to reduce over-fitting and improve gauge goodness of fit. This method optimises parameters across all gauges in the river system simultaneously. Optimisation requires a goodness of fit measure that aggregates performance across available gauges within the river system. To enable this, a weighting function has been used in previous studies. However the effect of the weighting function on individual gauge goodness of fit, parameter values and system states is unknown. System optimisation may have particular benefits for river models used for predictive purposes and scenario evaluations, and the effect of weighting methods needs to be assessed with these purposes in mind. The Murrumbidgee catchment in NSW was used as a test region to calibrate the AWRA-R river system model with various weighting functions. These weightings were; 1) Equal to all gauges, 2) by the length of the observed record and 3) by the sum of observed flows. In the lower reaches of the river system, weighting based on flow was lower than even weighting, since flow became progressively lower towards the downstream extremities of the study area. Goodness of fit was improved via even weighting relative to flow weighting in the lower gauges (at the expense of upper gauge fit). Model states show limited variability between weighting methods suggesting that the weighting scheme has less influence than the mode of calibration i.e., reach–by–reach or system.

Keywords: *River system model, system optimisation, model state, weighting function, AWRA-R*

Why do sub-period consistency calibrations outperform traditional optimisations in streamflow prediction?

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Abstract: A previous study showed that a calibration method that utilises the distribution of sub-period performances routinely performs better for prediction than traditional optimisations. Kim et al. (Determining probability distributions of parameter performances for time-series model calibration: a river system trial, *Journal of Hydrology*, in press) describes a new method that uses sub-period resampling to estimate probability distributions of performance for different parameter sets (Figure 1). The method is designed to identify more time-consistent (and therefore more robust) parameterisations than the traditional split-sampling optimal parameterisations. However, the underlying reasons for the superior performance are not fully understood. Several hypotheses have been proposed but as yet none have been properly verified. There are two key steps of the sub-period consistency calibration which are thought to be important for better predictions: (1) the sampling of sub-period performances; and (2) using the distribution of performances to formulate a weighted score of predictive capability. It is assumed that the sub-period consistency calibration returns parameterisations that spread consistent-sized errors throughout the calibration period. The calibrations are therefore not over-influenced by rare periods of good fit. Subsequently, they do not contain as many periods of poor fit and are less susceptible to over-fitting. Also, consistently performing parameterisations might fit to more frequent flow regimes, which might help gain better validation performances if calibration and validation periods have similar hydrological characteristics. This paper aims to investigate which factor is more important for improved predictions. Different sub-period sampling lengths are tested to see whether this makes an impact on the performance of the method and whether this is related to cyclical patterns in the residual error time-series examined in Fourier transform analyses. Three hydrological models are used in the study: AWRA-R, GR4J and Sacramento. Each model is tested using data from about 80 river gauging sites across Australia.

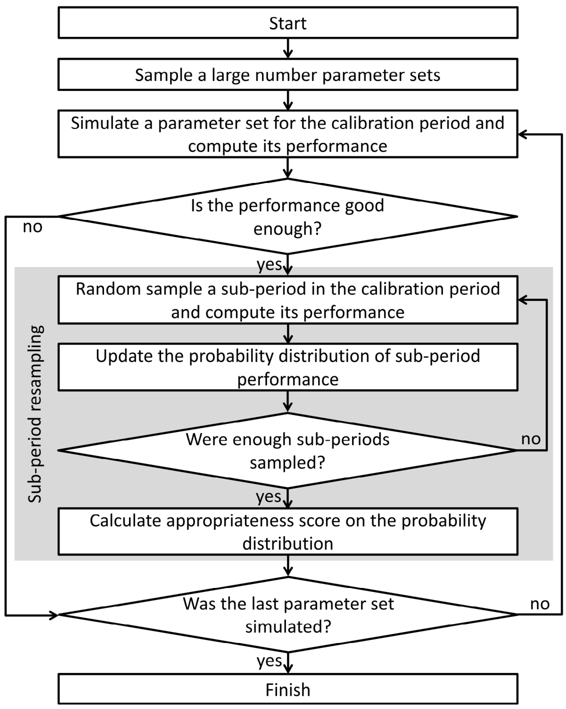

Figure 1. Flowchart of the sub-period consistency calibration method.

Keywords: *Sub-period, consistency, calibration, prediction, validation, time-series modelling*

Variation of the Nash-Sutcliffe coefficient with sample frequency

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Abstract: The Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) is used in hydrology to measure the similarity between model simulated and observed data. It is known that the NSE varies with sample frequency (daily, weekly …) and that this leads to a variable fit to the data according to the calculation time step used. There is a general view that NSE normally increases with data aggregation (e.g., higher values for monthly compared to daily NSE for any given time series) but the evolution of the NSE with the time step is not really clear yet. This study attempts to find out if there is a trend in the evolution of the NSE linked to the time steps. This study uses observed and model calibrated/simulated streamflow time series for 295 unregulated upland catchments spread across Australia. The observed data has been quality checked and the regional calibration across the 295 catchments using AWRA-L model (Vaze et al., 2013) had an overall NSE of 0.5. Detailed information about catchment characteristics and climatic variables are also available for each of the catchments. For each of the catchments, the observed and model simulated daily runoff time series were accumulated over 2, 3, 4, 5, 6 days as well as 1, 2, 3, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48 weeks and one year. This provided a total of 22 runoff time series with decreasing sample length (from 14065 to 6). This aggregation over longer time scales was undertaken with the starting date of 1 January and 1 July to investigate whether runoff seasonality plays any role in the NSE evolution.

For each catchment and for each of the 22 runoff time series for each catchment, NSE was calculated and the 295 catchments were sorted based on their daily NSE values (> 0.7, 0.6 < NSE < 0.7, …). For all the catchments within a daily NSE band, the NSE values at different temporal scales were plotted (y-axis) against the temporal scale at which the daily data has been aggregated (x-axis) to investigate NSE evolution with sample frequency. Figure 1 shows the NSE evolution with temporal aggregation of runoff time series for the top NSE band of > 0.7 for (a) 1 January start and (b) 1 July start. A median NSE for each of the temporal aggregation time scales NSE values was calculated and a trend line was fitted through these median NSE estimates (see Figure 1) to visualize the time evolution. The results indicate that the aggregation start date (seasonality) has no impact on the NSE values and the overall trend of the NSE evolution remains the same irrespective of the start date. The results also show that the overall trend of NSE evolution with temporal aggregation of the runoff time series is similar for all the catchments. There is a steady increase in the NSE as we aggregate from 1 day to about 12 weeks after which there is a steady decline but with the NSE values mostly staying above the daily NSE.

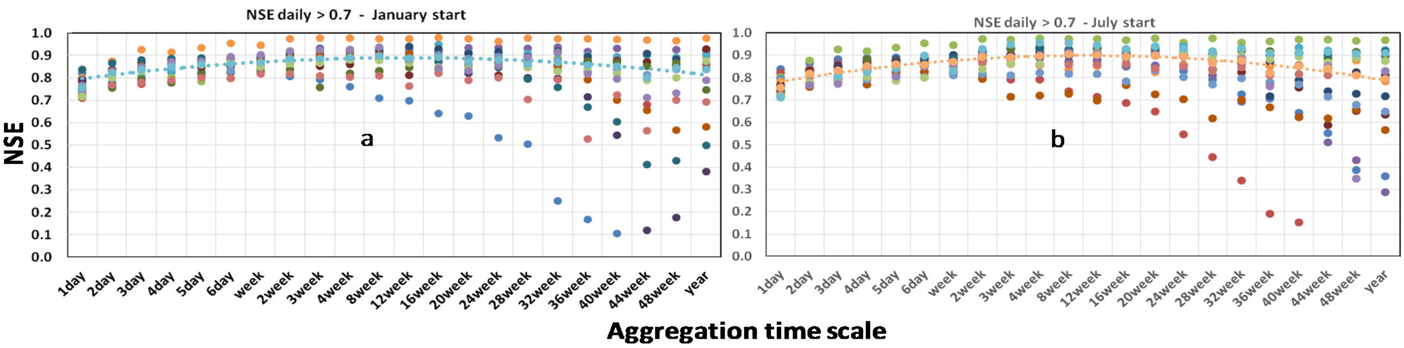

Figure 1. NSE evolution with temporal aggregation of runoff time series.

Keywords: *Nash-Sutcliffe efficiency, hydrological modelling, AWRA*

AWRA-L: global sensitivity analysis to guide future model development and parameterisation

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Abstract: The parameterisation and conceptualisation of the landscape component of AWRA-L is quite complex with a large number of parameters and often non-linear thresholds and feedback mechanisms to allow the simulation of all fluxes and stores of the water balance over the Australian continent. An expertly chosen objective function ensures that during calibration a parameter set is found that is an optimal compromise to populate water accounts and provide daily estimates of runoff at a regional scale.

While the calibration gives confidence in the model's ability to hind –and forecast, the calibration process provides little information to guide future model development and calibration. Through a comprehensive, global sensitivity analysis the effect of each parameter on prediction different fluxes and stores can be evaluated, which results in a much more targeted future development plan.

In the sensitivity analysis, 10.000 parameter combinations of 40 parameters are evaluated with AWRA-L 4.0 to generate daily historical runoff and deep drainage timeseries for 305 catchments throughout Australia from 1980 to 2010. While not all of these parameters directly affect runoff or deep drainage, the various non-linearities and interaction terms in the AWRA model make that all of the parameters have to potential to affect the runoff and deep drainage predictions.

Robust, density-based sensitivity indices for all parameter-catchment combinations for Nash-Sutcliffe efficiency, bias, mean deep drainage and selected percentiles of the flow duration curve are calculated. The parameters controlling the low flow component of the hydrograph consistently, across all catchments and output summary statistics, appeared the most important. A notable exception are the high flow percentiles of the flow duration curve that are most affected by the parameters controlling the split between storm runoff and infiltration.

Keywords: *Large scale water resource assessment, sensitivity analysis, Australia*

Evaluating water balance storage and flux estimates from the operational Australian Water Resource Assessment Landscape Model at a Catchment Scale

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Abstract: The Australian Water Resource Assessment Modelling System (AWRAMS) is being developed by CSIRO and the Bureau of Meteorology through the Water Information Research and Development Alliance (WIRADA). AWRAMS provides seamless Australia-wide water balance information and data for past and present, using observations where available, and modelling otherwise. It is a new integrated hydrological simulation system with two model components, representing water balance processes for landscapes and regulated rivers. The continental scale AWRA Landscape model (AWRA-L) has undergone many years of research and development, and has been operational at the Bureau of Meteorology since 2011.

In this study we evaluate AWRA-L over the period 1/1/02-31/12/11 for its ability to represent major state and flux quantities of the overall terrestrial water cycle at a catchment scale. The focus is on the 600km^2 Kyeamba Creek Catchment, within the Murrumbidgee River Catchment, in temperate southeastern Australia. This is an ideal test-bed for AWRA-L evaluation given the availability of multi-year independent hydrological datasets from a network of monitoring stations, in addition to relevant remotely sensed data. Evaluations are performed for AWRA-L v4.5 predictions of surface runoff, evapotranspiration (ET) and soil moisture. This is a primae facie study aimed at getting an overview of the model performance for multiple major components of the water balance simultaneously, with performance evaluated using daily statistics.

The AWRA-L model runs on a 0.05° (~5km) grid with a daily time step. The landscape is represented as two hydrological response units (deep and shallow rooted vegetation) within each model grid cell. AWRA-L v4.5 is calibrated (over the period 1/1/81-31/12/11) simultaneously to streamflow at 295 unimpaired catchments distributed across Australia, with one set of (21) parameters used throughout the Australian continent. This is referred to as a global calibration of AWRA-L. In this study the AWRA-L v4.5 model was also calibrated locally to streamflow from the Ladysmith and Book Book stream gauges in the Kyeamba Creek Catchment, with Book Book a 145km^2 subcatchment of the 545km^2 Ladysmith Catchment. The calibration to streamflow at Ladysmith covers 1/1/70-31/12/84, with the calibration to streamflow at Book Book for 1/1/86-31/12/00. The streamflow at Ladysmith has a data gap from 1987-2000, while the streamflow observations at Book Book commence in the year 1985. The remotely sensed CMRSET product was used to generate catchment average actual ET to Book Book and Ladysmith. Soil moisture observations to 90cm (measured with probes covering 0-30cm, 30-60cm and 60-90cm depth) were used to create catchment average soil moisture to Book Book and Ladysmith, with six soil moisture sites averaged to Book Book and twelve to Ladysmith. The ET, soil moisture, and streamflow observations cover the period 1/1/02-31/12/11, i.e. the evaluation period.

While the model is globally calibrated to streamflow, correlation with ET is good (0.72 at Book Book and 0.68 at Ladysmith). Correlation to streamflow at these sites is even better (0.77 at Book Book and 0.87 at Ladysmith), with NSE fair (0.47 at Book Book and 0.59 at Ladysmith). When calibrated locally to streamflow correlation with streamflow (and NSE) improves at Book Book to 0.83 (and 0.68) and Ladysmith 0.87 (and 0.72). Impressively, when calibrating locally to streamflow, correlation with ET also improves (to 0.75 for Book Book and 0.73 for Ladysmith). More impressive is that the correlation with catchment average soil moisture to Book Book or Ladysmith is extremely high at 0.96 or 0.97 respectively when using the default parameters from the global calibration, and remains high (0.95 for Book Book and 0.97 for Ladysmith) when the model is calibrated locally to streamflow. This indicates that AWRA-L can accurately simulate multiple water balance storage and flux estimates based on calibration to streamflow alone, and while performance is slightly improved when calibrating to local catchment streamflow, the default parameters in the operational AWRAMS result in very good estimates of the key water balance storage and flux variables at a catchment scale. The results provide valuable information for directing future model development towards better water balance representation across catchments in other parts of Australia.

Keywords: *AWRA, operational, AWRAMS, AWRA-L, WIRADA*

Long-term trends in the annual groundwater recharge estimates using the water table fluctuation method

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Abstract: Groundwater recharge is critical for sustainable water resource planning and modelling fluid and contaminant transport within the subsurface. Unfortunately, direct groundwater measurements are often too short to investigate long-term trends for many regions in Australia. Over the past, a number of methods have been developed to estimate groundwater recharge over different temporal and spatial scales. Among the most widely used techniques for estimating recharge, the water table fluctuation (WTF) method has been applied in numerous studies. In this study, we use the WTF method to estimate annual groundwater recharge at 438 groundwater monitoring bores in South Australia and analyse long-term annual groundwater recharge trends using the nonparametric Mann-Kendall trend test. The results indicate that the spatially averaged annual groundwater recharge has declined significantly with a trend of -0.92 mm/year for the period 1970-2012. Similar trend tests for the 237 groundwater monitoring bores with longer data records exhibit that 161 bores have downward trends of which 103 bores are statistically significant, whereas 44 bores have upward trends and 15 of them are statistically significant. Moreover, a linear extrapolation of annual groundwater recharge trend suggests that the mean will reach the lowest recorded annual recharge in history (2006 drought) by 2058 if the recent climatic trends continue over a longer period, indicating a potential threat to the hydrological and ecological regimes. Furthermore, the correlation analysis demonstrates that the dominating downward trends in annual groundwater recharge are affected by the large-scale hydroclimate variables (e.g. rainfall) in South Australia.

Keywords: *Annual groundwater recharge, water table fluctuation method, Mann-Kendall trend test*

Estimating the water and heat budget as an indicator for water resources management using an integrated watershed modeling tool

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Abstract: A water resources management considering not only water but also heat has become a crucial issue due to limited availability of water resources, increasing water contaminations and ground source heat utilizations. Indicators are useful to manage water resources. Water budget and Heat budget can be one of the major indicators for sustainable water resources management because detecting the disequilibrium of these budgets at an early stage makes it possible to implement effective measures.

However, many components required to estimate these budgets in a domain that include the surface and the subsurface are difficult to measure directly, for instance, the water and heat transported by recharge, and the groundwater discharge in a regional watershed scale.

An integrated watershed modeling technique allows to represent seamlessly the mass and heat transport behaviors from the surface to the underground in arbitrary temporal and spatial scales. Moreover, a spatiotemporal water flow behavior can be expressed without any explicit conditions for routing the paths of water movement. Therefore, this kind of modeling technique becomes efficient tool to estimate the components of these budgets.

First, the framework for estimating these budgets using an integrated watershed modeling tool is proposed in this study as follows:

- Collecting available data such as meteorology/ocean conditions, land use/land cover, topography, soil/geology, water use/heat utilization and monitoring data
- Associating these data with model parameters like porosity, heat conductivity and rainfall conditions
- Model construction by assigning parameters to each discretized mesh and calibration through comparison with monitoring data
- Estimating the water and heat budget

Then, the water and heat budget components which are classified into inflow and outflow for the surface and the subsurface domains are described. Additionally, the following applications to estimating the components of the water and heat budget using actual watershed models in various scales are presented briefly:

- Estimation of the recharge rate of whole Japan using a national-scale watershed model
- Water budget estimation using regional-scale watershed models
- Feasibility study of ground source heat utilization in a local-scale urban area

In order to perform the water and heat budget estimations more rapidly and with minimal cost, the authors are challenging the development of new data models updated continuously and re-used efficiently. The challenge in this domain is to provide information immediately to help the decision-making for watershed management.

Keywords: *Aater and heat budget, indicator, water resources management, integrated watershed modeling, GETFLOWS*

INVITED PAPER

EXTENDED ABSTRACT ONLY

An integrated continental hydrological modelling system – AWRA

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Abstract: The Australian Water Resource Assessment (AWRA) modelling system is developed to enable the Australian Bureau of Meteorology to meet its legislated role in providing an annual National Water Account (NWA) and regular Australian Water Resource Assessment Reports. The system uses available observations and an integrated landscape – river water balance model to estimate the stores and fluxes of the water balance required for reporting purposes (Figure 1). The National Landscape model (AWRA-L) provides gridded estimates of landscape runoff, evapotranspiration, soil moisture, and groundwater recharge/storage/lateral flow, and has been calibrated towards reproduction of a nationwide streamflow dataset. The gridded model structure provides an option of incorporating spatial variability of climate, land cover and soil properties. The model can be constrained only against observed streamflow or a combination of streamflow and remotely sensed soil moisture and evapotranspiration. The water balance fluxes from AWRA-L are used as inputs to the regulated river system model (AWRA-R) to undertake basin scale water balance modelling. The AWRA-R model includes river routing, irrigation diversions, reservoir storage, floodplain inundation and river to groundwater interaction components. All the AWRA modelling components are built within a software architecture which allows seamless interactions between the components at the appropriate spatial and temporal scales. The AWRA modelling system has been implemented across Australia and it provides estimates of water balance fluxes and stores which are substantially better than those from continental scale land surface models and similar to or better than those from widely used conceptual rainfall-runoff models. The system is currently being used for hydrological modelling in a number of large scale projects. The AWRA modelling system provides consistent, robust and repeatable water assessments at catchment, regional and continental scale which can be used to guide future water planning and policy development as well as water resources development across Australia and globally.

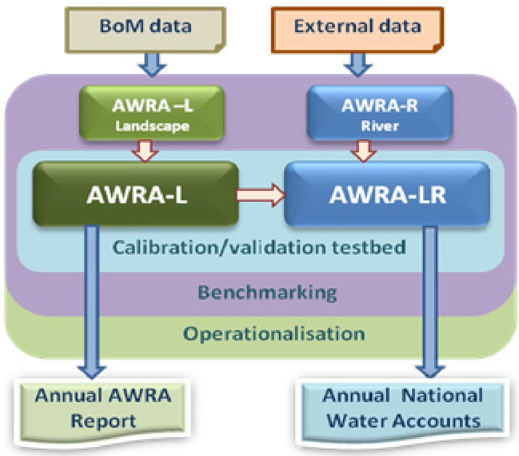

Figure 1. The AWRA modelling system. Where, AWRA-L: AWRA-Landscape model; AWRA-R: AWRA-River model; AWRA-LR: AWRA Integrated Regulated river system model.

Keywords: *AWRA, WIRADA, landscape hydrological modelling, river system modelling*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Large-scale regionalisation of the hydrological model AWRA-L for predicting impacts of coal resource development

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Abstract: The Bioregional Assessment (BA) program is being undertaken to assess the potential impacts of coal seam gas and large coal mining developments on water resources and water-related assets. The aim of the surface water modelling in bioregional assessments is to provide information on flow characteristics at locations in the stream networks that are relevant for key assets and receptors. In particular, the modelling needs to account for changes in flow regime that relate directly to the impacts of future coal developments.

Whilst observed streamflow data is available in some catchments for model calibration, there is a clear requirement for prediction in ungauged parts of the modelling domains. Furthermore, in order to provide estimates of the cumulative impacts of multiple developments on downstream flow conditions, a consistent and spatially coherent method of parameter regionalisation is desirable.

This requirement argues strongly in favour of a regional calibration approach, in preference to an alternative approach like nearest-neighbour regionalisation. Nearest-neighbour regionalisation involves using parameter values from a gauged catchment that is considered to share similar characteristics (climate, soils, vegetation, etc.) to the ungauged area. Often, it is found that the simple expedient of using parameters from the nearest gauged catchment is among the best regionalisation methods. Implicit in this nearest-neighbour approach is the assumption that catchments in close proximity are likely to share similar physical and hydrological characteristics and that therefore, optimal models of each of them will also share similar parameter values. However, there is a significant degradation in model performance with this type of regionalisation as regionalisation distance increases. Its prediction performance can also be unduly dominated by locally anomalous calibration catchments.

In contrast, a regional calibration approach involves simultaneous calibration of a model using observations from several nearby gauging stations. In this approach, the calibration procedure uses a single objective function that combines the prediction responses in all gauged catchments and results in a single set of model parameter values that provide best fit to the streamflow observations from all gauges. The key assumption is that if a single set of parameter values provides good predictions in the gauged catchments it might also be expected to provide good predictions in adjacent ungauged areas. Unlike nearest-neighbour calibration, the performance of regionally calibrated models does not degrade with distance from the calibration catchments.

The landscape model AWRA-L has been adopted for use in BA. Its key characteristic that makes it amenable for the type of large scale modelling that the BA program demands is that it is designed to provide spatially heterogeneous predictions of streamflow generation through its dependence on spatially explicit input of vegetation density, soil characteristics and climate. This means that it is particularly well suited to regional calibration.

This paper discusses the use of the large-scale regionalisation capabilities of the hydrological model AWRA-L for predicting streamflows in the BA program, together with the model's strengths and limitations for this purpose. Calibration against observed streamflows at a number of stream gauging locations within and near the modelling domain is employed to yield a single set of model parameters that are assumed to apply throughout the domain. This regionalisation method is also shown to provide estimates of the degree of uncertainty in the deterministic model predictions in both gauged and ungauged catchments. Finally, a Monte Carlo sampling approach is used to assess uncertainty in the impacts of coal resource development.

Keywords: *Streamflow modelling, regionalisation, AWRA-L, coal mining, CSG extraction*

Comparison of Modelled Groundwater Recharge – Australian Water Resources Assessment Model versus BioSim

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Abstract: The Bureau and CSIRO formed the Water Information Research and Development Alliance (WIRADA) initiative to develop the Australian Water Resources Assessment modelling system (AWRA MS). The paper compares the modelled recharge between AWRA-L version 4.5, the landscape component of AWRA MS with biophysical modelling toolbox, BioSim, of the EnSym modelling system. EnSym was developed by the Victorian Government Department of Environment, Land, Water and Planning. Both models are daily gridded-based (5x5km^2 for AWRA-L and 200x200m^2 for BioSim) biophysical models of the water balance between the atmosphere, soil, groundwater and surface water stores. The two models adopt different model conceptualisations. BioSim models recharge taking into account both rainfall and irrigation, while AWRA-L does not model irrigation processes due to coarse resolution. The model outputs for recharge are presented for the Port Phillip and Westernport region in Victoria over the period from 1991 to 2005.

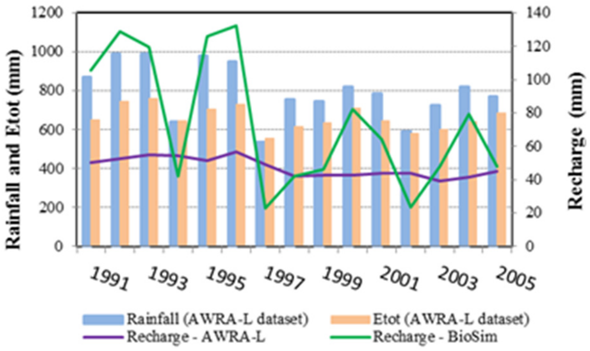

Figure 1. Time series of annual average rainfall, total evapotranspiration (Etot), modelled recharge and deep drainage.

Figure 1 shows the time series of annual average rainfall, total actual evapotranspiration and modelled recharge. The annual BioSim recharge ranges from 4% to 14% of the annual rainfall whereas the AWRA-L recharge ranges from 5% to 9% of annual rainfall. The mean of annual recharge from BioSim is 9% of the mean annual rainfall while the mean AWRA-L recharge is 6% of the mean annual rainfall. The commonly used long-term recharge to rainfall ratio is around 10%. In terms of year to year variation, the annual average variation of recharge for BioSim is 25% and for AWRA-L, it is 2% of the annual average variation of rainfall.

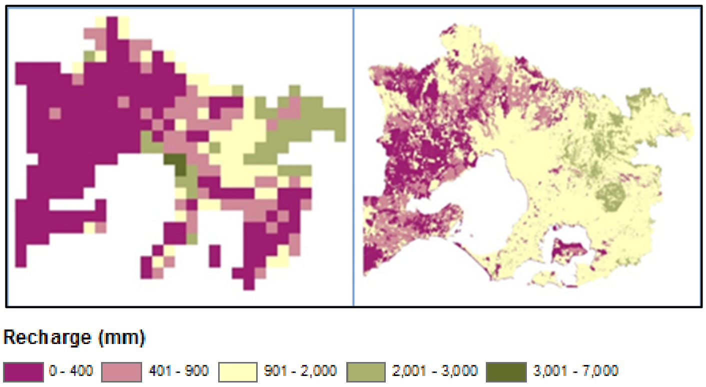

Figure 2. Spatial distribution of total recharge (mm) for the period 1991 – 2005: AWRA –L and BioSim, respectively.

The study results indicate differences in the spatial distribution pattern of the modelled recharge as shown in Figure 2. The differences in the model input parameters such as soil, vegetation and more importantly the model conceptualisations are likely to explain the differences observed between the modelled recharge. The effect of irrigation recharge included in BioSim is considered small. This study will be continued further with the comparison against modelled recharge from other similar models such as WAVES.

Keywords: *Groundwater, recharge, AWRA, BioSim*

A Holistic Approach to Rainfall Estimation for Operational Water Management

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Abstract: Natural hazards impinge on the ability of developing countries and countries that depend on climate reliant industries to grow socioeconomically. Fourteen of the twenty-five mega-cities are located in coastal regions and are thus more exposed to natural hazards. An increase in knowledge and understanding of how precipitation events that cause floods form and affect society can only lead to more prepared and resilient communities.

Significant social and economic savings can be realized by improved planning, preparedness and resilience measures. Flood forecasting is one such measure. However, the accuracy and precision of flood forecasts are highly dependent upon the quality of rainfall estimates generated by Quantitative Precipitation Forecasts (QPF). Therefore, this project focuses on improving flood forecasts by attaining a greater understanding of rainfall and its uncertainty and thus being able to add skill to QPFs.

Traditionally, rain is measured in-situ by rain gauges or remotely sensed via weather radar. Both methods have their advantages and disadvantages. However, studies attempting to retrieve rainfall and characterize the associated uncertainty from hydrologic models using streamflow observations have not been able to do so adequately. No studies have been conducted that attempt to retrieve "realistic rainfall distributions" from a model.

This project explores the possibility of retrieving realistic rainfall distributions from various hydrologic models and its possible uses. Since there has been no consensus amongst hydrologists on a methodology to estimate areal rainfall for input into rainfall-runoff models to date, it is necessary to first define a "realistic rainfall distribution" as being all possibilities of rainfall, that, when compared too other models, lead to accurate simulations.

The impact that model structural error, calibration methodology, uncertainty of observations, and the mathematical equations used to represent rainfall has on rainfall retrievals will be analyzed.

In order to obtain a "realistic rainfall distribution" it is necessary to describe rainfall as a function. Numerous functions have been assessed based on their ability to reconstruct rainfall over a ten year period for the 438 basins in the Model Parameter Estimation Experiment (MOPEX) data set. The metric used for comparison was the number of coefficients used to reconstruct rainfall against their resulting Normalized Root Mean Square Error (NRMSE).

Once a function to describe rainfall was chosen, both a synthetic study and a case study were conducted in which function variables were calibrated to obtain a posterior rainfall distribution using the Differential Evolution Adaptive Metropolis (DREAM) algorithm. Multiple hydrological models were used to eliminate any model structural uncertainty that was unique to an individual model.

By obtaining an initial estimate of rainfall and its uncertainty using mathematical functions, this research has potential for further exploration. Possible areas of further research involve, regionalization studies, reconstruction of rainfall in poorly gauged basins, and calibration of Numerical Weather Predictions (NWPs). With an increasing availability of good quality remotely sensed and in-situ data, it is also expected that an increased understanding of rainfall and the treatment of rainfall as probability distribution will be a step towards realistic calibration and validation of hydrologic model parameters, remotely sensed observations, QPFs and gauge based rainfall.

Keywords: *Rainfall, uncertainty, flood, forecast, inversion*

Development of a parallel computing enabled optimisation tool for hydrological model calibration

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Abstract: A river model is a semi-distributed hydrological model and it includes many processes such as flow routing, irrigation diversion, overbank flow, ground water interaction for simulating flows a river system for water resources planning and management. A number of calibration parameters are introduced in such models to represent various processes using simplified mathematical equations. Traditionally, a river model is calibrated using a reach-by-reach calibration approach starting from the top of the system cascading down to the end of the system. While the reach-by-reach approach is suitable for obtaining optimum model performance at a single river reach with high quality observed data, it does have the limitation of error propagation from upstream to downstream reaches if poor quality data are used in the calibration. A system-wide calibration approach has recently been developed for river system modelling in large river basins. Comparing with traditional reach-by-reach calibration, this new method optimises parameters of all river reaches within a region simultaneously using a weighted global objective function. The results of its application of this new approach in the Murray-Darling basin, Australia have shown its potential to overcome over-fitting and improve fitness of each individual gauge. However, due to the system-wide optimization of multiple reach parameters in a region, the search space and computational time required for system calibration increase exponentially with the increase of number of parameters. This limits the number of parameters that can be optimised and thus, the size of the region. To potentially overcome this limitation, a parallel computing enabled shuffled complex evolution (SCE) optimisation tool has been developed. A series of comparison studies have been conducted to evaluate the performance of this approach over normal SCE. These are: 1) comparison of computation time and performance for the same number of parameters; 2) comparison of performance with the same computation time and the same number of parameters and 3) comparison of the maximum number of parameters that can be optimised and performance within the same computation time. The results show that the run time with the new approach is about 25% of those with the normal SCE and its efficiency increases with increased number of calibration parameters.

Keywords: *River system model, Australian Water Resources Assessment, Shuffled complex evolution, parallel computing, optimisation*

Using hydrologic signatures to predict salient runoff characteristics and daily runoff in ungauged catchments

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Abstract: Hydrologic signatures refer to a set of hydrological indices or a time series of the response behaviour of a catchment at different time steps. They can be runoff coefficient, zero flow ratio, a measure of runoff seasonality, flow duration curves and daily time series of runoff. Hydrologists need to understand and predict hydrological behaviour under different climate or catchment conditions. Hydrologic signatures can be used for water resource management, catchment classification, and predicting runoff time series.

This study comprehensively compares the hydrological signature approach to traditional rainfall-runoff modelling (RR) for predicting daily runoff time series in ungauged catchments. In the rainfall-runoff modelling approach, hydrological models are first calibrated in gauged catchment, and then regionalised to predict daily runoff using spatial proximity to transfer calibrated parameters obtained from gauged to ungauged catchments. The hydrological signature approach includes three steps: (1) predicting FDC using three hydrological signatures (zero flow ratio, mean and standard deviation of daily flow) for ungauged catchments; (2) quantifying the exceedance probability of daily runoff for a given day; and (3) estimating daily runoff time series for the ungauged catchment using simple average and inverse distance weighting (IDW).

The two approaches were compared using an extensive dataset (228 catchments) for a large region of south-eastern Australia and provides guidelines for choosing the suitable method. The results show that 5-donor IDW was noticeably better than a single donor to predict daily runoff time series, especially for the hydrological signature approach. The RR modelling approach calibrated against daily runoff outperformed the hydrological signature approach for predicting high flows. The hydrological signature approach was better at predicting medium to low flows in traditional calibration against the Nash-Sutcliffe-Efficiency or Root Mean Square Error, but when calibrated against a low flow objective function, both the hydrological signature and rainfall-runoff models performed equally well in simulating the low flows. These results indicate that both methods can be further improved to simulate daily hydrographs describing the range of flow metrics in ungauged catchments. Further studies should be carried out for improving the accuracy of predicted FDC in ungauged catchments, including improving the FDC model structure and parameter fitting.

The major strength of the hydrological signature approach is predicting low flow and zero flow ratio. This is particularly important in arid and semi arid regions where rivers are often ephemeral. This approach requires fewer efforts than RR models, can also be used for river ecology studies and environmental flow managements. The daily observed runoff data in the gauged catchments is the only daily time series data used in the hydrological signature approach. Other data used are aggregated, such as aridity index, forest ratio and standard deviation of precipitation. Therefore, the hydrological signature approach can replace the RR modelling approach in ungauged catchments where there are considerable gaps in climatic forcing data or rainfall gauges are very sparse.

Keywords: *Hydrologic signatures, flow duration curve, rainfall-runoff modelling, ungauged catchments, daily runoff prediction*

Use of remote sensing data to improve hydraulic model for real time flood wave routing prediction

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Abstract: Floods are the most common natural disaster worldwide. An accurate prediction of the flood wave arrival time, depth and velocity in real time is essential to reducing fatalities and damage. Thanks to the increased availability of Remote Sensing (RS) data, the numerical modelling of flood wave routing has recently moved from being a "data-poor" to be a "data rich" problem. For instance, LiDAR data and airborne images of the floodplain support model implementation through information on surface geometry and land cover. Satellite or airborne optical and radar data taken during the flood event support model calibration, validation and real time constraint through the spatially distributed information on flood extent or water levels, the latter are derived by intersecting the flood extent map with a DEM. In particular, radar instruments are preferred due to their all-weather, all-time-of-day imaging capability. This project investigates the use of RS data for its ability to improve the accuracy of real time flood wave routing prediction. An overview of the project methodology and some preliminary results are presented here.

The research question is investigated through the numerical modelling of historical flood events that occurred in Australia. The numerical code is based on LISFLOOD-FP and it uses the finite difference method to solve the inertial approximation of the shallow water equations. Two significant flood events in the Clarence (NSW) and the Condamine-Culgoa-Balonne (QLD) catchments were selected as case studies. Available RS data include radar (ALOS-PALSAR, COSMO SkyMed, RADARSAT2) and optical (SPOT5-6, ASTER, LANDSAT) satellite images, airborne RGB images and LiDAR data. For each catchment, different combinations of field and RS data will be used to identify the most effective protocol for model calibration and validation using one flood event. The second flood event will be used to simulate a real time scenario in order to test the impact of RS data assimilation for operational purposes.

At this stage, results are presented for the flood event that occurred in January 2013 in the Clarence catchment. Techniques for the assessment of the roughness values and the modelling of specific features (e.g. bridges and levees) have been investigated. The results of the uncalibrated model were firstly compared with the water levels measured by ten gauging stations. The RMSE, when averaged over the ten gauging stations, was 0.30 m. A comparison with RS-derived flood extent observations pointed out that, despite providing rather satisfactory results at local level, the model failed the prediction of the flood extent in a relevant urban area. These results underline the limits of a punctual model-measurements comparison and highlight that more coherent and explicative modalities of comparison are possible thanks to the intrinsically two dimensional features of RS observations. Furthermore, the spatially distributed RS data supported the diagnosis of errors and allowed the identification of inaccuracies in the model implementation. Since the data assimilation strategies currently used are designed to filter noise and don't remove systematic errors, the contribution of RS data to the accurate model set-up and calibration is of paramount importance for real time forecast.

Keywords: *Flood forecast, hydraulic model, remote sensing data*

Performance of remotely sensed and modelled soil moisture products across Australia and implications for data assimilation

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Abstract: Soil moisture data is currently being used in a number of applications in Australia, such as numerical weather prediction, national water accounting, drought monitoring, flood prediction, and others. Data may be obtained from a range of sources including in situ measurements, satellite remotely sensed estimates and hydrological model output estimates, which are systematically different in the way they estimate soil moisture. Some products may provide better estimates than others in different landscapes and at different times.

To highlight the strengths and weaknesses of some commonly used data sets, performance of four products were compared across a variety of landscapes and climate zones in Australia, including two modelled products and two satellite remotely sensed products. The modelled products included the Australian Water Resource Assessment Landscape (AWRA-L) model and the Keetch-Bryam Drought Index. Satellite products included the Soil Moisture Ocean Salinity (SMOS) and Advanced Microwave Scanning Radiometer 2 (AMSR2) platforms, with soil moisture retrieved using the Land Parameter Retrieval Model.

Performance was based on correlation with in situ measurements and interrelationships between products explored using cluster analysis. In situ data from three separate networks around Australia were collated for this study, which when combined provide in situ measurements across a wider range of climate zones and landscapes than the individual networks. The networks included OzNet, OzFlux and CosmOz. OzNet is located in the south-east of mainland Australia and consists of over 60 monitoring stations measuring soil moisture with time domain reflectometry (TDR) sensors. OzFlux also employs TDR sensors, with over 30 stations spread across the country. CosmOz employs the more recent cosmic-ray technology to capture soil moisture information, and has nine stations located around Australia. From these networks, in situ data was used at 13 stations, selected based on several criteria including: at least 10 coincident daily values with all products considered, and at least one year of consecutive data available over the study period 2001-2014.

Agreement with in situ measurements varied between products and across locations. SMOS showed the strongest and most consistent performance across climate zones and locations considered. Other products showed an overall weaker agreement and a higher degree of variability across Australia. Results from the clustering analysis suggest these products do not share systematic commonalities in their error structure. This has implications for data assimilation, in that an ensemble of products may be created and used in the assimilation process without introducing bias into the model, potentially based on a best estimate of soil moisture.

Keywords: *Soil moisture, remote sensing, correlation, cluster analysis, modelling, data assimilation*

Evaluation of hydrological models for using soil moisture observations

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Abstract: As one of the most destructive natural disasters, river flooding regularly threatens people's lives and possessions. The development of emergency preparedness and risk mitigation has to a certain extent reduced flood-related mortality; however, floods remain one of the most dangerous disasters, causing an estimated 100,000 deaths and almost 1.4 billion affected people worldwide in the last decade of the 20th century. In Australia, floods are among the most common natural disasters and cause more loss of lives than any other disaster.

Flood forecasting techniques have experienced a rapid development in past decades. A timely and reliable forecast has great significance for warning delivery and emergency response. However, current operational forecasting systems still suffer from uncertainties in forcing data, initial conditions, model structure and parameters. To address these issues, batch calibration and data assimilation are being adopted to reduce systematic biases and short-term random errors.

To date traditional hydrological calibration and data assimilation have been implemented to introduce stream discharge measurements into forecasting models to improve forecasting accuracy. While recent advances in remote sensing techniques provide a new capability for large scale surface soil moisture monitoring, most of the operational hydrological models do not contain a surface soil moisture component that can easily accept the remotely sensed soil moisture data.

First is a comparison between GR family of models, including:

- the widely applied GR4H model, which has single bulk soil water storage,
- the GRHUM model, which has a surface soil moisture layer embedded into a bulk soil moisture, and
- the GRKAL model, which has a surface layer and a zoot-zone layer separately.

The three models are compared in a discharge-calibration scenario, with the results indicating similar forecasting skills, e.g., the Nash-Sutcliffe model efficiencies (NS) are 0.78, 0.79, 0.81 in calibration period and 0.70, 0.69, 0.70 in validation period for the GR4H, GRHUM, GRKAL, respectively. This is expected due to the similarity among the three models in ground water and routing parameterizations.

Second, a preliminary study on multi-objective calibration using both remotely sensed surface soil moisture (SMOS) and discharge measurements is conducted using the GRKAL. The result shows that compared with discharge-only calibration, the multi-objective calibration scheme has a slight decrease in flow prediction accuracy during the calibration period, e.g., the NS decreases from 0.81 to 0.76. However, during the independent validation period, including soil moisture information gives slightly better forecasts, e.g., the NS are 0.70 and 0.71 for the discharge-only and multi-objective calibration schemes. This indicates that although minimizing errors in soil moisture causes some decrease in flow prediction accuracy during the calibration, a more robust calibration is achieved resulting in better prediction skill during forecasts. Consequently, there is a potential to enhance the flow forecast accuracy further through real-time assimilation of remotely sensed soil moisture products.

Keywords: *Remote sensing, soil moisture, flood forecast, model calibration*

Assessing the importance of irrigation inputs for accurate predictions of streamflow and actual evapotranspiration in an irrigated catchment

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Abstract: Irrigation water use is a major component of mass balance in irrigated catchments. One of the challenges for hydrological modelling from the agricultural perspective is that the spatial and temporal distribution of irrigation inputs can strongly influence catchment streamflow and actual evapotranspiration (AET), yet our knowledge of these distributions is often highly uncertain.

In this study we compare a range of approaches for specifying irrigation inputs into spatially distributed hydrological models, including a new stochastic irrigation model that generates spatially variable event-based (SV-E) irrigation. This irrigation model, which modifies the stochastic irrigation model introduced by Githui *et al* (Hydrological Processes, in review), disaggregates measurements of spatially aggregated catchment irrigation into predictions of 'farm-scale' irrigation time series, utilising knowledge of farming irrigation practises (crop irrigation seasons and irrigation depths).

The different approaches to irrigation inputs are tested in a case study based on the Barr Creek catchment in the south east of Australia, where the Soil and Water Assessment Tool (SWAT) is applied to predict streamflow and AET based on observed rainfall and simulated irrigation. When the new spatially variable event-based (SV-E) irrigation model is used to provide input to SWAT, better predictions of daily streamflow and monthly catchment AET are obtained, compared with when simpler alternative irrigation models are used. For example, using spatially-uniform event-based (SU-E) irrigation leads to less reliable and less precise predictions of daily streamflow (Fig 1 a,b). Alternatively, using a spatially-uniform continuous (SU-C) irrigation leads to over-estimated AET compared with remote sensed estimates (Fig 1c).

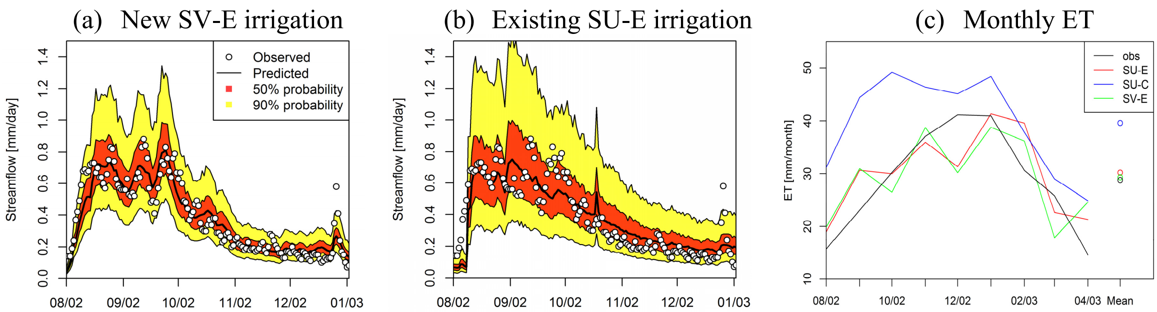

Figure 1. Total predictive uncertainty at the catchment outlet for (a) Streamflow for SV-E irrigation based on the new stochastic irrigation model, and (b) Streamflow for SU-E irrigation. (c) Observed and predicted monthly ET.

Keywords: *Irrigation, SWAT, evapotranspiration, stochastic, disaggregation*

Integrating GRACE and SMOS data into a hydrological model using an ensemble Kalman Filter

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Abstract: The ability to accurately estimate terrestrial water storage (TWS) and its components is essential for understanding the global water cycle. Each component of TWS, including surface soil moisture (SM), is a challenge to model accurately due to their high temporal and spatial variability. Satellite or ground-based observations can provide new constraints on hydrological models but do not provide comprehensive information on all water cycle components. Therefore, to achieve a more accurate and integrated global water cycle analysis, a combination of both modeling and observational capability is required. This study investigates the benefits of integrating Gravity Recovery and Climate Experiment (GRACE) derived TWS changes estimates, from temporal changes in Earth's gravity field, and Soil Moisture and Ocean Salinity (SMOS) retrieved surface SM, from emitted microwave radiation at L-band, into a global water balance model.

Experiments were conducted to assimilate SMOS near-daily surface SM and monthly GRACE TWS products both independently and jointly into the World Wide Water (W3) modeling system, a global implementation of Australian AWRA landscape hydrology model. The aim was to obtain more accurate modeling of the global water cycle. The impact of assimilating remote sensing observations and how they affected each water component was assessed. Tests were performed over a three-year period.

The ensemble Kalman filter (EnKF) was implemented to assimilate the satellite observations into W3 to generate ensembles of individual water storages components at daily time step with 1°×1° resolution. Precipitation data was perturbed using multiplicative error (of 60%). Covariance inflation with a factor of 0.05% was applied to minimize ensemble collapse. In addition, a fixed lower limit of 0.001 as enforced on modeled observation error variance to avoid overly confident assessment of model accuracy. Long term average of modeled TWS was added to the GRACE estimates to transform the TWS anomalies to the absolute TWS estimates. The observation models, which map model states into observation space, are the top-layer soil relative wetness and monthly average TWS (i.e. summed daily top-, shallow-, deep-layer soil water storage, ground- and surface-water storages). In this study the uncertainty of SMOS and GRACE data was assumed to be 5% and 20 mm respectively.

We compared the updated top-layer soil relative wetness and monthly average TWS across the Murray-Darling Basin (MDB) against the open-loop estimates and assimilated observations to examine the analysis increments and correlation changes. The assimilation of SMOS SM observations appears impacts the shallow soil profile values, leading to an increase in correlation between the model and SMOS of 0.1 (0.27 – 0.37), and only slight decrease in correlation assessed with GRACE TWS of 0.02 (0.3 – 0.28) compared to the open-loop simulations. The assimilation of GRACE TWS affects all water storage components, with an overall increase in correlation between GRACE and modeled TWS of 0.5 compared with open-loop (0.3 – 0.8), and slightly decrease in top-layer soil relative wetness against SMOS of 0.06 (0.27 – 0.21). Encouragingly, the joint assimilation of SMOS and GRACE into W3 increases agreement between the model and observations relative to open-loop simulated values, as expected, by 0.12 (top-layer soil relative wetness) and 0.51 (TWS). This indicates that the joint assimilation of the two datasets does not result in conflicting model performance.

Spatially across the MDB, the assimilation of SMOS and GRACE data made the greatest changes to TWS in southern (around the Murrumbidgee river) and northeastern (around Moonie river), and greatest change to top-layer SM in western (around Darling and Barwon rivers). Next steps are to assess whether the changes to model estimations (with greater agreement to both satellite products) could result in an improvement in model performance through evaluation with independent (specifically in situ or ground-based) observations.

Keywords: *Data assimilation, GRACE, SMOS, global water cycle*

Towards operational hydrological model calibration using streamflow and soil moisture measurements

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Abstract: Timely and reliable flood forecasting is critical for flood warning delivery and emergency response. As core components of an operational forecasting system, hydrological models are typically calibrated using streamflow measurements to minimize parameter uncertainties. The rapid development of earth observation techniques provides opportunities to obtain soil moisture information. As catchment discharge is strongly related to soil moisture, there is a possibility to improve streamflow forecasts by using soil moisture measurements for model calibration. The use of soil moisture observations has attracted increasing attention, however, there have been a limited number of studies.

This study aims to assess the impact of integrating soil moisture measurements for model calibration on the forecast skills of hydrological models. Experiments were implemented in the Adelong Creek (157 km^2) and the Upper Kyeamba Creek (190 km^2) catchments of the Murrumbidge Basin using a lumped rainfall-runoff model named GRKAL (modèle du Génie Rural Kal). Two calibration scenarios are performed: 1) a traditional streamflow-only-calibration; 2) a joint-calibration using both streamflow and in-situ soil moisture measurements. Outcomes are evaluated in a hind-casting mode for both a calibration and independent validation period.

Results show that, for the Adelong catchment, the joint-calibration led to a slightly worse match between the simulated and observed streamflow with a Nash-Sutcliffe (NS) value of 0.8173, as compared to the streamflow-calibration scheme (achieved a NS value of 0.8443) alone in calibration period. During the validation period, the joint-calibration achieved a NS value of 0.7952, performing better than the streamflow-calibration scheme which gives a NS value of 0.7586. This result indicates that although introducing the soil moisture measurements to the objective function lead to a sub-optimal match of simulated streamflow to the observed data during the calibration period, there exists the possibility that joint calibration potentially optimized the model parameters to be more realistic, resulting a more precise prediction in the validation period. However, for the Kyeamba catchment, the results tend to be worse: NS values derived from joint-calibration was less than that obtained by streamflow-calibration in both calibration and validation period. This may relate to the unphysically based model structure, equal-weighted objective function, and various sources of uncertainties.

In terms of the soil moisture prediction, it is consistent in both catchments that the joint-calibration illustrates a marginally better match to the observed value than the streamflow calibration during most of the study period.

It is concluded that while the joint-calibration will typically lead to poorer streamflow forecast results during the calibration period, it could lead to a more robust result in the validation/forecasting period. As this was not consistently the case, more objective functions (such as unequal-weighted NS and a combination of several frequently-used objective functions) need to be investigated to identify the best calibration strategy for using soil moisture information.

Keywords: *Hydrological model, calibration, soil moisture*

Introducing the Bureau's new Generation Flood Forecasting System

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Abstract: The Bureau of Meteorology is Australia's key agency providing forecasts and warnings for flood events. This year the Bureau commissioned its Next Generation Hydrological Forecasting System called HyFS. It incorporates the latest advances in hydrological and meteorological predictions into the Bureau's flood forecasting practice. The software is an extensible modelling framework and the Bureau has a five year strategy to enhance the 2015 operational system with new capabilities aimed at improving the timeliness and accuracy of the flood warning service.

HyFS is the first continental-scale hydrological forecasting system which will be used by more than 60 flood forecasters located around Australia to provide flood warnings at 500 locations in 144 catchments. The system completely replaces a bespoke hydrological modelling system called HyModel. The software also integrates within the single application the data analysis and visualization functions that were previously completed using a range of tools and web interfaces. In a geospatial interface forecasters are now able to view real-time rainfall and river level observations, multiple high-resolution rainfall forecasts produced from numerical weather prediction models, radar rainfall and nowcast fields as well as tidal observations and surge forecasts. One of the strengths of the system is that as new observation and forecast fields become available they can be easily integrated and made available to forecasters.

HyFS is based on the Delft-FEWS software platform that is used extensively around the world for operational flood forecasting. The Bureau worked with a team from Deltares in the Netherlands to extend and customize the software to meet Australian requirements. Three key extensions to the modelling capabilities included adding two hydrological models and support for empirical forecasting techniques based on historical peak flood data. The first model was the Unified River Basin Simulator (URBS) which is the primary tool used by the Bureau for event-based flood forecasting. The second model was a custom modelling package called the Short-term Water Information Forecasting Tools (SWIFT) which has the GR4H hydrological model at its core. This continuous modelling software is being used to provide seven day ahead streamflow forecasts at over 100 locations across more than 60 catchments.

Including a full disaster recovery and a level of availability expected of a system that supports emergency management operations, HyFS enables the Bureau to seamlessly deliver hydrological forecasting services to any region in Australia from any of the Bureau's regionally based flood warning centres and from the National Operations Centre in Melbourne.

The implementation of HyFS is supported by a comprehensive forecaster competency and training framework. HyFS - Water Coach is the flight-simulator of hydrological forecasting and enables forecasters to train and develop their flood forecasting expertise through being able to relive historical flood events.

This presentation will provide an overview of the capabilities of HyFS and technical challenges overcome during its implementation and illustrate how these advancements will improve the Bureau's flood forecasting and warning service provided to the Australian community.

Keywords: *Hydrological modelling, flood forecasting, HyFS, Delft-FEWS*

Ensemble seasonal streamflow forecasts for ephemeral rivers

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Abstract: Streamflows in intermittent and ephemeral catchments often exhibit strongly non-linear responses to rainfall, making them difficult to forecast. This is a particular problem for Australia, where intermittent and ephemeral streams are the norm, rather than the exception. In this presentation we describe attempts to improve the performance of the Forecast Guided Stochastic Scenarios (FoGSS) seasonal streamflow forecasting system in ephemeral and intermittent catchments.

FoGSS makes use of monthly rainfall forecasts that are generated by: i) calibrating rainfall forecasts from a coupled ocean-atmosphere model to remove bias and quantify uncertainty; ii) establishing statistical 'bridging' models that use forecasts of sea-surface temperature to forecast rainfall; and iii) merging the calibrated and bridged rainfall forecasts with Bayesian model averaging (CBaM). The calibration and produces unbiased and highly reliable ensemble forecasts, while bridging adds skill to the calibrated rainfall forecasts. The rainfall forecasts are then passed through the WAPABA monthly rainfall-runoff model and a 4-stage hydrological error model. The hydrological error model transforms flow with the log-sinh transformation to normalise errors and homogenise their variance (Stage 1), applies a simple bias-correction to transformed flows (Stage 2) and applies an auto-regressive error model to bias-corrected, transformed flows (Stage 3). Finally, forecasts are merged with climatology forecasts using the quantile model averaging algorithm (Stage 4). Stage 4 plays no role in generating forecast skill, but rather ensures that forecasts are at worst neutrally skillful. The result is ensemble forecasts of streamflow time series at a monthly timestep to lead-times of 12 months. We assessed FoGSS' performance with leave-five-years-out cross-validation of retrospective forecasts. FoGSS functioned well in perennial streams, producing reliable ensemble streamflow forecasts that are usually skillful at lead-times of 1-3 months, and in some instances are skilful to forecast lead-times of >6 months. As skill declined with lead time, FoGSS forecasts transition seamlessly to stochastic scenarios.

FoGSS showed least consistent performance in drier and more variable climates, particularly in ephemeral streams. To improve FoGSS forecasts for ephemeral streams, we attempt two strategies:

1. A more complex bias-correction. We develop a new two-parameter bias-correction, which, when combined with the transformation, is better able to capture the strongly non-linear errors that can occur in these catchments. The revised bias-correction was so successful that the fourth stage – merging with climatology forecasts – was no longer necessary, greatly simplifying the model.
2. Alternative monthly rainfall-runoff models. We trial two other rainfall-runoff models, GR2M and ABCD, for a range of ephemeral catchments from Queensland, the Northern Territory and Western Australia. While WAPABA performs best over the range of catchments, ABCD and particularly GR2M produce better forecasts in certain catchments. This is primarily because GR2M is able to better capture the rapid hydrograph recessions that are characteristic of some catchments.

The new 3-stage FoGSS model does not solve all problems, however, particularly in seasons and catchments where rivers flow very rarely (e.g. only once in every 5 years). In these instances forecast skill can be strongly negative (i.e., the forecasts are significantly outperformed by climatology forecasts). We conclude that a degree of customisation is required for ephemeral and intermittent catchments to allow FoGSS to produce reasonably skilful forecasts. We discuss prospects for improving forecasts in the most difficult catchments.

Keywords: *Ensemble prediction, streamflow forecasting, seasonal, ephemeral rivers*

EXTENDED ABSTRACT ONLY

Operational flow forecasting with a high resolution weather forecast NZCSM-TOPNET

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Abstract: Flooding and other water-related disasters are one of the most devastating worldwide hazards in terms of loss of human life and infrastructures. Operational flood forecasting can mitigate the impacts of these disasters by providing accurate and timely indication of the occurrence of major flooding events. Hydrologic forecasting systems are provided by coupling numerical weather prediction models with hydrological models, and hence are highly dependent on the quality of the weather forecast. The latest international advances in weather forecasting are being made by using very high-resolution models which are able to represent atmospheric processes more accurately.

This presentation shows the impact of coupling the hydrological model TopNet with the new high resolution New Zealand Convective Scale Model (NZCSM) in an operational flow forecasting system for two catchments in New Zealand. We compare the operational NZCSM-TopNet coupled model with the current EcoConnect flow forecasting system which uses the lower-resolution NZLAM operational weather forecast. Both numerical weather prediction models are local implementations of the UK Met Office Unified Model System (UM) for New Zealand, with a grid resolution of 1.5km for NZCSM compared to 12km for NZLAM. TopNet is a distributed hydrological model based on TOPMODEL concepts of runoff generation controlled by sub-surface water storage. It combines a water balance model within each subcatchment and implements a kinematic wave channel routing algorithm. TopNet uses nationally available information on catchment topography physical and hydrological properties derived from the River Environment Classification, soil, land use and geology databases.

Both operational flow forecasting systems use hydrological data assimilation with the recursive ensemble Kalman filter (REnKF) to assimilate stream-flow data. The REnKF iteratively updates past and present model states (soil moisture, depth to groundwater, and surface storages) with a catchment-specific time lag to improve model initial conditions of the next forecast.

Both forecasts are used as input into the hydrological model to operationally predict river flow at the outlet of two catchments in the West Coast region of New Zealand. The case study catchments are the Buller River, with a catchment area of 6350km^2 located upstream of Westport, and the Grey River, with a catchment area of 3820km^2 located upstream of Greymouth. The two rivers are relatively short but convey massive volumes of water from the heavy rain band along the New Zealand Southern Alps. Preliminary results of these case studies will be presented comparing several months of flow forecasts with both weather forecast resolutions.

The work focuses on how the weather data spatial resolution (12km, and 1.5km respectively) affects the flow forecast in the two case study catchments, by quantify the performance of the coupled models with performance scores (such as the Nash-Sutcliffe Efficiency). We assess and compare the performance of the recursive ensemble Kalman filter (REnKF) for the different grid resolution and discuss the error parameter sensitivity, ensemble spread, perturbation size and magnitude. We highlight some of the technical challenges associated with running an operational flow forecasting system with high resolution weather ensemble forecasts.

Keywords: *Flow forecasting, hydrological model, numerical weather forecast, deterministic and ensemble forecasts, data assimilation*

EXTENDED ABSTRACT ONLY

Improved reliability of dynamical seasonal rainfall forecasts using a lagged ensemble

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Abstract: In the Australia region, single start-date (burst) ensemble forecasts seasonal rainfall tend to be under-dispersed and hence produce overconfident forecasts of the probability of seasonal rainfall exceeding the long-term median. Overconfidence reduces the utility of the forecast for users who require reliable probabilities. This overconfidence is reduced through a lagged ensemble strategy: by combining successive forecasts initialised on multiple start dates, the spread of forecast outcomes increases, resulting in outlooks that are more reliable (forecast probabilities more consistent with observed frequencies). However increased reliability comes at the expense of accuracy, which is greater at shorter forecast lead time.

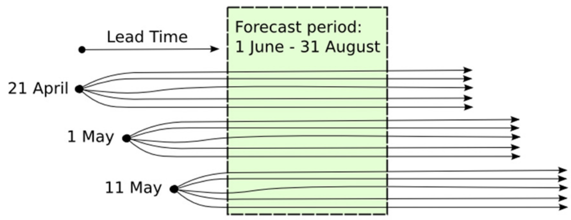

Figure 1. Construction of lagged ensemble.

A lagged ensemble composed of forecasts with lead times (period between the time the forecast is made and the forecast validity period) of 20 days, 30 days and 40 days was compared with single-start date ensemble forecasts using measures of forecast accuracy and reliability over the period 1981-2010 using the Bureau of Meteorology's dynamical model-based seasonal outlook system, POAMA.

As a measure of accuracy, percent correct (PC) is defined as the percentage of forecasts in which the observed category was forecast with the highest probability. A bootstrap resampling in time is used to calculate a 95% probability interval for PC. The large uncertainty stems from the short period available for verification and the large influence of a small number of ENSO events on predictability. The Brier Skill Score was calculated using climatological forecasts as reference. The extent to which forecast probabilities are reliable is measured by reliability term of the Brier score is also shown (REL).

Table 1. Performance of burst versus lagged ensemble.

Name	PC	95% Interval	REL	BSS %
Burst 10 day lead	63.5	(57.4,69.3)	0.48	3.40
Burst 20 day lead	60.2	(54.0,66.2)	0.51	2.65
Burst 30 day lead	54.2	(47.9,60.3)	0.46	2.53
Burst 40 day lead	53.7	(47.4,59.8)	0.42	2.17
Lagged 20/30/40 day lead	55.9	(49.6,62.0)	0.17	4.36
Lagged 10/20/30 day lead	61.6	(53.0,69.2)	0.15	5.16

Results are summarized in Table 1. As lead time increases, the accuracy of the seasonal rainfall forecasts decreases. A price is paid in accuracy when the lagged ensemble is used to improve reliability: the 20 day lead burst ensemble has a PC of 60.2%, compare to a PC of 55.9% for the 20 day lead lagged ensemble. The lagged ensemble has a higher BSS than even the shorter 10 day lead burst ensemble. The lagged ensemble is more reliable than any individual burst ensemble.

The reduction in accuracy may be a consequence of including forecasts with a very long lead time which risks including potential future states that have already been 'ruled out' since the initialization of the most recent member. An additional benefit to the improvement in reliability is that lagged ensembles reduce the tendency of forecasts can change from run to run, resulting in more consistent outlooks across issue dates.

Keywords: *Seasonal forecasting, lagged ensemble*

Seamless Hourly Rainfall Ensemble Forecasts

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Abstract: Typically, Numerical Weather Prediction (NWP) Direct Model Output (DMO) provide deterministic precipitation forecasts. However, these contain no information regarding forecast uncertainty. Additionally, different NWP models have varying spatial and temporal resolutions and forecast period lengths. Many users require a seamless forecast system with a uniform resolution over the entire forecast period. NWP ensemble systems typically produce a limited number of ensemble members, due to computational resources and time constraints, by perturbing initial conditions and/or model physics, providing an insight into the forecast uncertainty. Global NWP ensembles typically contain no more than 50 ensemble members at coarse temporal and spatial resolutions, in regional NWP ensembles that have higher spatial and temporal resolutions at the expense of the number of members, typically less than 25, and maximum lead time. Limited area ensembles have even higher spatial and temporal resolutions, at the further expense of members and lead time. Some applications, for example hydrological, require high resolution, both spatial and temporal, ensembles with 50-100 members. This is computationally prohibitive for dynamical NWP ensembles.

A large ensemble of rainfall forecasts has been generated by blending two deterministic NWP models with a stochastic model of forecast error, which has the space-time properties of observed rainfall. NWP uncertainties depend on the scale and forecast lead time, especially at long forecast lead times. By blending the models scale by scale, it is possible to recognise the increased skill of the models at short lead times and larger spatial scales. The stochastic model of forecast error is applied at each scale, adding increasingly more variability at small spatial scales and longer forecast lead times, while preserving the space-time structure of rainfall.

The Bureau of Meteorology's Australian Parallel Suite (APS, current version is APS1) Australian Community Climate and Earth-System Simulator (ACCESS) Global model (ACCESS G) ($\sim$40 km $\times$ $\sim$40 km, 3 hourly out to 10 days) and ACCESS-R (Regional) ($\sim$12 km $\times$ $\sim$12 km, hourly out to 3 days) models are blended over 1000 km $\times$ 1000 km domains. An ensemble of hourly, downscaled precipitation forecasts out to 10 days is produced with a resolution of 2 km $\times$ 2 km. A year of these ensemble forecasts (accumulated to daily totals) has been verified against the daily Australian Water Availability Project (AWAP) analyses (0.05° $\times$ 0.05° resolution). These results show the system is able to produce reliable forecasts out to five days over these domains. More recently, hourly (out to 10 days) ACCESS G forecasts (APS1 ACCESS G model outputting hourly fields, running in research mode) and ACCESS R have been used to create hourly forecast ensembles which are being compared to radar observations of rainfall.

Keywords: *Precipitation, ensemble, stochastic*

An alternative to the Brier Score for probabilistic forecast verification

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Abstract: Probabilistic forecasts considering the uncertainty of the forecasting system have become increasingly common in weather and climate systems and have obtained considerable attention in the hydrological literature. As a result, verification of these probabilistic forecasts has become important, and verification tools critical in ensuring acceptability with end users.

The Brier Score proposed by Brier in 1950, currently one of the most widely used verification tools for quantifying the quality of probabilistic forecasts, estimates the difference between the forecasted probability of falling within a certain (discrete) class, and observations (which is either 0 or 1) for binary or categorical events. The conditions necessary for the Brier Score (including the decomposed Brier Score) to give a reliable estimation of forecast error, however, are not easily satisfied under real application conditions. The Brier Score estimate can vary depending on not only the accuracy of the probabilistic forecasting system, but also the forecast conditions. Optimization of the forecasting system depending on the verification results from the Brier Score can be inefficient, increasing the risk of poorly detected hazards or misunderstanding of the error associated with the probabilistic forecast.

This study analyses the limitations of the Brier Score through synthetically generated data in which we control the quality of probabilistic forecasts and various application environments using a repetitive sampling scheme. The reasons behind the limitations of the Brier Score are identified and a new measure proposed as a viable alternative.

The proposed measure, termed the L_p-distance, is a new measure of distance between the forecasted and true event probabilities, which assumes smaller values as forecast quality improves, hence presenting an improved measure of "goodness-of-fit" for any probabilistic forecasting application in hydrology or climatology. The L_p-distance is presented as a verification measure for ensemble or probabilistic forecasts of continuous variables (e.g. time, temperature, rainfall, and runoff) rather than binary or categorical variables (e.g. rainfall occurrence) that the Brier Score is based on.

An application of the proposed measure along with that of the Brier Score for synthetically generated data illustrates that the L_p-distance consistently and effectively prunes the bias in the Brier Score, and, in addition, exhibits considerably smaller sampling uncertainty under the same observational constraints. These measures were also applied to real forecast of the El Niño Southern Oscillation by the International Research Institute (IRI ENSO) representing ensemble scenarios based on the dynamical and statistical models for sea surface temperature in the mid-Pacific region. While the Brier Score could cause one to misunderstand the accuracy and reliability of the ensemble forecast, the L_p-distance accurately recognized the quality by giving a markedly different result to the Brier Score.

Keywords: *Brier Score, reliability, verification, probabilistic forecast, ensemble prediction*

A model-based approach to the computation of area probabilities for precipitation exceeding a certain threshold

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Abstract: In order to provide consistent weather warnings it is essential to estimate the probabilities for certain weather events occurring. There are a number of operational numerical and statistical methods for estimating the probability that precipitation occurs at a fixed location (a point probability). However, there is a growing interest in the computation of probabilities for precipitation occurring somewhere in a geographical region (an area probability). An example would be the area of responsibility of a fire department, where an emergency occurs when there is intense rain anywhere within that area. The derivation of such area probabilities is difficult and no applicable method for their computation is known. In literature, some theoretical relationships between point and area probabilities are discussed under very simplifying assumptions. Furthermore, several stochastic models for precipitation cells have been proposed with none of them being suitable for our purposes due to restrictions such as e.g. spatial and temporal stationarity or inappropriate (or missing) model fitting. Recently, we proposed a (less restrictive and more robust) model-based approach to the computation of area probabilities for the occurrence of precipitation. This method is based on a non-stationary stochastic model for precipitation cells (basically a Cox germ-grain model with circular grains), which is characterized by a sequence of local intensities for the formation of precipitation cells and a cell radius. Furthermore, we proposed an approach for the algorithmic computation of all model characteristics from a sequence of point probabilities and described how area probabilities can be computed by repeated simulation of that model. In the present paper, we discuss an extension of this model by additionally including precipitation amounts. The available data contains sequences of point probabilities for precipitation exceeding various thresholds. At first, a gamma distribution is fitted to obtain moments of point precipitation amounts. Then, we briefly recall our model for the representation of precipitation cells. The most important and most recent results address the spatial stochastic modeling of precipitation amounts, which is done by assigning a response function to each precipitation cell. The response functions are then multiplied by random scaling factors and summed up to obtain precipitation amounts. We derive formulas for the expectation and variance of random point precipitation amounts in our model. Comparing the computed moments with those obtained from the data allows us to fit the distributions of the random scaling variables. Finally, area probabilities for the occurrence of precipitation exceeding a given threshold are estimated by repeated simulation of the precipitation model. We evaluate our results by analyzing how the choice of the response function and the distribution of scaling variables influence estimated point and area probabilities. The novelty of the presented approach is that, for the first time, a widely applicable estimation of area probabilities is possible, which is based solely on predicted point probabilities (i.e., no precipitation observations are needed). Furthermore, the method works in a quite reasonable computation time, which makes it suitable for applications in modern weather prediction.

Keywords: *Probabilistic weather prediction, area probabilities, precipitation amounts, spatial stochastic model, Monte Carlo simulation*

Value of ensemble merging for seasonal streamflow forecasts

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Abstract: The Bureau of Meteorology has recently released a new seasonal streamflow forecast product to registered users. Ensemble forecasts of 1-month and 3-month streamflow based on a dynamic approach (DM) are generated using the GR4J lumped conceptual hydrological model forced by rainfall forecasts obtained from the Bureau Predictive Ocean and Atmosphere Model of Australia (POAMA). In parallel, the Bureau has been operating a seasonal streamflow forecasting service based on the Bayesian Joint Probability (BJP) statistical model since December 2010. In this paper, the quantile averaging algorithm (Schepen et al., 2015) was used to merge BJP and DM forecasts for 111 forecast sites.

Figure 1.a shows the results of forecast verification using a 'leave-5-years out' cross-validation exercise over the period 1980-2008. The Figure presents the distribution of the RMSEP skill score for the three models BJP, DM and merging, for all seasons and all sites. This score is normalized with a maximum of 100 for a perfect forecast and value of 0 for a forecast similar to a climatological forecast. The score targets model performance during low flows periods. The figure suggests that the merged forecasts provide an improvement over both DM and BJP with a median skill score reaching 15.3 versus 12.4 and 9.6 for BJP and DM, respectively. Similar figures based on other skill scores covering other forecast attributes (e.g. reliability, not shown) reveal a similar pattern and confirm the improved performance of the merged streamflow forecasts. Further analysis was undertaken to compare the best of DM and BJP with merged forecast results. Figure 1.b shows a scatter plot of RMSEP skill score for merging plotted against the best RMSEP score from DM and BJP. With most points aligned along the 1:1 line, this figure suggests that the merged forecasts are comparable with the best model currently available, indicating that the merging algorithm is able to combine the DM and BJP forecasts effectively. Significant departure from the 1:1 are also visible, suggesting that merging can provide important improvements compared to the best forecast (above 1:1 line), but also large performance loss (below 1:1 line). To investigate the reason for these extreme behaviors, Figure 1.c compares the difference between the merged RMSEP skill score and the best from DM/BJP with the absolute difference between the DM and BJP score. This figure indicates that merging provides large improvement compared to the best DM/BJP when the difference between both models is small (left part of the figure). When this difference becomes large (right part of the figure), the merging is more prone to stay at a similar or lower performance level than the best DM/BJP. This result suggests, that the merging is more efficient when applied to models of similar performance level.

Overall, the merged forecast is shown to outperform both dynamic and statistical models, providing a promising avenue for an improved seasonal streamflow forecasting service. The new forecast merging method will be operationalized as a part of the Bureau's seasonal streamflow forecasting system and new merged forecasts will be released to the public in 2016.

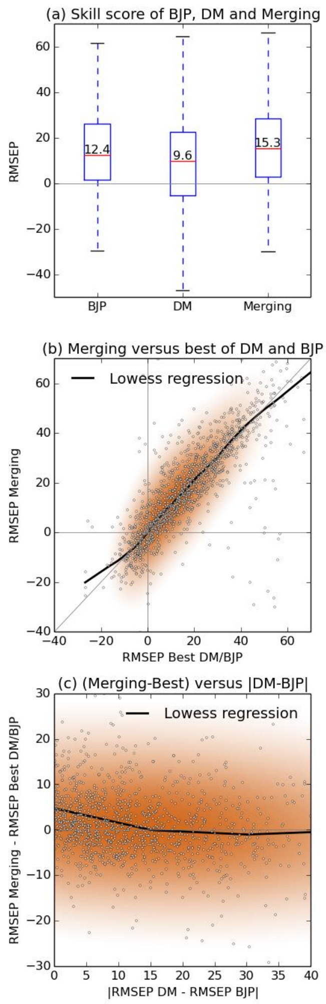

Figure 1: Model skill scores

Keywords: *Forecast merging, seasonal streamflow forecast, BJP, BATEA, GR4J, POAMA*

Multiple lead-time streamflow forecasts by a staged error modelling approach

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Abstract: Quantifying the uncertainty of streamflow forecasts enables risk-based flood warnings and supports rational decision-making. There are a number of sources of errors in streamflow forecasts, and it is highly difficult to separate the different sources of errors. A lumped error modelling approach deals with only the overall forecast errors without identifying the individual sources of errors and greatly simplifies the problem of error reduction and quantification. Traditionally, the lumped error modelling approach relies on a single error model to describe the complex behaviour of errors. The interactions between the parameters of the hydrological model and the error model can make it very difficult to calibrate the models jointly. We develop a new method for short-term and real-time streamflow forecasting, called error reduction and representation in stages (ERRIS). The novelty of ERRIS is that it runs a sequence of simple error models through four stages. At each stage, an error model is introduced to improve over the previous stage and to finalize the representation. Four stages in ERRIS can be summarized as follows:

- Stage 1 establishes the parameters of the hydrological model and the log-sinh transformation;
- Stage 2 applies a linear bias-correction;
- Stage 3 applies an autoregressive (AR) model to update the forecasts;
- Stage 4 applies a Gaussian mixture distribution to represent model residuals.

We test ERRIS at daily and hourly time steps, using slightly different versions in each case. For the application of hourly streamflow forecasting, we uses separate parameters at Stage 4 for the observations on the rising and falling limbs of the hydrograph.

We have carried out extensive testing and validation of ERRIS on hourly streamflow forecasts for a lead-time up to 48 hours for a range of Australian catchments. We find that

- Forecasts for perennially flowing rivers are generally reliable at all lead-times. Forecasts are most reliable at a 1-hour lead-time, with reliability decreasing with lead-times;
- The average width of the 95% confidence intervals tends to initially increase with lead-times and then stabilise at longer lead-times;
- The forecast mean at a 1-hour lead-time is extremely accurate. As forecast lead-times extend, the NSE approaches that from Stage 2;
- Streamflow forecasting for ephemeral and intermittent catchments is more challenging than for perennial catchments. Forecasts tend to become unreliable at longer lead-times;
- The forecasts of the rising limb of the hydrograph are generally less reliable than forecasts for the falling limb.

On the basis of these findings, we conclude that ERRIS provides accurate hourly streamflow forecasts and reliably quantifies the forecast uncertainty, even at longer lead-times. We recommend ERRIS for hourly streamflow forecasting.

Keywords: *Streamflow forecasting, multiple lead time, multi-stage error modeling, ensemble forecasting*

Projection in Hilbert Space for Flood Forecasting

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Abstract: A proper forecast of floods based on forecasted or occurring rainfalls is of great necessity for communities, government agencies and local authorities for the proper warning and management of the flood event before and during its occurrence. This abstract presents a new approach for flood forecasting of the Leith and Pomahaka Rivers in Otago, New Zealand. This methodology is based on the projection of hourly flows of a river at a desired site on the span of hourly rainfall data and/or previous flows of the same flow site or other flow sites. The projection theorem in Hilbert Space guarantees that the estimated parameters will produce a model with the least mean square error. The streamflow at time t "Q_t" (noted here as Q) is considered an element of a Hilbert space H, and other hydrologic variables, on which Q to be projected, are considered to constitute a closed sub-space S of H. These "other" hydrologic variables can be lagged flows $Q_{i,t-L}$ and rainfalls $R_{i,t-L}$ (noted here as X_i) at sites i, i=1 to N, and lagged L hours before time t, where L can range from zero to any integer L_{max}. The projection of Q in the sub-space S is denoted by $\hat{Q}$, where $\hat{Q} \in S$. In Hilbert space, $< Q - \hat{Q}\ , X_i >$ should equal zero for all $X_i \in S$, i=1 to N to produce the predictor $\hat{Q}$ with the minimum least squared error. .This is a consequence of Q - $\hat{Q}$ being orthogonal to X_i By the linearity of Hilbert space, this results in the system of N equations $<Q,X_i> = <\hat{Q},X_i>$, i= 1 to N.. $\hat{Q}$ can be a non-linear function of the "other" hydrologic variables X, but in this application, the linear projection of Q on the span of S (X_i, i=1 to N) is used ($\hat{Q} = \sum_{i=1}^{N} \propto_i X_i$). For this case, a system of N linear equations are produced which are solved simultaneously to obtain the corresponding coefficients for the "other" hydrologic variables X_i, i = 1 to N. Note that in Hilbert space $<X,Y> = E[XY]$.

The Leith River goes through Dunedin city in New Zealand, with a small catchment of about 45 km^2 with two rainfall sites within its catchment and one flow site in the city near the river's outlet to the harbor. To the contrary, the Pomahaka catchment is much bigger, with rural aspects and mainly agricultural activities. The Pomahaka catchment is about 1871 km^2, and has several flow and rainfall sites. The model for the Pomahaka is to forecast flows at Burkes ford site, which is the closest to its outlet to the Clutha River. Only 4 rainfall sites have been used for the Pomahaka catchment due to data availability. Hourly flows and rainfall data for the two catchments have been investigated and 25 high events of the Leith River at the University Foot Bridge in Dunedin, and 24 high flow events of the Pomahaka River at Burkes Ford, have been identified for the modeling process. Cross correlation analyses have been carried out between the river flows and other variables (rainfalls and/or previous flows) on which these flows will be projected. These cross correlations were utilized in estimating the lags between these variables and the modeled flows in the projection process. Results of the modeling process for producing a 10 hr forecast model for the Pomahaka River, achieved an overall value of 0.8 for R squared and 0.9 for Filliben correlation coefficient, while they were 0.8 and 0.89, respectively, for a 12 hr forecast model. This is not a significant difference, and of course it is preferred to have a longer forecast. The model underestimated several events, especially some big events, as its accuracy for simulating the maximum recorded flow was 80%. However, this might be acceptable for a forecast, as variability is usually high and it is hard to forecast precisely. The model performed well for many other high events. Non linear relations can be included in the modeling process between the projected flows and the variables on which they are projected. Future implementation of non linear relationship could result in an overall improvement of the model's performance. The produced model is easy to apply for real forecast, doesn't require a lot of information on the hydrological aspects/characteristic of the catchment areas, and can be used for real time forecast during an ongoing event or long term forecast based on forecasted rainfall over the following few days.

Keywords: *Flood forecast, Projection theorem, Hilbert space, rainfall-runoff modelling*

Roles of Expertise and Automation in Operational River Forecasting

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Abstract: Increased automation is becoming an attractive option for operational hydrologic forecasting agencies faced with growing complexity (e.g. increasing sources of information and demand for new products) as well as demands for increased service efficiency. Similar trends have been observed in meteorology and, while the meteorological community has had decades of open discussion about the relative roles of human expertise and automation in forecasting, the hydrologic literature has been nearly silent on the topic.

The presentation translates relevant findings from similar disciplines, such as meteorology but also psychology, decision support systems and interface design, into a hydrologic forecasting context. Psychologists indicate that intuitive judgment can only be developed in "high validity" environments (those with stable relationships between objectively identifiable cues and subsequent events or between cues and the outcomes of possible actions). The development of intuition also benefits from adequate opportunities for learning the environment (prolonged practice and feedback that is both rapid and unequivocal). These findings are relevant to aspects of forecasting that include workflows, verification, training, and others.

Certain tasks in the river forecasting process may be amenable to automation (e.g. some aspects of data quality control, product generation) and others would be difficult to automate (e.g. assimilating anecdotal information about non-modelled factors). Further, some enterprises have employed higher levels of automation, driven by, for example flash flood forecasting's need of fast response times, or extended predictions' relatively high levels of uncertainty and long delays between forecasts and observations. Short-range (i.e. 1-5 day) flood forecasting may be more challenging to automate and traditionally has been less automated than other types of forecasts, partly because of existing practices of interfacing with meteorologists and the difficulties in modelling human interaction in the water cycle (e.g. controlled storage releases or diversions).

The effective design of automated forecasting systems should consider three factors; 1. Processes change under automation and people may require new or different roles, 2. Automation changes the way people behave, sometimes negatively, and 3. People may not have accurate perceptions of the quality of the automated guidance.

Based on these findings, we recommend the best practices for forecasters and system developers: (1) use automation to clean and ingest data; (2) use well-designed forecasting interfaces; (3) have transparent systems; (4) separate the process of prognosis and diagnosis; (5) verify your forecasts; (6) always be learning the science; and, (7) redefine the forecaster's role.

Keywords: *Flood, models, prediction, decision making*

A strategy for quality controlling hourly rainfall observations and its impact on hourly streamflow simulations

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Abstract: Real-time streamflow forecasts are often produced at hourly and shorter time steps. To calibrate the hydrological models used to generate forecasts, archives of streamflow and rainfall observations are essential. The collection and archiving of sub-daily rain gauge observations is typically automated. Errors in rainfall observations can arise for many reasons and may manifest as anomalously high or low values for a single observation or longer periods of time. Quality control of sub-daily rainfall is onerous because of the large volume of data, and sub-daily rainfall data are frequently not quality-controlled when the data are archived in real-time. Errors in rainfall observations used to calibrate hydrological models can lead to poor out-of-sample model simulations and contribute to poor streamflow forecasts.

In this paper we describe a simple automated strategy for quality controlling archives of rain gauge observations. The strategy compares running totals of rain gauge observations with a reference rainfall data set. Where the differences between the observations and the reference dataset exceed a threshold, rain gauge observations are considered to be of poor quality and set to a missing value. The sensitivity of the quality control can be manipulated by adjusting the period over which the running totals are computed, and the definition of the difference threshold.

We apply the quality control strategy to hourly rain gauge observations from five catchments across Australia. For these applications we use the daily Australian Water Availability Project rainfall data set as the reference and quality control the hourly rain gauge observations at daily time steps. We seek only to remove gross errors in the rain gauge observations, where 5-day observed totals are greater than five times the reference or smaller than one fifth of the reference. We demonstrate the efficacy of the quality control strategy for hydrological models run at an hourly time-step with cross-validation experiments. The calibration and validation performance of hydrological simulations forced by the quality-controlled data are vastly superior to those forced by the raw rainfall observations. In some instances, improvements in validation Nash-Sutcliffe Efficiency values greater than 0.7 are achieved by using the quality-controlled rainfall observations. The performance of the hydrological simulations also tends to be more consistent between calibration and validation periods when quality-controlled rainfall observations are used.

The method allows rapid quality-control of large sub-daily rainfall datasets, allowing new streamflow forecasting systems to be established quickly.

Keywords: *Rainfall data quality, hydrological modelling and forecasting*

Comparison of Level 3 mean monthly GPROF products from GPM and TRMM microwave imager in estimating seasonal precipitation

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Abstract: Reliable and accurate measurement of precipitation plays a critical role in the studies of meteorology, hydrology and water resource management. In the past decades, satellite-based quantitative precipitation products have provided a suitable means to measure precipitation from space. An example is the TRMM (Tropical Rainfall Measuring Mission) microwave imager (TMI) products. It is well known that TMI products have an insensitivity to light precipitation and significant underestimation to heavy precipitation. In early 2014, National Aeronautics and Space Administration (NASA) and Japan Aerospace Exploration Agency (JAXA) successfully launched a new generation of satellite, Global Precipitation Measurement (GPM) Core Observatory. Onboard the GPM core satellite has a multichannel GPM microwave imager (GMI) which uses 13 different microwave channels to observe energy from the different types of precipitation through clouds for estimating everything from low to high precipitation. At present, several composite precipitation products with algorithms that related GMI and partner passive microwave sensors have been released, including Level 2 gridded Goddard Profiling GMI (2GPROF-GMI) and Level 3 mean monthly GPROF-GMI (3GPROF-GMI) products. It is therefore important to investigate whether these new GMI products are more reliable in estimating precipitation than those of TMI. In this study, differences between 3GPROF-GMI and 3GPROF-TMI products were compared over different surface types on a near-global scale for different seasons. The results show that a systematic difference (3GPROF-GMI > 3GPROF-TMI) for low and high precipitation. High positive correlation coefficient (CC) values are mainly in the Caribbean region, South Atlantic and over the African continent. Low CC values concentrate in equatorial regions, North Atlantic and Northwest Pacific. In addition, high mean absolute difference (MAD) and root mean square difference (RMSD) values dominate over the Tropics. By contrast, low negative MAD and RMSD values are found in the Inter-Tropical Convergence Zone (ITCZ). Histograms of both products are very similar; however higher frequencies for 3GPROF-GMI are found in the low and high precipitation ranges than those of 3GPROF-TMI. Statistics for different precipitation ranges reveal more details on the systematic differences over land and ocean. For low and relatively low precipitation, the MAD and RMSD values over land are slightly lower than those over oceans; on the other hand, the CC values over land are larger than those over oceans. For medium precipitation, the MAD, RMSD and CC values over oceans are in general higher than those over land in all seasons; but for relatively high precipitation, the opposite is found. The results of this study enhance the understanding of the difference between these two products, and provide a viable validation analysis for the updated GMI products.

Keywords: *Precipitation, Comparison, GPM, TRMM, GPROF*

Evaluation and Post-processing of the rainfall forecasts from NWP models for use in streamflow forecasting

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Abstract: Ensemble quantitative precipitation forecasts (QPFs) from NWP models have a wide range of applications, and are used routinely by experts to prepare for weather conditions in coming days. In hydrology, ensemble QPFs are used to force rainfall-runoff models to produce ensemble streamflow forecasts that characterise the forcing uncertainty. Ensemble streamflow forecasts are valuable to water managers and emergency agencies for making robust decisions. However, raw QPFs from Australian NWP models are deterministic and often contain systematic errors. Furthermore, the spatial resolution of the NWP model is often too coarse to resolve the scale and processes relevant for hydrological applications.

We apply a post-processing method to deterministic raw QPFs to produce calibrated QPF ensembles that are bias free, more accurate than raw QPFs and reliable for use in streamflow forecasting applications. The method combines a simplified version of the Bayesian Joint Probability (BJP) modelling approach and the Schaake shuffle. The BJP modelling approach relates raw QPFs and observed rainfall by modelling their joint distribution using 9 parameters. It corrects biases in the raw QPFs and generates ensemble forecasts that reflect the uncertainty in the raw QPFs. The BJP modelling approach is applied to each lead time and each forecast location separately. The Schaake shuffle generates spatially and temporally coherent calibrated forecasts by linking samples from forecast probability distributions at each consecutive lead time within the entire forecast and each forecast location (subarea) within the catchment.

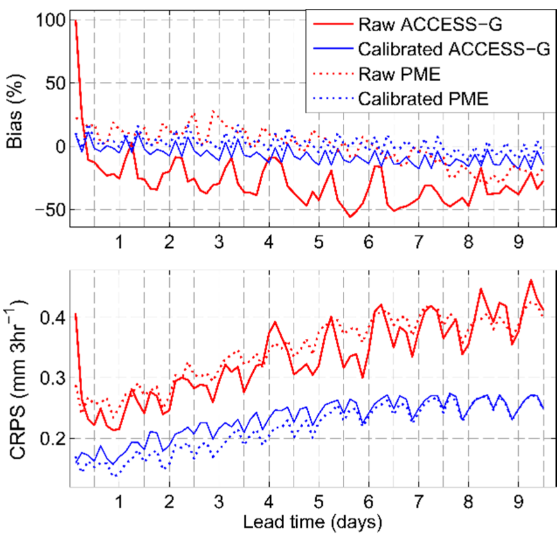

Fig 1. Bias and CRPS in the South Esk catchment

The post-processing method is applied to rainfall forecasts from two QPFs: the ACCESS-G (The Australian Community Climate Earth-System Simulator) NWP and the PME (Bureau of Meteorology's Poor Man's Ensemble) mean at a catchment scale. The performance of the raw and calibrated QPFs is evaluated on 14 Australian catchments that cover a wide range of climatic conditions and sizes varying from 246 to 19671 km^2. The evaluation is done using a leave-one-month-out cross-validation procedure for a period from 2010 August to 2013 December. We use a range of verification scores including bias, continuous rank probability score (CRPS) and probability integral transform to evaluate the quality of the forecasts. The results demonstrate that calibrated QPFs are bias free, contain smaller forecast errors than that of the raw QPFs and reliably quantify the forecast uncertainty out to 9 days. The deterministic PME rainfall forecasts outperform ACCESS-G rainfall forecasts, and post-processed PME rainfall forecasts are marginally better than post-processed ACCESS-G rainfall forecasts.

The ensemble rainfall forecasts generated by the post-processing method will be used to force hydrological models to produce ensemble streamflow forecasts. The Bureau of Meteorology has started adopting the method developed in this study to operationalise the ensemble flood and short-terms streamflow forecasting services in Australia.

Keywords: *Post-processing, Schaake shuffle, ACCESS-G, PME, Ensemble rainfall forecasts*

EXTENDED ABSTRACT ONLY

A post-processing approach to improve rainfall and streamflow forecasts at a range of Australian sites

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Abstract: Seasonal streamflow forecasts can provide valuable information for water resource management. The Bureau of Meteorology uses statistical and dynamical modelling approaches to generate seasonal streamflow forecasts. The dynamic approach uses catchment scale daily rainfall-runoff models forced by daily rainfall forecasts to generate seasonal streamflow forecasts. However, due to limitations of global circulation models and downscaling approaches, rainfall forecasts often have significant biases which can have a detrimental impact on streamflow predictions.

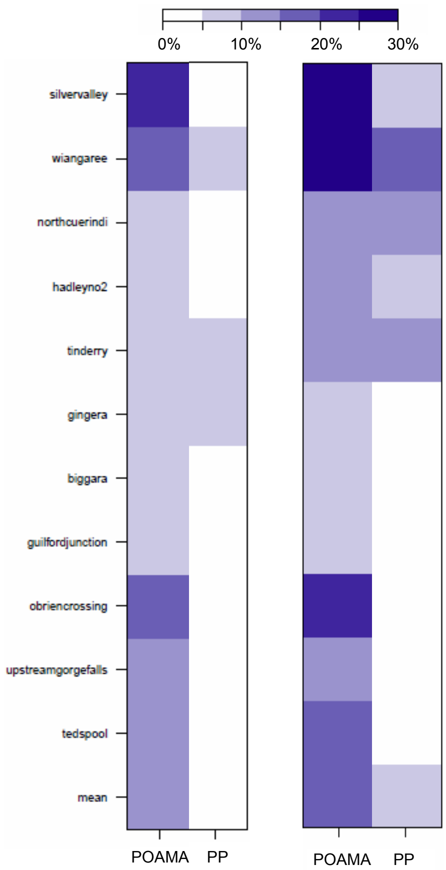
In this study we apply a post-processing (PP) approach to daily rainfall forecasts to correct these rainfall biases and assess the impact of using the improved PP rainfall forecasts on both daily and monthly streamflow forecasts. In particular, we implement a two-stage approach similar to Robertson et al (Hydrology and Earth System Sciences, 2013, 17: 3587–3603) with: 1) a multivariate normal approach with a logsinh transformation and censoring to correct the marginal and conditional statistics of the rainfall forecasts, and 2) the Schaake shuffle used to capture persistence in rainfall.

We consider 12 case study sites from around Australia, covering a wide cross section of climatologies and hydrological conditions. Rainfall forecasts are obtained from the Predictive Ocean Atmosphere Model for Australia (POAMA) M2.4 that have subsequently been downscaled to the catchment scale using the analogue downscaling approach (POAMA_DS). The POAMA_DS rainfall forecasts have biases that vary by month and lead time, so the PP approach takes this into account.

Evaluating the PP approach by comparison against POAMA_DS using leave-out cross validation found that it consistently reduced biases in mean daily rainfall (from 5-30% for POAMA_DS to 5-10% for PP - see Figure 1). With similar reductions in biases for proportion of rainfall days and amount of rain on wet days. The PP increased the probabilistic reliability of the rainfall forecasts (50% better, based on the reliability component of the CRPS), at the expense of decreased precision (0-30% worse, in terms of average standard deviation of predictions).

The improved rainfall forecasts are shown to have a significant improvement on streamflow predictions obtained using the GR4J conceptual rainfall runoff model (prior to streamflow bias correction). The reductions in bias for streamflow were higher than rainfall (from 10%-40% for POAMA_DS to 5-10% for PP – see Figure 1). Similarly, the improvement in probabilistic reliability was higher for both daily and monthly streamflow than rainfall, albeit with a decrease in precision.

Overall, the PP approach provides significant improvement in rainfall forecasts across a wide range of sites. This highlights its potential for Australia-wide application.



(a) Rainfall (b) Streamflow

Figure 1. Forecast Bias.

Keywords: *Forecasting, post-processing, rainfall*

Dimension reduction techniques to improve multivariate hydroclimatic forecasting models

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Abstract: The process of developing statistical hydroclimatic forecasting models is often faced with the problem of large numbers of potential input variables such as spatially distributed ocean-atmospheric state variables. In multivariate regression-type models, high dimensionality of predictors poses the risk of calibration overfitting and subsequent poor validation. This study overviews several different methodologies of dimensionality reduction in forecasting models.

Firstly, the LASSO (Least Absolute Shrinkage and Selection Operator) is mentioned as one of a family of regression-type prediction models which eliminate uninformative predictor variables. The reduced models tend to have good validation performance from the resulting simpler predictive expressions. The LASSO is a linear model, however, and may fail to detect potentially useful non-linear relations between response and predictor variables.

Secondly, a brief evaluation of selected data mining methods is considered. Data mining as a general exploratory tool has some advantage in that there is no reliance on assumed continuous functional relationships between causes and effects as with multiple regression models.

A preliminary application of the respective methods seeks to identify variables associated with river inflows to hydropower lakes in the Waitaki catchment, New Zealand. The aim here is to isolate predictor variables for season- and month-ahead inflow forecasting, extracting predictors from seasonal and monthly-averaged gridded Pacific variables – Fig.1.

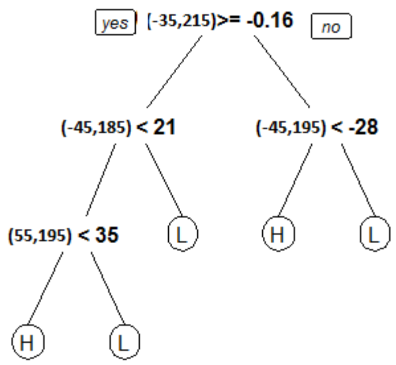

Figure 1: Preliminary decision tree of associations between gridded monthly 700hpa geopotential heights and the high (H) and low (L) monthly inflows in the Waitaki catchment. The first branch of the tree divides low and high flow situations (bracketed values are geographic coordinates) with respect to the anomalies of geopotential height around a point with (35S,215E) coordinates. The lowers branches utilizes information of geopotential heights around three more geographic points.

Keywords: *Data-based hydroclimatic forecasting, data mining, dimension reduction*

Statistical techniques for water forecasting

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Abstract: As we move into an era of probabilistic forecasting, suitable statistical techniques are needed to achieve as much forecast skill as possible and to reliably represent any remaining forecast uncertainty. However, hydrological variables and prediction errors are often not readily amendable to treatment using classical methods from statistical textbooks. In the last few years, our water forecasting research team in CSIRO has developed a number of statistical techniques. Examples of the statistical techniques are

- developing a new (log-sinh) transformation for normalising data so that homoscedastic Gaussian distributions can be used;
- treating zero (or other threshold) values of data as censored data so that continuous distributions can be used instead of the much less tractable discrete-continuous distributions;
- using joint probability models to make it easier to deal with non-concurrent data, missing data, zero values, multiple sites and multiple predictands;
- re-parameterisation of models to speed up solutions;
- using hierarchical models to exploit, from data, commonality and individuality of model parameters for different cases (for example seasons and catchments) to reduce model parameter and prediction uncertainty;
- using hierarchical models to break down large and complex problems to smaller and simpler components that are more tractable, leading to more efficient solutions;
- using restricted auto-regressive models for updating predictions to avoid over-correction and degraded performance of base hydrological models;
- using a multi-stage approach for robust calibration of hydrological models and error updating and quantification models; and
- using model combination to take advantage of individual strengths of multiple models.

These techniques have been used in developing

- the Bayesian joint probability (BJP) statistical model, which has been the operational model used by the Bureau of Meteorology for seasonal streamflow forecasting since December 2010;
- the calibration, bridging and merging (CBaM) method for post-processing outputs from dynamical climate forecasting models, to produce ensemble seasonal forecasts of rainfall and temperature with improved skill and reliable uncertainty spread;
- the forecast guided stochastic scenarios (FoGSS) model for producing ensemble time series forecasts of monthly streamflow out to 12 months;
- the ensemble spatial data imputation and interpolation model (ESDIIM) for generating ensemble climate surfaces from gauged data with non-concurrent and extensively missing data records;
- the rainfall post-processor (RPP) for post-processing rainfall forecasts from numerical weather prediction models to produce unbiased and reliable forecasts;
- the error reduction and representation in stages (ERRIS) method for hydrological modelling;
- the system for continuous hydrological ensemble forecasting (SCHEF) to lead times of 9 days; and
- the Bayesian model averaging (BMA) and quantile model averaging (QMA) methods for merging forecasts from multiple models to improve skill.

This presentation will give an overview of these techniques and their applications.

Keywords: *Transformation, censored and missing data, re-parameterisation, Bayesian joint probability model, hierarchical model, model averaging*

Calibration of a flood model using the MIKE FLOOD modelling package employing the direct rainfall technique

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Abstract: The MIKE FLOOD modelling package (2012 release) was used to develop and calibrate a hydraulic flood model for the Punrak catchment (located approximately 56 km south of Perth, Western Australia). The model was developed in a coupling environment where 1-D MIKE 11 channel flows interact with the 2-D MIKE 21 overland flows. The interactions take place via a series of well-defined lateral linked cells and standard linked cells. The lateral linked cells run along both banks of the channels/drains. Standard linked cells are located next to the upstream ends of the channels/drains and both ends of a culvert. Rainfall is applied on each computational cell and the runoff is routed within the hydraulic model. In this study, the developed model was calibrated to the 1996 winter event at two gauged locations of the model domain, one at the centre (Hopelands Rd gauging station) and the other at the outlet (Yangedi Swamp gauging station) of the catchment. The predicted results in terms of peak discharge, peak flood level, time to peak and volumes were compared with the observed data. There was fair agreement between predicted and observed results. The peak flood level and total storage volume at the outlet of the catchment were underpredicted by 0.5% and 1.2%, respectively, whereas, the peak discharge was overpredicted by 2.4%. The model results were obtained based on a 10 m grid resolution. A finer grid resolution would have improved the modelling results. It was not considered in this study as this would increase the computational cost significantly. This would also affect the project budget and time-frame. This paper explores the application of the direct rainfall technique, a comprehensive model setup of the MIKE FLOOD model for the study area and detailed comparisons of the calibration results.

Keywords: *MIKE 11, MIKE 21, channel flow, overland flow, direct rainfall technique*

Open source flood simulation with a 2D discontinuous-elevation hydrodynamic model

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Abstract: A new finite volume algorithm to solve the two dimensional shallow water equations on an unstructured triangular mesh has been implemented in the open source ANUGA software, which is jointly developed by the Australian National University and Geoscience Australia. The algorithm supports discontinuous-elevation, or 'jumps' in the bed profile between neighbouring cells. This has a number of benefits compared with previously implemented continuous-elevation approaches. Firstly it can preserve lake-at-rest type stationary states with wet-dry fronts without using any mesh porosity type treatment (mesh porosity treatments allow the bed to absorb some water as though it were porous). It can also simulate very shallow frictionally dominated flow down sloping topography, as typically occurs in direct-rainfall flood models. In the latter situation, mesh porosity type treatments lead to artificial storage of mass in cells and associated mass conservation issues, whereas continuous-elevation approaches with good performance on shallow frictionally dominated flows tend to have difficulties preserving stationary states near wet-dry fronts. The discontinuous-elevation approach shows good performance in both situations, and mass is conserved to a very high degree, consistent with floating point error.

A further benefit of the discontinuous-elevation approach, when combined with an unstructured mesh, is that the model can sharply resolve rapid changes in the topography associated with e.g. narrow prismatic drainage channels, or buildings, without the computational expense of a very fine mesh. The boundaries between such features can be embedded in the mesh using break-lines, and the user can optionally specify that different elevation datasets are used to set the elevation within different parts of the mesh (e.g. often it is convenient to use a raster digital elevation model in terrestrial areas, and surveyed channel bed points in rivers).

The discontinuous-elevation approach also supports a simple and computationally efficient treatment of river walls. These are arbitrarily narrow walls between cells, higher than the topography on either side, where the flow is controlled by a weir equation and optionally transitions back to the shallow water solution for sufficiently submerged flows. This allows modelling of levees or lateral weirs which are much finer than the mesh size.

A number of benchmark tests are presented illustrating these features of the algorithm. All these features of the model can be run in serial or parallel, on clusters or shared memory machines, with good efficiency improvements on 10s-100s of cores depending on the number of mesh triangles and other case-specific details.

Keywords: *Shallow water equations, finite volume methods, discontinuous-elevation, flood modelling*

Construction of depth-discharge relation for inundation simulation

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Abstract: This study aims to construct a depth-discharge relation for inundation simulation in the Mekong River considering hydraulic resistance. This relation links to the conveyance capacity of a river channel, one of the key components of inundation models, which means that understanding of the relation is necessary to conduct inundation simulation. A depth-discharge rating curve is constructed based on the simple assumption that discharge increases in a simple increasing function as depth increases. However, it is well recognized that this assumption is not valid in some cases: e.g., 1) rating curves constructed with only small-scale flood data are not always readily applicable to larger floods since extrapolation is often needed in this case, generally causing inaccurate estimation, and 2) rating curves cannot be maintained when river bed elevation changes, which means that they need to be checked periodically. One of the reasons for these cases is that hydraulic resistance varies as river bed shear stress changes during a flood. Accordingly, construction of the depth-discharge relation requires the knowledge of fluvial hydraulics, e.g., bed form and hydraulics resistance which is composed of velocity, water depth, hydraulic slope and bed material. A number of studies have been conducted on the relation between micro-scale bed form and hydraulic resistance. Engelund focused on the relation between dimensionless total and grain shear stress (the $\tau_* - \tau_*'$ relation). Kishi-Kuroki included the concept of relative water depth in the $\tau_* - \tau_*'$ relation. They also formulated a bed roughness (n_1) for each bed form. Yamamoto developed diagrams which indicate the relation among velocity factor, dimensionless total shear stress, and relative water depth.

Aiming to construct the depth-discharge relation based on field observation data and the relation between micro-scale bed form and hydraulic resistance, the authors analyze $\tau_* - \tau_*'$ relation by using observed data obtained by ADCP and the $\tau_* - \tau_*'$ relation proposed by Engelund. The target points of the river are selected from observation stations in Cambodia on the following conditions: 1) the river width is 1.0-2.0 km, 2) the maximum water depth is 30-40 m, and 3) the maximum discharge is 60,000 m^3/s during a severe flood.

Based on the observed results, the $\tau_* - \tau_*'$ relation agrees with the one proposed by Engelund under the condition of that n_1 is identical to the bed roughness calculated with Manning's equation. The discharges calculated based on the $\tau_* - \tau_*'$ relation reproduce the discharges observed by ADCP in 2009. In addition, the calculated discharge with roughness composed of only grain roughness reproduces the peak discharge in 2011 estimated by the Mekong River Commission. The results will be useful to estimate discharges as a boundary condition. Moreover, the knowledge acquired in this study will help modeling bed roughness with respect to hydraulic force for further study related to inundation simulation.

Keywords: *Hydraulic resistance, micro-scale bed form, field observation, Mekong River*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Floodplain inundation modelling: Why, How and Where from here?

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Abstract: Flooding is a global phenomenon that causes casualties and property loss in every inhabited continent on earth. With an average annual cost of $314 million (Bureau of Transport Economics 2001), and sometimes a single bill as high as $30 billion (Queensland floods 2011), floods are estimated to be the most costly natural disaster in Australia. The situation is expected to exacerbate, as flood events are likely to increase, both in frequency and intensity, due to global warming. Future climate projections from the majority of the global climate models indicate that the future climate will be more extreme with longer dry periods and more extreme weather events. On the other hand, the impact of floods is not always negative as they are a part of a natural cycle and can have great environmental and social benefits particularly in areas which have suffered from prolonged drought. Periodic scouring floods are even crucial for ecosystems in most riverine and coastal wetlands. It is of interest to various state and federal disaster management agencies, local councils, catchment management authorities, water resources managers and planners, insurance companies, as well as general public to better understand, assess, and predict flood events and their impact. Floodplain inundation models are therefore required to support any decision-making related to floods.

In the past century, many methods/models have been developed for this purpose. Two groups of approaches have attracted the most attention and are the subject of ongoing research: empirical methods such as surveys, measurements, remote sensing and statistical models evolved from these data-based methods; and hydrodynamic models including 1D, 2D and 3D methodologies that simulate water movement by solving partial differential equations (PDEs) derived from applying Newton's second law to fluid motion with varying degree of complexity. The recent advances in the former group are mainly related to remote sensing. More launches, better sensors, shorter return period have resulted in higher quality remotely sensed data becoming more readily available. Algorithms, data-mining techniques and decision trees have been developed to extract more accurate and larger amount of information from data. The latest progress in the latter group includes improvements in numerical solutions of the governing PDEs, in particular, shock-capturing wetting and drying algorithms. With advances in computing power, the performance of hydrodynamic models has improved exponentially. Parallel computing and distributed workflows are frequently used to meet the high computational demand. The accessibility of the models has been broadened from research to commercial and now open-sourced. Apart from improvements of the individual method/model, the combination of models is receiving wider recognition as it allows almost limitless possibilities for maximising the benefits of 1D, 2D and 3D modelling approaches. Remarkable progress has been achieved in integrating remote sensing with hydrodynamic models too. LiDAR and SRTM DEM, both derived from remote sensing, have become the foundation of flood modelling. Remote sensing–derived flood inundation area, stage and discharge are also widely used for data assimilation in hydrodynamic models.

Despite the above mentioned developments, rapid and accurate floodplain inundation modelling at high spatio-temporal resolutions remains a significant challenge in hydrology and hydraulics research. In recent years, a third group of approaches is increasingly gaining popularity for modelling very large floodplains (such as national scale flood risk assessment) and data sparse regions. These models are based on much simpler representations of physical processes and have run times many orders of magnitudes shorter than hydrodynamic models. They are suitable for stochastic modelling to produce probabilistic estimates and to quantify model uncertainty.

Combined with climate models, hydrological models, and river models, the application of floodplain inundation modelling has been extended from traditional flood hazard mapping and flood risk/damage assessment, to scenario modelling that formulate and implement climate adaptation and risk mitigation strategies. They can be linked to streamflow forecasting models to provide real-time flood inundation forecasts. Reliable and robust simulation of inundation characteristics also makes it possible to effectively plan environmental flows in order to maintain healthy aquatic ecosystems. There are endless potentials in improving and applying inundation models to investigate the impact of floods on human society.

Keywords: *Flooding, natural hazard, large floodplain, high resolution, 1D, 2D, 3D hydrodynamic model*

A comparison of Landsat and MODIS flood inundation maps for hydrodynamic modelling in the Murray Darling Basin

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Abstract: The mapping of spatial inundation patterns during flood events is important for environmental management and disaster monitoring. Remote sensing technologies provide an affordable means of capturing flood extent with reasonable spatial and temporal coverage for flood monitoring. Landsat and MODIS are commonly used for producing flood inundation maps since they can cover large remote regions, are readily available and easy to process. Hydrodynamic modelling tools are widely used for floodplain inundation modelling to a high accuracy, but they are resource intensive, making them impractical to use for large catchments. There are also few hydrological floodplain inundation modelling tools which represent the detailed floodplain hydraulics using simplified hydrological concepts and equations partly overcoming the issues associated with hydrodynamic models for large scale applications. Remote sensing products are useful and to some extent necessary for both calibrating and validating hydrodynamic and hydrological floodplain inundation models, as well as extending the coverage. The higher spatial resolution of the Landsat data (30-m pixel size) makes it ideal for many flood mapping applications, however its temporal frequency (16 days) is not always suitable for short duration flood events. The MODIS sensors acquire imagery up to two times a day – once on the TERRA platform in the morning, and once on the AQUA platform in the afternoon – however its spatial resolution ranges from 250-m up to 1000-m, which is not ideal for fine-scale flood events. This paper performs a detailed comparison of flood maps derived from Landsat data (based on the Normalized Difference Water Index), and MODIS data (based on the Open Water Likelihood algorithm) for a number of selected flood events in the Murray Darling Basin (MDB) in Australia. It directly compares and analyses the advantages and disadvantages of both the Landsat and MODIS sensors for mapping the flood events. The outputs from MODIS and Landsat data for a selected flood event in the Murrumbidgee floodplain in the MDB are also compared to the simulated inundation results from a two-dimensional hydrodynamic model.

Keywords: *Flood mapping, remote sensing, floodplain inundation*

A MODFLOW–based approach to simulating wetland–groundwater interactions in the South East region of South Australia

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Abstract: Groundwater resources in the South East region of South Australia are comprised of a highly-utilised karstic limestone aquifer indirectly overlying a confined sand aquifer. Due to shallow water tables, many wetlands in the South East interact with the unconfined aquifer. Many of these wetlands are environmentally significant; e.g. Bool Lagoon is managed in accordance with the RAMSAR Convention on Wetlands. As part of the Goyder Institute's South East Regional Water Balance Project, a regional-scale numerical model was developed to inform the broad scale understanding of groundwater flow in the South East region. One aspect of the groundwater flow system that cannot be addressed using this regional-scale model is the interaction between the unconfined aquifer and various wetlands that are present across the region. This is due to disparities in scale: the dimensions of finite difference cells used in regional groundwater flow models are typically ~1 km, which is greater than the spatial extent of many South East wetlands. Of particular interest to water resources management is the potential for managed surface water inflows to negate the effects of long-term water table decline on the persistence of wetland surface water levels. A local-scale conceptualisation of wetland-groundwater interactions was therefore developed, which included all hydrological processes considered relevant at the local-scale. Wetland water processes included precipitation, evaporation, transpiration, and surface water inflows. Shallow groundwater processes included recharge, lateral flows, and changes in storage. Fluxes between the two domains were computed as a function of depth to groundwater, which was manipulated by adjusting groundwater boundary conditions on the lateral model boundaries. The model conceptualisation was designed so that these time-varying boundary conditions can be sourced from a regional-scale model. Alternatively, these may be informed by observed data. This conceptualisation was implemented as a vertical cross section numerical model using a recently-developed variant of the widely-used finite difference groundwater flow code MODFLOW (i.e. MODFLOW-OWHM). The numerical model featured a novel approach to the representation of groundwater recharge and evaporation fluxes by combining these into 'net recharge'. In this approach, both fluxes were simulated concurrently using a piecewise-linear function. Such functions represent the combined effects of plant water use and soil type. A function appropriate to the South East region was produced by a companion Goyder Institute project. This approach to representing net recharge was implemented using the Riparian Evapotranspiration (RIP-ET) package for MODFLOW-OWHM. Two versions of the net recharge function were specified for model cells located either adjacent to or below a wetland. For the former, the net recharge flux applied when the water table was at or above groundwater surface (i.e. at the top of the model cell) was set to potential evapotranspiration. Conversely, to simulate net recharge fluxes from cells directly located below a wetland (i.e. below Lake package cells), the net recharge flux applied when the water table was at or above the top of the cell was set to zero. Using a realistic synthetic input dataset, the model was used to successfully simulate the extent and duration of wetland inundation.

Keywords: *Wetlands, groundwater, net recharge*

EXTENDED ABSTRACT ONLY

Using a fast conceptual river model for floodplain inundation forecasting and real-time flood control - a case study in Flanders, Belgium

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Abstract: Due to climate change, the risk of floodplain inundations will further increase in many regions of the world. Therefore, there is a need for climate adaptation and improved flood control management. In densely populated areas as the Flanders region of Belgium, where open spaces are limited, building new infrastructure and large retention reservoirs has its limits. For these areas, but also for many other areas, it is important to use the existing infrastructure in the most optimal way. This research investigates how this can be achieved by making use of a fast conceptual river model for floodplain inundation forecasting and real-time flood control. The developed method is tested for the case study of the Demer basin in Belgium, but is generally applicable to other places.

River models are required to forecast floodplain inundations. The Flemish Environment Agency (VMM) has developed full hydrodynamic river models, implemented in the Infoworks™-RS software for all the important river basins in Flanders. These models solve the Saint-Venant equations explicitly, which makes them very time consuming and not appropriate for the purpose of real-time flood control. Therefore, a fast conceptual model is calibrated, whereby the floodplains are modeled explicitly. This reservoir-type model is combined with damage – water level functions to assess economic flood consequences for each of the floodplains in the basin. These damage functions express the damage cost that occurs during floods in monetary values based on the water levels in the floodplains. In this way different floodplain inundation forecasts and different flood control strategies can be quantified and compared in an objective way.

To date, retention reservoirs and hydraulic structures in Flanders are controlled by fixed regulation rules. They involve a local, instantaneous and static regulation, which results in a suboptimal flood control. In our research, we apply the Model Predictive Control (MPC) technique whereby a hydraulic river model and precipitation forecasts are used to predict the future states of the river network. In this way a regional, anticipating and dynamic regulation can be achieved. In this research, a genetic algorithm (GA) is used to generate different future control strategies. These strategies are applied to the conceptual river model to forecast floodplain inundations and their corresponding damage costs. By evaluating these damage costs, the best control strategy can be selected and applied. During each optimization step, new control strategies are generated and mutations are carried out on the best control strategy so far. Due to the specific nature of the MPC-GA algorithm, different control strategies can be considered in parallel, which leads to a huge increase in computational efficiency.

After application of the above technique to the Demer basin case study for a number of rainfall events, the MPC-GA algorithm strongly reduces the total damage cost compared to the current fixed regulation. This shows the added value of real-time flood control based on floodplain inundation forecasting.

Keywords: *Floodplain inundation forecasting, real-time flood control, Model Predictive Control (MPC), genetic algorithm (GA), conceptual model*

Development of an improved flood frequency curve applying Bulletin 17B guidelines

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Abstract: Flood frequency curves for gauging stations are developed by fitting the logarithms of annual peak flows to a Pearson Type 3 distribution. Such a curve is sensitive to the mean, standard deviation and skew coefficient computed from the logarithms of the annual peak flows. If a gauging station is identified as a short record site then adjustments of the mean, standard deviation and skewness are required as suggested in Bulletin 17B, developed by the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey. The mean and standard deviation can be improved by undertaking a regression analysis for the short record site with a nearby long record site. The estimate of the station's skew coefficient can be improved if it is weighted by the regional skew coefficient. In this study, annual peak flow data of 80 gauging stations in Western Australia are analysed to estimate the regional skew coefficient for the area of interest. The regional skew coefficient estimation technique applied in this study is rudimentary which does not follow the complete instruction of the Bulletin 17B. The improvement of the mean and standard deviation is done by following the complete instruction provided in Bulletin 17B. A software tool is developed using MATLAB to carry out the current study. This tool is GUI-enabled which takes flood data from the users and generates flood frequency curves based on the two station method mentioned in the Bulletin 17B. A flood frequency curve is developed for the Kentish Farm gauging station (614005) using this software tool. The Mundlimup gauging station (614073) is used as a long record site for the adjustments of the mean and standard deviation to improve the flood frequency estimates.

Keywords: *Generalized skew coefficient, flood frequency curve, LP3 distribution, Bulletin 17B, Western Australia*

A New Probabilistic Rational Method for design flood estimation in ungauged catchments for the State of New South Wales in Australia

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Abstract: Design flood estimates for ungauged catchments are needed in the planning and design of bridges, culverts and many other water infrastructure projects. The most commonly used methods of flood estimation in practice for the ungauged catchments include the Index Flood Method, quantile regression technique and Probabilistic Rational Method (PRM). In Australia, the regional flood frequency estimation (RFFE) methods recommended in Australian Rainfall and Runoff (ARR) 1987 include PRM for eastern New South Wales (NSW) and Victoria States. In the upcoming ARR 2016, the recommended RFFE method is based on regression and region-of-influence approaches for NSW, which is referred to as RFFE Model 2015. In this study, a new PRM is developed and tested for NSW.

A total of 106 catchments are used to develop and test the new PRM. These data are obtained from ARR Project 5 Regional Flood Methods. The catchment areas for the selected catchments range from 1 to 1010 km^2. The mean and median catchment areas are 273 km^2 and 169 km^2, respectively. The streamflow record lengths range from 20 to 82 years, with a mean of 38 years and median of 35 years.

Twelve different forms of PRM are examined, which are formed based on different combinations of observed runoff coefficients (C_{10}) and frequency factors (FF_Y). The C_{10} values at a test catchment site are estimated using inverse distance weighted method based on different combinations of the at-site C_{10} values i.e. (i) nearest one site; (ii) two nearest sites; (iii) three nearest sites; and (iv) five nearest sites. The FF_Y values are estimated using three different approaches. A leave-one-out (LOO) validation approach is adopted to compare various forms of the PRM. At-site flood frequency analysis (based on the log Pearson Type 3- Bayesian method) is used as the 'benchmark' for this LOO validation.

It is found that the best PRM case is achieved when C_{10} value is estimated from the three nearest sites and FF_Y is taken as the median value over all the model catchments. The results of this study reveal that the new PRM can be used to accurately predict the peak flow rates for small-to-medium sized catchments in the NSW region. For the new PRM, the typical median relative error values based on the leave-one-out validation is 45% to 55% for 20% to 1% annual exceedance probabilities. However, for the 50% AEP flood, the median relative error value is 77%. These relative error values are comparable to ARR RFFE Model 2015. The main advantage of the new PRM against the ARR 1987 is that it does not need a contour map to estimate the runoff coefficient and it can be automated in an application tool like the ARR RFFE Model 2015. The new PRM is being extended for other states of Australia.

Keywords: *ARR, RFFE 2015, PRM, floods, regional flood frequency estimation, ungauged catchments*

Development and Validation of Artificial Intelligence Based Regional Flood Estimation Model for Eastern Australia

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Abstract: This paper presents the development and validation of an artificial intelligence based regional flood frequency analysis (RFFA) model for application in ungauged catchments of eastern Australia. The artificial intelligence based techniques with a flexible model structure and non-linear approach can overcome the limitations of the conventional RFFA models, which are generally based on linear relationship between flood statistics and catchment characteristics. Till now, there have been limited applications of artificial intelligence based techniques to RFFA problems in Australia. This study has developed four artificial intelligence based RFFA models for eastern Australia, using a comprehensive flood database available as a part of Australian Rainfall and Runoff (ARR) revision 'Project 5 Regional flood methods'. These four RFFA models are based on artificial neural network (ANN), genetic algorithm based artificial neural network (GAANN), gene-expression programing (GEP) and co-active neuron fuzzy inference system (CANFIS).

A total of 452 catchments from the states of New South Wales, Victoria, Queensland and Tasmania have been considered by this study. These dataset is divided into training and validation sets. Data of 362 catchments (training data set) have been used to train the model and the data from the remaining 90 catchments (validation data set) used to validate the model. The models have been trained/calibrated using the training data set that involved minimisation of the mean squared error between the observed and predicted flood quantiles by the model (being trained) for a given ARI for the training data set. Six average recurrence intervals (ARI) flood quantiles (2, 5, 10, 20, 50 and 100 years) were considered in this study. Four evaluation statistics are adopted to assess the model accuracy: median ratio of the predicted flood quantile (Q_{pred}) and observed flood quantile (Q_{obs}), denoted by Q_{pred}/Q_{obs} ratio, plots of Q_{obs} and Q_{pred}, median relative error and coefficient of efficiency. This is initially done for the training data set and then repeated for the validation data set.

The artificial intelligence based RFFA models have been ranked based on their relative performances in relation to the above criteria to identify the best trained/calibrated model. It has been found that none of the four models is superior across all the six ARIs against the adopted criteria. The ANN based RFFA model has a better ranking score in terms of training/calibration; therefore, it is suggested that the ANN-based RFFA model is the best calibrated model among the four artificial intelligence based RFFA models for eastern Australia.

Keywords: *Floods, genetic algorithm, regional flood frequency analysis, ungauged catchments, ANN*

Development of a regional flood frequency estimation model for Pilbara, Australia

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Abstract: This paper presents the development of regional flood frequency estimation (RFFE) models for Pilbara, Western Australia as a part of Australian Rainfall and Runoff (ARR) revision. The Pilbara is an economically important arid region, which is rich in natural resources and mining activities. A total of 11 catchments are selected from the Pilbara region to develop the RFFE models. The selected catchments are arid with average annual rainfall values are in the range of 200 and 350 mm. For each of the selected catchments, flood quantiles are estimated for 6 annual exceedance probabilities (AEPs), which are 50%, 20%, 10%, 5%, 2% and 1% using two estimation approaches: (i) annual maximum flood series (AMS): Log Pearson Type 3 (LP3) distribution-Bayesian procedure and (ii) partial duration series (PDS) (with average number of events per year equal to 0.5): Generalised Pareto distribution and L moments procedure. The AMS consists of maximum discharge value in each calendar year; however, the PDS consists of all the independent peak flows over a certain threshold. Two different RFFE models are developed (using AMS and PDS data) using an index flood method where the 10% AEP flood quantile (Q_{10}) is used as the index variable and a dimensionless growth factor for AEP of x% (GF_x) is used to estimate Q_x (where, x = 50%, 20%, 10%, 5%, 2% and 1%). The prediction equation for the index flood is developed using an ordinary least squares regression with two predictor variables (catchment area and design rainfall intensity). The results demonstrate that the performance of the two RFFE models is quite similar. For AEPs of 50% to 1%, the absolute median relative error values of the estimated flood quantiles are found to be in the range of 23% to 46% and 42% to 56% for AMS and PDS based RFFE models, respectively. The results reveal that both the models are able to generate flood quantiles with a good accuracy; however the AMS-based RFFE model outperforms the PDS-based model.

Keywords: *Pilbara, RFFE, ARR, arid region, semi-arid region, floods*

Regional Flood Estimation for NSW: Comparison of Quantile Regression and Parameter Regression Techniques

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Abstract: Australian Rainfall Runoff (ARR) (1987) recommended a number of regional flood frequency estimation (RFFE) techniques to estimate design floods in ungauged catchments in Australia. These include Probabilistic Rational Method (PRM) for eastern New South Wales (NSW) and Victoria, and Index Flood Method (IFM) for western NSW. The PRM method uses a probabilistic runoff co-efficient map based on linear geographical interpolation, while the criterion of regional homogeneity required by the IFM method is rarely satisfied for Australian regional flood data. Recent studies on regression-based RFFE techniques have demonstrated that these can provide quite accurate flood quantile estimates in Australia using only a few predictor variables. Two regression-based methods, Quantile Regression Technique (QRT) and Parameter Regression Technique (PRT) have been tested recently in Australia. The QRT develops regression equation for individual quantile; however, PRT develops regression equations of the parameters of a probability distribution. For example, in the case log-Pearson Type 3 (LP3) distribution, the PRT develops regression equations for mean, standard deviation and skew of the logarithms of annual maximum flood series data.

This study presents a comparison between the PRT and QRT methods for NSW State in Australia using data from 96 small to medium sized gauged catchments. Out of 96 catchments, 12 are selected randomly as test catchments to make an independent validation of the PRT and QRT methods. The results show that both the PRT and QRT perform very similarly, with relative error values in the range of 36% to 45%. Further studies using data from different geographical regions of Australia need to be conducted before recommending an appropriate RFFE method for application in Australia.

Keywords: *Ungauged catchments, quantile regression technique, parameter regression technique, annual maximum flood series, LP3 distribution*

EXTENDED ABSTRACT ONLY

The use of 2D hydrodynamic modelling to estimate flood discharge in a wet tropical river catchment

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Abstract: Underestimation of flood discharge has been recognised in many rivers, both in Australia and internationally. Most of the water discharged from Australian rivers occurs during floods. Discharge during these flood events is usually significantly underestimated by standard river gauges. There are two main reasons for this; (i) water which goes over bank and bypasses the gauge and (ii) the use of rating curves that are developed for in-bank flows. One way to improve flood discharge estimation is to use two-dimensional (2D) hydrodynamic modelling which uses a grid based flow computation technique. Being able to quantify bypass flow is crucial when estimating sediment and nutrient loads to ocean during floods. This study investigated the application of a 2D floodplain hydrodynamic model (MIKE 21) to estimate flood discharge in a wet tropical river catchment (Tully-Murray) in the northern Queensland where on average 2 to 3 floods occur each year. We used LiDAR (Laser Altimetry) derived 3 m DEM to reproduce floodplain topography and stream networks in the model. The DEM was resampled to 30 m in the actual simulation to reduce the computational time. The computational domain for the present setup covered 720 km^2 of the floodplain (30×24 km) with 800,000 computational grids. Computational time increment was derived after satisfying numerical stability criteria. A time step of 4 sec was used as this produced a stable solution for floods with an average recurrence interval of up to 50 years. Model outputs (i.e. stage height and flow flux) were recorded at two hourly time step.

The model was calibrated and validated using observed in-stream stage height and floodplain inundation depths. The calibrated model was used to simulate 20 flood events that occurred between 2006 and 2010. Flood discharges at two hourly time step were calculated using the MIKE 21 hydrodynamic tool and accumulated for the flooding period to obtain flood flow volume. Results were compared with gauged flow for the same period (Figure 1). In all cases simulated flood flow was found larger than the gauged flow. A linear regression model was fitted for the observed versus simulated flood flow. On average simulated flood volume was found 47% greater than the observed flow with correlation coefficient of 0.97. It is important to note that the stream gauge is located about 30 km upstream from the catchment outlet. We found that flood volume at the catchment outlet is 3% higher compared to simulated flood volume at gauge. It is clear from the above study that floods can play a major role in the transport of sediment and nutrient to the ocean and that if their discharge and water quality are not measured correctly this can lead to very large underestimates of marine sediment and nutrient loads. Uncertainties on simulated discharge were not estimated in this analysis. This will be addressed in subsequent studies.

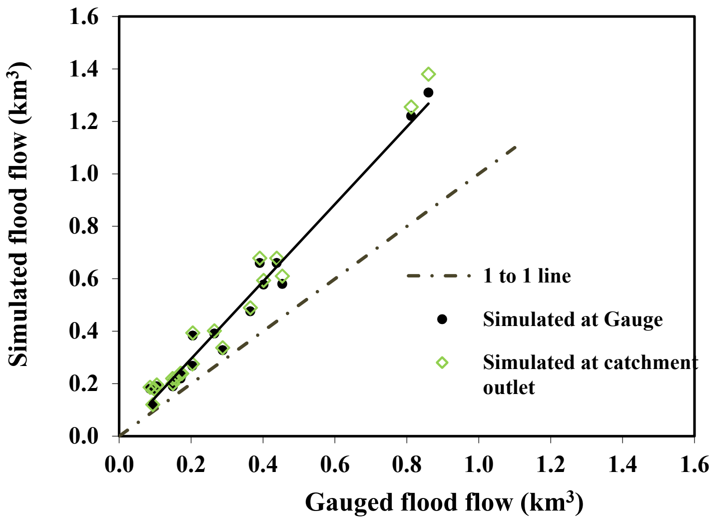

Figure 1. Comparison between observed and simulated flood flow.

Keywords: *Floods, hydrodynamic modelling, discharge, LiDAR, rating curve*

Uncertainty Estimation in Design Rainfalls: A Modelling Framework for Qatar Arid Region

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Abstract: In stormwater system design, flood insurance studies and flood protection works, hydrological models are adopted to estimate design flows. Design flows are referred to as a runoff discharge associated with a given average recurrence interval (ARI) or annual exceedance probability (AEP). These models require design rainfall as the most important input among other inputs such as catchment characteristics representing runoff routing behaviour and losses. The design rainfall, often known as intensity-duration-frequency (IDF) data, is generally derived using a regional frequency analysis approach based on a group of rainfall stations that form a homogeneous region. An Australia, design rainfall is known as intensity-frequency-duration (IFD) data. A large degree of uncertainty is associated with IDF data, which often is not quantified and considered in majority of hydrologic modelling applications.

This paper presents a modelling framework to quantify uncertainty in design rainfalls for Qatar due to uncertainties arising from limited data length and parameters of the adopted probability distribution model. Qatar is situated in arid region, which has limited rainfall data in terms of number of stations, resolution of data (e.g. only daily rainfall data is available for most of the stations) and record length of the available data. The proposed modelling framework accounts for the uncertainty in the rainfall data using a Monte Carlo simulation technique where a multivariate normal distribution is adopted in accounting for the uncertainty in the parameters of the log Pearson Type 3 (LP3) distribution. A bootstrapping method is adopted to estimate the mean and standard error values and the correlations among the three parameters of the LP3 distribution to define the multivariate normal distribution. A total of 10,000 simulations are carried out to develop the 90% confidence intervals for the 24-hour duration rainfall quantile. It has been found that uncertainty in IDF curves is quite high; to reduce the uncertainty band in estimated rainfall quantiles, a higher record length is needed, which however is not currently available in Qatar region.

The proposed modelling framework is in the developmental stage, which is applied in this paper to a single station and for one rainfall duration (24-hour). The proposed method is being enhanced by adding other sources of uncertainties in design rainfall estimation e.g. uncertainty due to data quality and climate change. Furthermore, other rainfall durations from a large number of stations will be considered, which will enable better quantification of the uncertainty in the design rainfalls in Qatar.

Keywords: *Arid regions, floods, IDF, Monte Carlo simulation, Qatar, rainfalls*

Assessing components of the natural inundation regime to restore through infrastructure projects

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Abstract: Alteration to the natural flow regime of rivers and their floodplains has had a variety of impacts, including a reduction in habitat due to change infrequency and duration of inundation events and a corresponding reduction in abundance, distribution and condition of floodplain communities. Furthermore, aquatic habitats with hydraulic complexity, particularly those offering fast flowing habitat, have significantly declined under river regulation. The River Murray is an example where alterations to the flow regime associated with water extractions and regulation have resulted in degradation of ecological function and condition. With the implementation of the Basin Plan, overbank inundation events are expected to become more common compared to the recent past. However, under the Basin Plan the frequency and duration overbank events is still likely to remain lower than that of the natural water regime. Infrastructure projects and engineering solutions can be used to further restore a more natural inundation regime, extending the area of inundation for a given flow. For those biotic communities that are primarily driven by the duration and frequency of inundation events, this would be expected to increase their abundance, distribution or condition. As part of these infrastructure projects, the South Australian Riverland Floodplains Integrated Infrastructure Program (SARFIIP) has been initiated to improve the condition of the biotic communities of Pike Floodplain and Katarapko Floodplain, two important floodplain complexes of the River Murray in South Australia.

This paper presents the hydrological and hydraulic investigations undertaken as part of SARFIIP to assess inundation and hydraulic regimes of these two floodplains for a range of conditions:

- Without development; without modifications to the floodplains or development influences on flow in the River Murray,
- Baseline; current floodplain structures and the flow regime expected based on pre-Basin Plan conditions,
- Basin Plan; current floodplain structures with a range of Basin Plan water recovery scenarios considered,
- Intervention; proposed floodplain infrastructure of SARFIIP and Basin Plan water recovery scenarios considered.

The hydraulic modelling was done using MIKE FLOOD modelling platform and Inundation extents were modelled by simulating a range of flow rates for each Floodplains. The results indicated that the frequency of inundation of a given location on the floodplains was significantly reduced in the current and Basin Plan flow regimes compared to the natural flow regime. The ecological implications of this are that even under the Basin Plan, it is likely that native vegetation condition and extent will continue to decline resulting in the loss of habitat for fauna dependent on that habitat.

Comparison of inundation extents, frequencies and durations within the floodplain between natural conditions and Basin Plan conditions indicates that additional flows delivered to the Murray–Darling Basin through the Basin Plan alone cannot be expected to achieve full ecological benefits provided by natural conditions. Through the use of infrastructure solutions, the modelling suggests that inundation events can be created that align with the natural extent for the same frequency and duration of an events, particularly for longer duration events that are more difficult to restore through higher flows. This work has demonstrated the combined benefits of improving inundation regime through the Basin Plan, along with complimentary infrastructure projects.

Keywords: *River Murray, South Australian Riverland Floodplains, infrastructure projects, hydraulic modelling, MIKE FLOOD*

Sampling Variability in Flood Frequency Analysis: How Important Is It?

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Abstract: Flood quantile estimation using available streamflow records, known as at-site flood frequency analysis (FFA), are widely used in hydrology. The estimated flood quantiles by at-site FFA are used in the planning and design of many water resources management tasks. However, FFA estimates often suffer from high sampling variability, in particular when length of streamflow record is relatively short. This aspect of FFA has not been fully examined for Australian catchments. As the hydrology in Australia suffers from a very high degree of variability, it is likely that the sampling variability in FFA is also very high.

This paper presents results from a case study based on three different gauged stations located in New South Wales, Queensland and Victoria using the FLIKE (an extreme value analysis package) software. These stations represent different hydrological regimes (e.g. Victoria is dominated by winter rainfall and Queensland is by summer rainfall). Two widely used probability distribution functions, Generalized Extreme Value (GEV) and Log Pearson type 3 (LP3) distributions are adopted in this case study. We have used updated flood data which have been prepared for Australian Rainfall and Runoff Project 5. The selected streamflow data length ranges from 58 to 102 years. The annual maximum flood data at each of these stations have been sub-divided into three sub-sets: full data set, 50% split and 25% split, which enables to carry out this test with sample sizes in the range of 14 years to 51 years.

The study shows that for all the three stations, at-site flood quantile estimates are more affected by the sampling variability in the case of the LP3 (Bayesian) distribution than the GEV (L moments) distribution. Based on the results of this empirical study, it has been found that for 50, 40, 30, 20 and 15 years of annual maximum flood data lengths, the sampling variability estimates are in between -41% to 326% (for LP3 distribution) and -42% to 39% (for GEV distribution) relative to the full data length.

The findings of this study have crucial implications in the field of FFA as at-site FFA estimates are generally taken ‘accurate’ in decision making. Furthermore, in assessing the performances of the regional flood frequency estimation models and calibration of runoff routing model, at-site flood frequency analysis estimates based on about 25 years of data are considered ‘robust’ and ‘accurate’, which seems to be not the case. This exercise is being conducted to a greater number of stations by applying boot-strap and Monte Carlo simulation techniques, which will enable to generalize the findings of this study.

Keywords: *Flood frequency analysis, LP3 distribution, GEV distribution, sampling variability, FLIKE*

Features of Regional Flood Frequency Estimation (RFFE) Model in Australian Rainfall and Runoff

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Abstract: Flood estimates at ungauged catchments are generally associated with a high degree of uncertainty. For the upcoming Australian Rainfall and Runoff (ARR) 2015 (4th edition), a new regional frequency estimation (RFFE) model known as ARR RFFE Model 2015 has been developed. This RFFE Model 2015 is based on the concept of regionalization, which is a data driven approach where data from gauged catchments are utilized to make flood quantile estimates at ungauged locations. This paper presents the modelling approach that underpins the RFFE Model 2015.

In the RFFE Model 2015, Australia is divided into humid coastal areas and arid/semi-arid areas. In the humid coastal areas, a region of influence approach is adopted to form sub-region by drawing a number of nearby gauged catchments for a location of interest. This in essence attempts to reduce the degree of heterogeneity in forming local region at the location of interest. For estimating flood quantiles, a regional log Pearson Type 3 (LP3) distribution is adopted where the location, scale and shape parameters are estimated based on prediction equations. A Bayesian Generalized Least Squares (GLS) regression approach is adopted to develop prediction equations in the humid coastal areas. The main advantages of GLS regression is that this accounts for inter-station correlation and variation in streamflow data lengths across different sites in a region. Furthermore, GLS regression differentiates between the sampling and model errors and hence provides a more rigorous approach of dealing with uncertainty in regional flood modelling compared with the ordinary least squares regression.

For the arid/semi-arid areas, an index flood method is adopted where 10% annual exceedance probability (AEP) flood is taken as the index variable. The prediction equation for the index variable is developed using an ordinary least squares regression approach in the arid/semi-arid areas. The regional growth factors are estimated from the at-site flood frequency analysis where LP3 distribution is fitted to the annual maximum flood series data. The Multiple Grubb-Beck test is used to censor the zero and low annual maximum flood series data points, which is typical in the arid regions. A total of 798 gauged catchments are used from the humid coastal areas and 55 catchments from the arid/semi-arid areas to develop and test the ARR RFFE model. The data from these catchments are prepared adopting a stringent quality control procedure that involved infilling the gaps in the data, checking for outliers, trends and rating curve extrapolation error.

In developing the confidence limits for the estimated flood quantiles, a Monte Carlo simulation approach is adopted by assuming that the uncertainty in the first three parameters of the LP3 distribution (i.e. the mean, standard deviation and skewness of the logarithms of the annual maximum flood series) can be specified by a multivariate normal distribution. In the ARR RFFE model, the model coefficients have been embedded in an application software (known as RFFE Model 2015), which enables the user obtaining design flood estimates relatively easily using simple input data such as latitude, longitude and catchment area of the ungauged catchment of interest.

The RFFE Model 2015 is applicable to any catchment that has similar attributes and flood producing characteristics as the catchments used in the derivation of the flood estimation equations embedded in the RFFE model. Catchments which do not satisfy this requirement can be divided into three groups: (i) catchments which have been substantially modified from their natural characteristics and for which the RFFE model is not applicable and should thus not be used (ii) catchments for which flood estimates must be expected to have lower accuracy such as arid region catchments; and (iii) 'atypical catchments' where additional catchment attributes need to be considered and adjusted for such as catchments with large natural flood plain area.

Keywords: *RFFE, GLS regression, ARR, ungauged catchments, index flood method*

A framework for attributing the uncertainty in hydrologic model simulations to different sources

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Abstract: Determining an appropriate forecasting model is a vital phase in water resources planning and design. Substantial gaps in our present understanding and quantification of hydrological systems make many key modelling decisions uncertain. Our research quantifies the dependency of hydrologic model uncertainty on the observed model inputs, defined model structure, model structural identifiability and specified objective functions. We evaluate the relative importance of model parameter identification, available observations, selected objective functions and assumed model structures as sources of stream flow forecast uncertainty. We introduce here a new uncertainty metric, the Quantile Flow Deviation or QFD, to assess the relative uncertainty due to each of these sources under a range of catchment conditions. As the name suggests, the QFD assesses uncertainty by measuring the deviation in flows at a given quantile across a range of scenarios. By using a quantile based metric, we can assess the change in uncertainty across individual percentiles, thereby allowing uncertainty to be expressed as a function of time. The QFD method is vastly flexible, and can be disaggregated to examine at any part of the modelling process including the selection of certain model subroutines or certain forcing data. The QFD method can be regarded as a quantification of flow diversity with different model choices. One of the main benefits of the QFD approach is the ability to disaggregate the modelling problem and look at model variability at any level. For example, when considering different model structures the metric can be evaluated on different model types. Say a general modelling approach is used whereby the model consists of a soil moisture accounting routine coupled with a reservoir routing routine. The impact of different soil moisture accounting approaches can be evaluated by holding the routing component constant, and vice versa. The ensemble based approach to quantifying flow forecast variability via the QFD metric helps demonstrate specific sources of model variability. In this way, it can help target ways to constrain predictive uncertainty. Evidence to the variability of uncertainty and quantification of the main drivers will helps the decision and policy makers to trust the findings.

Cross-catchment comparison is done for several catchments of different size and hydrologic regime. We investigate the relative importance of rainfall uncertainty (due to poor spatial coverage of observations) on model simulations using interpolated observations and multi-site rainfall generators. Input uncertainty is analyzed for different catchment of diverse size and location. We use FUSE (Framework for Understanding Structural Errors) to analyze our model hypotheses. By considering multiple model structures, we are able to assess (i) when each of these sources of uncertainty become more important, (ii) how the uncertainty varies across different case study catchments; and (iii) how the uncertainty varies depending on the length of available observations.

Keywords: *Input uncertainty, Quantile Flow Deviation (QFD), multi-site rainfall, hydrologic model structure*

Improved spatial interpolation of rainfall using Genetic Programming

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Abstract: Rainfall data provide an important input for various water resources management tasks. Hydrologists are often required to estimate areal average rainfall over the catchment and/or point rainfall values at unsampled locations from observed sample measurements at neighboring locations. Accurate spatial distribution of rainfall can be achieved through a dense network of rain gauges. However, the rain gauge network is usually sparse in most cases and thus sufficient point rainfall measurements are not available, which are often unable to characterize the spatial distribution of highly variable rainfall. Spatial interpolation method plays an important role in such cases to estimate rainfall at unrecorded locations (i.e., missing data) using the observed rainfall available at surrounding locations.

Conventionally, variance-dependent stochastic spatial interpolation methods such as kriging are the most commonly used methods for estimating the point rainfall values at any desired locations based on the available recorded values at neighboring rain gauges. However, traditional kriging has a major weakness because it requires a priori definition of mathematical function for the variogram model that represents spatial correlations among data points and thus significantly impacts the performance of the methods. The robustness of kriging methods heavily depends on how the variogram model is constructed. Moreover, selection of appropriate variogram model, finding the optimal variogram parameters (i.e., nugget, range, sill) and the computational burden involved are some of the difficulties involved with the traditional kriging.

More recently, data-driven models using evolutionary and biological principles including genetic algorithms, artificial neural networks have been used with kriging for spatial interpolation of rainfall. Genetic programming (GP) is another evolutionary data-driven modelling technique to approximate function. The key advantage of GP is that it does not assume any a priori functional form of the solution and GP inferred models offer some possible interpretations to the underlying process. The aim of this study is to investigate the suitability of GP for variogram modelling to derive the variogram model and use of the GP-derived variogram model in combination with traditional ordinary kriging for spatial interpolation of rainfall. This new variant of kriging is referred to as genetic programming-based ordinary kriging (GPOK) in which the GP-derived variogram model replaced the standard parametric variogram models (i.e., exponential, gaussian, spherical) in the traditional ordinary kriging.

Developed genetic programming-based ordinary kriging (GPOK) method was then applied to estimate the unknown rainfall values at a rain gauge station through spatial interpolation using the historical rainfall data from 19 rain gauge stations in the Middle Yarra River catchment of Victoria, Australia. The results indicated that the GPOK method outperformed the traditional ordinary kriging method for spatial interpolation of rainfall and yielded better rainfall estimates. The results also showed that the function approximation capability of GP produces the best fitted GP-derived variogram model compared to the standard models. Moreover, variogram model fitting by GP was very quick since GP did not require identifying the variogram parameters in advance unlike the standard variogram models in the traditional kriging method. Thus, use of GP, as a universal function approximator, for variogram modelling eliminates the time consuming and tedious job of trial and error for determining the optimal variogram parameters as necessary with the standard variogram models. This results in the significant reduction in the computation complexity by the GPOK method. Therefore, the GP-derived variogram model seems to be a potential alternative to variogram models used in the past and the proposed GPOK method is recommended as a viable option for improved spatial interpolation.

Keywords: *Genetic programming, ordinary kriging, variogram model, rainfall data, spatial interpolation*

EXTENDED ABSTRACT ONLY

Toward auto-simplification of rainfall-runoff and groundwater models

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Abstract: A formalised means of simplifying hydrological models concurrent with calibration is proposed for use for the general case when nonlinear models can be initially formulated as over-parameterised constrained absolute deviation regressions of nonlinear expressions. This provides a flexible modelling framework for approximation of nonlinear situations, while allowing the models to be amenable to algorithmic simplification. The degree of simplification is controlled by a user-specified forcing parameter. That is, an original over-parameterised linear model is reduced to a simpler working model which is no more complex than required for a given application. The degree of simplification is a compromise between two factors. With weak simplification most parameters will remain, risking calibration overfitting. On the other hand, a high degree of simplification generates inflexible models. The linear LASSO (Least Absolute Shrinkage and Selection Operator) is utilised for the simplification process because of its ability to deal with linear constraints in the over-parameterised initial model.

Focus here is primarily on rainfall-runoff models, while also drawing attention to application simplification of finite difference groundwater models. One approach to rainfall-runoff model construction in the required linear format is to specify individual runoff hydrographs as finite mixture distributions (weighted by catchment variables) with as many component distributions as possible eliminated in the calibration process. An advantage of the forced simplification is seen in Fig. 1 where a 13-parameter model gives good calibration but poor validation (Fig.1a). However, when simplification forcing reduces the model to 6 parameters there is a much improved validation fit with little reduction in calibration fit (Fig.1b).

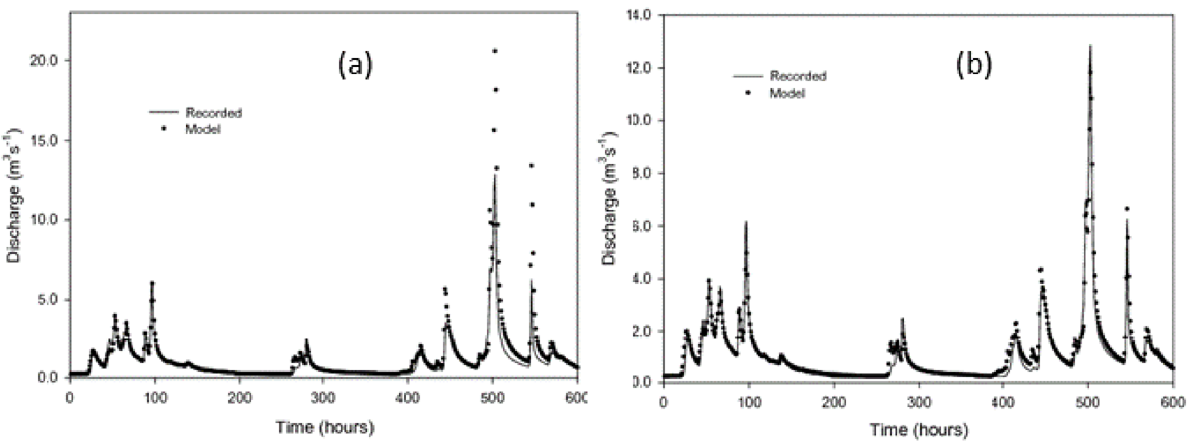

Figure 1: Effect of model simplification forcing on validation data fit. Calibration data is 0-400 hours, validation data is 400-600 hours. Fig 1a shows overfitting effect of a 13-parameter model. Fig.1b has improved validation fitting when force-reduced to 6 parameters during calibration.

Finite difference groundwater models are already in linear form and thus directly amenable to simplification by forcing many cell head gradients to zero during calibration. The motivation for LASSO simplification of a groundwater model is likely to be different from simplification of a runoff model. Having a groundwater model with a considerable extent of forced local zero head gradients (maximum simplicity) may be far removed from known hydrogeological reality. However, the simplified models in this case could play a role as groundwater emulation models, which will serve the same purpose and also run more quickly.

Keywords: *Model simplification, linear LASSO, finite mixture distributions, runoff models, finite difference groundwater models*

Simulation of daily rainfall across a range of space and time scales

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Abstract: Modelling spatial rainfall is important for understanding catchment dynamics, especially at the daily scale for determining runoff time series. While there are a number of models that stochastically generate rainfall at multiple sites at the daily scale there are few that also consider the spatial infilling of the region covered by those gauges.

To simulate rainfall, some models adopt a Markovian state structure to represent wet-dry patterns and then condition amounts on those patterns. A parsimonious alternative is to use a latent-variable that has a single distribution to model both the rainfall occurrence and the amount. The latent-variable distribution is a multivariate Gaussian distribution which is obtained by applying a power transform to observed rainfall. The correlation structure is separable and uses a powered exponential for the spatial correlations, and an auto-regressive correlation structure for updating the spatial fields in time. To obtain rainfall fields that are continuous over the region it is necessary to adopt a contemporaneous correlation structure. The model is unconditional, which means that it simulates values at observed locations (as with multisite rainfall models) but also infills space between the gauges producing more accurate estimates of catchment rainfall. This approach is more realistic that alternatives such as Thiessen polygons which use fixed weights based on geometric location rather than properties of the rainfall field.

A case study using the Onkaparinga catchment in South Australia is presented to evaluate and demonstrate the performance of the model. The model is calibrated to daily rainfall recorded at 22 gauges throughout the catchment, having 73 years of observed data (1914 - 1986). For each month on record, the model is calibrated to at-site means and standard deviations as well as the overall probability of a wet day. The model is evaluated against the monthly at-site statistics for means, standard deviations, totals, number of wet days, wet-spell and dry spell durations, auto-correlations and number of jointly-wet sites. While the model tends to perform well for most evaluated statistics, it appears to oversimulate the number of single wet day-events and undersimulate the length of dry-spells (even though the total number of wet days and distribution of wet-day amounts is correct). The model performs well at reproducing rainfall amounts across all scales down to the daily scale. Figure 1 shows a comparison of the number of jointly-wet sites between observed and simulated data for cases such as isolated wet sites, moderate but patchy coverage and widespread rain coverage. For each of these categories the model performs well suggesting that the spatial patterns of rainfall occurrence are realistic. The model could be further improved, by allowing for additional parameters to represent the temporal persistence to better reproduce the number of consecutive wet days.

The model's ability to infill space shows considerable promise for hydrological applications such as distributed catchment modelling as well as derived flood frequency curves.

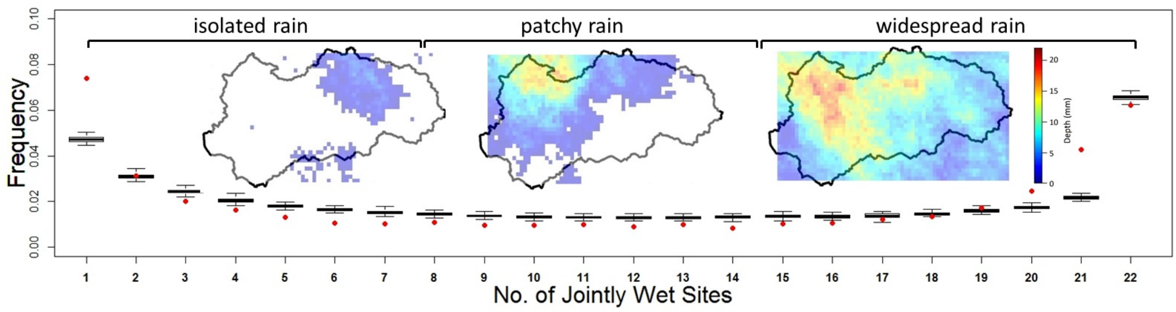

Figure 1. Distribution of the number of jointly wet sites

Keywords: *Spatial rainfall, continuous simulation, latent variable*

The role of evapotranspiration in the spatio-temporal variability of streamflow end-members in a humid catchment

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Abstract: The use of tracer data in end-member mixing analysis (EMMA) provides a powerful tool for discriminating between different sources of streamflow in catchments and makes greater use of available water quality data. EMMA uses end-member signatures, based on principal component analysis of water quality data, to determine linear mixes of these end-members comprising streamflow. The method requires that the different sources/pathways of streamflow (e.g. rainfall, groundwater, surface runoff, interflow) have distinctive and invariant compositions that approximate well mixed 'reservoirs'. However, significant spatial and/or temporal variations in composition of the end-members may confound the analysis. While some end-members (e.g. rainfall and groundwater) do not typically show significant temporal variations in composition, cyclical climatic patterns of rainfall and evapotranspiration may result in significant changes in soil water composition seasonally and interannually. We explore the end-member mixing technique in a perennial, highly seasonal river with a humid climate in south-western Victoria. EMMA analysis showed that higher salinity streamflow from one of the major tributaries was a dominant driver of variation in end-members (Figure 1). Open system evaporation modelling (5% addition of rainfall end-member at each evaporation step simulating an environment open to external inputs during the evaporation process), using the modelling code PHREEQC (pH-REdox-Equilibrium-Code), showed that streamflow from both low (e.g. Lardner Ck) and high salinity (e.g. Love Ck) tributaries was consistent with evapo-concentration of a rainfall end-member at different evaporation steps. Smaller tributaries either fell on the rainfall evaporation trajectory or followed a slightly different trajectory shown by groundwater samples. This indicates that residence time of water in the soil profile will be a key driver of discriminating between different sources of streamflow and this residence time is likely to be controlled by soil texture and permeability. In addition to the evapo-concentration process, many of the groundwater samples show a relative enrichment of sodium, indicating probable wall rock interaction from feldspar weathering, while the higher salinity streamflow samples show a relative depletion in sodium, indicating possible sodium exchange in the soil profile (Figure 1). The results show that relatively simple evaporation modelling can add considerable value in interpreting EMMA results from routine major ion concentration data, even in a humid Australian catchment.

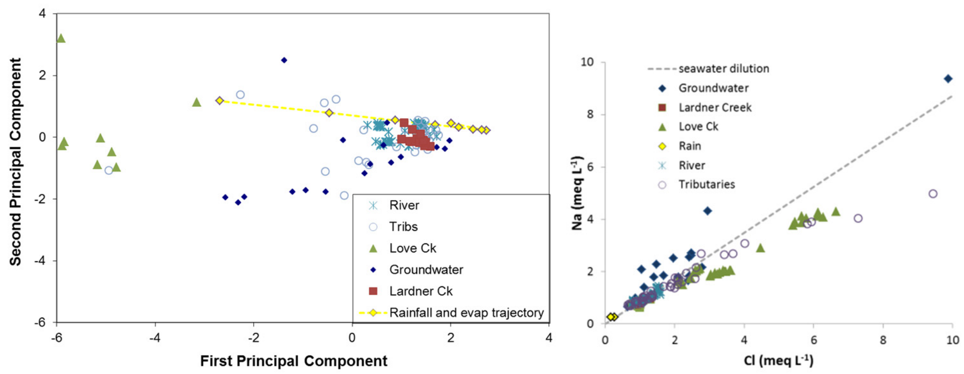

Figure 1. EMMA plot (left) of streamflow and groundwater samples, including an evaporated rainfall trajectory, shown for the first two principal component axes. Most streamflow samples plot close to the trajectory shown by the evaporation modelling of the rainfall end-member. A Na-Cl cross-plot (right) shows that river and Lardner Ck samples plot on the seawater dilution line but more saline Love Ck samples and some tributaries show relative depletion in Na and groundwater samples show enrichment. Differences in sample positions relative to the evaporation trajectory may be caused by differences in Na depletion and enrichment processes.

Keywords: *End member mixing analysis (EMMA), evapotranspiration, hydrochemical modelling*

Quantifying uncertainty of upper air climate variables in GCM atmospheric simulations for the future

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Abstract: Uncertainties in climate modelling affect hydrological modelling and water resources planning and design. This uncertainty arises because of inherent variability in the natural system, simplified conceptualization of models and lack of data. In this research we assess the impact of the uncertainty associated with atmospheric simulations of possible future climates with the intention of using them in hydrological applications at a later stage. Three sources of uncertainty are considered in this research. Firstly model uncertainty based on different choices by modelling groups conceptualize and to parameterize climate process. The next source of uncertainty is due to the Representative Concentration Pathways (RCPs) which describe possible climate futures. The third source of uncertainty in this research is initial conditions of model (ensembles) which reflect natural variability of climate.

Previous studies focused on quantifying the total uncertainty in General Circulation Models (GCMs). However, the way that uncertainty propagates through a downscaling model and affects precipitation is still poorly understood. This research aims at quantifying the contribution of individual sources of uncertainty of atmospheric variables which may be used in statistical downscaling of precipitation. The variables assessed in this study are geopotential height, specific humidity, eastward wind, northward wind, and the gradient of geopotential height. The climate variables are selected from eight GCMs from the World Climate Research Programme (WCRP) Couple Model Inter-comparison Project Phase 5 (CMIP5). At least three ensemble runs are considered for three RCPs (RCP2.5, RCP4.5, and RCP8.5).

This research follows the framework presented by previous studies that have used the variance of a set of GCM simulations to represent uncertainty in climate modelling. The Square Root Error Variance (SREV) has been used to quantify total uncertainty and the contribution of different sources of uncertainty (models, scenarios, and ensembles) for each variable. To compare uncertainty across the different GCMs, the time series of each climate variable has been interpolated onto a common grid. A Nested Bias Correction (NBC) has been applied to correct the bias of GCMs data compared to the reanalysis data from the National Centers for Environmental Prediction- National Center for Atmospheric Research (NCEP/NCAR); addressing errors in the mean, variance and lag-1 autocorrelation at monthly time scale. The global average contribution of the three components to the total uncertainty is estimated for raw and bias corrected GCM simulation. As expected, bias correction leads to smaller contributions for the model uncertainty than using the raw GCM simulations.

The temporal evolution of uncertainty is considered, by examining results for early in the 21st century and later in the century at the 850 hPa and 500 hPa pressure levels. At different pressure levels, there are distinct temporal and spatial patterns for the climate variables that have been analyzed. The contribution from the three sources of uncertainty varies over both time and space. For wind speed and the gradient of geopotential height, the total uncertainty is relatively constant over the 21st century and model uncertainty contributes the majority of the total uncertainty. However for geopotential height and specific humidity, the total uncertainty increases in 21st century and scenario uncertainty has the largest contribution. The results of this research will be useful in understanding how uncertainty from climate variables affects statistical downscaling results.

Keywords: *Uncertainty, climate change, GCM, SREV*

Classifying short-duration extreme rainfall events by triggering mechanism

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Abstract: Extreme rainfall events can have severe impacts on existing infrastructure and need to be considered in the planning of future development. In the last decade, there have been some efforts by the scientific community to identify mechanisms associated with heavy rainfall events, such as atmospheric instability induced by orographic lifting, the passage of atmospheric fronts, thermal convection, tidal variations in pressure, or local sea breezes. Improved understanding of the rainfall triggering mechanisms is important for forecasting heavy rainfall events and for projecting what may happen in the future due to anthropogenic climate change.

In this study, we consider a number of approaches to classifying extreme events based on their triggering mechanisms. We examine short-term extreme rainfall events in Sydney and investigate which triggering mechanisms are responsible for the events, and how these vary at seasonal and annual scales. Our classification of triggering mechanisms is based on 30 years of sub-hourly rainfall and wind data and synoptic temperatures, humidity and cloud type at Sydney Airport. We consider a number of event durations ranging from 5 minutes to 24 hours. We make recommendations as to the most effective methods for classifying rainfall mechanisms and consider how these methods may perform in other parts of Australia where the mix and type of rainfall mechanisms may be quite different.

Keywords: *Extreme rainfall, causative mechanisms, Sydney*

Time-series model calibrations – influence and estimation of different error types

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Abstract: Calibration of time-series models traditionally attempts to reduce the total model prediction error by changing parameters so that simulations match or closely resemble observations. However, a shortcoming of this approach is the assumption that the observational error in the forcing input and output response data is insignificant. In most practical applications this is not the case. In addition, inappropriate model structures may provide good results even though they are actually not suitable representations of the true system of interest. Consequently, calibrated parameters can account for error, resulting in misleading performance and underestimated uncertainty. It is clearly necessary to validate calibrated parameters based on whether they produce realistic errors. Is there a way to estimate the "true" uncertainty in time-series models? Typically, the errors of model simulations are examined as the difference between the simulation output and the corresponding measured values, commonly referred to as the residual error time-series. These residual error time-series encapsulate error from multiple sources, including error in the observed input and output data, and error due to model structure problems and/or poor parameterisation. Estimation of the uncertainty within each of the potential error sources is ideally informed *a priori* but this requires detailed knowledge of the measurements or estimation techniques. In the absence of such information, the residual error time-series can be separated into different source components using data-based techniques. However, this requires the assumption that the nature of the errors are distinct for each of the different components. This study describes and tests a simple method that estimates separately the forcing input error and the output response error in state-dependent models. A major assumption of the method is that errors in the input data produce autocorrelated errors in the output of state-dependent models. In this paper, the assumptions of the method are tested using a simple state-dependent model. The method is outlined and a proof of concept performed using controlled conditions.

Keywords: *Autocorrelation, over-fitting, residual error, state-dependent models*

Using Generalized Additive Model (GAM) to interpret catchment flow response processes

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Abstract: Optimal representation of the hydrological processes of a catchment is a major challenge even with hydrological models that can be interpreted in a more physically meaningful ways. Although there is a recent trend in development of physically based models, stimulated by the increased amount of available data, physically based models still represent the average behaviour at the model scale. In contrast, data-driven empirical or black-box models do not focus on physical processes, but establish a relationship between input and output state variables and directly predict the output variables. These models can also be used for the prediction of hydrological variables (e.g. streamflow, evapotranspiration) using the abundant data both from ground and space for operational applications. Among empirical models, statistics based methods are quite extensively used and are based on probability distributions describing the residual behaviour. In particular, non-parametric regression techniques can capture non-linear and non-monotonic relationships typical of hydrological data. Several studies have used regression techniques (particularly, linear regression techniques and a few non-linear techniques) for variable predictions either at a monthly or annual temporal scale. However, little effort has been put into understanding the physical processes that can be described by the statistical relationships between input and output state variables. In this study, a Generalized Additive Model (GAM), which is a non-parametric, flexible, non-linear regression model, is used to predict streamflow (response variable) at a daily temporal scale and to describe the underlying catchment response processes as inferred from the relationships between predictor and response variable.

Model predictions were performed at a variable catchment scale using time-lagged streamflow for different periods and climatic variables (e.g. rainfall and temperature) as predictors. Model selection was performed to identify which predictors were significant in the model. The model selection showed that there is a strong relationship between the selected time-lagged of streamflow and the residence time of the catchment system. In particular, the identified significant time-lagged streamflow relate to the particular storage delays of the catchment. The study shows that greater number of selected lag periods indicate longer memory of the system and vice versa. Further, the memory of the system can be related to the quick flow and slow flow system within the catchment as indicated by the response behaviour of the selected time-lagged streamflow in the hydrograph.

One-day time-lagged streamflow was commonly selected for the studied catchments (Muttama, Jugiong, Adjungbilly and Goodradigbee catchments located at south-western side of the Murray-Darling Basin, Australia), indicating the average time of concentration for the surface runoff is about one day. However, longer lag periods indicate flow paths through different storage delays or storage capacities of the catchment. Catchments with a low response to high magnitude one-day time-lagged streamflow indicate fast recession or a rapidly falling hydrograph after the peak of an event. Alternatively, this represents quick releases from the storage system. In contrast, catchments with a higher response to high magnitude one-day time-lagged streamflow exhibit a delayed response from the catchment storage system. Alternatively, slower releases from the storage system. Further, seasonal analysis with the lag flow of one day indicates that the catchment response varies between seasons, therefore gives an indication of the dynamic response behaviour of the catchment. In addition, the selected longer period of time-lagged streamflow (e.g. 8 day, 24 day, and 50 day) shows the partial contribution to the response variable. Essentially, the response patterns of longer time-lagged streamflow period are likely to be consistent to the time-lagged streamflow of one-day (i.e. some of the storage delay has faster response pattern whilst others are slow).

The identified flow lags are suggested to be a representation of the distinctive memory pattern of the flow in the selected catchment. Process identification across seasons is useful to diagnose the flow response behaviour of the catchment. This is useful information for developing more physically based hydrological model structures. Overall, data-driven GAM modelling is a useful tool, which can be applied for streamflow prediction and to identify catchment storage response behaviour.

Keywords: *Flow paths, GAM, hydrographs, lag flows, memory and storage response*

Bias Correction of Precipitation Extremes Conditioned on Synoptic Weather Patterns

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Abstract: When using the precipitation extremes simulated by a regional climate model (RCM) in climate impact studies, the bias has to be first corrected. Commonly used bias correction methods are designed to match statistics of the simulated precipitation with observations. This study proposes a new approach to account for the potential change of different precipitation types; the approach accounts for different precipitation mechanisms having different bias characteristics. Different precipitation types are identified by self-organizing map classification of the weather synoptic patterns. The rationale for using synoptic patterns to classify the extreme precipitation is that these large-scale circulation patterns may be better simulated by the RCM than precipitation data itself.

Considering the simulations of a very high resolution Weather Research and Forecasting (WRF) RCM for a domain over south-eastern Australia, a slight change in the proportions of the synoptic weather patterns was found, indicating a possible change in the composition of the total extreme precipitation in the future. A new Synoptic Pattern Bias Correction (SPBC) approach was developed that could account for these changes. The SPBC method lead to marginally different results compared to a conventional bias correction method, namely quantile mapping.

To understand under what conditions significant differences will result between the SPBC method and quantile mapping a comprehensive synthetic study has been defined. The properties of the bias, the changes in the synoptic patterns and the differences in the rainfall amounts from the synoptic patterns were among some of the factors that were explored in a synthetic study. From over 600,000 synthetic cases, 46% were found to have significant differences in the future simulations from the two bias correction methods. It was also found that the differences between the methods depends on several factors including the change in proportion of each precipitation type, the difference in the correction factor for different precipitation types and the magnitude of the overall change in precipitation extremes. Among these factors, the between-cluster difference in the correction factor seems to dominate the significance of the results.

Keywords: *Bias correction, extreme rainfall, synoptic weather patterns, self-organizing map classification, regional climate simulation*

Modelling input uncertainty in coupled hydrologic models via ABC

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Abstract: An ongoing challenge in hydrologic science is developing predictive catchment models that are efficient and robust while still being representative of complex, dynamic and nonlinear system processes. Of critical importance in model development is explicitly quantifying the uncertainty associated with input data, models assumptions and parameter values. Advances have been made in developing robust Bayesian approaches for characterising hydrologic input uncertainty, which may be defined as the error arising from observed climatological variables that are used to drive hydrologic models (such as precipitation, snowmelt, and evapotranspiration). These approaches are typically very high dimensional, requiring specification of large numbers of variables that represent statistical uncertainty in the model inputs.

Recent developments in Approximate Bayesian Computation (ABC) methods (originating in genetics) may provide an efficient, intuitive alternative to the formal Bayesian approach. ABC is commonly used in situations where we have a model that is easy to simulate from, but where the likelihood is difficult or impossible to calculate. In an ABC model specification, parameters are estimated based on the simulated distance from a summary statistic derived from observations. Typically, uncertainty in hydrologic model inputs is described via stochastic error models that relate the observed data (e.g. precipitation) to the non-observable 'true' data. These models may take the form (for example) of multiplicative mathematical functions, and are typically very high-dimensional. These types of error models provide an ideal test-bed to investigate the usefulness of ABC for hydrologic applications. The ABC approach may be similarly useful when considering coupled hydrologic systems, such as in ecohydrologic models or snowmelt-hydrology simulations.

This study presents results aimed at establishing the effectiveness of ABC for hydrologic systems, emphasising hydrologic input error and the propagation of error in coupled hydrologic models. The ABC approach is implemented in multiple hydrologic case studies using a conceptual rainfall-runoff model, the Probability Distributed Model. This hydrologic model is coupled to a precipitation simulator, which relates 'observed' precipitation to 'true' precipitation by way of a stochastic mathematical function. We describe a baseline ABC framework for characterising uncertainty in hydrologic models, including a Sequential Monte Carlo sampling algorithm whereby a population of parameters is propagated from an initial prior distribution, through a sequence of intermediary distributions, until it represents a sample from the target distribution. We additionally use a locally linear regression model of the relationship between our simulated data and model parameters to correct the discrepancy between the simulated and observed data. This can significantly improve the accuracy of the approximation and reduces the impact of the assumed tolerance threshold in ABC. We compare multiple summary statistics aimed at capturing different aspects of the system response, including hydrologic signatures such as the streamflow elasticity, flashiness, and rising limb density. We summarise several case studies investigating how hydrologic input uncertainty is manifested and can be modelled across a range of scenarios. The approach is first established using synthetic data from the Leaf River catchment, and then applied to real data for multiple Australian catchments.

Overall, ABC provides a generic, flexible framework to characterise the impact of uncertain model drivers on parameter estimation and subsequent model predictions. A significant benefit lies in the ability to constrain model parameters with very limited information, such as simple hydrologic summary statistics. Limitations in the ABC approach arise due to computational costs, as the input error model used may require many simulations to appropriately characterise true model input. In such cases, regression adjustment and similar post-processing techniques can improve the accuracy and efficiency of the approximation.

Keywords: *Hydrologic modelling, uncertainty, approximate Bayesian computation*

Importance of a proper bias correction approach in hydrology and water resources related applications

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Abstract: General circulation models (GCMs) are often used to obtain climate information necessary to run the catchment models dealing with the assessment of impacts of climate change on hydrology. However, output of these climate models is often subjected to systematic errors. Postprocessing of raw outputs from GCMs is, therefore, normally considered an essential step before their use in any modeling application. The quantile matching (QM) or distribution mapping bias correction approach is often used to correct output of GCMs in climate change impact assessment studies. The standard QM deals with the biases at a selected single time scale (day, month or year) and ignores the biases in persistence attributes. We propose a multivariate time nested bias correction approach by expanding the standard quantile matching approach to multivariate multi-time scale setting (MQM). The approach corrects for the biases in distribution and persistence attributes at daily, monthly quarterly and annual time scales (Figure 1). The implication of the approach in hydrology and water resources related applications is demonstrated by feeding the CSIRO mk3.0 A2 GCM bias corrected atmospheric data (QM and MQM) as an input to a rainfall stochastic downscaling model over Sydney, Australia and comparing the downscaled results. The MQM is shown to reproduce better the variability and persistence related attributes for the current climate and is expected to perform so in future also (Table 1).

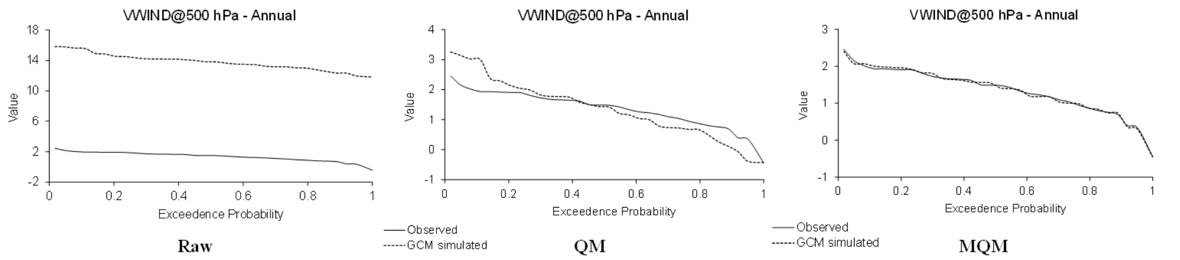

Figure 1. Empirical distribution plots of observed and GCM simulated raw and bias corrected V-WIND@ 500hPa at annual time scales over Sydney, Australia.

Table 1. Percent changes in simulated future climate (2070-2099) rainfall attributes with respect to current climate (1979-2008) over Sydney, Australia.

Rainfall attributes	QM	MQM	Rainfall attributes	QM	MQM
Seasonal and annual rainfall			Seasonal and annual daily max rainfall in mm		
Autumn	-6	-12	Autumn	-11	-9
Winter	-26	-8	Winter	-14	-3
Spring	-16	-2	Spring	-2	0
Summer	8	2	Summer	5	2
Annual	-8	-4	Annual	-3	-2
Average annual occurrences of wet spells of durations			Average annual occurrences of dry spells of durations		
Short (<4 days)	-5	-2	Short (<9 days	-7	-4
Medium (5-7 days)	-7	-4	Medium (9-18 days)	9	4
Long (>7days)	-9	-3	Long (>18 days)	33	23

Keywords: *Quantile matching based multivariate recursive nesting bias correction, Low frequency variability, Climate change, Downscaling*

Improved Bias Correction Spatial Disaggregation method using Rank Correlation

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Abstract: GCMs outputs cannot be directly used for hydrologic modelling as they cannot predict climate variability at the local scale properly and are therefore downscaled. Bias Correction Spatial Disaggregation (BCSD) method is one of the popular statistical downscaling methods. The advantage of BCSD method using quantile matching is the ability of reducing biases from the frequency and amount when compared with the computed frequency and amount at grid nodes based on spatially interpolated observed rainfall data. Bias correction step in BCSD using quantile mapping is done at a course scale before disaggregation to match the simulation with the observation and it is expected that the distributions of GCM simulations at fine scale will match the observations. This study focused on the identification of the key limitation of current BCSD method; hence proposed an improvement of the limitation for better rainfall prediction at local scale.

In the current BCSD, the rainfall distribution at fine scale doesn't match with the distribution of the observation. The general practice in BCSD is to use the mean monthly anomaly field at grid scale. It is found that the temporal variation of the anomaly is significant, and the use of mean anomaly field potentially masks this variation. It is, therefore, intended to identify to create an anomaly field that gives more accurate results compared to the observations. The rank correlation test shows that there exists a positive correlation between observed rainfall and anomalies. Therefore, the use of rank anomaly field improved the cumulative probability distribution of BCSD rainfall (Figure 1).

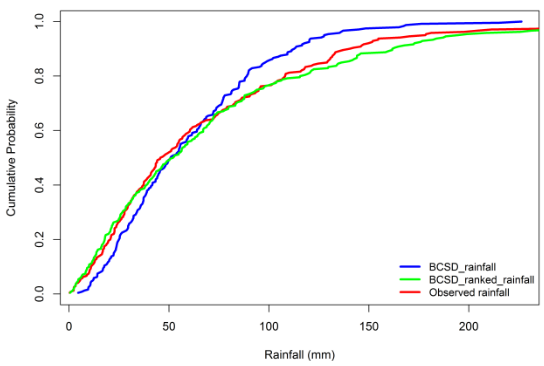

Figure 1. Improvement of CDF in rank BCSD. Red, blue and green lines are the CDFs of observation, BCSD and rank BCSD.

Kolmogorov-Smirnov (K-S) test, which measures the difference between two rainfall distributions, shows that K-S statistics between observed and normal BCSD is significantly higher than the K-S statistics between observed and ranked BCSD. This indicates improvement in the distribution of simulated rainfall when ranked anomaly is used.

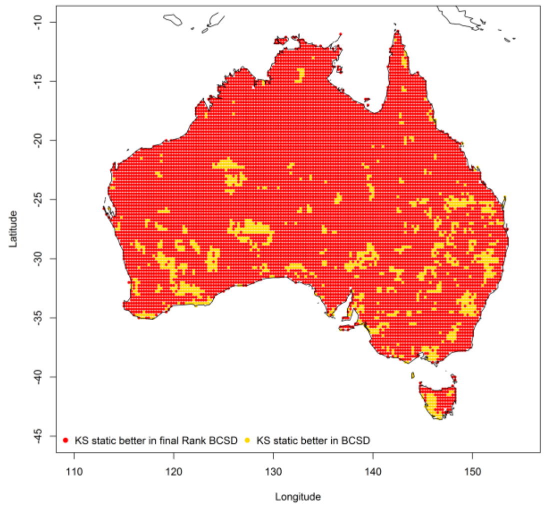

Figure 2. Improvement in rank BCSD. Red color indicates the location where distribution improved in rank BCSD

Although, this improvement is not consistent over the continent, clear improvement is observed in most of the regions of Australia (Figure 2).

Keywords: *Downscaling, anomaly, rank BCSD, rainfall distribution*

Correcting for systematic biases in GCM simulations in the frequency domain

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Abstract: Statistical post-processing or bias correction of meteorological variables derived from General Circulation Models (GCMs) has become customary to remove inherent biases in GCMs before their use in either spatial downscaling or impact assessment studies. Commonly used bias correction approaches correct variables at a single time scale or at multiple *pre-defined* time scales; therefore, they do not take into account statistical biases across a range of time scales. Furthermore, an improper selection of time scales may lead to sub-optimal representations of the observed statistics at time scales not included in the bias correction procedure. This study develops a bias correction approach that works in the frequency domain, called a frequency-based bias correction (FBC) and, therefore, is independent of time scale.

The performance of the approach is demonstrated by applying it to the raw monthly precipitation output of MIROC5 GCM over the Australian landmass and comparing the results in cross-validation with two other bias correction approaches, namely empirical quantile mapping (EQM) and recursive nesting bias correction (RNBC), in terms of reproducing various observed statistics over a range of time scales. Our results show that while the FBC approach is comparable with EQM and RNBC in reproducing the first and second order moments, it outperforms in the representations of the observed persistence and low-frequency variability attributes in the bias corrected results (Table 1 and Figure 1). As a result, it offers a great promise for use in spatial downscaling or climate change impact assessment models, particularly in climate change impact studies on water resources systems where low-frequency variability plays an important role.

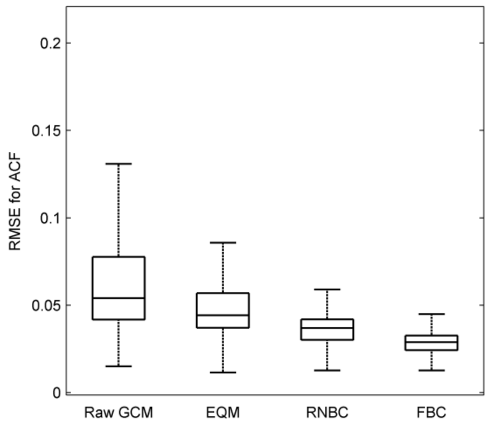

Figure 1. Boxplots of the averaged RMSE of the autocorrelation statistics over 120 lags for the raw GCM, EQM, RNBC and FBC bias corrected results over Australia (in cross-validation). Outliers are not shown.

Table 1. Root Mean Square Errors (RMSE) of statistics of interest over Australia based on the raw GCM time series and bias corrected time series using EQM, RNBC and FBC (in cross validation)*

Statistics	Raw GCM	EQM	RNBC	FBC
Monthly mean (mm)	35.01	**0.34**	1.84	2.59
Monthly standard deviation (mm)	28.26	1.74	1.63	**1.57**
Seasonal standard deviation (mm)	70.37	7.90	3.61	**3.57**
Annual standard deviation (mm)	72.34	22.55	14.96	**12.80**
3 Year minimum rainfall total (mm)	1004.24	172.43	160.27	**134.86**
5 Year minimum rainfall total (mm)	1742.91	281.66	271.08	**217.60**
Monthly lag-1 autocorrelation	0.075	0.063	0.020	**0.019**
Monthly lag-2 autocorrelation	0.061	0.055	0.041	**0.027**
Annual lag-1 autocorrelation	0.139	0.164	**0.093**	0.115
Annual lag-2 autocorrelation	0.140	0.163	0.149	**0.107**

***** The bias correction method with the lowest RMSE across Australia is highlighted in bold

Keywords: *General circulation models, frequency-based bias correction, bias correction, low-frequency variability*

Cost-effective groundwater quality monitoring network design using stochastic simulation and cross-entropy optimization

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Abstract: Cost-effective design of groundwater quality observation networks is essential for detection, prediction and management of risks posed by contamination. Optimization of the monitoring well locations to maximize the worth of the data collected is particularly important when the drilling cost involved is huge. We propose a new statistical approach to identify the optimal locations for a given number of monitoring wells, which minimizes the uncertainty of predicting the contaminant plume characteristics. Multiple realizations of the contaminant plume were generated using stochastic simulation of the groundwater flow and transport processes using MODFLOW and MT3D models. Calibration constrained simulation using a Null-space Monte Carlo approach ensured that all of the realizations of the contaminant plume had equal probability of occurrence. Following this, we used Singular Value Decomposition (SVD) to identify a small set of spatial basis functions that captured the common spatial patterns amongst the stochastic simulations and that could be used to predict the full spatial field from a small number of observations at well locations. The Cross-Entropy method was then used to identify the optimal well locations that minimized the error in the predictions, assuming that the set of stochastically simulated plumes represented the true distribution that might be observed in nature.

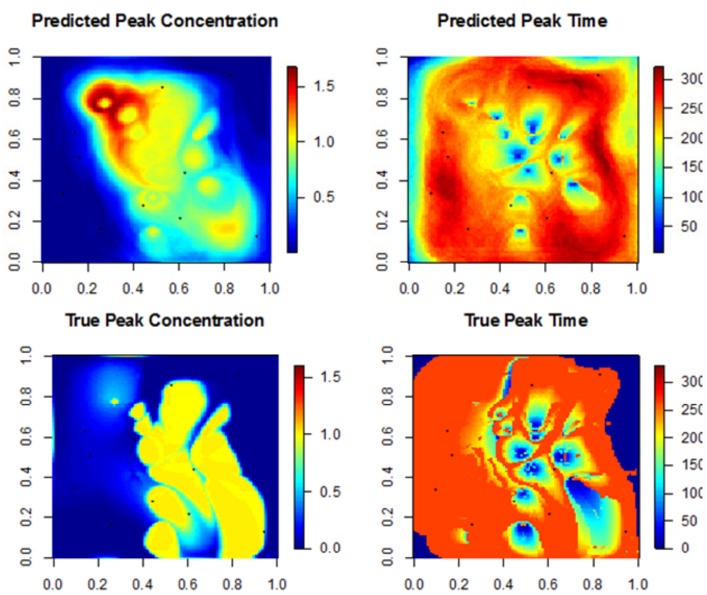

Figure 1. Comparison of peak concentration (relative value – unit less) and peak time (months) predicted using the observations at 10 optimal locations to the true values. The monitoring locations are shown by the black dots.

The application of the proposed method is illustrated for the design of a monitoring network for an injection well field for which injection tracer tests were conducted. Transport of conservative contaminant from 12 wells triggered by high pressure injection was considered for the design of the monitoring well field. Optimal locations for 10 wells were identified by considering peak concentration and peak time (arrival time of peak concentration) as the two desired plume characteristics to be monitored and modelled. The contaminant plume characteristics predicted using the designed monitoring network with 10 locations showed appreciable match with the true plume characteristics.

Keywords: *Optimization, groundwater monitoring network design, stochastic modelling, Null space Monte Carlo, contaminant transport*

Fault Detection of Non-Residential Water Meters

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Abstract: City West Water (CWW) provides water services to the CBD and western suburbs of Melbourne, Australia. The water industry constantly faces the problem of non-revenue water, i.e. water lost for various reasons including bursts, leaks, and metering inaccuracy. Effective asset maintenance is a vital part of ensuring water companies can both reduce non-revenue water and continue to provide services to their customers.

To fairly bill customers for water consumption, a water meter is located at each customer's property to measure the volume of water being supplied from the water main to the property. However, these meters can read inaccurately over time and, if inaccurate, most of the time record less than the actual consumption. This results in under billing customers for the water they consume, contributing to CWW's non-revenue water loss. Despite the small number of non-residential (business) customers serviced by CWW (9% of customers), these customers account for over 50% of total water consumption each year. Therefore it is vital to ensure the meters servicing these customers are maintained correctly.

Most water meters are read only quarterly so consumption history data is quite sparse. Without removing a meter from service, or at least physically running tests at the property itself, it is uncertain whether or not these meters are performing with satisfactory accuracy. Previous replacement programs replace a meter after it has recorded up to a certain volume of water, but for meters that under record volumes, this level may never be reached and thus faulty meters remain in service indefinitely. For this reason, it is important to monitor these water meters by other means.

Unlike residential meters, there was no existing data from non-residential meter tests, so it was not possible to probabilistically determine which meter characteristics (model, age, size etc.) typically lead to faulty water meters. Instead MATLAB was used to develop an algorithm which was given the name Checkmate Lite. The purpose of Checkmate Lite is to assist CWW choose which meters servicing non-residential customers may need to replaced. Checkmate Lite uses an algorithm that attempts to identify anomalies in a meter's consumption history. These meters are flagged by Checkmate Lite. The user can then interactively review the properties of these meters and their consumption histories to decide whether or not any of the meters should be replaced. With no non-residential meter test results, the current accuracy of the algorithm is unknown, hence it is being used to assist in decision making, and not make the final decision itself.

Keywords: *Water meter, non-revenue water, non-residential customer, sparse data*

Short-term prediction of flood events in a small urbanized watershed using multi-year hydrological records

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Abstract: The application of various artificial intelligence techniques to short-term flood prediction shows that the majority of low-flow events are predicted accurately while the forecasting of high-flow events has a high level of uncertainty. The differences in forecast accuracy can be attributed to the imbalance of water flow data which mainly represent low-flow events with fewer measurements corresponding to flood events. Furthermore, the hydrological conditions of a watershed vary from year to year, so that the annual occurrences of high-flow events fluctuate notably from year to year. As a result, for some years with very few high-flow events the predictors cannot be trained. In data-driven modeling, the quality of a predictor depends on both the applied algorithm and the data set used for training it. To address the issues of imbalanced data in application of supervised machine learning algorithms to short-term flood prediction, we investigated approaches to constructing training data sets which could improve the prediction ability of classification algorithms. The approaches were examined on the hourly records of rainfall and water levels from April to December for the years of 2008, 2011, 2012 and 2013 in the highly urbanized Spring Creek watershed, Ontario, Canada. The Spring Creek is a small stream with a baseflow of about 0.20 m^3/s. Its watershed has an area of 50 km^2. A constructed ensemble of five classifiers, C4.5, CART, RepTree, NNge, and JRip, has provided very accurate predictions of low-flow events and demonstrated satisfactory performance for high-flow events for one-hour lead time in some years while for years with fewer high-flow events the prediction accuracy declined. In this study, we explored three approaches including: 1) maintaining low-flows of each year and oversampling high-flow data for the same year; 2) training the ensemble of classifiers using the wet year; and 3) maintaining low-flows of each year and combining high flows of multiple years. Two performance measures: F-score and misclassification rate were employed to compare the results of the ensemble on various data sets. The performance of the ensemble of classifiers on the raw data set was used as a benchmark. We ran the experiments for up to a two-hour lead time. Some of the classification algorithms in the given study worked better on non-flood events while others predicted high-flow events more accurately. From a management perspective, an improvement in the prediction of high-flow events is more important than that of low-flows, however, misclassification of low-flow events also has some negative effects. Therefore, the developed models have to improve both high- and low-flow predictions and minimize the number of misclassified tuples. The ensemble of classifiers produced the most accurate predictions for a one-hour lead time for all of the investigated years. Although oversampling is typically recommended for dealing with imbalanced data, the results of the study did not support this suggestion. Applying the ensemble of the classifiers on the oversampled data set increased the number of misclassified tuples. For all of the investigated wet years, the best predictions were generated by applying the ensemble on the combined data sets. For the dry year, the prediction results of ensemble on the combined data set were satisfactory but still lower compared to the wet years. The results suggest that the combined approach can be used for short-term hydrological forecasting. The developed classifier does not require a resource-consuming model parameterization. Its site-specific calibration is implemented at the training step using data readily available. It makes classification algorithms very attractive as a tool for flood management in small watersheds. However, training classifiers on real-time data at the beginning of the wet season may not be possible because tuples for flood events may not be available. The proposed combined approach may help to address this issue, and hydrological events can be predicted using historical records. The development of such a framework is the subject of further investigation.

Keywords: *Flood prediction, classification algorithms, imbalanced data, oversampling, combined approach*

Complex networks for studying the structure and dynamics of hydrologic connections

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Abstract: Connections are everywhere in hydrology. Unraveling the nature and extent of connections in hydrologic systems, and their interactions with other earth, environmental, and socio-economic systems, has always been a fundamental challenge in hydrology. Despite the significant progress in this direction, our understanding of these connections remains far from adequate. A key reason for this situation is the absence of a strong scientific theory to represent all types of connections.

In the context of connections, significant advances have been made in recent decades, especially through studies in the field of complex systems science. In particular, studies on *complex networks* have delivered some new discoveries and provide new avenues for studying connections. For instance, the concepts of *small-world networks*, *scale-free networks*, *network motifs*, and *community structure* are highly relevant as to the structure and dynamics of connections encountered in hydrology. Indeed, it is argued that the theory of complex networks is a suitable tool for studying all types of hydrologic connections and, thus, can offer a generic theory for hydrology.

The purpose of the present study is to discuss the relevance and applicability of the concepts of complex networks for studying various connections in hydrology. After a review of the basic concepts of network theory, the relevance of complex networks for studying connections in hydrologic systems is explained through several key examples, including the hydrologic cycle, hydrologic data monitoring networks, river networks, and global climate model (GCM) outputs. To test the applicability of the complex networks concepts in hydrology, several network-based methods are applied to examine connections in various hydrologic networks. Among the methods applied are: clustering coefficient (a measure of network local density), degree distribution (a measure of network spread), average shortest path length (a measure of network distance), and community structure (for identification of communities or groups in networks). These methods are applied to study: (1) spatial connections in rainfall over a large region (monthly data from 230 stations in Australia); (2) spatial connections in streamflow over a large region (monthly data from 639 stations in USA); (3) spatial connections in groundwater levels over a large region; (4) temporal connections in river flow at a gaging station (151 years of daily data from the Mississippi River at St. Louis, Missouri, USA); (5) spatial connections in river flow in a large-scale basin (daily data from 2023 stations in the Mississippi River Basin, USA); and (6) optimal number of gages for rainfall and streamflow (monthly data from Australia and USA).

The results indicate that the concepts of complex networks are useful for studying many different types of connections encountered in hydrology. They also suggest the existence of different types and behaviors of networks in hydrology that are different from our traditional view of random graphs. Based on the present results, a discussion is also made on the implications of the present study for hydrology and water resources, including for interpolation and extrapolation of hydrologic data, classification of catchments, and prediction of hydrologic system dynamic evolution.

Keywords: *Hydrologic systems, complex networks, clustering coefficient, rainfall, streamflow*

A toolkit for investigating the importance of prior distribution in Bayesian hydrology

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Abstract: Conceptual Rainfall-Runoff Models (CRRMs) are widely used for catchment hydrological simulations over the years. Numerous approaches for quantifying the uncertainty in hydrological modeling have been developed. Among these, Bayesian inference is one of the most popular tools for quantifying the uncertainties in hydrological modeling with the development of Markov Chain Monte Carlo (MCMC) techniques. In Bayesian theory, the posterior distribution is a combination of our existing knowledge about the parameters (prior distribution) and the data being observed (likelihood function). Although much research has been conducted on the investigation of various likelihood functions, little work is routinely done on evaluating the impact of the prior distribution on the posterior distribution and defining meaningful prior distributions for different models. In recent years the importance of prior information and the influence of expert knowledge on model specification have gained increasing recognition. Our study aims to develop a toolkit that can be used to quantify the importance of prior information and examine parameter sensitivity to the prior that may be applied in multiple case studies.

In our study, we examine two methods for measuring the dissimilarity between prior and posterior distributions, the Kullback-Leibler Divergence (KLD) and Hellinger Distance (HD). The KLD and HD are used to calculate the divergence/distance between different priors and the corresponding posterior distributions across multiple real and synthetic data case studies. We additionally introduce the concept of prior information elasticity to describe the posterior distribution sensitivity to various aspects of the prior distribution (e.g. the prior mean or variance) or the study data (e.g. the number of years of data). The prior information elasticity is calculated based on the change in the KLD (or HD) with respect to these various factors.

Results from the application of the toolkit quantify the importance of the prior in different cases. The variations in the KLD and HD values using increasing amounts of data help quantify the importance of the prior especially when the available data is limited. The KLD and HD values for different parameters are compared across different cases to examine the parameter sensitivity to the prior and available data. Results shows in some cases that an improper prior can lead to a totally different posterior distribution, especially for insensitive parameters. In addition, the concept of prior information elasticity helps demonstrate that the posterior distribution is more influenced by a change in the mean of the prior than a change in the variance of the prior for a synthetic case study. The methods describe here may be widely applied across hydrologic case studies and should encourage a more routine assessment of prior specification in hydrologic studies.

Keywords: *Bayesian hydrological modeling, prior distribution, parameter sensitivity, prior elasticity*

EXTENDED ABSTRACT ONLY

An entropy-based approach to identify equally informative input subsets for hydrological models

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Abstract: Input Variable Selection (IVS) is the process by which an optimal set of inputs is selected from a larger candidate set in order to characterize a preselected output. This selection process is an essential step in hydrological model construction. Whilst most existing IVS algorithms select a unique subset of inputs, the presence of redundant variables can result in the selection of different, but equally informative, subsets. In this study, we show how this problem can be surmounted using a novel IVS approach, named Wrapper for Quasi Equally Informative Subset Selection. W-QEISS adopts a global optimization algorithm to find a set of subsets that optimizes four objective functions. It maximizes the accuracy of an underlying data-driven model, minimizes the cardinality of the input vector, and optimizes two entropy-based measures of relevance and redundancy. The relevance measure ensures that the information content of each subset is maximized, while the redundancy measure guarantees that the cross-dependence between the variables in a subset is minimized. The approach has three notable benefits, which are guaranteed by the adoption of the Borg Multi-objective Evolutionary Algorithm and Extreme Learning Machine. First, it does not require any assumption on the statistical properties of the input dataset. Second, it can characterize non-linear relationships. Third, it is computationally efficient.

The approach is applied to a daily streamflow prediction problem in the Yampa River basin (US). The hydrological dataset comprises multiple, interrelated, hydro-meteorological variables – rainfall, snow depth, snow water equivalent, specific conductance, and maximum and minimum temperature – measured at eight different stations across the catchment. Model performance is benchmarked against four other popular IVS algorithms (PMI, PCI, mMRMR and IIS). Results show that W-QEISS identifies a rich and diverse set of equally informative input subsets, which assist in the interpretation of the main hydro-meteorological processes and help to determine the relative importance of each input variable. Moreover, the availability of multiple subsets allows for a more detailed trade-off analysis between different, conflicting metrics of prediction accuracy, accounting for model performance on low flows, high flows and across the whole spectrum of streamflow data. For most of these metrics W-QEISS is able to identify a large number of subsets that outperform those found by the benchmark algorithms.

Keywords: *Input variable selection, Extreme Learning Machine, entropy, relevance, redundancy*

Low flow impact analysis of climate change considering an ensemble of hydrological model structures

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Abstract: Recent studies have shown high uncertainty in projecting low flow conditions for the future climate in Belgium. This uncertainty can be partly explained by the high uncertainty in the low flow results of hydrological models applied to assess the climate change impact. An ensemble approach is proposed to quantify the model uncertainty. It employs a flexible modelling framework that allows implementation and easy interchange of different model structures, even at the level of individual model components. It also enables flexibility in spatial resolution from lumped to finer scales depending on the applications and at the same time assures consistence in the results at any spatial detail. However, moving from lumped to spatially distributed scale requires to include more spatial catchment information, which means more model calibration parameters, causing calibration difficulties such as equifinality.

A data-based methodology for disaggregation of model parameters from lumped to finer resolutions, making use of basic spatial catchment characteristics (topography, soil types, land uses) is therefore developed to limit the overparameterization problem. Such calibration approach is different from the traditional ones for spatially distributed hydrological models by putting constraints considering the average value of model parameters at the lumped catchment scale. In this approach, some of the lumped conceptual parameters (obtained from a well-calibrated lumped model at catchment scale) that are related to subflow splitting or soil storage or are defined per unit area are firstly mapped to uniformly spatial values. For some parameters, the spatial scale difference is taken into account in that process. After that, spatial variations are given to the parameter maps using catchment properties. This is done in a relative way against the uniform values, which means the spatial average for each parameter is taken equal to the uniform value. Only a few additional model parameters are added to calibrate and fine-tune the spatial disaggregation process. Next to the consistency of model parameters and consequently also simulation results at different scales, this new calibration approach has the additional advantage that the time for spatial calibration is much reduced. After calibration, the simulation results given by the lumped and distributed models are evaluated for total flows and subflows, cumulative volumes, and hydrological extremes, including low flows and peak flows. The spatial model results are evaluated based on flow measurements at the internal flow gauging stations and groundwater head levels at observation wells. The projected impact trends of both lumped and distributed models for future climate conditions are also inter-compared.

The methodology has been implemented in PCRaster-Python and tested for two Belgian case studies and for existing model structures (NAM, PDM and VHM). The model performance evaluations of the lumped and distributed model versions for the three model codes in both case studies prove that the disaggregation approach can be applied to obtain the spatial distributed models from the lumped ones and with good accuracy (similar accuracy at the catchment outlet) with only slight additional calibration.

Keywords: *Flexible hydrological modelling, disaggregation, spatial model*

A synthetic study to characterize alluvial groundwater responses to overbank flood recharge

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Abstract: Groundwater recharge in alluvial river floodplains is a complex process driven by variation in river water levels, overbank flooding, rainfall over the floodplain and subsequent evapotranspiration. In many floodplains, floods are strongly correlated with local rainfall which makes it difficult to quantify groundwater recharge resulting from floods only. This paper investigates the groundwater response characteristics to overbank flooding and rainfall in different synthetic river-aquifer settings. Sets of coupled MIKE SHE/MIKE11 models are developed using 54 years (1960-2013) of river data (water level and discharge) and climatic data (rainfall and evapotranspiration) from the Loddon River, Australia, containing at least 20 overbank floods along a 5 km wide river floodplain.

Results from four different sets of models are compared to compute overbank flood recharge. They are: 1) models with time series of rain and river level data (M1 model), 2) models with time series of river level data but no rain (M2 model), 3) models with time series of rain and river level data (modified for within bank floods only) (M3 model) and, 4) models with data of rain and base flow in the river (M4 model). While the relationship between different overbank flood recharge processes is nonlinear to some degree, in estimating the overbank recharge contribution, we assume linearity. Three different forms of floodplain recharge are lateral recharge from the channel, vertical recharge from the inundated floodplain and rainfall recharge. The results show that the greatest groundwater recharge occurs in strongly connected river-aquifer zones and is controlled by lateral flow from river stage rather than vertical infiltration from rainfall or overbank flow. Omitting rainfall from the model (in the presence of evapotranspiration) results in lower overall water table conditions. Without rain, the model is also not effective in capturing the spatial variations of overbank flood recharge.

In the synthetic river-aquifer systems considered, the key parameters influencing overbank flood recharge are aquifer saturated hydraulic conductivity, floodplain slope, and floodplain permeability. Larger groundwater fluctuations occur in more conductive aquifers as they can transmit groundwater faster and are capable of accepting rapid recharge during flood events, but because of greater transmissivity value, fluctuations quickly dissipate, hence the amount of total recharge by flood sources (lateral + vertical) is lower. Floodplain slope is important in this work as it controls the inundated area of overbank flood events, with high recharge occurring up to the distance to which the floodplain is inundated. A flat model (with slope=0) is found as the most effective river-aquifer setting for allowing the greatest amount of recharge in any form (both lateral recharge and vertical recharge). Floodplain soil clogging also plays an important role for overbank flood recharge by controlling the infiltration rate through the clogged layer. A more conductive floodplain allows the flooded water to infiltrate quickly throughout the clogging layer, leading to greater amounts of recharge, even from short duration floods. The duration of inundation from large floods is important in determining the amount of recharge in heavily clogged floodplain.

The findings from this research work are currently being used to develop time series models to separate flood recharge from rainfall recharge in alluvial valley settings.

Keywords: *Groundwater recharge, overbank floods, rainfall, evapotranspiration, river-aquifer interactions*

Optimal water infrastructure planning under deep uncertainty: Balancing robustness, flexibility and adaptability

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Abstract: Optimal long-term planning plays an important role in many water infrastructure problems. However, this task is complicated by deep uncertainty about future conditions, such as the impact of population dynamics and climate change. One way to deal with this uncertainty is by means of robustness, which aims to ensure that water infrastructure performs adequately under a range of plausible future conditions. However, this is likely to result in infrastructure systems that are over-designed and unlikely to make best use of financial resources.

Another way to deal with deep uncertainty is by means of adaptation, the purpose of which is to respond to changes in future conditions. However, this is difficult to achieve, as infrastructure systems generally have long life-spans. In addition, solutions that are optimal in the short-term might not be optimal in the long-term. In order to address this conundrum, a structured approach to optimal infrastructure planning under deep uncertainty is presented. The approach identifies optimal long-term infrastructure portfolios for alternative plausible future pathways (e.g. population, climate change). Next, a decision as to which component(s) of these portfolios to implement at the present time is made based on trade-offs between long-term planning objectives (e.g. life cycle costs, reliability), short-term robustness (e.g. how sensitive the system is to failure under a range of plausible future conditions until further changes to the system can be made) and flexibility (e.g. to what degree the selected component(s) are part of optimal portfolios under a range of plausible future conditions). Finally, the portfolios are adapted at a future time period based on current best-known information.

The proposed approach is illustrated for the optimal sequencing of water supply augmentation options for the southern portion of the water supply for Adelaide, South Australia. A 40 year planning horizon and a 10 year staging interval are adopted. Therefore, there are five decision stages over the 40 year planning horizon. The selected objectives include the minimization of the present value (PV) of economic cost and the PV of greenhouse gas (GHG) emissions. The existing water supply sources, including three reservoirs and supply from the River Murray, are included in all sequence plans at the beginning of the planning horizon. Supply augmentation options, including a desalination plant, a number of stormwater harvesting schemes and household rainwater tanks are considered as potential additional water supply sources at each decision point. The decision variables correspond to the sequencing of these supply augmentation options. Population, rainfall and temperature are considered as the uncertain variables, as they have a direct impact on supply and demand. Different combinations of these uncertain variables are considered as part of seven scenarios. In order to illustrate the impact of the adaptive nature of the approach, two different simulated realities are considered.

The results indicate that the approach is successful in adapting to changing conditions, while optimizing longer-term objectives and satisfying water supply security constraints along the planning horizon, in highly uncertain planning environments. This is evidenced by the differences in the optimal solutions obtained for the different realities, as well as the favorable performance of the adaptive plans compared with those fixed at the beginning of the planning horizon.

Keywords: *Multi-objective optimisation, deep uncertainty, water infrastructure sequencing, robustness, flexibility, adaptability*

Water Consumption Pattern in the Traditional Villas of Abu Dhabi

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Abstract: The municipal water consumption in the Emirate of Abu Dhabi, United Arab Emirates, is extremely high (565 to 920 litre per capita per day (lpcd)), despite of their limited water resources. The residential activities account for about 52% of their expensive desalinated water. In 2013, the total available desalinated water in the Abu Dhabi was about 244,666 million imperial gallons. This high residential water consumption is driven by their high indoor and outdoor water end uses. It was informed by the water authorities that the residential water consumption rates in the Abu Dhabi are particularly high in the traditional villa type detached houses. This study investigated the pattern of water consumptions in medium sized villas and identified the factors affecting their water consumption. The water meter reading data for a consecutive 12 month period were collected from 100 villas located in a residential compound in Abu Dhabi. All villas are uniform in their plot (2050 m^2) and building (750 m^2) sizes. The villas are connected to the water distribution system by a service connection pipe (Medium Density Polyethylene) of diameter 20 mm, except three villas that have two service connection pipes. In order to verify the collected meter reading data from individual villas, the district area meter (DAM) reading was also collected for the same period. It was found that the supplied water (DAM reading) was approximately 5% more than the accumulated water consumption in all villas. This additional water was used for network flushing, fire demand and lines losses. The average monthly sewer flow (wastewater volume) from all villas were also collected. After collection of the number of people information on villas, it was found that the average per capita water consumption rate is more than 2500 lpcd. The summer (May –August) consumption was found about 5% more than that of other months. The average indoor water consumption rate was estimated approximately 350 lpcd. The regression analysis confirmed that water consumption in the villas is not significantly dependent on the number of people live in villas, which is attributable to the fact that about 85% of water are used for outdoor activities (plantation, car washing, etc.). Finally, it was recommended to reduce the outdoor water consumption by introducing alternative water sources such as the treated sewage effluent and the treated greywater.

Keywords: *Water demand, traditional villa, indoor water use, outdoor water use*

Allocating limited water: linking ecology and economics

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Abstract: Available water is limited in quantity with many potentially competing uses, including irrigation, environmental amenity and domestic supply. A question is how to allocate a limited water quantity to different uses for society. Economically we allocate water to equate marginal social benefits across different uses. For environmental amenity this framework relies on ecological response functions and prices. The economic framework uses prices to represent social welfare - representing social willingness to pay for extra ecological amenity. Valuation (pricing) of ecological improvements involves non-market valuation; estimates are available for ecological amenity improvements.

An economic decision framework for environmental water requires flow regimes (the decision variable) on the x-axis and ecological responses or endpoints (e.g. for Golden Perch in the Goulburn River) on the y-axis. This analysis characterises the ecological response functions relatively simply with several steps to translate existing ecological response curves into functions suitable for economic analysis. First was harmonisation of x-axes to total volume of water. The overall response of a complex organism like Golden Perch to flow regimes consists of separate sub-responses to different components of the flow regime - spawning from a spring high flow (fresh); survival of larvae from provision of shallow, slow flowing habitat over summer; and adult condition from provision of deep pools through autumn and winter. Each of these sub-responses was expressed graphically with ecological response on the Y axis, and total volume of environmental water used to achieve the response on the X axis. Having common units on the X axes allowed the three sub-responses to be combined for the economic analysis.

Second was harmonisation of y-axes to estimate population size. Strictly speaking, the sub-components listed above are realized as number of eggs produced, larval survivorship, and adult survivorship, respectively. For the economic analysis, these endpoints were translated to an estimate of impact on total population size - by translating previously held 'traffic light' (i.e. good, moderate, poor) outcome scores to estimates of the Golden Perch population from previous research carried out in the Goulburn-Broken catchment.

Third was translation of piece-wise linear functions to smooth equations. We translated those functions to smooth equations, allowing us to characterise the economic model in terms of marginal responses.

Fourth was the issue of combining sub-responses. A compound function for Golden Perch production was derived by assuming that the temporal periods for each of the sub-responses do not overlap. Therefore the overall production function is driven by spawning in spring, slow-flow habitat in summer, and pool habitat in autumn and winter. This assumption is untrue for real systems; however, within the bounds of our other uncertainties and simplifications, this assumption is minor.

The economic model maximises total social (defined here as environmental plus irrigation) benefits expressed in dollar equivalent terms for water allocation decisions. The total quantity of water available is limited, hence the economic problem for social welfare. Decisions are made for water allocations to environmental assets or endpoints, and agricultural outcomes.

The shadow price of water is derived for limited water shared between an environmental and agricultural use.

Keywords: *Economic model, ecological responses, water allocations, Golden Perch, irrigated dairy*

Valuing environmental water – lessons from a transdisciplinary ecological-economic study

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Abstract: Managing environmental water is an important strategy for maintaining and restoring freshwater ecosystem health. Information on the extent of ecological and economic benefits of environmental water is important for assessing alternative ecological outcomes and demonstrating 'value for money' in the supply and management of environmental water. However, these benefits are difficult to quantify.

A transdisciplinary study was undertaken to investigate the ecological and economic benefits of environmental water using the Macquarie Marshes, Australia as a case study. The study brought together eco-hydrologists, ecological economists and modellers to link hydro-ecological models with economic models to assess the economic benefits of different environmental watering outcomes. The approach links the NSW hydrological model (IQQM), a habitat suitability ecological model and a novel survey approach to value ecosystem attributes. The survey aimed to determine people's willingness to pay for the environmental attributes that could be benefited by deliberate watering in the Macquarie Marshes.

The survey targeted people who have professional experience in freshwater ecology, resource economics or water management, as opposed to sampling the general population of Australia. 116 valid respondents were received from the three target groups: ASL (Australian Society for Limnology), AARES (Australian Agricultural and Resource Economics Society) and CRN (Collaborative Research Networks) partners. A further 44 respondents had a zero willingness to pay (WTP). The total non-zero WTP distribution is negatively skewed, with a median of $55 and mean of $186 paid for a change in the provision of the number of flow events that would benefit ecological attributes. The average WTP estimates varied according to preference for species and the context of the watering regime. Among five surveyed species, river red gum receives the highest weight in terms of distributing the total WTP.

In this presentation, we focus on the lessons learnt by the study team as we worked together to link the different modelling approaches. We illustrate two key challenges faced during the study: namely communication of environmental change and heterogeneity of preference structure. The formulation of quantitative environmental indicators for non-market valuation (NMV) is not trivial, especially for situation where multiple reference points (e.g. current and natural (without development) flow conditions) could reasonably influence a person's preference. Economic studies tend to consider change from current condition whilst bio-assessments often represent departure from 'natural' conditions. To avoid potential bias that both these approaches may introduce when eliciting preferences we represent environmental change using a qualitative graphical approach. Our results provide a clear indication that both natural and current reference points influence preferences of the survey respondents. Additionally, we identified from the survey four types of preference structure: one linear and three non-linear. The heterogeneity in the elicited preferences structures among respondents highlights that an assumption of a set preference structure (common in NMV studies) was not valid in this study. This heterogeneity increases the complexity in interpreting WTP and applying the results for environmental watering options.

Keywords: *Environmental water, non-market valuation, transdisciplinary, wetlands, ecological model*

Using Decision Support for Water Quality Improvement Planning: the CAPER DSS

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Abstract: Water Quality Improvement Plans (WQIP) are an ecosystem-based approach to integrated water cycle management. They aim to integrate the best available science for decision making coupled with a strong participatory approach. A WQIP is a comprehensive plan for water quality protection and improvement in the face of pressures from future development. Plan recommendations are developed in consultation with the community to ensure they are feasible, cost effective and will achieve the environmental outcomes required.

This paper describes the Catchment Planning and Estuary Response (CAPER) Decision Support System (DSS) which has been designed to support the development of these plans. To date this approach has been or is in the process of being used in the development of ten water quality improvement plans. CAPER integrates metamodels of more detailed catchment and receiving water quality models such as the Source Catchments model, MUSIC model and DELPH-3D model with other empirical and literature based approaches to allow testing of the impact of alternative future land use and land management options. An easy-to-use interface has been developed to allow development of scenarios and exploration of the impacts of alternative options. This paper describes the generic CAPER approach and its application to developing WQIPs for several case studies in the Northern Territory, NSW and Tasmania.

Keywords: *Decision support system, CAPER, water quality improvement plan*

A Plan for Water Quality Improvement in the Tamar Estuary and Esk rivers

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Abstract: The Tamar Estuary and Esk Rivers (TEER) catchments cover nearly 15% of Tasmania's landmass. The North and South Esk Rivers drain into the Tamar Estuary which extends approximately 70 km from Launceston to Bass Strait. The region sustains a diverse range of land uses, including grazing, dairy, cropping, plantation and native forestry, mining, heavy industry, urban, rural residential and nature conservation areas. It provides substantial input to Tasmania's economy as well as sustaining key ecological assets and communities. There are 26 wastewater treatment plants discharging into the rivers and estuary, many of which are near the end of their lifecyle and in need of upgrade.

The Tamar Estuary is a mesotidal drowned river valley, the only estuary of this type in Tasmania. It is tidal for its whole length to the First Basin on the South Esk and on the North Esk to St Leonards, with a 3.5 metre tide occurring twice a day in Launceston. The upper estuary has a long history of dredging and community concern over sediment build-up. Other water quality issues relate to elevated nutrient and pathogen levels in areas of the estuary and its tributaries as well as heavy metal contamination in some areas of the estuary and parts of the freshwater system.

To provide a coordinated management approach and guide for investment in activities to protect, maintain and restore the health of the catchment, NRM North established the Tamar Estuary and Esk Rivers Program (TEER) in 2008. A key goal of the TEER Program is to improve scientific understanding of the issues impacting upon the health of waterways so that priority areas requiring investment in on-ground works can be better identified and targeted. The TEER Program is a regional partnership between the agencies with a statutory responsibility for waterway management and includes local and state governments, Hydro Tasmania and TasWater. The TEER Program also fosters collaborative partnerships and works closely with a range of industry, business, research, government and community groups to coordinate activities to reduce pollutants entering waterways and to monitor and report on waterway health.

The TEER Program has developed a Water Quality Improvement Plan to provide a long-term blueprint for maintaining and improving water quality in the estuary and its tributaries. The TEER program is strongly collaborative and the Plan has been developed using the strong linkages already developed as well as through additional collaborative and consultative efforts with the broader community. A computer-based decision support system, the CAPER DSS, has been constructed to support development of the Plan. This DSS builds on detailed modelling already undertaken in the catchment and estuary as well as a substantial body of knowledge that has been developed through other studies in the catchment and elsewhere. The DSS allows alternative scenarios to be considered and costed for the Plan, to inform selection of appropriate management strategies. The aim is to develop a Plan with strong community support through a collaborative, consensus building approach. The Plan contains recommendations across the full range of activities undertaken in the catchment, with no simple fix-all solutions.

This paper describes the WQIP development process before providing an example of the type of scenario analysis undertaken with the CAPER DSS that has been included in the Plan. This scenario illustrates one recurring theme of the Plan – that change can be both a threat and an opportunity in terms of water quality. With high levels of adoption of best management practice, land use changes can in some cases be accommodated with little impact on water quality, or even with small benefits to water quality where land uses that are poorly managed or otherwise associated with high pollutant loads are replaced.

Keywords: *Water quality improvement plan, decision support system (DSS), CAPER DSS*

A comparison of socio-ecological frameworks for integrated assessment modelling of agricultural groundwater use

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Abstract: Water management options for a given issue must be designed within the context-specific system comprising linked social, hydrological, ecological and economic components. Consideration must be given as to how an option operates within and between these sub-systems. Particularly complex to manage are groundwater systems, which historically have been somewhat 'out of sight and out of mind' for water policy makers despite spatially-distributed and time-varying connectivity with surface water. This has led to its extensive over-allocation of groundwater in many parts of the world with subsequent depletion of quantity, quality and dependant ecosystems. Despite this challenge, groundwater remains key to the future of irrigated agriculture due to its typically high reliability-to-cost ratio, slow response to climate variability, ability to be independently accessed by farmers, and potential benefit of reducing salinity and waterlogging due to its spatially-distributed nature.

The significant challenge of representing complexity in natural systems to improve understanding and allow analysis of responses to change has typically been approached with a multitude of tools. Integrated assessment modelling is an approach that allows translation of the system into a workable, numerical representation by systematically integrating knowledge; key to this is defining relationships between the component sub-systems whilst acknowledging their changing nature in time and space. Additional benefits of model-based processes include their potential to engage and share understanding with stakeholders, and to evaluate management options and trade-offs in the system under applied scenarios whilst taking account of uncertainties both in future conditions and in the model representation. Given that human support is essential for the successful execution of a given water management strategy, the linkages between natural systems and social values should also be integrated into analysis as recognised by socio-ecological systems theory. The ecosystem services approach has emerged to conceptualise this link from an anthropocentric viewpoint through the benefits that people obtain from services provided by ecosystems. This is particularly valid for application to groundwater resource use given the multiple, spatially-distributed beneficiaries of groundwater systems. A number of conceptual frameworks are available to link ecosystem services to human wellbeing through varying structures and differing insights into priority components of the relationship. These are explored to assess the operational benefits and challenges that these socio-ecological frameworks provide as conceptual bases for the integrated assessment modelling of agricultural groundwater use, with reference to three considerations of model design: model purpose; availability of qualitative versus quantitative data; and spatio-temporal scale.

Keywords: *Groundwater, conceptual modelling, integrated assessment, socio-ecological frameworks*

The regional feasibility of augmented local water storages

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Abstract: Local water storages can contribute significantly to meet regional demands for water and offer governments a strategy for reducing or delaying investment in large-centralised water infrastructure. Local water storages include ponds, canals, drainage systems and subsurface aquifers. Augmentation of local water storages and determination of their regional feasibility is not fully understood. Cost-effectiveness, physical characteristics, interactions between measures and interactions with the national water system are of crucial importance here. Dutch national and regional water managers currently negotiate about water distribution and regional self-reliance. However, in the Dutch negotiation, the potential of local groundwater storage, as a way to overcome periods of drought, is generally underestimated.

In this study, we assessed the potential of local groundwater storage measures, regarding technical storage capacity (in cubic meters (m^3)) and costs (euro/ha/year and euro/m^3), in a case study area in the Netherlands (Wieringen+Wieringermeerpolder) by means of a novel dynamic modelling method, called the Fresh Water Options Optimizer (FWOO).

The first results of the FWOO method show that Wieringen+Wieringermeerpolder is able to store between 35 million cubic meters (Mm^3) and 80 Mm^3 with the seven local groundwater storage measures that are taken into account. This is 80% to 180% of the summer demand, based on a water demand of 200 mm during the growing season. The costs for the combination of measures in Wieringen+Wieringermeerpolder are between 0.10 euro/m^3 and 0.13 euro/m^3.

The FWOO is not ready yet. Not all dynamics of augmenting local waters storage measures are (modelling wise) properly addressed. For example, temporal aspects of water supply and demand are not yet taken into account. Besides, preferences and needs of other water users (nature, industry, and urban areas) might lead to undiscovered options to store and reuse water. To inform regional water managers, efforts to compare the costs of local measures with centralized water storage and provision strategies are needed.

Although the model is still under improvement, these first results open new perspectives on the potential of regional self-reliance and should be taken into account during negotiations around water distribution between national and regional water managers.

Keywords: *Fresh water supply management, scale issues, regional self-reliance, decision making*

Is the north our next food bowl? A comprehensive assessment of surface water storage potential in northern Australia

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Abstract: In recent years there has been a resurgence of interest in developing the water resources of northern Australia, predominantly for irrigation. Although about 65% of Australia's runoff is generated in northern Australia, northern Australia (including the Fitzroy catchment in Queensland) has less than 8% of Australia's irrigated area.

This study (https://publications.csiro.au/rpr/pub?pid=csiro:EP147168) sought to broadly estimate how much land in northern Australia could potentially be irrigated using large dams by giving simultaneous consideration to surface water storage potential and the proximity of land resources suitable for development of irrigated cropping and horticulture. It also sought to identify those catchments in northern Australia where future detailed field studies for irrigation potential may be most productive.

The study utilised the DamSite model, a series of algorithms that automatically determines and evaluates favourable locations in the landscape as sites for intermediate to large water storages. Over two billion potential dam sites across northern Australian were assessed at 1 m increments, up to a height of over 100 m at some sites, in a consistent and objective manner.

Soil, surface water and potential large in-stream dams sufficient to support 1.4 m ha of irrigated agriculture exist in northern Australia. Development of this area would require the construction of approximately 90 of the more viable large in-stream storages (including the Burdekin Falls and Ord River dams, which are already constructed) and a large number of reregulating structures (e.g. weirs). Increasing the area under irrigation in northern Australia to 1.4 m ha would result in a ~50% increase in Australia's total irrigated area. Approximately 40% of this area, 600,000 ha of irrigated agriculture, could be secured by constructing ~20 of the more promising large in-stream storages in northern Australia. Clearly, there are declining marginal returns to dam construction; in part because it is attractive to build the best dams first, but also because additional dams may in some places 'compete' for the same water supply.

It has been estimated that groundwater could support approximately 100,000 to 150,000 ha of irrigated land in northern Australia. This is approximately 10% of the land that could potentially be irrigated using large in-stream storages in northern Australia.

Although large in-stream storages are able to support a greater area of irrigation development, groundwater will often be a more cost-effective option where it is available in sufficient volumes. Groundwater is often overlooked as a source of water for irrigation, largely because the process of characterising groundwater is comparatively expensive and uncertain. When the costs of groundwater characterisation are amortised across a development, however, groundwater will frequently prove more cost-effective than large in-stream storages.

Some parts of northern Australia may lend themself to water harvesting and off-stream storage of water, and managed aquifer recharge. In some cases, there may also be opportunities to augment and extract water from natural waterholes and wetlands to supply farm-scale irrigation developments. Although each of these approaches is capable of supplying far smaller (5–100 times lower) volumes of water than large in-stream dams, each may have a role to play in maximising the cost-effectiveness of water supply.

Keywords: *Irrigation, northern Australia, dams, hydrology, DamSite*

Modelling dam resilience with a bottom-up 'decision-scaling framework'

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Abstract: Typically, hydrological modelling of future water availability and system resilience is modelled with a 'top-down' method: future climate projections are obtained from GCMs, downscaled to catchment or point scale, and used as input into calibrated rainfall-runoff models. With the top-down framework, it is difficult to identify and quantify the considerable uncertainty associated with each step of this process. Perhaps more importantly, it is not clear how future runoff time series, or even expected changes to runoff characteristics, can be used to make infrastructure planning decisions. Furthermore, the top-down method ignores the behaviour of the water systems that we are ultimately interested in (such as dams), and these systems are only considered after the modelling has finished.

An alternative pathway to reconciling uncertainty is bottom-up modelling, of which the 'decision-scaling framework' is an example. Here, water-supply system vulnerabilities and critical thresholds are identified at the outset by a sensitivity study using stochastically generated future climate series. Risks to the system under consideration are related to statistical characteristics of plausible future climates. GCM selection and downscaling choices are informed by the behaviour of the system itself. Statistical features of GCM output are then considered in relation to the system vulnerabilities. Ultimately, this results in computationally much simpler system modelling, and it is argued that uncertainty of future scenarios is much more transparent than using top-down modelling. This uncertainty information can then be explicitly considered in making infrastructure decisions. We present an example of the decision-scaling framework applied to future resilience of the Cotter Dam, ACT, and discuss other potential applications.

A simple dam model is developed, with hypothetical management rules based on 95% yield over a 50-year time period. Plausible future climate time series are generated as stochastic replicates based on the observed historical climate time series using the Stochastic Climate Library (SCL). A range of climate statistics are calculated on the stochastic data and related to the dam yield from each replicate. We then relate the climate statistics from GCM output to the system resilience.

Keywords: *Decision scaling, bottom-up, dam resilience, future hydrological projections*

Introducing Velocity Index for Water Distribution Systems

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Abstract: Planning and hydraulic modelling phase in Water Distribution Systems (WDS) are playing an enormous role for water authorities. Making wise decisions in planning phase will ease the future recurrent budget for Capital Expenditures (Capex) and Operating Expense (Opex) to guarantee achieving the acceptable quality of service in WDS encountering population growth and land developments. The conventional methodology for planning of WDS includes the population growth impact assessment on the system and then proposing new assets to comply with the local water distribution code. Potable water networks need asset planning, augmentation strategies and rehabilitation schemes in consistence with the new assigned loads to them. Planning strategies are usually based on sophisticated hydraulic models and a determined and pre-defined time intervals to maintain the level of service after occurrences of increase in design serviced population, asset ageing and/or serviced area. Systems rehabilitation studies require significant amount of budget which is the main constraint for the water authorities for the implementation of any augmentation plan.

Two main factors are playing roles in WDS asset planning strategies. The first parameter is the acceptable Level of Service and the second factor is the “Associated Cost” of the asset planning. The main goal of a proper planning in a WDS is the prediction of a system’s behavior in future and suggestion of efficient set of solutions for the predicted demand. The most critical criteria to be addressed and augmented in a typical urban WDS are water pressures and water velocities. Water pressure is the first tangible measure that customers feel and the water velocity has impact on energy loss in the system which is an indicator of applied shear stress from water to inner side of the pipes. The water pressure and the water velocity are two main hydraulic factors which are affected by population growth and therefore capital expenditure needed to rectify them.

Authors earlier introduced a Pressure Index (PI) for WDS and studied the relationship between PI improvements and augmentation costs per connection. Authors’ earlier publication considered the modification and improvement of pressures in the water systems. In the current paper, development and calibration of further hydraulic models (using Innovyze InfoWorks WS model) for water systems are presented. In addition to the introduced PI factors, in this paper a new index (Velocity Index, VI) is introduced for the assessment of WDS from the water velocity point of view. Relationships between improvements of Level of Service (considering VI) and “Associated Cost” in WDS are presented.

Keywords: *Level of service, network planning, velocity index, upgrade cost, water distribution system*

Long distance water transfer: Socio-economic development and environmental sustainability

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Abstract: Population growth, better living standards, increase in agricultural and industrial activities, degradation in water quality, and many other factors have and continue to increase the demands for freshwater around the world. During the past century, large-scale water projects, especially large dams, have been playing a key role in meeting these increasing demands, both in the developed world and in the developing world. In recent years, there has also been serious consideration into large-scale and long-distance transfer of water from 'water-excess' regions to 'water-deficit' regions.

There is no doubt that large-scale water projects bring a great number of global, regional, and local socio-economic benefits. For instance, large dams supply water for about 30–40% of the total irrigated land around the world and also generate about 20% of the world's total electricity. However, there are also serious concerns about their negative environmental and social impacts. For example, large dams and diversions have already caused severe fragmentation of about 60% of the world's 230 largest rivers (leading to degradation of ecosystems in many) and also displacement of an estimated 40–80 million people from their homes (leading to negative socio-economic consequences). As a result of these, there have been serious debates on the role of large-scale projects in our societies and on their future.

The present study is intended to contribute to further advance our discussions and debates on large-scale water projects. In particular, the study looks into large-scale and long-distance water transfer projects in the developing world. For this purpose, two projects are examined: (1) the South-North Water Transfer Project in China; and (2) the National River Linking Project in India.

The South-North Water Transfer Project aims to channel about 44.8 billion cubic meters of fresh water annually from the Yangtze River in southern China to the more arid and industrialized north through three canal systems: the Eastern Route, the Central Route, and the Western route. A significant portion of this project has already been completed. The aim of the National River Linking Project is to link India's rivers by a network of reservoirs and canals and, thus, to reduce persistent floods in some parts and water shortages in other parts of India. The project is split into three parts: a northern Himalayan rivers inter-link component (14 projects), a southern Peninsular component (16 projects), and an intrastate rivers linking component (37 projects). It is still in its preliminary planning and implementation stages.

The enormity of these two projects as well as their estimated benefits and costs, with important implications for the socio-economic development and environmental sustainability in the two most populous countries in the world, inevitably lead to a number of key questions. For instance: (1) What have been the most critical reasons for their proposal? (2) Have there been sufficient assessments on their benefits and costs? (3) Have other alternatives, if any, been sufficiently explored? and (4) What lessons have been learned during the planning/implementation stages of these projects, as appropriate? The present study attempts to answers these questions. Based on such examination on one hand and the major challenges in future water planning and management on the other, the future of large-scale and long-distance water transfer projects, especially in the developing world, is also discussed.

Keywords: *Large-scale long-distance water transfer, socio-economic development, environmental sustainability, China's South-North Water Transfer Project, India's National River Linking Project*

Estimating Volume of Water Harvested by Farm Dams in Murray-Darling Basin

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Abstract: With limited water resources available, farmers in many parts of Australia have resorted to building farm dams to supplement water for irrigation and stock. While the impact of an individual farm dam on a catchment is relatively small, the cumulative impact on runoff from a large number of farm dams on may be significant. To give an example of scale, the Murray-Darling Basin (MDB) has over 650,000 farm dams at present. This paper aims to quantify the effect of the farm dams on the water resources in the Murray–Darling Basin.

Through the Water Act 2007, the Bureau of Meteorology (the BoM) has the responsibility to produce an annual National Water Account (NWA) which provides information on water stores and fluxes, water rights and water use across Australia. The Australian Water Resource Assessment Modelling System (AWRAMS) is being developed by CSIRO and the BoM through the Water Information Research and Development Alliance (WIRADA) initiative. AWRAMS is a new integrated continental hydrological simulation system that has two modeling components to represent processes between the atmosphere and the landscape (AWRA-L) and in gauged rivers (AWRA-R), including all major water storages and fluxes in and between these components (surface, subsurface and groundwater). One of the fluxes described in the NWA is the runoff to rivers/reservoirs accounting for interception and storage by farm dams.

The Spatial Tool for Estimating Farm Dam Impacts (STEDI), developed by SKM, was used in the production of the NWAs for 2010 and 2011. STEDI carries out a water balance for each farm dam at each monthly time step using contributing catchment inflows, rainfall, evaporation and on-farm demand. The contributing catchment inflows were obtained by lumping the contributing catchment's runoff generated by the grid-based AWRA–L model. Running the STEDI model is time consuming in terms of preparing and inputting the data into the model and applying it over large areas as the number of farm dams in a model run must be less than 10,000 (requiring 105 regions in the case of the MDB). In order to streamline and speed up the production of the NWA, a farm dam model (FDM) similar to STEDI was coded in FORTRAN, run over the NWA Canberra region and then evaluated by comparing the results to those from the original STEDI model. Following successful evaluation, the developed FDM model was applied to the recent NWAs (NWA 2011, NWA 2012, NWA 2013 and NWA 2014) over the MDB.

The current FDM approach used in the NWA has two limitations: all farm dams are assumed to be directly connected to the catchment outlet and the spatial variation in the input is ignored by lumping them. Also, currently the farm dam modelling is undertaken separate from the AWRAMS although there are plans to integrate the two in the future. This paper will present the development of a farm dam model and its application to the MDB for the production of the NWA reports. Future direction of farm dam modeling through model integration with the BoM's operational AWRAMS is also presented at the end of the paper.

Keywords: *Farm dam modelling, water harvesting, National Water Account, Murray-Darling Basin*

EXTENDED ABSTRACT ONLY

Adaptive and optimal scheduling of environmental water management alternatives using environmental water allocation forecasts: A South Australian River Murray Case Study

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Abstract: The conflict for water is intensifying due to rapid increases in global populations and the threat of climate change. As a result, there is limited water to meet all the needs of the environment, including all the different flow requirements for a wide range of species and processes. This is further complicated by the fact that there are multiple environmental water management alternatives (e.g. releases, regulator operations, pumping) that also have spatial and temporal dependencies. One approach that can consider these complexities and identify alternatives that achieve environmental benefits, with limited amount of water is optimisation. Optimisation has been used extensively for water resource planning related to environmental flow management, particularly in long-term planning where historical flow data are used or assumptions are made on future available environmental water allocations. However, these methods are not applicable in an operational setting where environmental water availability changes annually due to natural hydrological variability (e.g. dry, average, wet years), and as such there is a need to develop an approach that takes this into account.

In this presentation, an adaptive multi-objective ant colony optimisation framework that can be used to schedule environmental water management alternatives (i.e. environmental water releases and wetland regulator operations) is proposed. It develops an environmental water forecasting model using artificial neural networks and uses this to predict likely available water for the environment. Optimal schedules are then updated at regular intervals in order to consider changes in predicted hydrological conditions. Finally, an additional objective function is incorporated to ensure alterations made to the schedules are kept to a minimum, such that interruptions made to existing operational plans are kept to a minimum

To demonstrate and assess the utility of the proposed approach, a case study of a reach between Locks 1 and 2 in the River Murray in South Australia is used. A simple hydrological model of the river, wetland floodplain system is used to represent the region, while predictions ecological response for different species (e.g. fish, vegetation, waterbirds) are estimated using the Murray Flow Assessment tool. A range of investigations have been conducted, including (i) a comparison of the proposed approach with that of long term planning approaches (i.e. benchmark and deterministic approaches) (ii) assessing whether ecological response can be maintained while minimising number of schedule interruptions and, (iii) examining the benefits of using a forecasting model in the adaptive approach. The results suggest that the proposed approach improves the ecological response in an operational setting (with the use of environmental water allocation forecasts) when compared with previously developed long-term planning approaches. The approach can also minimise the number of alterations made to existing optimised schedules during the update stage, while preserving the ecological health of the system. This can potentially aid managers in reducing the number disruptions made to long term planning of environmental water delivery actions and in turn reduce the resources (e.g. costs) required to implement these actions. In addition, the approach can assist managers in ensuring efficient operation of environmental water management alternatives, such that the maximum ecological outcomes can be potentially achieve in times of limited water availability and varied annual environmental water allocations.

Keywords: *Operational planning; environmental water decisions, multi-objective ant colony optimisation, South Australian River Murray, environmental flows*

Geological weighing lysimeters for real-time surface water budget monitoring of climatic shifts and trends?

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Abstract: Time series of ecosystem-scale water storage change should signal climatic change because storage amount reflects the integrated environment. Direct measurement of area-averaged land storage change is now possible through either gravity observations or geological weighing lysimeters (gwl). Gravity satellite systems such as GRACE monitor water storage changes over extensive regions at coarse time and space scales, while gwl stations monitor over hectares in real time. The gwl approach comprises accurate measurements of deep static pore water pressures (derived, for example, from seismic monitoring) which monitor near-surface water storage changes. Similarly, direct gravity monitoring to detect the local storage change signal of climate change might be achieved using existing deep underground physics laboratories, if in a suitable location By the combined use of new and existing monitoring, it is suggested that a global network of ecosystem storage change be set up in localities likely to be most impacted by climate change effects. This proposal follows from a concept presented at the Melbourne IUGG. Since then the International Continental Scientific Drilling Program confirmed at the 2015 EGU Vienna meeting that they would consider favourably a multi-national application for funding establishment of a network of gwl stations around the world toward detecting climatic variations as evident in ecosystem water storage shifts and trends.

The gwl concept is particularly simple but requires suitable subsurface hydrogeology with confined isolated aquifers having pore pressures influenced only by static effects due to surface loading from ecosystem water storage change. The aquifer pore water pressure thus acts as a weighing fluid and area-integrated ecosystem storage change (as length units of water) is derived by utilisation of the aquifer loading coefficient. This enables storage change to be monitored in real time over a scale of hectares from a confined aquifer in the order of 50 metres or more below ground surface. Use of two or more aquifers in the same locality serve as independent replicates to ensure that any shifts or trends are true eco-climatic effects as opposed to a change in deep recharge or other dynamic influence. A two-aquifer gwl system can yield surprisingly accurate measurements of surface / subsurface water storage change. For example, Fig. 1 shows a period of time at a pasture field site where water storage change is almost entirely taken up as rain water accumulating in the soil without evident evaporative loss.

Inevitably, some gwl's in a global monitoring network will fail because of aquifer leakage effects or other unforeseen effects. However, if a sufficient number can be established and verified via replication, in a range of climatically-sensitive ecosystem locations, then they would provide a useful reference base for monitoring climatic shifts in the years to come.

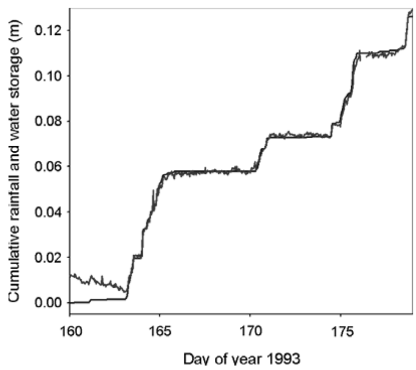

Figure 1: Similar accuracy of a rain gauge and gwl in monitoring cumulative rainfall as storage change.

Keywords: *Ecosystem storage change, gravity monitoring, mass change, climate change*

Global warming accelerates the degradation of desert vegetation in Central Asia

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Abstract: Over the past half century, almost all regions of the world have experienced a warming process. The rising temperature accelerates the global water cycle, exacerbates extreme hydrological events, intensifies the degradation of desert vegetation, and leads to a much more fragile water-based ecosystem in Central Asia. Changes in the spatial and temporal changes of water resources due to climate change will lead to the severely contradiction of water resources supply and demand between the oasis and desert. The ecosystems are also intensely sensitive to global climate change. Based on recent research results, this paper analyzes the impacts of climate change on hydrology and ecology. The analysis results show that:

- The temperature experienced a "sharp" increase in 1997, since then has been highly volatile, the average temperature during 1998-2013 is about 1.11℃ higher than the average of 1960-1998 in the arid region of Northwest China in Central Asia. Precipitation remained relatively stable from 1960 to 1986, and then showed a sharp increase in 1987. Since the beginning of the 21st century, however, the increasing rate of precipitation has diminished. Water resources mainly come from natural precipitation in mountains and mountain snowmelt water that is greatly affected by temperature. For instance, climate change impacts glacier movements and snow distribution, and can also lead to increases in heavy precipitation days and flood frequency. However, when some glaciers disappear in the future, water resources in the arid region will be not optimistic.
- Based on the land use/cover classification data during the past 30 years, land use in the Tarim River Basin in Central Asia has experienced considerable change, especially in the last decade, with most notable phenomena of cultivated land expansion. The cultivated land expansion at a rate of 686.42 km^2 / year. Almost all of the water resources are used for irrigation in the extreme arid region, which causing the ecological water lack seriously. The large-scale reclamation of irrigated land leading to the decline of the underground water level, reducing the water storage, e.g. the total water storage in the Tarim River Basin in Central Asia decreased at a rate of 1.3 billion m^3/year during the past 13 years. Then the extreme events and drought intensity is intensified. The changes of water resources will cause the mismatched features of water resources and the spatial distribution of productivity to become increasingly dire.
- Vegetation dynamics are highly sensitive to climate change, especially in arid region. The high volatility of temperature and diminished precipitation have broken the original natural balance, this, coupled with a significant decline in water storage and shallow groundwater levels, accelerates the plant evapotranspiration and soil water dissipation and causes the shallow roots of desert plants to weaken and die, thereby reducing species diversity and vegetation cover. Specifically, the NDVI of natural vegetation in Central Asia during 1982-2013 exhibited an increasing trend at a rate of 0.004 per decade prior to 1998, after which the trends reversed to decrease at a rate of 0.003 per decade. Moreover, shrub cover and patch size exhibit a significant increase, even shrub encroachment in grasslands.

Water resources, generated from mountain regions, are critical for feeding ecosystems and society in oases in piedmont alluvial plains surrounding the desert. Potential changes in these limited water resources generate huge concerns about further degradation of vegetation, and expansion of the desert intrusion. Under the impact of global climate change, the vulnerability of ecology system and uncertainty of water resources are increasing. Therefore, we should pay attention to the ecosystem change and conservation in the peripheral area of oasis and desert. Meanwhile, in the process of resources development, we should follow the priority protection rules in order to adapt to the effects of global warming.

Keywords: *Climate change, water resources, ecological effects*

Spatial variability of Australian ecosystem water use efficiency

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Abstract: Ecosystem carbon production and water use are two intrinsically coupled processes. Carbon uptake per unit water use, or water use efficiency (WUE), is one of most important properties of ecosystem functioning. It is also a fundamental constrain for predicting future carbon budget, food security and water availability under change. Our knowledge about WUE at leaf scale is well advanced. However, our understanding of WUE at ecosystem scale, typically defined as the ratio of ecosystem gross primary production (GPP) to evapotranspiration (E), is still limited. In this study, spatial variability of Australian ecosystem WUE and its uncertainty are investigated at a spatial resolution of 0.5 degree using land surface models (LSMs). Ecosystem WUE was modelled by 7 LSMs during 1982-2011 with TRENDY global meteorological forcing dataset. The LSMs are CABLE, CLM4.5, ISAM, JULESS, LPJ, LPJ-GUESS and ORCHIDEE. The spatial variability of Australian ecosystem WUE is shown in Figure 1a, as the median of the ensemble mean annual WUE of all models. Estimated mean WUE over the Australia continent is about 1.19 g(C)/mm(H_2O), with an interquartile range (IQR) of 0.66–1.56 g(C)/mm(H_2O). As expected, the Australian ecosystem WUE shows a distinct pattern of higher WUE in the wet regions and lower WUE in the arid regions, similar to the spatial patterns of precipitation gradient and vegetation cover. We also quantify the uncertainty using median absolute deviation (MAD) and its relative percentage to the median (see Figure 1b and 1c). The mean MAD is 0.50 g(C)/mm(H_2O), indicating that the higher WUE regions have larger MAD, and vice versa (Figure 1b). Relatively, the MAD is about 40% of the estimated WUE with an IQR of 32–54% over all land cells. The south and east part of the arid region has the largest uncertainty among different models, where the relative MAD to median is larger than 50%. The uncertainty in WUE is mainly sourced from the differences in the estimated GPP and/or E among different models. This study provides a new characterization of the level of our understanding of the coupling between ecosystem water use and carbon production in Australia, of which about 75% is as semi-arid/arid region. With respect to the facts that semi-arid region suffers high water scarcity but plays a dominant role in the variability of global carbon cycle, this study suggests that understanding about ecosystem WUE in the semi-arid region requires the largest attention for improving our ability to project the future climate change and water availability.

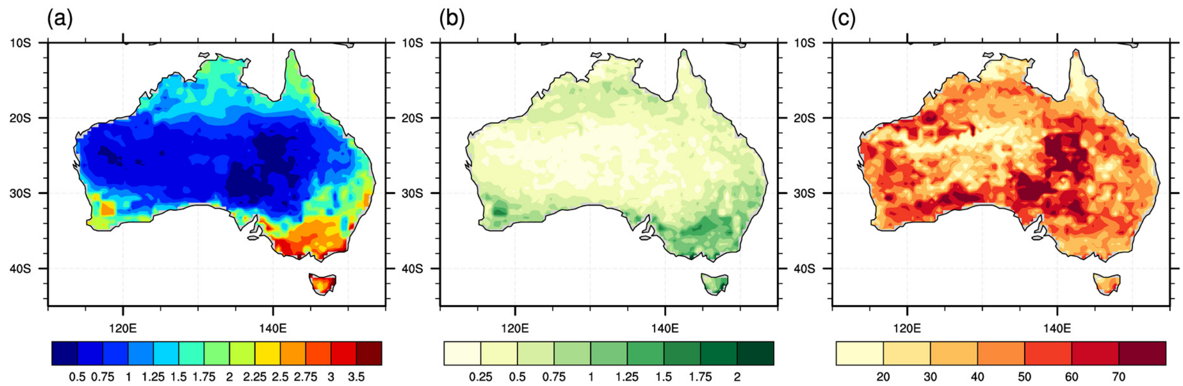

Figure 1. Contour plots showing the spatial details of the Australia ecosystem WUE and its uncertainty among different LSMs. (a) and (b) are the median and MAD of the mean annual WUE in g(C)/mm(H_2O), respectively; (c) is the relative MAD to median in percentage.

Keywords: *Water use efficiency, water and carbon, coupling, Australia*

Seasonal patterns and long-term trends of runoff and water quality component in the Yangtze River, China

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Abstract: At both regional and global scales human activities have great impacts on hydrological cycle, which plays an important role in surface water chemistry and ecology. Runoff of both river water and suspended sediment play important roles in aquatic ecosystems and contribute to bottom material composition, water-column turbidity, and chemical constituent transport. Especially, changes in stream flow may impact long-term trends in water quality concentration and the potentially subtle effect of shifts in stream flow may be missed if only measured water chemistry concentrations are considered. In this study, the seasonal patterns and long-term trends of runoff and water quality component will be studied for the Yangtze River, China. The principal control parameters of flood events and climatologic parameters and the relationships between corresponding hydrologic process and water quality will be described. The method used in this study will illustrated how short records of daily discharge and components concentration can be combined to obtain meaningful estimates of seasonal suspended sediment and water quality loads. Meanwhile, the results will indicate that changes in runoff have an important impact on trends in water quality concentration. The estimated seasonal loads were highly variable from 2004 to 2014, with the greatest loads occurring in the summer and the smallest loads occurring in the winter, reflecting fluctuations in discharge as a result of the combined effects of seasonal runoff patterns, the exact timing of which vary from year to year. It demonstrates that the long-term generation of runoff and associated processes is important in understanding water quality under changes in climate and land use, especially the establishment of dams. For example, according to the estimated suspended sediment at the Yichang river discharge monitoring station, up to 60% of sediment entering the Three Gorges Reservoir was trapped during the high-discharge months (June–September) in recent years. These findings provide a sound foundation for use in water quality modelling at regional scale in the Yangtze River basin.

Keywords: *Seasonal patterns, long-term trends, runoff, nutrient, Yangtze River*

Trends in hydrological variables in large basins in Tibetan Plateau

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Abstract: The Tibetan Plateau is the source area of many major rivers in Asia, including the Indus River, Ganges River, Brahmaputra River, Yangtze River and Yellow River. It plays a key role in both hydrologic cycle and climate in eastern and south-eastern Asia. Recent studies have shown that the majority of the plateau area has experienced significant warming since the mid-1950s. This paper investigates hydrological and climatic trends for six large river basins (Yalung Zangbo River, Salween River, Mekong River, Tongtianhe River, Yalongjiang River and Yellow River) in the Tibetan Plateau during 1956–2013, and determines whether the changes in streamflow in these basins are mainly driven by the variation of climatic elements (precipitation and temperature). Our results show that during the past multi-decades, the six river basins did not exhibit distinct trends in annual streamflow ($p > 0.05$). Yarlung Tsangpo River at Nuxia station and Yellow River at Tangnaihai station showed a slightly decreasing trend (-0.009 mm yr^{-2}, -0.19 mm yr^{-2}) in annual streamflow while others showed a slightly increasing trend. Annual mean temperature and precipitation at all stations except for Luning showed noticeably increasing trends. The impact of global warming on streamflow is complicated. On the one hand, annual evaporation could increase under warmer and drier air conditions, which will result in decreasing streamflow. On the other hand, meltwater will increase under global warming, which will increase streamflow. Our results suggest that climate warming in the Tibetan Plateau has speeded up the water cycle, indicated by the slight increase in streamflow. Further hydrological modelling studies should be conducted to quantify future streamflow changes and their uncertainty across the Tibetan Plateau.

Keywords: *Tibetan Plateau, climate change, streamflow, precipitation, temperature*

Development and evaluation of global land surface evaporative flux records

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Abstract: Understanding the spatial and temporal behavior of evaporation at regional and global scales is important for improving our understanding of the water, energy and carbon cycles. In recent years, there have been a number of efforts to develop global products of land surface heat flux, spanning a range of space and time scales and utilising a variety of different forcing and underlying model structures. In the context of the GEWEX-LandFlux and WACMOS-ET projects, the efforts have been guided by a need for independent and observation driven predictions of the heat fluxes, using remotely sensed data where available and supplementing with other forcing when required. The GEWEX based project has provided long-term records of fluxes that will enable an assessment of trends and variability to be examined, while the WACMOS-ET project, operating over a shorter period, has offered insights into the inter-model variability of flux response over many regions. These data sets provide a means to better understand the cycling of water through the Earth system, examining not only the absolute range of flux observed, but also how this changes in space and time. Here we will present some of the key outcomes and findings of these efforts, together with some of the lessons learned in delivering long-term, consistent flux records. Results focusing on examining the multi-model and multi-scale assessment of flux products will be presented, together with an evaluation of product differences and areas where future work is required to improve flux characterization. Issues of product independence, model structure, forcing data and model sensitivity will also be explored.

Keywords: *LandFlux, WACMOS-ET, GEWEX, latent heat flux, global evaporation*

Assessment and Comparison of Alternate Conceptual Ecohydrological Models

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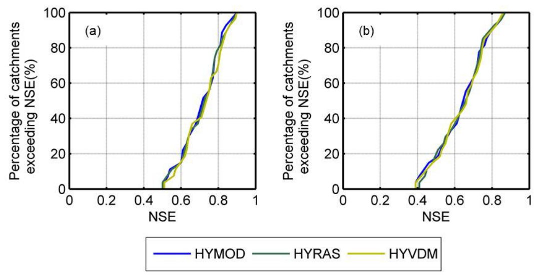
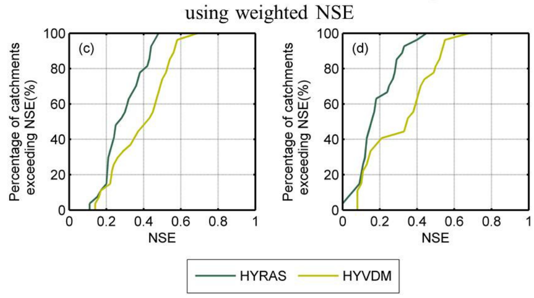
Abstract: A merging of a conceptual hydrological model with two dynamic vegetation models is presented to understand the catchment behavior for streamflow prediction. Two conceptual dynamic vegetation models with differing representation of physical processes are merged with a lumped conceptual hydrological model (HYMOD) to improve the ability to simultaneously predict catchment scale streamflow and vegetation properties (represented by leaf area index (LAI), denoted as HYRAS and HYVDM. The validation is based on comparing outcomes from these models with observed data (runoff, LAI) with the following specific objectives: 1) to assess how the complexity of ecohydrological models will affect streamflow predictions; and 2) to assess the performance of ecohydrological models for simultaneous optimization of streamflow and LAI through single-objective and multi-objective calibration algorithms. To assess the performance of these models, data for 27 catchments of 90 – 1600km^2 in size located in the Murray – Darling Basin in Australia are used. The results show that the merged models were capable of improving prediction of streamflows compared to hydrological models alone. Similarly, both merged models show good predictions of LAI using single-objective optimization (Figure 1).

Our results illustrate that when single-objective optimisation was focussed on one response output to maximize the objective function for that response, the other un-calibrated predicted outcome (LAI if streamflow is the focus) was consistently compromised. Thus, single-objective optimization cannot take into account the essence of all processes in the conceptual ecohydrological models. However, multi-objective optimisation showed great strength for response outputs, streamflow and LAI. Both response outputs were better simulated by HYVDM than HYRAS due to better representation of physical processes such as net primary productivity (NPP) in HYVDM. Our results highlight that simultaneous calibration of streamflow and LAI using a multi-objective algorithm proves to be an attractive tool for improved streamflow predictions.



(a) calibration and (b) validation for streamflow prediction using weighted NSE



(c) calibration and (d) validation for LAI simulation using weighted NSE

Figure 1. Distribution of calibration and validation performance across all catchments using single-objective optimization.

Keywords: *Ecohydrological models, multi-objective calibration, streamflow prediction, LAI*

Cross-basin comparison of water availability and use from global hydrological models

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Abstract: Global future water resources will be constrained by the potential effects of climate change and population and economic growth. Robust global water resources assessments under future climate and development rely on the ability of global hydrological models (GHMs) to simulate historic availability and water use with reasonable accuracy. GHMs can simulate water abstraction and flow regulation by large dams, albeit through simplified but consistent approaches. In data sparse basins, outputs from GHMs may be the only timely source of information to assess water resources and potential impacts of climate change and human interference. This study compares water availability and use of the state-of-the-art GHM PCR-GLOBW to water use-accounts (WUAs) developed for ten of the world's largest (> 300,000 km^2) basins. The WUAs link 'known' quantities in the water balance, such as rainfall and streamflow measured at gauging stations, with simple conceptual models to estimate water availability as well as dryland and irrigated water uses, storages and losses at the catchment (sub-basin) scales. The cross-basin comparison, carried on a monthly basis from 1960 to 2000, is used to indicate the degree of uncertainty in GHMs estimates through indicators of model performance that quantify pattern similarity (correlation coefficient r^2), accuracy (Nash Sutcliffe Efficiency, NSE), the amplitude of the variations (%bias) and trends between WUAs and GHMs water availability and use. WUAs were calibrated using observed streamflow at 172 gauging stations, some of them downstream dams. Good streamflow patterns were simulated in 75% of catchments (r^2>0.75). Conversely, good agreement was found for only 30% of catchments (NSE>0.75). Generally, the variance in NSE was greater than the variance in r^2, indicating model over- or underestimation. The large difference between the mean and medians, both for NSE and %bias (more than a 100% on average, whereas r^2 changes are small), highlight that a limited number of catchments are highly skewed and degrade the basin mean simulated agreement. The mostly negative %bias values showcase a systematic underestimation of simulated streamflow, large in some of the mentioned catchments. Basin-scale comparisons of PCR-GLOBW with WUAs show mixed results. Comparisons of dryland evapotranspiration ($ET_{dryland}$) patterns are generally modest to good (0.28< r^2<0.85), with WUAs $ET_{dryland}$ larger than PCR-GLOBW in most basins (except for the Ganges and Mekong) and trends generally following the same direction and magnitudes, with notable exemptions. Landscape runoff (R_0) show modest to good patterns (0.34<r^2<0.8), with PCR-GLOBW R_0 being larger than PCR-GLOBW's and trends generally following the same direction and magnitudes. The largest differences occur in evapotranspiration from irrigation (ET_{irr}) due to differences in data and assumptions used to quantify the extension of irrigated areas. Whilst WUAs use static areas throughout the study period, PCR-GLOBW shows a gradual increase in extent based on country-level statistics, and hence ET_{irr} demand.

Keywords: *Climate, global water resources, trends, evaluation, simulations, water use-accounts*

EXTENDED ABSTRACT ONLY

Statewide space-time water table mapping: Victoria's water table over 30 years

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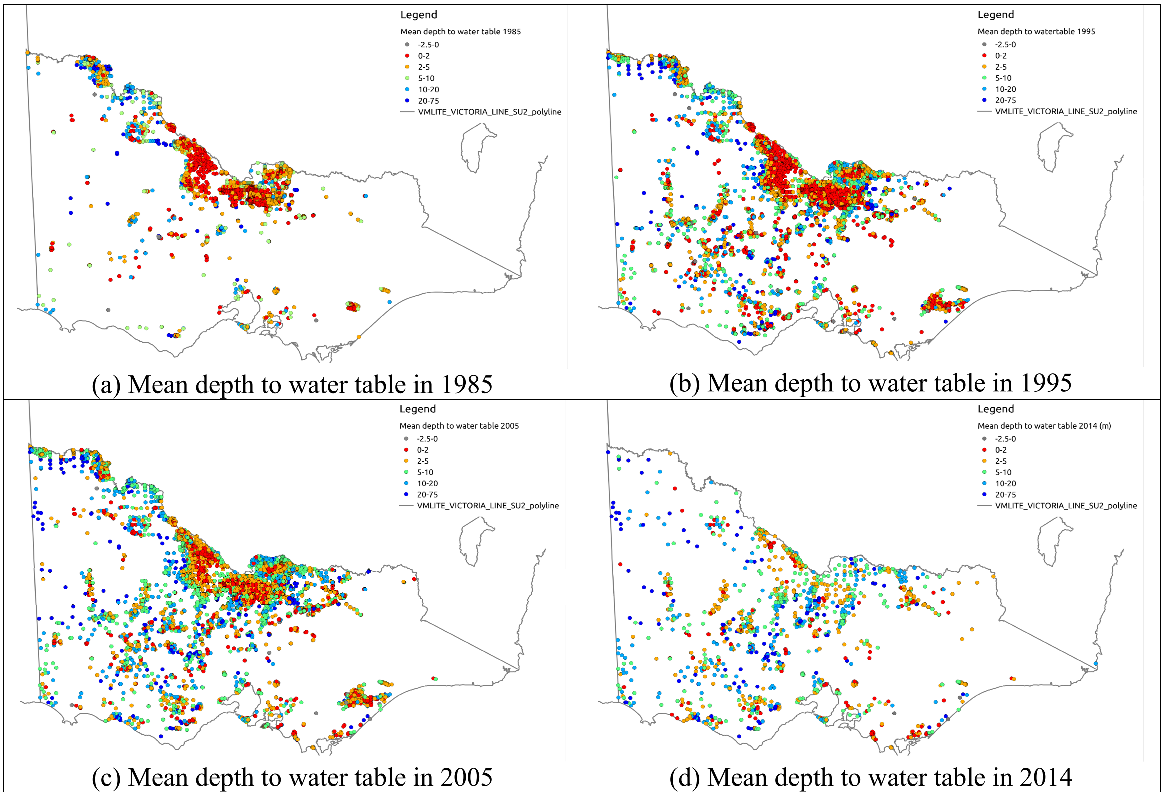
Abstract: Interpolating sparse unconfined groundwater level observations to map the water table has most commonly been undertaken at a local scale and at one point in time, often simple using an average water level over a year or season. These deficiency arises from the numerical challenges of regional scale mapping and irregular and infrequent water level monitoring, which makes the estimation of head at single point in time, where no field measurement exists, challenging. Consequently, a detailed understanding of the water table dynamics over time has been compromised. The focus on local scale processes has limited the inclusion of regional scale processes in the interpolation, such as average rainfall, and has potentially limited the utility for regional scale groundwater management.

This paper explores the possible insights from time-specific regional scaling water table mapping using a novel multivariate colocated cokriging approach for water table mapping combined with the temporal interpolation of groundwater head using the Peterson & Western (2014) time-series model. The approach is then applied to map the monthly water table across Victoria from 1985 to 2014 (Fig. 1 shows the input point data). Using these maps, the location and the nature/magnitude of major changes were identified and the surface-groundwater connectivity of major rivers was estimated (as a gaining or losing gradient) over time.



(a) Mean depth to water table in 1985
(b) Mean depth to water table in 1995
(c) Mean depth to water table in 2005
(d) Mean depth to water table in 2014

Figure 1. Mean annual observed depth to water table across Victoria for years 1985, 1995, 2005, 2014.

Keywords: *Geostatistics, water table mapping, potentiometry, groundwater*

Trends of water and energy fluxes and their implications to water resources in Haihe River Basin, China

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Abstract: Haihe River Basin located in North China is facing severe water shortage. This study investigates water and energy transfer over the basin using a simple land surface model. The key features of this model includes that (1) the linear weighted sum of area percentage of different land use types is used for the simulation of the heterogeneous grids, and (2) irrigation practice is taken into account for the simulation of croplands. The model explicitly simulated daily water and energy fluxes in the basin at a spatial resolution of 8 km over past 28 years (1981–2008), driven by remotely sensed and meteorological data. Our model simulations are well compared to the actual evapotranspiration (ETa) measured by the Eddy Covariance method in croplands, river flow discharge observations in a mountain catchment, and groundwater level observations over the piedmont plain (Figure 1). The good model performance gives confidence to analyze the spatial and temporal distribution and changes in fluxes over the past 28 years. Our results show that ETa rates in plain areas are higher than those in mountain areas despite of higher net radiation (Rn) occurred in mountain areas (Figure 2). This is because the plain areas show higher air temperature and much larger area of irrigated farmland, compared to the mountain areas. High sensible heat flux (H) and low ETa in urban areas occurred because of less vegetation cover, impervious surface, rapid drainage and heat island effect in cities. Over the past 28 years, the water deficit continuously occurred in plain areas because of extensive pumping for irrigation to meet the deficit of crop water requirement. However, irrigation has led to significant groundwater depletion, which poses a challenge on the sustainability of water resources. The distribution and change features in water and energy fluxes across the Haihe River basin make the water issue more complicated and call for more attentions to integrated river basin management.

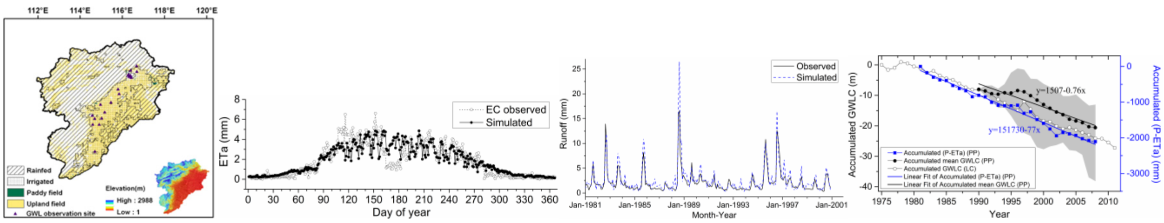

Figure 1. Distributions of irrigation and rain-fed cropland, paddy field and upland field, groundwater level observation sites and elevation in the HRB and validations using multi-source observation including ETa, Runoff and groundwater level changes.

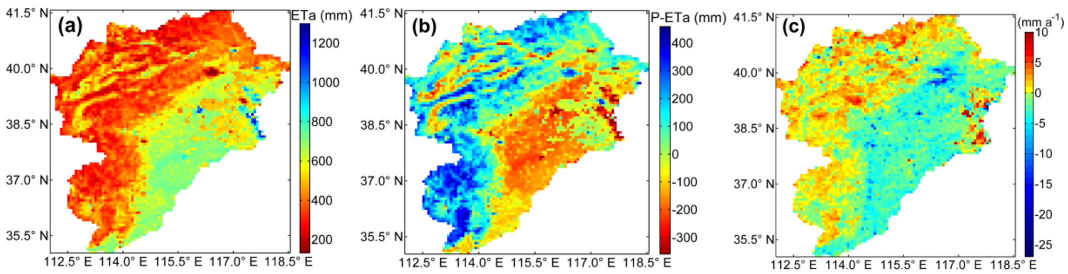

Figure 2. Distribution of mean annual (a) ETa, (b) P-ETa and (c) temporal trend of ETa during 1981–2008 in the HRB.

Keywords: *Evapotranspiration, water budget, climate change, water shortage, modeling*

Covariance partitioning: a new approach to evaluating hydrologic models

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Abstract: In hydrologic/climatic modeling, there is an ongoing debate on "whether past performance of hydrologic/climate models has any guarantee of future skill". A recent important example is that in ranking climate models prepared for the Fourth and Fifth assessment report by the Intergovernmental Panel on Climate Change (IPCC), the ranks of models in simulating air temperature are not stable over different periods when the temperature anomaly is used but are reasonably stable when the actual temperature is used. That debate presents a grand challenge in applying climate model outputs and can be extended to a more general argument that "can we predict inter-annual variations when models have reasonable performance over intra-annual timescales, e.g., daily, monthly". To contribute to that debate we start with our recently developed analytical approach that partitions the variance between space and time. We show that the same framework can be used to answer the question by incorporating the covariance. The covariance (and therefore the correlation coefficient) between models and observations across space and time can be partitioned between space and time. And the covariance over time can be further partitioned between the intra- and inter-annual covariance. To examine it, we use the monthly air temperature output from the IPCC AR5 climate models and monthly historical air temperature from the CRU datasets. We find that the intra-annual covariance dominates the covariance of using the actual temperature and is in fact very stable in climate model ranks. And when the temperature anomaly is used, the covariance is for the inter-annual covariance and is not stale in ranks. The same framework can also be applied to hydrological modeling assessments. This approach allows the multiple representations that are needed for handling a hydrologic/climate model ensemble. The covariance partitioning scheme can accommodate variations at various space and time scales. Our results show that the argument arose originally because of incorrect handling of intra- versus inter-annual variations.

Keywords: *Covariance/variance partitioning, hydrologic modelling, variability*

Air temperature, missing data and interpolation

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Abstract: Long term climate data sets are crucial to drive land surface and hydrological models. However, the limited number of sites and the uneven distribution of meteorological stations would definitely occupy different weights and large data gaps almost always exist in climate datasets and therefore interpolations of some kinds are needed. In this study we use air temperature, the most commonly used data, as an example. When interpolating data of air temperature, we in fact include information like its geographical location and elevation implicitly, which have great effects on air temperature. To investigate the possible effects above on air temperature through interpolation, here we use the data from all available meteorological stations in China and interpolate its monthly mean air temperature as well as latitude and elevation from January 1951 to December 2013. We extract values at exact location of all 756 sites as well as 122 sites with data of 4 seasons (at least one month record in each season) from 1951-2013 which have better data integrity and then generate the geographic information like latitude and elevation to form yearly mean data series.

We hope to evaluate the possible effects about these implicit information after interpolating and since the station distribution is relatively stable after 1961, we use the mean values of air temperature, latitude and elevation during 1961-1990 and calculate the anomalies from 1951-1960 of two selected groups of stations. The result shows that the latitude change is non-significant and it can be neglected and the lapse rate in China as a whole is about -5.032℃/1000m according to the ordinary Kriging method. We use this value to make adjustment of air temperature from 1951-1960 and 1991-2013 to reduce the effect of elevation interpolation. The newly adjusted air temperature can better show the temperature change since 1950s and better correlation with the average temperature of 122 sites and the gridded data sets which is newly generated after DEM adjusted. The correlation coefficients are 0.993 and 0.994 compared with the original one, which are 0.922 and 0.848 at 99% confidence level. Here we argue that the implicit information like geographical location and elevation has been overlooked in previous studies when using interpolated/gridded data in hydrological and land surface models to assess changes in global or regional water and energy cycles.

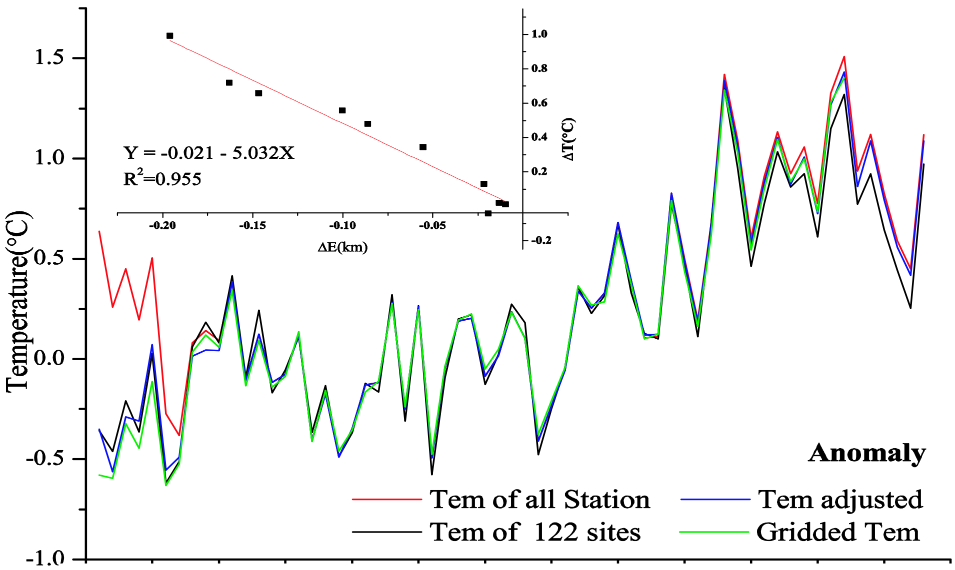

Figure 1. Changes of different groups of air temperature anomalies from 1951-2013. The anomaly of air temperature between all stations and selected 122 sites agrees quite well with that of elevation.

Keywords: *Interpolation, air temperature, meteorological stations*

The effects of deforestation on the water cycle in Amazon

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Abstract: Changes in land surface may affect climate and the hydrological cycle. The Amazon basin, the largest watershed in the world (with a drainage area > 7 million km^2), holds more than 40 % of all remaining tropical rainforests and it has been the focus of main studies about the impacts of land surface changes. While many macro-scale land surface models (LSM) have been used to study the water cycle and the effects of deforestations in Amazon, these LSM outcomes do not agree with each other and are not consistent with findings from various mesoscale. Despite significant modelling and monitoring efforts made in Amazonia the amount of water stored and moving through the Amazon River Basin are largely unknown and the deforestation effects on the lateral movement of water storage has not been studied thoroughly. We will simulate land cover change effects on hydrology using two LSMs, the GLDAS/NOAH and Ecosystem Demography (ED) model, and compare them with various hydrological monitoring data observed from the ground stations (of stream flow and eddy flux tower) and derived from the GRACE satellite. The LSM model outputs, especially ET components, will be compared thoroughly to better understand vegetation dynamic effects on the water cycle. The ED model incorporates heterogeneous land-cover change processes and vegetation dynamics and it may offers an excellent opportunity to investigate the hydrological effects of deforestation at the regional scale. The LSM outputs will be used to derive the monthly soil moisture from the total water storage from GRACE. The satellite-derived dynamic soil maps will be used to constrain the routing of the lateral movement of surface water storage and to find the mean optimal velocity for the lateral movement. This improved routing will provide more accurate estimation on the water storage and dynamics in the Amazonia, and it will particularly help to elucidate the hydrological effects of deforestation at the regional scale. This study directly contributes to the scientific community's ongoing efforts to improve the model parameterization/calibration via assimilation of satellite data and to evaluate the land use change impacts in the Amazon water cycle.

Keywords: *The water cycle, Amazon, land surface model, satellite observation, deforestation*

EXTENDED ABSTRACT ONLY

Contrasted evapotranspiration drivers across global humid and dry land surface

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Abstract: Investigating major drivers for land surface actual evapotranspiration (ET_a) is a hot topic in hydrology and climate communities for last several decades. A theory to explain relationships between ET_a and its major driver is the complementary relationship hypothesis. This hypothesis suggests that there exists a feedback mechanism between ET_a and potential ET (ET_p) for homogeneous surfaces with low advection of heat and moisture. Therefore, ET_a is limited only by the available energy on a wet surface where the available energy on a wet surface where ET_a and ET_p are close to the wet environmental ET (defined as the ET_a rate from a saturated surface with a constant energy supply); ET_a fall below ET_p because of limited soil water availability, and an amount of excess energy becomes available for sensible heat flux to warm and dry the atmosphere, resulting in increasing ET_p. This theory has been used to estimate ET_a in various regions, such as Australia, conterminous US and the Tibetan Plateau. Another theory is the Budyko framework, which has long been regarded as a well-established method for estimating mean annual ET_a because it estimates mean annual ET_a from a catchment by balancing the energy available for evapotranspiration (or ET_p) and the amount of available water (or precipitation). The Budyko framework has been also used to estimate ET_a at a fine time resolution from daily to monthly to take into account variability in surface soil moisture and vegetation.

Terrestrial ET_a mainly consists of soil evaporation and vegetation transpiration, which provide strong ecohydrological links between ecosystems and water cycle. The existed theories do not explain the ecohydrological links between ET_a components and its drivers. Here, we used gridded global meteorological and satellite data (from 1982 to 2008) together with a process-based framework to estimate soil evaporation and vegetation transpiration across global land surface and to investigate how major drivers control spatio-temporal dynamics of soil evaporation and vegetation transpiration. We found that relationships between ET_a and precipitation are complementary with those between ET_a and ET_p across the global land surface. Generally in wet regions, ET_p is strongly positively correlated to vegetation transpiration which, in turn, determines the bulk of ET_a; compared to this, precipitation is weakly and negatively correlated to vegetation transpiration and ET_a. On the contrary, in dry regions the variation of ET_a is positively correlated to soil evaporation which is, in turn, controlled by precipitation; compared to this, ET_p is weakly and negatively correlated to soil evaporation and ET_a. Our results provide a comprehensive explanation on the main ET_a drivers across global land surface. The strong links between ET_a and its ecohydrological drivers suggest that it is important to investigate ET_a components for accurately estimating variation and trends in ET_a.

Keywords: *Evapotranspiration, soil evaporation, transpiration, major drivers, precipitation*

Adaptive management of groundwater resources

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Abstract: As a society-sustaining resource, groundwater has been overexploited in many large aquifers. Declining groundwater aquifers, deterioration of groundwater quality, degraded groundwater dependent ecosystems, and increasingly intensive competition among groundwater users are widespread around the world. Managing groundwater sustainably has been a critical issue. However, groundwater aquifers are complex systems, and coupled with variable climate systems, connected surface water systems, and linked ecosystems. Also, the impacts of management changes may be explicitly observed over decades, or even millennia. As a result, sustainable management of groundwater resources is difficult.

In this paper, we argue that a combined use of systems modelling and adaptive management is a promising approach to addressing the above issue. A systems model plays a decisive role in adaptive management of groundwater resources. It captures the dynamics of the groundwater use system and is used to predict future states of the system over a specified prediction horizon. The systematic responses to predicted disturbances and management actions can be produced by this model. Adaptive management usually includes an explicit learning and adaptation process to make iterative decisions under uncertainty. It provides a promising way of managing groundwater systems despite the inherent uncertainty by incorporating new information and learning from the outcomes of management intervention, thereby improving future management.

This work reviews state-of-the-art adaptive management tools and illustrates how systems modelling and adaptive management are coupled for achieving sustainability goals of groundwater resources management.

Keywords: *Groundwater resources, adaptive management, uncertainty, systems modelling*

Identifying key influences for managing mine water

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Abstract: The Australian coal mining industry is currently facing tough challenges of securing enough water for operations during water-limited periods and avoiding non-compliant discharge of mine-affected water during extreme rainfall events.

Major Australian coal mines operate in one of the most highly variable climates in the world. Severe droughts exacerbate the conflict between water users. The climate conditions lead to great difficulty in mine water management and traditional methods of developing regional water infrastructure cannot entirely addressed these challenges. The focus moves to development of improved water management strategies. However, mine operators lack tools to manage both climate-influenced drought and discharge challenges. Mine operators need to understand dynamics of mine water circuits under extreme climate variability. The mine water circuits are complex systems with feedbacks. External perturbations (for example, variability in climate) and management strategy changes may lead to unexpected system consequences. To make better-informed strategies, mine operators still need to learn: which system factors have significant impacts on severe system consequences (for example insufficient water supply for production and unpermitted discharge of mine-affected water)? Are these critical factors different for different mine sites and under different extreme climate conditions (extreme 'dry' and extreme 'wet' conditions)?

In this paper, we argue that answers to these questions can come from a combined use of systems modelling and global sensitivity analysis. Our methodology builds on a newly created hierarchical systems model (HSM) of mine water circuits. The systems model emphasises the whole mine water system without full detail of the site configuration. Elements in the mine water system, such as individual physical stores, 'input' and 'output' fluxes, and uses of water, are aggregated as a set of water objects.

Then, we complete the methodology by applying a variance-based global sensitivity analysis method (the extended Fourier Amplitude Sensitivity Testing, eFAST) into the HSM under different extreme climate conditions. We illustrate the methodology by selecting 16 coal mines in the Bowen Basin in Queensland, Australia as a case study. The findings show that the method provides crucial insights to impacts of highly variable climates, model structure, and uncertainty drivers. These insights allow mine water managers to understand key influences on which to focus well-informed decision-making and data collection.

Keywords: *Mine water management, water resources management, systems modelling, sensitivity analysis, eFAST*

High Resolution Spatial Modelling Approaches for Monitoring Surface Water and Erosion Impacts of Coal Seam Gas Infrastructure

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Abstract: Coal Seam Gas (CSG) development within the Surat Basin of Queensland, Australia, is expanding, with petroleum leases already approved for tenements covering over 24,000 km^2. Many thousands of kilometres of access tracks will be developed to allow transport of vehicles to each of the CSG wells (Figure 1). Studies from agricultural watersheds across the globe have shown that rural roads provide a disproportionate contribution toward sediment loads into water ways. With CSG development, the intensity of roadways in agricultural land will increase significantly and there is a risk that erosion losses will increase likewise. We have evaluated the use of surface water flow models derived from fine-scale digital elevation models for identifying areas where CSG infrastructure has altered surface hydrology and areas of erosion risk.

Aerial digital photogrammetry with a ground sample distance of 20 cm was used to create elevation models for a 1200 km^2 focal region currently undergoing CSG development. Baseline digital terrain models were processed using a multi-direction flow-path prediction model. The ground elevation model (GEM) was evaluated using survey data at three different sites (a road cross section, a gravel pad, a road crossing a gully) obtained using a hand held Real-time Kinematic Global Navigation Satellite System (RTK GNSS). The water flow model was assessed using manual recording of visible water paths observed in open agricultural field conditions and within native forests where a significant canopy cover could influence predictions of soil surface elevation.

Comparison of the GEM with ground surface elevation measurements showed good agreement with many of the predictions showing an error of less than 5 cm. This accuracy is approaching that of the RTK GNSS system (±2 cm) used in the ground surveys. A subset of predictions showed higher levels of error. Investigation found these to predominantly include points where sudden changes in elevation occurred, which suggests error introduced by smoothing algorithms used in creating the GEM. Comparison of predicted water flow paths against those mapped directly indicates that the model is able to accurately identify the location of many water flow paths across roadways. The model was effective in locating the major water flow paths under forest conditions, even when some of the soil surface may be obscured by foliage.

Exploration, interpretation and discussion of the datasets with agricultural landholders and CSG staff developed interest in portraying the information as water flow maps such as those presented here.

Figure 1. Aerial photograph of the CSG development area, near Condamine, Queensland, showing a network of access tracks connecting CSG well pads.

Keywords: *Coal seam gas (CSG), erosion, water flow modelling, digital elevation model (DEM)*

Generic, robust model -and data-independent uncertainty quantification

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Abstract: The Bioregional Assessment Programme seeks to quantify the direct and indirect cumulative impacts of coal mining and coal seam gas production on water related assets in Australia. Crucial in this impact assessment is the propagation of uncertainty throughout a chain of models, linking geology, hydrogeology, hydrology and ecology. In order to carry out an uncertainty analysis at such a scale for a multitude of predictions, combining several models in an often very data scarce environment, an uncertainty methodology is developed that is model independent and can accommodate both hard data and expert information. This numerical uncertainty analysis is complement by a systematic, qualitative assessment of the assumptions and choices that underlie the modelling and how they can affect the predictions.

Keywords: *Bioregional assessment, uncertainty analysis, Australia*

Bioregional Assessments: Evaluating the impacts of coal mining and coal seam gas extraction on water-dependent assets

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Abstract: The Australian Government has implemented a programme of research termed 'bioregional assessments' to investigate the potential water-related impacts of coal seam gas and large coal mining developments. This research will provide scientific information for the Independent Expert Scientific Committee (IESC) to use in developing their advice to Commonwealth and state government regulators. These bioregional assessments are now being carried out in six bioregions across Australia, namely the Lake Eyre Basin, Clarence-Moreton, Northern Inland Catchments, Northern Sydney Basin, Sydney Basin and Gippsland Basin bioregions.

The Bioregional Assessment Programme is a collaboration between the Department of the Environment, the Bureau of Meteorology, CSIRO and Geoscience Australia. It aims to provide a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and coal mining on water-dependent assets. Further details of the Programme can be found at <http://www.bioregionalassessments.gov.au>.

This presentation will provide an overview of the issues related to the impacts of coal mining and coal seam gas extraction on water-dependent assets across the bioregions being examined as part of the Bioregional Assessment Programme. The methodology used to undertake bioregional assessments will be described, and results of the programme to date will be presented, with a focus on the modelling results obtained through application of the MODFLOW groundwater modelling package and AWRA surface water modelling.

Keywords: *Bioregional Assessments, cumulative impacts, coal resources, groundwater modelling*

EXTENDED ABSTRACT ONLY

The role of 3D geological models in assessing potential impacts of CSG activities: an example from the Clarence-Moreton bioregional assessment

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Abstract: The Australian Government has commissioned the Bioregional Assessment (BA) Programme, a scientific analysis that provides a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas (CSG) and large coal mining development on water resources. The Clarence-Moreton bioregion, which covers an area of approximately 25000 km^2 in north-eastern New South Wales and south-eastern Queensland, was selected as a priority region for the BA due to the presence of confirmed CSG resources.

Prior to the development of numerical models for the prediction of potential impacts of CSG extraction on water resources, it is critical to assess the geometry and internal architecture of aquifers and build realistic conceptual models of the potential connectivity pathways between aquifers as well as those with the surface water system. In the Clarence-Moreton bioregion, this task requires the integration of shallow alluvial aquifers (typical thickness of less than 30 m), volcanic aquifers (typically up to 200 m thick) and deep Triassic to Cretaceous bedrock aquifers, which can have a combined thickness of up to approximately 3000 m in some parts of the basin.

While these shallow alluvial aquifers are often described only as "overburden" and are of no relevance in petroleum reservoir simulation studies, they are of utmost significance in the BA Programme as they host most of the water-dependent assets that can potentially be impacted by CSG developments. To address the challenge of different vertical scales and resolutions, we have developed a series of 3D geological models from elevation (DEM), seismic and stratigraphic data using GoCAD and SKUA (Paradigm Geophysical Pty Ltd®) 3D geological modeling software. While stratigraphic data from exploration wells together with seismic data form the key input data sets for the modeling of boundaries between deep sedimentary bedrock formations, the definition of the interface between alluvial and volcanic or sedimentary bedrock aquifers is based on lithological data from more than 12500 bores following extensive data quality checks.

The multiple 3D geological models developed during the Clarence-Moreton BA combined with water chemistry, recharge estimation and potentiometric surface maps form the basis for conceptual models of potential connectivity pathways between the major alluvial, volcanic and sedimentary basin aquifers, as well as connectivity pathways between groundwater and surface water in the Clarence-Moreton bioregion. The developed 3D geological models and conceptual models then underpin the structure of a MODFLOW numerical groundwater model, which informs the risk assessment of any potential impacts of CSG production on water-related assets within the basin.

Keywords: *3D geological model, bioregional assessment, Clarence-Moreton Basin*

Assessment of the cumulative groundwater impacts of CSG and coal mining developments in the Surat Cumulative Management Area

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Abstract: The Australian Government has been undertaking the Bioregional Assessment Programme to better understand potential water related impacts of coal seam gas (CSG) and large coal mining developments. The cumulative impacts of operational and future CSG and coal mine developments in Surat and Bowen Basins in southern Queensland were studied in the bioregional assessment for Maranoa-Balonne-Condamine (MBC) subregion. Cumulative impacts of seven coal mines and five coal seam gas development projects within the Surat Cumulative Management Area (QWC, 2012a) were assessed. The numerical model developed by the Office of Groundwater Impact Assessment (QWC, 2012b) was used for groundwater flow simulation. Development pathway of CSG operations as accounted in this model for preparation of the Underground Water Impact Report (QWC, 2012a) was used in the present study as well. In addition, drawdown impacts caused by five existing and two proposed coal mines were simulated by defining time-varying boundary conditions in the model at locations corresponding to the seven mine sites. Given the relatively coarse scale of the model with a resolution of 1.5 km × 1.5 km, the objective of the modelling exercise was to provide a conservative estimate of regional scale cumulative drawdown impacts rather than precise simulation of drawdown around individual mine sites. For this reason, detailed representation of local-scale mine progression was considered irrelevant and the spatial and temporal discretization of the model was retained as reported in the Underground Water Impact Report (QWC, 2012a). In order to quantify impacts of future coal resource development pathways on water dependent assets, two scenarios were modelled. The Baseline scenario considered all groundwater stresses including agricultural water use, urban, stock and domestic water use, mine dewatering and coal seam gas depressurization as at the last quarter of December 2012. The Coal Resource Development Pathway (CRDP) scenario considered, in addition to the baseline scenario stresses, groundwater stresses arising from development of future coal mines and coal seam gas operations. Accordingly, 5 existing mines and all CSG projects were included in the Baseline scenario and two coal mines that were commencing operations post-2012 were included in the CRDP scenario. The simulated drawdown contours for the Baseline scenario indicated that drawdown in the Walloon Coal Measures caused by the coal seam gas operations and coal mining marginally overlap along the eastern fringe of the Surat Basin. Simulated drawdown resulting from mining operations is more localized compared to CSG induced drawdown. Modelled differences in groundwater levels and flows in different aquifers between the two scenarios informed the potential impacts of future coal resource development in the MBC subregion. Uncertainty in drawdown predictions was estimated by performing Null-space Monte Carlo simulations using 200 sets of alternative calibration constrained model parameters previously developed by the Office of Groundwater Impact Assessment.

We acknowledge the integral role of the Queensland Office of Groundwater Impact Assessment (OGIA) in completing this study. In addition to providing access to the Surat Cumulative Management Area model and parameter sets OGIA also provided computing resources and staff time to undertake the required Null-space Monte Carlo simulations.

Keywords: *Bioregional assessment, Coal Seam Gas (CSG), coal mining, water impacts*

Blending NPP-VIIRS and Landsat OLI Images for Flood Inundation Monitoring

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Abstract: Measuring surface water using remote sensing technology is an essential research topic in many research areas, including flood-related studies and water resource management. Recent advances in satellite remote sensing have provided more efficient ways of monitoring surface water from space. Several sensors, such as the Visible Infrared Imaging Radiometer Suite on board Suomi National Polar-orbiting Partnership (Suomi NPP-VIIRS) and Operational Land Imager (OLI) on board Landsat 8, have begun to monitor earth surface in recent years. They have been continuously providing enormous remotely sensed images. Nevertheless, it has to be noted that tradeoffs between spatial and temporal resolutions of these images still exist. Medium- to high-resolution images, such as Landsat OLI, are typically available fortnightly or less often, which limits their applications for intensively and continuously monitoring flood inundation dynamics. Whereas coarse-resolution sensors, such as NPP-VIIRS, scan the earth's surface once or several times a day, but their coarse spatial resolution hampers the correct mapping of flooded areas. This study, therefore, aims to blend NPP-VIIRS and Landsat OLI images in order to gain high spatial resolution from Landsat OLI and high temporal resolution from NPP-VIIRS simultaneously. Two classic fusion models, namely the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) and the Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model (ESTARFM) were tested and evaluated. Particularly, the fusion results of both models were compared with the actual Landsat images in order to evaluate the accuracy of these fusion results. It is hoped that this study will enlighten other studies that require remotely sensed data with both high spatial and temporal resolutions.

Keywords: *Surface water, image fusion, image blending, Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM), Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model (ESTARFM)*

Towards reliable hydrological model calibrations with river level measurements

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Abstract: Streamflow prediction based on hydrological models generally requires model calibration using observed discharge derived from a rating curve that requires accurate, frequent and sustained measurements of the flow rate. However, the remoteness of many catchments increases the difficulties and costs of measuring discharge data in these areas. Even at gauging stations with some discharge measurements, the resulting relationship can still has high uncertainties, particularly for larger magnitude flows where discharge measurements are absent.

In this study, methods to calibrate streamflow models using only the time series of stream level measurements, without converting it to discharge values, are explored. With an emerging remote sensing technique that estimates stream level using satellite altimeters, the methods can potentially enable streamflow model calibration over ungauged catchments. Two prospective calibration schemes, which are not reliant on observed discharge data, are examined: i) Spearman Rank Correlation (denoted by SRC) based calibration between observed stream level (h_{obs}) and modelled streamflow (Q_{est}); ii) Inverse Rating Curve (IRC) function based calibration using Nash-Sutcliffe Efficiency (NSE) between the estimated water level (h_{est}), which is calculated from the modelled streamflow using an inverse rating curve, and the observed water level data (h_{obs}). The new calibration schemes are applied to two catchments (604053 and G8110004 from the Bureau of Meteorology's Hydrologic Reference Stations) and the efficacy of the methods are examined by comparing the modelled discharges, which are calibrated by the new schemes, to the observed discharge. A control case that is conventionally calibrated against observed discharge is also applied in the efficiency analysis.

The results show that the new calibration schemes could properly predict the runoff events and timings, with the linear correlations between the modelled and observed discharges ranging between 0.675-0.889. However, compared to the control cases that show adequate prediction of the observed discharge with R>0.77 and NSE>0.58, the biases between the results and the observations remain large and are deemed unacceptable. The reasons for the biases are associated with the underlying principles of the calibration schemes. In particular, the SRC-based method is more sensitive to the rank of the data than to the differences between modelled and observed magnitudes. The IRC-based method has difficulty in reproducing the shape of the actual power function using only observed and modeled water levels. Of the two new calibration schemes, the IRC-based scheme has better performances than the SRC-based method, although the SRC-based method incurs less computation cost by calibrating fewer parameters.

The results give cause for optimism in devising a reliable calibration scheme with reduced reliance on large quantity of discharge measurements. Future work will focus on conjunctive use of river level data and small number of discharge measurements to overcome the aforementioned problem of biases and applications at more catchments and with satellite altimetry data.

Keywords: *Hydrological modelling, model calibration, Spearman Rank correlation, inverse rating curve*

Land surface brightness temperature retrieved from Landsat data

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Abstract: Land Surface Temperature (T_s) is an important boundary condition in many land surface modelling schemes. It is also important in other application areas such as hydrology, urban environmental monitoring, agriculture, ecological and bushfire monitoring. Many studies have shown that it is possible to retrieve T_s globally using thermal infrared data from satellites. Development of standard methodologies that routinely generate T_s products would be of broad benefit to the utility of remote sensing data in applications such as hydrology and urban monitoring.

AVHRR and MODIS datasets are routinely used to deliver T_s products. However, these data have a 1 km spatial resolution, which is too coarse to detect the detailed variation of land surface change of concern in many applications, especially in heterogeneous areas. Higher resolution thermal data from Landsat (60-120 m) is a possible option in such cases.

To derive T_s, two scientific problems need to be addressed, the first of which is the focus of this paper:

- Remove the atmospheric effects and derive surface brightness temperature (T_B),
- Separate the emissivity and T_s effects in the surface brightness temperature (T_B).

For single thermal band sensors such as Landsat 5, 7 and due to a stray-light issue on Landsat-8, the multi-band methods used to derive T_B, such as the split window methods used for NOAA–AVHRR data (Becker & Li, 1990) and the day/night pairs of thermal infrared data in several bands used for MODIS (Wan et al., 2002) are not available for correcting atmospheric effects. The inputs used for retrieval of surface brightness temperature T_B from Landsat data therefore need more attention, as the accuracy of the T_B retrieval depends critically on the ancillary data, such as atmospheric water vapour data (precipitable water). In the past, it has been more difficult to retrieve a reliable T_B product routinely from Landsat due to limited availability (time and space) of accurate atmospheric water vapour information.

To test the possibility for retrieving a good quality T_B product routinely from Landsat, in this paper, T_B products are derived from four current and routinely available global atmospheric profiles, namely the NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA); the National Center for Environmental Prediction (NCEP) reanalysis I, the National Center for Environmental Prediction reanalysis II and the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis. These products were evaluated against the T_B derived from the near coincident ground-released radiosonde data (balloon data) using a physically based radiative transfer model MODTRAN 5. The results from this comparison have found:

- The global data sets NCEP1, NCEP2, MERRA and ECMWF can all generally give satisfactory T_B products and can meet the 1 K accuracy levels demanded by many practitioners.
- The ECMWF data set performs best. The root mean square difference (RMSD) for the 9 days and 3 test sites are all within 0.4 K when compared with the T_B products estimated using ground-released radiosonde measurements.

The results show that using single thermal band Landsat, accurate T_B can be delivered operationally using a robust physically based radiative transfer model such as MODTRAN 5 and operationally available global atmospheric profiles, particularly the ECMWF interim reanalysis data.

Keywords: *Surface brightness temperature, Landsat, atmospheric correction, precipitable water*

Towards LPRM-based soil moisture retrievals with multi-angular microwave observations from SMOS

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Abstract: Passive microwave remote sensing by the Soil Moisture and Ocean Salinity (SMOS) satellite enables observations of surface soil moisture at global scale. This involves a retrieval process that uses a radiative transfer model to relate satellite-observed radiances to geophysical variables such as soil dielectric constant and soil moisture. The L-MEB (L-band Microwave Emission of the Biosphere) based retrieval products of SMOS have previously been evaluated to show reasonably good agreement with ground measurements. An alternative product is based on the Land Parameter Retrieval Model (LPRM), which has been adapted for a wide range of X- and C-band sensors to retrieve soil moisture from single-angle observations. From the implementation viewpoint, LPRM is attractive in its limited requirements for additional auxiliary parameters and in its simple geophysical parameterization. The research gaps lie in the limited previous study on retrieving SMOS multi-angular observations using LPRM. The development of a LRPM-retrieved SMOS product is also motivated by establishing an algorithmic consistency across multiple C-, X- and L-band sensors, allowing them to be compared more directly for relative performance.

This study considers the LPRM-like retrieval algorithm based on generic Radiative Transfer Equation (RTE) and uses a controlled numerical experiment to determine the properties of LPRM when acting on synthetic multi-angular SMOS observations. The influences of observational uncertainties, model parameter uncertainties and multi-angle observations (c.f. single-angle) are evaluated on the retrieval performance. In particular, the Markov Chain Monte Carlo (MCMC) algorithm is used to quantify the uncertainties in, and correlations between, retrieved parameters, under these influences.

The main findings of this study are listed as follows,

- According to retrieval sensitivity analysis, vegetation optical depth (τ) and surface temperature (T_s) are more critical parameters in the retrieval model compared to surface roughness and scattering albedo, and they may be retrieved simultaneously with soil moisture in a 3-parameter retrieval configuration;
- The uncertainty in brightness temperature (T_B) has more significant impact on a vegetated-wet scenario than on a bare-dry case: vegetated-wet surface can tolerate 2K brightness temperature uncertainty to achieve the target retrieval accuracy whereas bare-dry surface can tolerate as much as 8K T_B uncertainty;
- MCMC results demonstrate the advantages of LPRM soil moisture retrieval with multi-angular T_B observations over single-angle retrievals in terms of higher robustness and less uncertainty in retrieval results.

This work therefore provides guidance to adapting LPRM for SMOS data and soil moisture retrieval at continental scale.

Keywords: *Microwave remote sensing, soil moisture retrieval, Soil Moisture and Ocean Salinity (SMOS), Land Parameter Retrieval Model (LPRM), sensitivity analysis*

The impact of assimilation of streamflow and downscaled satellite soil moisture observations for hydrological forecasting

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Abstract: The present study investigated the added value of assimilating streamflow and remotely sensed soil moisture observations into the local-scale hydrological model, OpenStreams wflow_sbm (OSWS), and its potential to improve model estimates, when driven by either coarse- or high-resolution meteorological data. The study area chosen is the Murrumbidgee River Basin in the southeast of Australia, because of the variety of land uses in the region, the amount of measured data available for a large number of relatively unimpaired catchments, and the extensive body of previous studies observing and describing the hydrologic patterns across the basin.

A 1 km resolution version of the OSWS locally calibrated hydrological model was forced with downscaled global meteorological data (from approx. 50 km downscaled to approx. 1 km resolution) obtained from the Water and Global Change (WATCH) EU-project Forcing Data methodology applied to the ERA-Interim reanalysis data (WFDEI) and a local high resolution gauging station based gridded dataset (approx. 5 km). Downscaled satellite derived soil moisture (from approx. 50 km downscaled to approx. 10 km resolution) from AMSR-E and streamflow observations collected from 23 gauging stations were assimilated using an ensemble Kalman filter (EnKF) for the time period 2007-2010.

Assessment of the performance was based on a comparison with estimations from the OSWS model, which was locally calibrated using streamflow observations from 34 gauging stations for the time period 1990-2006. Several scenarios were analysed to explore the impact of data assimilation considering both local and global meteorological data, in which discharge and soil moisture observations were either independently or jointly used: (i) open loop (base scenario), (ii) independent assimilation of discharge, (iii) independent assimilation of soil moisture and (iv) assimilation of both observations, discharge and soil moisture.

Discharge forecasting time series generated from each scenario were validated with additional in situ stream gauge data not used in the EnKF, as an independent validation data set. The quality of these time series was inter-compared using a set of graphical and numerical verification metrics, including root mean square error, Nash-Sutcliffe efficiency, Brier skill score and mean continuous ranked probability skill score.

Results show that the assimilation of soil moisture observations results in the largest improvement of the model estimates of streamflow. The joint assimilation of both streamflow and downscaled soil moisture observations leads to further improvement in streamflow simulations.

Furthermore, results show that the added contribution of data assimilation, for both soil moisture and streamflow, is more pronounced when the global meteorological data are used to force the models. This is caused by the higher uncertainty and coarser resolution of the global forcing. Overall, these results highlight the potential of remotely sensed soil moisture observations to improve streamflow forecasting in large catchments, while also providing insight on the significance of the meteorological data.

Keywords: *Data assimilation, ensemble Kalman filter, AMSR-E soil moisture, hydrological forecasting*

Evaluation of remotely sensed evapotranspiration products in a large scale Australian arid region: Cooper Creek, Queensland

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Abstract: Accurate estimation of evapotranspiration (ET), as the second largest term of the water budget after precipitation, is necessary for arid zone catchments, where conservation of limited water resources is vital for the natural environment and human lives but where reliable ground measurements are sparse due to low population densities. Emergence of remotely sensed products has given promising results in better quantification of spatial and temporal behaviour of evapotranspiration, but these products are mainly calibrated in more humid zones with almost stable land cover, and the emphasis is on transpiration as the main term of water loss. Therefore, utilization of remotely sensed ET products requires further evaluation in arid regions. MOD16 and CMRSET are two of the most well-known actual ET (AET) datasets available for Australia, provided by NASA and CSIRO respectively. In order to validate the accuracy of these products, a 480 km reach of Cooper Creek in the Lake Eyre Basin (LEB), with an area of 22,000 km^2, was chosen. Transmission losses (TL) in this large-scale, low gradient floodplain were estimated by considering rainfall, gauged (inflow and outflow) and ungauged streamflow volumes for 14 flood events between 2000 and 2012. It was assumed that satellite AET retrieved during and post-flooding should approximate to the transmission loss estimated for individual flood events. Results indicate that CMRSET AET performs well in large events (TL>9500 GL) with less than 8% absolute error, but its performance decreases for medium sized floods (TL= 4000-8000 GL), with an absolute error of 17-48%, and the highest error occurs at 406% for the smallest flood (TL= 496 GL). AET time-series of 8-day ET volume reveals that CMRSET estimates a higher than expected minimum of 85 GL/8-day for the floodplain during prolonged droughts but reproduces dynamics that well correlate with variation in the inundation area and responds to both water and vegetation land cover variations. MOD16 underestimates AET for all the floods, only accounting for 17-37% of total loss and it is does not correlated well with the inundation extent. Pixel based comparison of MOD16 time series also shows very low ET values for peak vegetation in this arid region. For CMRSET, it is expected that a lower limit for minimum AET from non-inundated pixels could improve water balance estimates for medium sized floods but will have a lesser effect for small floods. The error in the latter case will also be due to the limitation of MODIS spatial resolution in properly capturing land cover changes (i.e. inundation extents and vegetation responses). Misclassification of land cover and the dependency of the MOD16 model on estimating water cover fraction based on relative humidity are suggested to be the main sources of error for this product.

Keywords: *MOD16, CMRSET, evapotranspiration, arid regions, Cooper Creek*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Assessing irrigated agriculture's surface water and groundwater consumption by combining satellite remote sensing and hydrologic modelling

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Abstract: Irrigated agriculture in semi-arid and arid regions is often supplemented by a combination of surface water and groundwater. In the Murray-Darling Basin (MDB), irrigated agriculture constitutes only 2% of the total agricultural land, but accounts for 66% of Australia's agricultural water consumption and generates 31% of the basin's gross value of agricultural production. Although buffered by large reservoirs, water availability in the MDB is constrained by dry and wet years that result in contraction or expansion of irrigated areas and a switch from surface water to groundwater use during dry periods. Notwithstanding their economic importance, the retrospective geographic extent and source (either surface water or groundwater) of water used in many important irrigated areas remains uncertain. This study attempts to assess the dynamics of irrigated agriculture including: year-to-year irrigated area extent, water use and source. The assessment is conducted for water-years (June to May) characterised by a dry and wet cycle (2004/05–2010/11) and for irrigated areas in the Namoi and Gwydir sub-basins (northern MDB). Both sub-basins rely on surface water extractions (SWE) and groundwater extractions (GWE) to supplement irrigation, summer cotton in particular. Accurate mapping of irrigated areas in this area is challenging because the irrigation season coincides with the summer rainy season in which native vegetation can mimic irrigation development. In this study, irrigated areas and associated evapotranspiration are identified each water-year through a Random Forest Model which uses remotely-sensed (RS) vegetation phenology and RS actual evapotranspiration as predicting variables. The resulting irrigated areas and actual evapotranspiration are used to constrain a monthly river-reach (a modelling unit, defined as the runoff contributing area between two streamflow gauging stations) model which determines the irrigated area that can be serviced with SWE, and the remainder area (as determined by the Random Forest Model) that is assumed to be supplemented by GWE. Irrigated areas mapped on a year-to-year basis show generally good agreement with published areas, with Pearson's correlation coefficients >0.75 and normalised root-mean-square-error <25%. The modelled SWE generally capture the observed interannual patterns and magnitudes, with Pearson's correlation coefficients >0.8 and normalised root-mean-square-error <30%. In terms of magnitude, the results were as accurate as or better than those of more traditional irrigation modelling. Modelled GWE did not compare well with observed GWE, which is unsurprising due to the high uncertainty in observed GWE. Results suggest that RS irrigated areas and actual evapotranspiration can be used to constrain irrigation models in data scarce regions, as well as pinpointing areas that require better monitoring.

Keywords: *Image classification, Random Forest, mapping, hydrology, diversions, evapotranspiration*

Verifying Temperature Lapse Rates in the Eastern Himalayas using Landsat 7 and 8

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Abstract: This paper investigates the use of Landsat-7 and Landsat-8 thermal bands to assess the accuracy of temperature lapse rate relationships used in hydrological modelling for the Eastern Himalayan region. The temperature at high altitude is an input to conceptual gridded and lumped hydrological models that many studies use to understand and predict the relative contribution of melt-water to streamflow for Himalayan catchments.

Temperature observations in the Eastern Himalayas are limited to meteorological stations below 2000m above sea level (ASL), except for a few stations near Mt Everest, that are part of the Ev-K2-CNR project, and some observations from short field campaigns. Many studies extrapolate temperatures at high altitudes from local meteorological observation stations using a temperature lapse rate. The most common method is to develop a seasonal temperature lapse rate from averages of ground-stations, typically between 1000mASL and 2000mASL.

The aim of the analysis was to: a) determine if accurate temperatures at higher altitudes can be calculated from Landsat imagery; b) understand if a linear lapse rate can be inferred from Landsat imagery; and c) investigate the relationship between air temperature and land surface temperature for snow. The method involved (1) identifying cloud-free areas of snow, (2) generating temperature surfaces from Landsat thermal bands using algorithms from Jiménez-Muñoz et al. (2009) and Jiménez-Muñoz et al. (2014), and (3) generating lapse-rate relationships from comparison with elevation surfaces (derived from Aster). The lapse rates generated were cross referenced with ground station measurements and a serendipitous field campaign.

It was found that the correlation between observed temperature at Pyramid station (5035mASL) and Landsat inferred temperature was 0.82 R^2 (see Figure 1). The correlation degraded as elevation reduced (i.e. to 0.35 R^2 at 1732mASL). The statistical methods applied were not capable of distinguishing between the contribution of error from the Landsat classification and the error from extrapolation of a linear lapse rate, so it was not possible to determine if the drop in temperature with elevation was linear or non-linear. Further work is required to use this method to confirm that a linear temperature lapse rate is reliable at high elevations. As expected, there were clear differences between temperatures on the northerly and southerly facing sides of mountains. These were especially pronounced during winter.

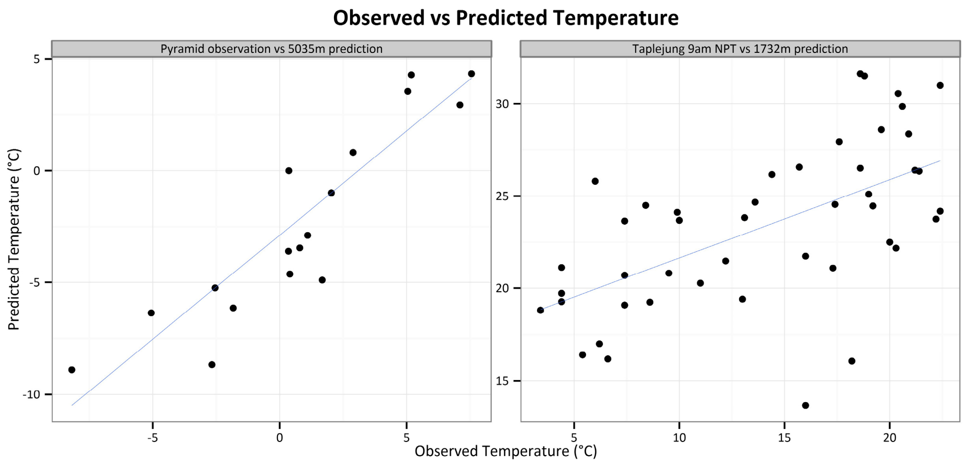

Figure 1. Comparison of observed temperature at meteorological stations to Landsat derived temperature.

Keywords: *LandSat 8, Temperature Lapse Rates, Himalayan Catchments*

Identifying sources for systematic and random errors in microwave satellite soil moisture over Australia

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Abstract: Long-term soil moisture (SM) time series is needed in climate change assessment, and for calibrating hazard warning services relating to heat waves, floods, bushfire, droughts and identifying areas of vulnerability. Observations from historic and present satellite-based sensors are the only available resource to create such a data set at the regional-to-global scale by combining them. This however requires a consistent characterization and deep understanding of the systematic differences (i.e., biases) and errors in individual satellite SM (SSM) products, which vary due to changes in instruments, calibration schemes and algorithms, amongst other factors.

This work uses lagged-based instrumental variable (LV) analysis of Su et al. (2014) to provide consistent characterization of systematic and random errors across nine active and passive SSM products over Australia, with combined time coverage of 1978-present. The passive products are derived from Scanning Multi-channel Microwave Radiometer (SMMR/Nimbus-7), Special Sensor Microwave Imager (SSMI/DMSP), Tropical Rainfall Measuring Mission Microwave Imager (TMI/TRMM), Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E/Aqua), WindSat (Coriolis), Advanced Microwave Scanning Radiometer-2 (AMSR2/GCOM-W1), and Microwave Imaging Radiometer with Aperture Synthesis (MIRAS/SMOS), while the active products from Active Microwave Instrument (AMI/ERS-1,2) and Advanced Scatterometer (ASCAT/MetOp-A). Seven of these SSM products are currently used in the construction of a SM climate record (v2) within the European Space Agency Climate Change Initiative. The modelled SM from MERRA (Modern Era Retrospective-analysis for Research and Applications)–Land is used to provide a common reference to define the additive and multiplicative biases in all SSM products at subseasonal and seasonal-to-interannual (coarse) timescales. In other words, the mean-squared error (MSE) between the SSM and MERRA-L SM can be decomposed into these constituent components, representing a detailed error profile for each SSM product.

Our results reflects spatial variability of the biases and random errors over Australia, with associations with regional land-surface characteristics related to vegetation cover, terrains, urban cover, and water bodies. The error profiles are not systematic across the SSM products or between SM components at the separate (subseasonal and coarse) timescales. First, the amplitudes of the satellites' coarse-scale SM are generally smaller than those of the MERRA-L (negative multiplicative bias), and this is the opposite for their subseasonal-scale components (positive multiplicative bias). Second, the MSE is dominated by additive and multiplicative biases at the coarse timescale, contrasting with the subseasonal component that is generally dominated by random errors. This is expected because the variance of the coarse-scale SM component is generally larger than that of the subseasonal-scale component. Thirdly, there is an overall incremental improvement of signal-to-noise ratio (SNR) in the later passive microwave satellite missions (TMI, AMSR-E, etc), relative to the early missions (SMMR and SSM/I). Differences in performance based on SNR are however less striking amongst these later passive SSM (AMSR-E, WindSat and AMSR2) and between the two active products. These contrasts in biases and SNR must be taken into consideration when merging these SSM products, or assimilating SSM into models.

Multivariate linear regression analysis is subsequently applied to explore the effects of land-surface and climatic characteristics on the spatial variability of the errors (response variables). The 13 explanatory variables related to vegetation, soil wetness, elevation, spatial heterogeneity, water cover, urban cover and tree cover, are considered. The best regression models, typically consisting of 8-11 variables, are chosen based on Bayesian Information Criterion, and can explain 15-74% of the spatial variance of the response variables for sample sizes of 8837-11029. On the whole, there is however no consistent set of explanatory variables across the response variables, and the levels of influence of individual explanatory variables also vary. However, there are similarities between the regression models prescribed for TMI, AMSR-E, WindSat and AMSR2, and the models for ERS and ASCAT. Importantly, these models can be used to explain sources of errors, causes for error cross correlation, and for predicting individual error components in the SSM products.

Keywords: *Satellite soil moisture, microwave remote sensing, error estimation, instrumental variable, multivariate regression models*

Geo-referenced exposure modelling of down-the-drain chemicals in river basins supports selection of adequate reduction strategies

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Abstract: Organic contaminants such as pharmaceuticals have been ubiquitously detected in rivers worldwide. To achieve the good chemical status as laid down in the EU Water Framework Directive concentrations of micropollutants need to be kept as low as possible. Respective decisions on adequate reduction strategies require basin-wide information on the chemical contamination of the river system.

Surface water concentrations are temporally and spatially variable due to different regional emission patterns and fluctuating hydrological conditions. Exposure assessment by monitoring alone is both laborious and expensive, especially if large river basins are to be assessed. Moreover, such monitoring delivers only single information in time and space, which renders it impossible to draw a consistent picture of the overall contamination in a catchment. Spatially explicit model approaches can be used to simulate spatio-temporal surface water concentrations for the entire river basin. Respective simulation results allow for identification of likely hot spots and optimized setups of monitoring programs significantly reducing cost and workload. The task of our work was to bridge the gap between science and practical requirements by adopting and enhancing a sound scientific model into a tool for daily work of regulatory authorities. Adding the possibility to simulate the effect of various countermeasures (reduction scenarios), allows for *a priori* evaluation of adequate management options and promising mitigation strategies in accordance with legal regulations.

The geo-referenced model GREAT-ER 4 (Geography-referenced Regional Exposure Assessment Tool for European Rivers) has been developed by our group and already successfully applied for exposure assessment of various contaminants (e.g. pharmaceuticals, zinc, detergent) in a number of European catchments. Here, we show for the German *Main* river basin (approx. 27,300 km^2, about 7 million inhabitants) how the model can be used by authorities to predict spatially resolved steady-state concentrations of selected pharmaceuticals under mean and low flow conditions. For Clarithromycin, a macrolide antibiotics prescribed in cases of respiratory and skin infections, the map of surface water concentrations shows a spatially heterogenous pattern with low to moderate concentrations in most rivers except for locally high concentrations caused by unfavorable dilution factors. Generally high concentrations are simulated downstream of congested urban areas and in River *Main* itself.

Adapting spatially explicit models developed by academia to practical daily-work-tools for strategic and operational water resources management is a challenging task. Triggered by official requirements, the user interfaces in GREAT-ER were supplemented with additonal features for scenario building and semi-automatic analysis of simulation results. This allows a priori evaluation of the effectiveness of countermeasures and reduction strategies. In the presentation, the strength and limitations of the model tool to support decision making in river management are demonstrated by evaluation of two scenarios, namely (i) technical enhancements of selected large STPs by additional ozonation treatment and (ii) a societal measure of reducing the antibiotic consumption in a highly populated area. While for *Main* river technical measures are suitable to reduce local concentrations, societal measures proved to be more effective on a regional scale.

Keywords: *Geo-referenced model, surface water, pharmaceuticals, mitigation strategies*

Combining water supply and flood mitigation requirements in multi-purpose reservoir optimization

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Abstract: Optimising the planning and management of reservoir systems by integrating multi-purpose objectives has been the subject of extensive research work since the 1990s, especially when the multiple benefits of reservoir system operation (e.g., supplying demand systems) and the reduction of natural risks (e.g., flood mitigation) are to be combined.

The issue is frequently simplified by considering the second requirement (flood mitigation) as a pre-defined constraint working on system operation optimisation and, therefore, modelling for the first requirement (design and management of multi-purpose reservoirs for water supply). The European Flood Directive 2007/60/CE requires that flood-risk evaluation should be in agreement with a cost-benefit analysis and a rational decision-making tool must be used for optimising the flood mitigation system. The study background underlines the importance of the water depth-damage functions as one of the elements of a decision-making tool designed to evaluate the economic damage expected in flood-prone areas.

The assessment and evaluation of potential flood damages in quantitative terms need to reconsider existing flood risk management plans to endorse their approach to reducing potentially damaged areas. This requirement has to be considered in areas affected by heavy flood events, such as Mediterranean areas. In the proposed combined approach WARGI decision support system (DSS) simulates the management of multi-reservoirs and multi-user systems, considering the resource priorities and users' preferences in the light of hydrological deficiencies and, consequently, water scarcity conditions. A link between the WARGI simulation and hydrologic and hydraulic models defining the vulnerability of flood-prone areas has been constructed in order to verify flood damage reductions and their economic evaluation. The link is used to quantify cost-benefit relations to obtain a rational decision-making optimisation tool.

A significant test case has been developed by applying the proposed methodology on the island of Sardinia (Italy). In this region several reservoirs have been built mainly for water supply and hydropower generation. The Regional Flood Mitigation Plan requires the assessment of the impacts of possible changes in reservoir management and the construction of new infrastructures for flood damage reduction. The River Coghinas has been investigated with regard to the interactions of flood mitigation requirements and upstream reservoir management. The river is the pilot basin for the Sardinian Regional Administration's development of the flood risk management plans required by EU and national legislation. In this pilot basin regulation reservoirs are located in the upstream river, and in the downstream floodplain area residential, touristic, commercial, industrial and agricultural areas and different types of roads and infrastructures are located.

Keywords: *Decision support system, flood mitigation, reservoir management optimisation*

Adapting ANUGA model for border-check irrigation simulation

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Abstract: Infiltration is a major process in irrigation, varying over both time and space during irrigation events. To simulate infiltration in border-check surface irrigations, one-dimensional (1D) models are commonly used. However, 1D models cannot simulate surface irrigations adequately when the surface of the irrigation bay is not uniform or bay micro topography is modified to improve surface water drainage. The 2D surface water flow model ANUGA, developed by the Australian National University and Geoscience Australia was used to model border irrigation performance. Use of a 2D model is part of our research work that seeks to evaluate the performance of surface irrigation based on different micro topography bay designs with the aim of reducing water ponding on the bays and improving irrigation efficiencies. Although ANUGA has the capability of applying infiltration as 'negative' rainfall, it does not simulate soil water infiltration. Therefore, we developed an infiltration algorithm using the empirical Modified Kostiakov (MK) equation which calculates infiltration as a function of ponding time. Ponding time is the duration since the commencement of surface inundation, ending when inundation ceases. The MK equation could not be applied directly in ANUGA because different areas of the model domain commence ponding at different times and are ponded for different durations during a simulation. In addition, the infiltration depth calculated by the MK equation at a given time is sometimes greater than the water depth on the surface.

The ANUGA model is set up by defining a study area (called a 'domain' in ANUGA) represented by a mesh of triangular cells. The mesh attributes include the land elevation, water surface elevation and frictional resistance. In our algorithm, the model time step at which each triangular mesh cell first has surface water is stored as the start of ponding on that cell. Ponding duration is calculated for each cell as the time between the current model time step and the time step ponding commenced. Based on the ponding duration, an infiltration depth is calculated for each 'wet' mesh cell. If there is sufficient water on the cell to satisfy the current infiltration depth, this depth is subtracted by the rate operator from the surface water. If there is insufficient surface water on a cell, all surface water is removed and the remaining, unsatisfied infiltration depth is carried forward into the next model time step. The cell ponding duration is incremented only when the infiltration depth is less than the depth of water available on the surface. This approach ensures that the irrigation advance propagates through the triangular mesh at a rate constrained by infiltration.

The data used to set up and run an irrigation event in ANUGA included bay microtopography, inflow to the bay, Manning's roughness coefficient '*n*' and infiltration parameters. Manning '*n*' and infiltration parameters were obtained from the 1D SISCO model using the measured data of inflow to the bay, and water advance and depth data within the bay. The modelled outputs of water advance, depth hydrographs, infiltration and runoff volumes were compared with the measured data.

Results showed a reasonable agreement between measured and simulated water depth hydrographs, measured and predicted water advance, runoff volume and cumulative infiltration. This study showed that the implementation of the MK infiltration algorithm in ANUGA was successful and that the adapted ANUGA model adequately simulated a border-check surface irrigation.

Keywords: *Surface irrigation, 2D model, Kostiakov*

The Bureau's Operational Australian Water Resources Assessment Modelling System (AWRAMS): From Science to End Users Applications and Future Directions

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Abstract: The Australian Water Resources Assessment Modelling System (AWRAMS) has been developed under the WIRADA initiative between the Bureau of Meteorology (BoM) and CSIRO. It has two modelling components; AWRA-L (landscape) to estimate the landscape water balance fluxes and AWRA-R (river) to estimate the river water balance fluxes. AWRA-L currently covers the whole Australian continent and is used to underpin the Bureau federally mandated water information products such as the National Water Account (NWA) and Water in Australia (WIA) reports. The AWRA-R model is currently parameterised for three NWA reporting regions (Murray Darling Basin (MDB), South East Queensland (SEQ) and Melbourne) and being trialled for that purpose. Since 2013, the Bureau's AWRAMS team has worked extensively in the AWRAMS Implementation (AWRAMSI) Project to operationalise the modelling system by recoding the developmental system code of the AWRA-L and AWRA-R models so that the AWRAMS becomes platform independent, while also being more efficient, functional, and easily maintainable and shared with the research community. The Bureau's operational AWRAMS code base is predominantly Python, with the AWRA-L and AWRA-R model kernels coded in Fortran and C respectively.

This paper presents the Bureau's operational AWRAMS, applications of the landscape and river basin model as well as the findings of the joint case studies carried out for both models with the external stakeholders in selected catchments across Australia. Lastly, this paper also presents the on-going work on publicly accessible website for sharing AWRA-L modelled outputs with the staekholders. The paper also presents the community modelling system framework to share the code of the AWRAMS to the research community.

Use of AWRA-R provides a platform for quantifying river fluxes (not available through observations) leading towards reduction in reporting of unaccounted differences in NWA reporting regions. Extensive model testing and evaluation were done in-house to gain confidence in AWRA-R performance. This includes comparing model outputs with observed data, outputs of peer models such as IQQM and previously published numbers where available. Water balance testing was also performed using field observation data over the Murrumbidgee catchment. In 2015-16, the Bureau plans for the first time to use the AWRA-R model to produce water balance fluxes for regulated rivers over NWA MDB region operationally. The Bureau has also planned to rollout the AWRA-R model progressive to the other remaining seven NWA regions.

The operational model of AWRA-L is running on a daily schedule with the modelled outputs (soil moisture, evapotranspiration, recharge and gridded runoff), generated each night to extend the century record to now and available at 9am. All modelled outputs (and inputs) are also being shared on regular basis with the registered users from various water agencies (ABARES, WaterNSW and universities) and their user case studies are reported. Daily updated (scheduled run) AWRA-L model outputs are used to underpin a new dynamic and interactive web application for the public to visualise, investigate and download modelled data across Australia. Hydrological variables displayed on the website are key components of the continental water balance including precipitation, evapotranspiration, soil moisture and runoff for the past few years. In addition, the website will also provide a portal for registered users to request the full 100 year AWRA-L modelled dataset.

The Bureau is planning to share the operational AWRAMS with third parties, including sharing the code such that third parties can create and test system improvements through further development by the university sector and become a true asset for Australian water resource management. By making the AWRAMS available, the Bureau is planning to encourage the hydrological modelling community to use a model that has been built primarily for hydrological applications. In March 2016, the Bureau is planning to organise a workshop on the AWRAMS by inviting interested hydrologists from state and commonwealth organisations, the research and university sector to discuss plans to undertake activities aimed at encouraging community uptake and improvement of the modelling system.

Keywords: *Australia, AWRAMS, landscape and river modelling, water information, water balance fluxes*

Application of Anuga as a 2D surface irrigation model

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Abstract: The dairy industry in the southern Murray Darling Basin (sMDB) is a major consumer of irrigation water, with over 90% of water applied to pastures and crops using border irrigation. While substantial investments have been made to improve regional and farm irrigation supply systems within the sMDB in the last decade, there has been little attention paid to improving the efficiency of conventional border irrigation design within fields. Border-check irrigation bays are typically rectangular, 40 to 80 m wide, 200 to 800 m long, and with surface elevation gradients of between 1 in 200 and 1 in 1000. Conventional border irrigation designs are based on smoothly graded bay surfaces. These facilitate uniform application of water but are very inefficient with respect to surface drainage, with adverse consequences for irrigation efficiency, plant growth and water losses to deep drainage.

Investigation of alternatives to conventional border irrigation bay designs has been constrained by the lack of alternatives to conventional 1D surface irrigation models, which are of little use for simulation of water flow on non-uniform surfaces. The application of 2D models in studies of surface irrigation has to date been limited. For our purpose a model was required that adequately represented the processes of both flooding and draining of uneven surfaces with low elevation gradients. To address this we have applied the 2D hydrodynamic surface water flow model, Anuga, and tested it against field data acquired from irrigations both before and after modification of a field surface.

Our irrigation bay was 39.1 m wide and 253.1 m long with a mean elevation gradient of 1 in 650. The bay modification was installation of four shallow surface drains evenly spaced across the bay and extending from 10 m from the top to the end of the bay. Anuga simulations of three irrigations on the unmodified bay surface corresponded closely with measured data and output from SISCO, an established 1D surface water flow model. After modification of the field surface, simulations of a further three irrigations with Anuga corresponded well with measured data, capturing the reduction in surface drainage duration in measured data. A simplified representation of the surface drains installed on the bay also provided satisfactory simulations of irrigation events on the modified bay while substantially reducing model run times.

Successful application of Anuga for simulation of border irrigation provides an exciting opportunity for development of more efficient border irrigation bay designs. Candidate designs for future field evaluation are now being explored.

Keywords: *Anuga, 2D surface irrigation model, border irrigation*

Improved simulation of groundwater in river operations simulations: seamless integration of MODSIM and MODFLOW

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Abstract: Surveyed hydrologic/river-operations model couplings found in the scientific literature adopt loose-coupling approaches, sometimes referred to as a "feed-forward" approach. As such, their respective solutions are not synchronized when either solution advances in time. When model time-steps are long (> 1 week) or, alternatively, the feedbacks between river operations and hydrogeology [via groundwater surface-water (GW-SW) interactions] are highly variable even at short time-scales (< 1 week), an integrated solution with detailed simulation of spatio-temporal accounting of GW-SW exchange is needed. To fill this need, recent efforts have focused on overcoming this overly-simplistic coupling between hydrologic and river-operations models by instead passing information through memory and synchronizing the model solutions before advancing to the next time-step, regardless of time step length. MODSIM, a generic river basin management decision support system capable of simulating complex, large-scale surface-water networks that excels in the area of administering water in systems governed by water rights, administrative constraints, and agreements, has been integrated with a dynamic link-library (DLL) version of MODFLOW, the world's most widely-used model for simulating regional- to basin-scale GW-SW interaction. Use of a hypothetical model simulating daily time steps in an agricultural setting has revealed that it commonly takes between 3 to 7 within-time step iterations between MODSIM and MODFLOW to achieve convergence, highlighting the inadequacy of feed-forward approaches. Through the use of the implicitly coupled MODSIM-MODFLOW model, current efforts are focused on (1) evaluating the impact uncertain hydrogeologic parameter values (e.g., hydraulic conductivity, streambed conductance, aquifer storage properties) have on simulation of river operations during high and low flow conditions, and (2) applying the implicitly coupled model to a real-world river system in Carson Valley, Nevada, USA. Presented results demonstrate the potential for significant mass balance errors that can result from a loosely-coupled ("feed-forward") approach between a river operations and hydrologic model simulation. This newly developed code will provide water planners and managers in over-appropriated systems with a more robust decision making support tool than either model could achieve when applied independently, or in a loosely-coupled approach.

Keywords: *River operations modelling, integrated environmental modelling, conjunctive use, MODFLOW, MODSIM*

Bayesian Network and System Thinking modelling to manage water quality related health risks from extreme events

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Abstract: The occurrence of extreme events can challenge the capacity of water utilities to deliver potable water of sufficient quality with respect to minimising health risks to consumers. As a consequence, proactive risk-assessment and decision support tools are necessary to assist in managing and mitigating such critical events effectively. However, the utility of these tools can be limited due to the lack of comprehensive data and a high degree of epistemic and stochastic uncertainty.

We use a combination of Bayesian Network (BN), System Dynamics (SD) and participatory modelling to develop a risk assessment tool for managing water-related health risks associated with extreme events. The combination of BN and SD modelling offers a number of advantages over other environmental modelling techniques; the capacity for dealing with a high degree of uncertainty, the use of feedback loops (SD only) and the ability to elicit and integrate quantitative and qualitative data (including expert opinion).

The risk assessment tool developed is applied to the raw water delivery system supplying Prospect water filtration plant system (Sydney, Australia), which is the main source of potable water for the Sydney metropolitan region. Key-stakeholders were engaged in developing and populating the conceptual models that form the basis of developing the BN and SD models. Conceptual models were developed by the stakeholders around the key indicator parameters of turbidity, water colour and *Cryptosporidium sp.* levels. These three conceptual models were combined into a single risk model and used for developing separate BN and SD models. Additional stakeholder workshops were conducted to refine the models (structure and parameter values) and to provide validation of the model outputs.

Here we present the development of a BN model designed to understand the risk of extreme events on the ability to provide potable water of a specified quality. The model has undergone development and preliminary parameterization via two participatory workshops. However, its development is an ongoing process with the next stage involving supplementing the 'expert opinion' used to parameterize the model so far with 'hard' data.

The completed models will quantify the sensitivity of the Prospect raw water delivery system to different types and combinations of extreme events (both natural and anthropogenic). The BN model will provide a risk management tool for estimating the probability of (top-down modelling), and requirements for (bottom-up modelling), meeting water quality guidelines. The SD model will provide a means of testing the implementation of different management scenarios and the impact that this has on water quality for different time horizons.

Overall, these complementary modelling methodologies will assist water treatment operators, water managers and other stakeholders in developing evidence-based mitigation strategies leading an to enhanced resilience of the system.

Keywords: *Bayesian networks, system dynamics, extreme events, water quality*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Multiple sources of uncertainty in modelling future hydroclimate

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Abstract: This paper presents a synthesis of the relative sources of uncertainties in predicting climate change impact on water resources and hydrological characteristics, based on extensive studies in south-eastern Australia over the last decade. This large region is an interesting test bed because of the large variation in hydroclimate spatially (from temperate to arid) and temporally (very large inter-annual variability and the recent unprecedented 1997–2009 Millennium Drought).

The paper will present multiple lines of evidence pointing towards a drier winter in the region (when most of the runoff is generated), but the uncertainty in future climate projections remain very large. Weighting future projections on a subset of the 'better' GCMs can provide a false sense of reduced uncertainty because the use of different criteria to assess the GCMs often results in different model choices. Limited downscaling runs also present the same problem as they may not describe the full range of uncertainty and different downscaling models may show different results. In most applications, different hydrological models generally give similar responses to changes in hydrological fluxes and stores (compared to the range in rainfall projections) from a changed climate input. However, the uncertainty in hydrological modelling can be as large as the uncertainty in climate projections when we extrapolate hydrological models developed and calibrated using past observations further into the future under significantly warmer and higher CO_2 conditions.

Despite the large uncertainties from various sources, the paper explains that, for many parts of the world including south-eastern Australia, we can project likely changes in key hydrological characteristics like long-term average streamflow, seasonality and security of water supply. Predicting the tails of the distribution and changes to extreme hydrologic metrics will remain difficult. It is therefore important to adopt an integrated climate-hydrology modelling and interpretation tailored specifically to the impact assessment and adaption being considered.

The key papers (and the references therein) that describe the issues discussed in this presentation include Chiew et al. (2014) (Observed hydrologic non-stationarity in far south-eastern Australia: implications for modelling prediction, Environmental Research and Risk Assessment, 28, 3–15, doi:10.1007/s00477-013-0755-5), CSIRO (2012) (Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative) and Post et al. (2014) (Decrease in south-eastern Australian water availability linked to ongoing Hadley cell expansion, Earth's Future, 2, 231–238, doi:10.1002/2013EF000194).

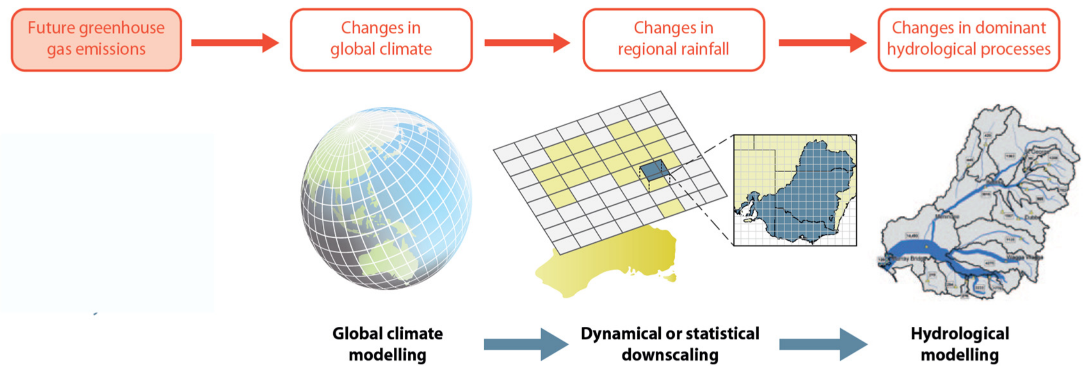

Figure 1. Integrated climate-water modelling.

Keywords: *Climate change, hydrology, streamflow, modelling, uncertainty*

Disentangling climate change effects on Australian streamflow

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Abstract: The effects of climate change are likely to influence water resources, especially in Australia (Chiew and McMahon 2002, Chiew et al. 2009, Betts et al. 2007, Chien et al. 2013) where the last major drought has increased concerns about water availability (Leblanc et al. 2012). So far, most of the research on future water availability has concentrated on running rainfall-runoff models with climate data from downscaled global circulation models for future scenarios (Chiew et al. 2009, Chien et al. 2013, Leblanc et al. 2012, Vaze et al. 2011). Essentially, this work suggests a magnification of the rainfall reductions in the predicted streamflow. This suggests a major effect of evapotranspiration (ET) on streamflow (Q) as the future reductions in P appear to amplified, either through changes in timing, or due to interaction with temperature. However, only a few studies worked with real observations.

Here we investigate whether 40 years (1970 – 2010) of stream flow data from small forested headwater catchments in Australia indicates the same amplification effect that is observed in the modelling. In particular, it is of interest whether these changes can be attributed to changes in rainfall and temperature, or other factors. For example, changes in geomorphology, or vegetation, could introduce steep gradients.

Thirteen hydrologic reference catchments smaller than 250 km^2 were selected for the study. Rainfall and maximum temperature data were obtained for nearby rainfall stations. Flood frequency curves were derived and compared for the different decades, and trends in weekly and monthly data were analysed using a Mann Kendall test and using a linear trend taking into account the significant autocorrelation un the data. For the Mann Kendall test, bootstrapping was used to identify whether the observed trends were different from trends in random data. The weekly data was also fitted with generalised additive mixed models (GAMM) assuming a simple water balance, where: $Q = P - ET$, thus assuming the catchments are closed systems. Trends in the residuals of the models were once again analysed using a Mann Kendall test, and by including a linear trend in the model.

In general, the stations in the South East of Australia were more likely to have a declining trend in both the rainfall and streamflow. Maximum temperature data (maxT) all indicated the expected strong significant ($p<0.05$) increasing trends. Only 6 stations indicated a significant (declining) trend in streamflow, while only 7 stations indicated significant ($p<0.05$) declining trends in rainfall. However, overall, all trends were very small (< 0.1mm yr^{-1}). The streamflow stations showing declining trends match the spatial distribution of trends for the hydrological reference stations. Only 2 stations indicated an amplification effect, where the trend in streamflow was greater than the trend in precipitation. The flow duration curve results confirmed the Mann Kendall trend analysis. The effect of ET (using the interaction between P and maxT as proxy) was only small in the data.

After the GAMM modelling, the same 6 stations identified earlier, mainly in southeastern Australia, indicated remaining significant ($p < 0.05$) declining trends in the residuals. This remaining trend was therefore not explained by changes in maxT (and therefore ET) and changes in P. The amplifying effect is most likely due to changes in the Pl timing and distribution, suggested by a shift towards more low rainfall depth events. Our on-going work analyses more stations to confirm that the spatial patterns are stable.

Overall the research supports the notion of a clear decreasing rainfall and streamflow trend in southeastern Australia (excluding Tasmania). One of the two western Australian stations indicated a trend, and inclusion of further stations in the west might clarify this further. None of the northern Australian indicated trends, confirming a lower climate change signal in the tropics.

Keywords: *Climate change, stream flow, head water catchments, rainfall change*

Drought assessment in the Pampanga River basin, the Philippines - Part 3: Evaluating climate change impacts on dam infrastructure with standardized indices

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Abstract: In the final part of this study, the drought assessment is conducted with standardized indices to evaluate dam infrastructure effectiveness under climate change in the Pampanga River basin, the Philippines. In previous two parts, we utilized standardized indices to determine the role of the Pantabangan and Angat dams in historical droughts (Part 1) and introduced the comparative approach for quantifying climate change impacts with standardized indices (Part 2). In Part 1, the standardized reservoir storage index (SRSI) was utilized to characterize potentially available water in reservoirs, the standardized inflow index (SII) - hydrological droughts as well as the standardized precipitation index (SPI) to characterize meteorological droughts in the Pampanga River basin. In Part 2, the comparative SPI was computed using general circulation model (GCM) outputs to quantify meteorological droughts for the present (1979-2003) and future (2075-2099) climates.

In this study, we utilize standardized SPI, SII and SRSI indices introduced in Part 1 with the comparative approach of Part 2 to conduct the climate change drought assessment at for the Pantabangan and Angat dams. To obtain SII and SRSI, we utilize calibrated 15-arcsec (about 0.45-km) grid BTOP model to simulate dam inflows, reservoir water storage and dam water discharges of irrigation water supply from the Pantabangan and Angat dams in the present (1979-2003) and future (2075-2099) climates. For the Angat dam, we also included the municipal water supply for the Metro Manila City situated next to the Pampanga River basin. In addition, we evaluated trans-basin inflows of the Casecnan and Umirai diversion tunnels that are located in the neighboring basins and contribute to the water availability of the Pantabangan and Angat dam, respectively.

Keywords: *BTOP model, SPI, SII, SRSI, climate change impacts*

Drought assessment in the Pampanga River basin, the Philippines – Part 2: A comparative SPI approach for quantifying climate change hazards

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Abstract: The change of climatic patterns is a major concern in the Pampanga River basin, the Philippines, and may intensify the magnitude of drought and flood hazard events under climate change uncertainty. Most of municipal water demand requirements for the Metro Manila relies on the Angat dam, which drains only 546 km^2 at the headwaters of the Pampanga River basin, as mentioned in Part 1 of this study. In this study, the climate change impacts were investigated for the RCP8.5 greenhouse gas emission scenario using 13 of higher-resolution general circulation models (GCMs) in CMIP5 and 4 ensemble members of the 20-km super high resolution atmospheric GCM, MRI-AGCM3.2S, with different sea surface temperature (SST) and sea ice distributions. The simulated daily precipitation was bias-corrected with the daily gridded rain gauges dataset as a reference observation, after the bilinear interpolation from the coarse grids of GCMs to the fine grid of the observation dataset. To estimate the meteorological hazards of droughts and floods due to climate change, we compared the precipitation characteristics between present (1979-2003) and future (2075-2099) climate projections using the standardized precipitation index (SPI) and the comparative SPI (cSPI).

The cSPI is a new concept designed to intuitively evaluate the meteorological drought in target datasets on the basis of the reference dataset. Computing the SPI by substituting future climate precipitation in the cumulative distribution function (CDF) with parameters derived from the corresponding present climate, we can compute the cSPI in future climate projections on the basis of the present climate projection. The cSPI could estimate not only the probability change of extremes but also the change of mean precipitation due to climate change simultaneously.

From cSPI results, the interannual variability of the cSPI in future climates increased significantly, but the average of the cSPI was almost the same as in present climate projections in the SST ensemble average of MRI-AGCM3.2S. As the result, both the meteorological drought and flood increased in MRI-AGCM3.2S simulations. In the higher-resolution model ensemble average CMIP5, the interannual variability of the cSPI in future climate was almost the same as in present climate projections, but the average of the cSPI significantly increased. As the result, the meteorological drought might be decreased in future but the heavy wet conditions could be increased in CMIP5 multi-model ensembles. It would be required to adapt to the heavier wet condition in the Angat dam in the end of the 21st century under the RCP8.5 emission scenario than the present climate condition.

The comparative standardized index concept of the cSPI approach, computing standardized index by substituting target datasets in the CDF with parameters derived from the reference dataset, is applicable to the other standardized indices, such as the standardized streamflow index (SSI), the standardized reservoir storage index (SRSI), and the standardized precipitation evapotranspiration index (SPEI), which is obtained with various probability distributions. For example, the comparative SRSI is utilized to evaluate socio-economic droughts under climate change in Part 3 of this study.

Keywords: *Standardized precipitation index (SPI), comparative SPI (cSPI), meteorological drought, precipitation, climate change*

Challenges and practicalities associated with water resources management and climate change adaptation in the Mekong River Basin

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Abstract: The Mekong River Commission (MRC) was established in 1995 between the governments of Cambodia, Laos, Thailand and Vietnam. The MRC Mission is: "To promote and coordinate sustainable management and development of water and related resources for the countries' mutual benefit and the people's well-being by implementing strategic programmes and activities and providing scientific information and policy advice". The MRC's Climate Change and Adaptation Initiative (CCAI) started in August 2009 as a regional collaborative initiative to support Lower Mekong Basin (LMB) countries in adapting to the impacts and new challenges of climate change. This presentation will focus on the recent climate change impact assessment and adaptation planning work that MRC CCAI have undertaken. The criteria and methodology used to develop climate change scenarios for the LMB, which cover a wide range of stakeholder needs and plausible climate futures while also quantifying and dealing with uncertainty, will be presented. The strengths and weaknesses of the approach employed will also be discussed along with other aspects that need to be considered in addition to the impacts of climate change.

It is emphasised that the approach employed here is the most practical, cheapest and quickest approach available to provide sufficient information for MRC's water resource management, climate change impact assessment and climate change adaptation activities. This should not be mistaken to imply that the approach employed is necessarily the 'best' approach rather it should be considered the first stage in a multi-stage process where the complexity, time and cost of the approaches considered increases incrementally. Given the significant doubt as to whether the information produced by the more sophisticated GCM selection or downscaling approaches will be any better or more practically useful than the information emerging from the simple approach employed here, the use of more sophisticated and expensive approaches could not be justified at this point in time. Recommendations will be given regarding the future work needed to determine whether or not the simple approach employed here needs to be replaced, or used in conjunction, with a more advanced approach or combination of approaches in the future (and also what that more advanced approach should be).

Keywords: *Water resource management, uncertainty, climate scenarios, flood, drought*

Comparative performance of GR4JSG and J2000 hydrological models in the Dudh Koshi catchment of the Himalayan region

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Abstract: Hydrological models are widely applied to make informed decisions in water resources planning and management. However, the representation of hydrological processes in a model is subject to uncertainty due to the conceptualization of those processes. The choice of models is a trade-off among availability of data and understanding of processes in the catchment. In this study, we compared the performance of two hydrological models, the conceptual GR4JSG and the process based J2000 hydrological model in a glaciated alpine catchment in the Himalayan region. Both models were adapted to simulate the glacier melt runoff in which seasonal snowmelt and glacier icemelt occurs. Regarding the spatial heterogeneity, the catchments are represented by numbers of hydrological response units (or functional units in GR4JSG).

Both models were calibrated for the period 1986-1991 and validated for the period 1992-1997. The models were able to represent the overall hydrograph with a Nash Sutcliffe Efficiency (NSE) in the J2000 model of 0.84 and 0.87 for calibration and validation, respectively, and for the GR4JSG model, the NSE was 0.87 and 0.89 for the calibration and validate periods. Although the models simulated baseflow and medium range flows (recession and rising limbs) reasonably well, the peak flows were underestimated in some instances. On average, the percentage bias is below 3% in both models. The hydrograph suggested that the GR4JSG tends to underestimate observed hydrograph during pre-monsoon season. Similarly, GR4JSG tends to overestimate July-September compared to J2000. The glacier melt contribution to stream flow is about 13% and 17% for GR4JSG and J2000 respectively. The variation can be expected due to conceptualization of hydrological processes in both models.

Keywords: *GR4JSG model, J2000 model, Himalayan region, snow and glacier, melt runoff*

A statistical model for estimating future low flows

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Abstract: Low flows can be critically important for the health of ecological systems, particularly in semi-arid and highly seasonal climates. Yet the nature of rainfall-runoff models and their calibration means that low flows can be difficult to predict and model. Objective functions are typically weighted more towards high-flow events in order to provide accurate volumetric estimates. Rainfall-runoff models calibrated in this way are often used to generate future runoff predictions, from which low-flow metrics can easily be calculated. However, these metrics can be heavily biased and using them to make ecological and water planning decisions could be fraught with problems.

A statistical model is proposed and developed for predicting annual low-flow metrics (e.g. baseflow index, low-flow discharge volumes and low-flow spells). We start with the observed daily streamflow data, which can (and does) contain missing data. Low-flow metrics of interest are calculated for each year of data. A number of annual rainfall characteristics are then calculated on the catchment rainfall time series such as annual rainfall, variance of daily rainfall, maximum daily rainfall, number of rain days, etc. A stepwise regression is carried out between the annual low-flow metrics and rainfall characteristics. Annual streamflow completeness ratios (with 0 indicating all data missing, and 1 a complete year of data) are used as weights in the regression in recognition of the effect of missing periods on the calculated low-flow metrics.

This regression model can then be used to create future low-flow projections based on GCM outputs. The main benefits of the statistical approach are that: (1) rainfall-runoff model calibration is not needed, and the statistical models are easily fitted and applied, and (2) confidence/prediction intervals can be calculated alongside the prediction itself, and this provides a range of uncertainty, which can help in decision making.

Keywords: *Low flows, statistical model*

An Imbalance Assessment of Coastal Water Supply and Demand in a Highly Populated Area: A System Dynamics Approach

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Abstract: The imbalance of a coastal water supply and demand system is temporally affected by both natural and anthropogenic processes that are interactions between interdependent components with many feedbacks. Water availability is influenced over time by interactions among sea level rise, river flows and salt-water intrusion. Water demand is affected by population growth, agricultural and industrial production. The interactions of these factors will lead to increases or decreases in the imbalance of the coastal water supply and demand over time. Understanding temporal interactions of these drivers and their effects on the imbalance of the coastal freshwater system over time is necessary to improve coastal freshwater management.

This study proposes a new approach that applies a system dynamics modelling tool to investigate the imbalance between water supply and demand over time in a highly populated coastal area, Hai Phong, Vietnam. More specifically, this paper investigates the effects of sea level rise, river flows and salinity intrusion on a coastal freshwater availability, together with the effects of population growth, agricultural and industrial production on water demand.

The interrelationships among interdependent variables causing the imbalance of the coastal water supply and demand system are depicted by a "Drifting goals" system archetype with two balancing loops. Both two goal seeking loops (B1 and B2) are capable of relieving the imbalance of the system. However, the goal seeking loop B1 generally takes more time and efforts to achieve a goal than the goal seeking loop B2. This conception plays an important role for stakeholders in identifying management interventions for the coastal freshwater system. A preliminary imbalance model of the coastal water supply and demand system was developed. The key data requirements and equations for calibration and simulation of the model were also initially identified.

A number of methods will be used to reduce uncertainties inherent in, and validate the performance of the models. The uncertainties associated with climatic and socio-economic unpredictability will be reduced by developing a range of scenarios of sea level rise, river flow, and domestic use, agricultural and industrial production. The validity of the models will be calibrated by using expert and stakeholder judgements, historical data, previous hydrodynamic studies, and field measurements of river flows and salinity in the study area.

This study has a high potential for novelty as it incorporates both climatic and non-climatic drivers into one framework to assess the imbalance between coastal water supply and demand in a developing country. More specifically, it will provide an understanding of the present and future imbalance of a water supply and demand system in highly populated coastal areas with a high rate of urbanization and population growth, together with sea level rise and precipitation decrease. This study will directly contribute to the development of collective and decisive adaptation actions that aim to secure efficient freshwater resources for the socio-economic development in the port city of Hai Phong, Vietnam.

Keywords: *Land use change, population growth, river flow, salinity, sea level rise*

CMIP5 climate change projections for hydrological modelling in South Asia

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Abstract: Climate change will impact water and related sectors. Temperature and potential evaporation will be higher. Changes in future precipitation will be amplified in the river flows. Security of water supply will be compromised due to longer and more severe droughts, more precipitation falling as rain rather than snow, increased seasonality of river flow and retreat of glaciers. Flood risk will increase due to more intense heavy precipitation events.

This paper presents the analyses of all the CMIP5 global climate model (GCM) runs to derive a consistent baseline climate change projection database for the South Asia region (5.25°–40.25° S, 60.25°–100.75° E) for the Sustainable Development Investment Portfolio (SDIP) run by the Department of Foreign Affairs and Trade (DFAT). The database presents 'empirical scaling factors' for 0.5° grids (~50 km) that reflect changes in six climate variables (precipitation, heavy precipitation, potential evaporation, daily average temperature, daily maximum temperature and daily minimum temperature) for a future (2046–2075) period relative to current. The projected changes in the climate variables are derived for each of the 12 months, four seasons and annual values for two future representative greenhouse gas concentration pathways. These are presented for each ensemble modelling run from each of the 42 CMIP5 GCMs, as well as the median and range (uncertainty) of plausible projections. These consistently derived climate change projections will be used in various hydrological modelling and integrated water management projects across South Asia to inform water management, planning and development, and their interactions with the energy and food sectors.

There is strong agreement between the GCMs in the temperature projections. Averaged across the South Asia region, the median projection for RCP4.5 and RCP8.5 is an increase in daily average temperature of 2.1°C and 2.9°C respectively by 2046–2075 relative to current. The projected increases are slightly higher for minimum daily temperature and slightly lower for maximum daily temperature as compared to the daily average temperature. The projected temperature increase is slightly higher in winter than in summer, and greater in the high altitude areas in the north. Averaged over the South Asia region, potential evaporation is projected to increase by 4.5% and 6.2% respectively by 2046–2075 relative to current. The projected increase in potential evaporation is mainly driven by the increase in temperature.

There is much greater uncertainty in the precipitation projections, with significant variations between GCMs, and in the different seasons and regions. The range of projections from multiple ensemble runs of some GCMs can also be as high as the range of projections from the different GCMs. Nevertheless, a higher proportion of GCMs project an increase in precipitation, particularly in the north-east and much more so in the summer monsoon than winter. The projections also indicate likely intensification in the high extreme precipitation. The results also indicate that weighting the projections towards the better GCMs, assessed against their ability to reproduce the observed historical annual precipitation amounts and variability, do not reduce the range of uncertainty in the projections. As such, it is probably best to use the entire set of available GCMs in climate change impact studies to represent the entire range of plausible uncertainty.

Keywords: *Climate change projections, South Asia, CMIP5 GCMs, precipitation, water*

On the non-stationarity of hydrological response in anthropogenically unaffected catchments: An Australian perspective

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Abstract: Increases in greenhouse gas concentrations are expected to impact the terrestrial hydrologic cycle through changes in radiative forcings (affecting precipitation and temperature) and plant physiological and structural responses. Here we investigate the nature and frequency of non-stationary hydrological response as evidenced through water balance studies over 166 anthropogenically unaffected catchments in Australia using data from the Australian network of Hydrologic Reference Stations (http://www.bom.gov.au/water/hrs/). Non-stationarity of hydrologic response is investigated through analysis of long term trend in annual runoff ratio (1984-2005). Results indicate that a significant trend ($p < 0.01$) in runoff ratio is evident in 19 catchments located in three main ecoregions of the continent. Runoff ratio decreased across the non-stationary catchments with the exception of one catchment in northern Australia. Non-stationarity of runoff ratio is caused by complex interactions between changes in precipitation, climate variability, plant physiological and structural responses to elevated CO_2, landscape characteristics (soil and topography), and the hydroclimatic condition of a catchment. We use precipitation-productivity relationships as the first order control for catchment classification under climate change. Monthly fractional vegetation cover from the Advanced Very High Resolution Radiometer (AVHRR) sensor is used as a measure of vegetation productivity. This first order grouping of catchments will help to generalize catchment behaviour in terms of changes in runoff ratio and vegetation productivity due to changes in precipitation. Eleven out of 19 catchments present a positive precipitation-productivity relationship possibly enhanced by CO_2 fertilization effect. In the remaining catchments, nutrient limitations may be impacting productivity. The proposed classification framework provides a general guideline for projecting the likely changes in catchment water balance in response to climate variability. However, uncertainty about the terrestrial ecosystem response still remains as productivity is impacted by factors such as availability of water, nutrients and light, vegetation developmental stage, space constraint and prevalence of pests. In addition, it is expected that frequency and duration of extreme events such as fire, drought and floods to increase in future. These changes are expected to further alter ecosystem response and water availability.

Keywords: *Non-stationary, runoff ratio, catchment classification, ecohydrology*

Hydrologic nonstationarity and modelling under change

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Abstract: Since the commentary of Milly et al. in the journal Science in 2008, the catch phrase 'hydrologic nonstationarity' has been used to describe many things ranging from different climate-runoff relationships evident in different periods within a long hydrological time series to changes in hydroclimate characteristics and dominant hydrological processes in an increasingly warmer and higher CO_2 world. Hydrologists have always represented stationarity and nonstationarity (which is difficult to distinguish statistically in natural systems) as best they could and their implications on the management and planning of water resources systems, but modelling this adequately will become increasingly challenging in a world driven by anthropogenic changes. Hydrologists have excelled in developing models for numerous applications, through analysing and interpreting climate and hydrologic data to understand hydrologic processes, conceptualising the processes in hydrological models, and calibrating and testing models against observations. These models, when developed adequately using relatively long historical records that encapsulate the range of hydroclimate conditions, are particularly good in predicting the streamflow response to changes in climate inputs and catchment characteristics over the near and medium term. However, extrapolating hydrological models to predict further into the future that is influenced by anthropogenic change is challenging as we will then be predicting system behaviours that are beyond the range of observed variability in the instrumental record (changed rainfall characteristics, higher temperature, higher CO_2) or that result from significant alterations to the physical system characteristics.

This paper presents examples of observed hydroclimate and hydrologic nonstationarity, using mainly examples from far south-eastern Australia. The prolonged 1997–2009 Millennium Drought in south-eastern Australia exposed various aspects of nonstationarity including changing rainfall-runoff relationship, different hydroclimate and hydrologic regime, influence from different dominant hydrological processes and general inability of models developed using past observations to simulate the streamflows during the drought. The paper also provides an overview of discussions on hydrologic nonstationarity in key international forums over the past several years, in particular the International Association of Hydrological Sciences decadal initiative of prediction under change.

This paper also presents some of the approaches that has been used to predict the future under nonstationarity. Hydrologic responses to changed climate inputs are generally modelled using hydrological models informed by climate projections from the large range of global and regional climate models. Improved understanding of vegetation behaviour and hydrological responses to warmer climate and higher CO_2 are increasingly incorporated in the more complex hydrological models. Improved conceptualisations are being introduced to hydrological models, particularly when they are used in studies predicting into the future under prolonged extreme conditions. Examples include parameterising semi-distributed hydrological models or adapting existing models to simulate processes under extreme conditions like long dry spells (farm dam interception and surface-groundwater connectivity) and learning from catchments experiencing different or changing conditions. Some studies use existing models, but with smart approaches to parameterise and calibrate the model, for example with time varying parameters dependent on storage levels, multi-criteria optimisation that also considers low flow simulations and predicting the future with parameters from model calibration against a similar climate period as the future climate projections.

"Stationarity is dead". However it is not apparent what if any alternative methods should be used as a replacement for the different types of hydrological applications. For example, existing approaches may be sufficient for operational water management and short-term planning, but key aspects of 'nonstationarity' must be taken into account for certain hydrological design and long-term planning. Predicting the future is always difficult if not impossible and hydrologic planning will always need to consider probabilistic or multiple plausible realisations and scenarios and adopt adaptive risk management with systems planned for particular levels of security or reliability.

Keywords: *Hydrologic nonstationarity, hydroclimate, hydrological modelling, prediction under change*

Modelling catchment response to anthropogenic driven non-stationarity

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Abstract: Non-stationarity normally refers to a change in the statistical properties of a signal. This can include, for example, a change in rainfall and evaporation due to climate change, and the subsequent impact on streamflow. Other drivers which can also impact on the streamflow response include: installation of dams (both large instream dams, and smaller, distributed farm dams), extraction of surface and groundwater, environmental flows. Such non-stationarity leads to variability in the values of model parameters if the effects of these changes are not handled in the model structure and inputs.

Extraction of water can be for a number of reasons, for example, irrigation, urban water supply, stock and domestic use, salt interception schemes, etc. Dams can be managed to maintain water supplies, provide environmental flows, flood mitigation, etc. The impact these activities will depend on how the water is used. For example, irrigation leads to an increase in near surface moisture. Rain events after irrigation can have a higher runoff coefficient that would be the case without the irrigation, though how significant this effect is depends on the timing.

This paper will focus on analysis of catchments with observed anthropogenic driven non-stationarity, primarily the impact of water extraction on streamflow. The goal is to be able to determine how to model such effects, including defining the necessary input data as well as the model structure needed. The base model is the IHACRES rainfall-streamflow model, which is a hybrid conceptual-metric model that consists of two components: a conceptual module to convert rainfall into effective rainfall and a transfer function based Unit Hydrograph to generate streamflow. The modifications needed to the IHACRES model to capture the behaviour in sample catchments in Australia, Africa and Greece will be presented, and the impact of these changes on the model performance will be discussed.

The first step in the process for each catchment is to use data analysis tools (cross correlation analysis and deconvolution) to explore the response signatures, and assess how well the standard model will be able to reproduce these signatures. The deficiencies in the model structure are then identified, and possible ways of modifying the structure of the model considered. Examples of the modifications considered include: use of non-linear storages and losses in the Unit Hydrograph, partitioning effective rainfall between quick and slow flow components inside the conceptual module, and also alternate functional forms for the conceptual module.

Keywords: *Non-stationarity, rainfall-streamflow, groundwater, IHACRES*

Trend Detection in Short and Long Duration Storm Events: A Case Study for NSW, Australia

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Abstract: Anthropogenic climate change is one of the key challenges the earth is facing today, which affects many aspects of the environment. Climate change affects hydrological cycle including rainfall, evaporation, soil moisture and catchment runoff. Change in rainfall has significant implications as it influences floods, droughts, vegetation and ecology. There have been numerous studies on trend identification in annual rainfall data; however, a trend in extreme rainfall data has received relatively less attention. Trends in the extreme rainfalls would affect design and operation of many engineering structures in near future. This paper examines the trends in annual maximum rainfall data from 20 pluviograph stations in New South Wales (NSW), Australia by using two non-parametric tests, Mann-Kendall (MK) and Spearman's Rho (SR) tests. Rainfall events data are analysed for fifteen different durations ranging from 6 minutes to 3 days. The relationship between the observed trends and elevations of pluviograph stations, mean annual rainfall and Southern Oscillation Index (SOI) are examined. It is found that trends are generally influenced by these catchment and climate indices; however, no significant link could be established. The results of the MK and SR test statistics are found to be modestly correlated with the mean annual rainfall and the elevation of the pluviograph stations, with a maximum correlation coefficient of 0.31. It has been found that the correlation coefficient between MK test statistic and mean annual rainfall is higher for the longer durations than the shorter duration rainfall events. In case of correlation between the MK test statistic and elevation, it has been found that the correlation coefficient is higher for the shorter durations than the longer duration events. It has also been found that the SOI index is weakly correlated with monthly maximum rainfall data. Overall, this study shows that there are little trends in the rainfall events data in NSW that could be deemed to be significant.

Keywords: *Mann-Kendall test, Spearman's Rho test, design rainfall, annual maximum rainfall, Southern Oscillation Index*

Is inter-basin groundwater exchange required in rainfall–runoff models: The Australian context

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Abstract: Inter–catchment groundwater exchange is a process included in some rainfall runoff models, most notably GR4J, to account for transfer of groundwater in and out of catchments. This process has been validated in European conditions, but not in Australia. It is unknown if inter–catchment groundwater exchange can be justified in Australian environments. The rainfall-runoff models GR4J and GR7J are outlined. Simulated inter-catchment groundwater fluxes for 137 calibrated catchments from each model show that this term comprises a significant part of the simulation water balance. In a random sub-sample of catchments (n=30), the inter–catchment groundwater exchange parameter (x_2) is set to zero (effectively shutting off the process). GR4J and GR7J were re–calibrated , and evaluated with this modification during identified extended drought periods. Results suggest that the x_2 parameter can be set to zero for the GR7J model without any deterioration in predictive performance. GR4J goodness of fit is degraded in both calibration and evaluation by setting x_2 to zero. Catchment water balance is evaluated for 137 catchments within eastern Australia using observations of precipitation, potential evaporation and stream flow. Analysis of these data could not detect imbalances that suggest significant inter-catchment groundwater exchange. It is proposed that inter–catchment groundwater exchange process in a calibrated rainfall–runoff cannot be justified in the study conditions without additional contrary evidence.

Keywords: *Drought, rainfall–runoff model, non-stationarity, groundwater–surface water connection, objective functions*

Intensification of storms due to warmer temperatures

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Abstract: The potential for increasing intensity of future rainfall events has significant implications for flooding and the design of infrastructure. How precipitation will vary in a possible future warmer climate has been the subject of much recent research. Due to the difficulty in accurately simulating rainfall for a future climate many studies have focused on relationships between observed historical variables. This has given rise to a field of research that looks at the relationship between rainfall intensity and temperature termed scaling. The Clausius-Clapeyron (C-C) relationship predicts an approximately 7%/°C increase in the water vapour holding potential of the atmosphere. Assuming a constant relative humidity one could expect extreme precipitation to scale at a similar rate and this has been found to be true on a global scale in observational records.

Locally and regionally, however, scaling that differ from the expected 7%/°C have been observed and hence led to conjecture on how rainfall will behave in a future climate and the mechanisms causing this change. In particular scaling rates up to double C-C (so called super C-C scaling) have been observed. This has led to speculation on whether storm bursts may intensify at warmer temperatures due to possible latent heat release and the ability of the storm to draw in additional moisture from its extents. In this study we aim to investigate whether there is any empirical evidence for intensification of storm bursts. Using observational records of pluviograph rainfall and temperature records across Australia the scaling of spatial and temporal patterns is investigated.

Temporal pattern scaling was investigated using weather stations with 25 years or more of recorded data. In all, 79 stations across all Australian climates were analysed. The largest 500 hourly storm bursts at each station were chosen and matched to their coincident average daily temperature. Each hourly storm burst was then split into five 12 minute periods and each period ranked from largest to smallest. Each period was divided by the corresponding storm burst volume to find the rainfall fraction in each rank and the scaling of these fractions, for each rank, was calculated. Regardless of the study site the scaling of the largest precipitation fraction was positive (with increasing temperature) and the scaling of the smallest precipitation fraction was negative, suggesting that storm burst temporal patterns are less uniform at higher temperature. In addition, it was found that the scaling of the precipitation fractions in the temporal pattern was greater than scaling of the overall precipitation depth of the storm burst. This has significant implications for planning, especially in tropical areas of northern Australia where negative storm burst scaling has been observed. Incorporating the scaling of temporal patterns into future flood predictions showed that the flood peak can increase from changes in the temporal pattern despite decreases in the precipitation depth of the storm.

An additional analysis was undertaken to investigate the scaling of spatial patterns. As the data requirements for a spatial analysis are larger we restricted our analysis to stations with more than 10 years of data that had at least four neighbouring weather stations. In all 88 stations were considered in the analysis. Spatial statistics were calculated using a central station of interest and all neighbouring stations within a 50km radius. Spatial fields were found by picking the peak one hour precipitation from independent storms events at the central site of interest with the coincident rainfall at the neighbouring sites. The scaling of the coefficient of variation and fraction of zeros with average daily temperature was then calculated. Both statistics consistently showed a positive scaling with temperature regardless of site location. In addition the peak precipitation at the central site also scaled positively suggesting that at warmer temperatures storms are less uniform and indeed moisture is drawn from storm extents into the centre of the storm.

The results presented here suggest a decrease in the uniformity of the storm pattern and hence an intensification of the storm at higher temperatures. If historical relationships are indicative of possible future changes due to a warmer climate, these results suggest more intense and destructive storm cells arriving with warmer temperatures. The result would be an increase in the destructive force of possible future floods.

Keywords: *Climate, rainfall extremes, Clausius-Clapeyron scaling, scaling with temperature, spatial, temporal*

Seasonal forecasts for reservoir systems operation with an over-year carryover capacity – what is their value?

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Abstract: Recent advances in weather and climate forecasts have brought fresh energies to studies on operation of reservoir systems with the prospect of improving their performance by assisting decisions through forecasts of water availability. Most of the studies available in the literature focus on stylized schemes with one, single- purpose, reservoir with constant demand and analyse parametrically the effect of forecasts using more or less simplified operation models. While these studies play a fundamental role in creating a general framework for analysis, there is the feeling that the diversity of the boundary conditions (climatic contexts and purposes) to the problem of reservoir management calls for more detailed analyses on specific types of reservoir systems. In this paper, we concentrate on systems with over-year behaviour that are widespread in arid and semiarid areas of the world. The question is if and in what sense streamflow forecasts can help improve reservoir operation in this type of systems, the ones that probably would most benefit from them, given their exposure to droughts.

To answer this question, we set up a real time management model of a multi-reservoir, multi-purpose system based on the rolling horizon technique (RHT). The model uses current reservoir levels and inflow forecasts over a forecasting horizon of 24 months to schedule allocations to the system's demand centres with the objective of minimizing the sum of standardized squared monthly municipal deficits and of standardized squared yearly irrigation deficits. Of this schedule, only decisions at the first time step are implemented because actual inflows become available, so that the new actual reservoir levels are available and the decision-making process can continue for the next month based on updated forecasts. We simulate the RHT over a period of 480 months in a system of two reservoirs with side irrigation demands and municipal demands in parallel. We use three types of forecasts: the two extremes of forecasting quality (average inflows and real inflows) and a simple data-driven univariate technique, denoted as Quantile Generation (QG). QG generates future inflows to the end of the current water year by equalling the quantile of cumulated inflows from the current month to the end of the water year to the quantile of the observed cumulated inflows from the beginning of the water year to the current month. We simulate the system with different demand levels, thus obtaining scenarios with different drift indexes covering a wide range of over-year storage behaviours.

We show that, perhaps not surprisingly, the RHT using forecasts of the best possible quality (real inflows) provides very similar performances, from the standpoint of total standardized squared deficits, to those obtained using worst quality forecasts (average inflows) and that the RHT with QG performs even worse than with average inflows. This would confirm that, especially in systems where the value of water is levelled out across the various demand centres, as is the case when allocation criterion is the minimization of squared standardized departures from targets, the largest value of forecasts does not reside in their ability to improve system's performances. We then explore another dimension of forecasts, by concentrating on the different ability of the RHT to provide suitable predictions of annual deficits with one-year lead when associated to the three forecast types. As expected, we find that RHT in association with real inflows is able to provide the best forecasts of actual deficits and that there is a value of the drift index above which the QG outperforms average inflows in providing forecasts of annual deficits. We conclude that the real value of forecasts in the management of this type of systems relies in their ability to provide information on future water restrictions with an advance suitable to enforce mitigation measures. If no mitigation measure is possible, then there is little scope for using forecasts to manage this type of systems. On the contrary, mitigation measures based on a timely recognition of future possible use restrictions are likely to benefit from accurate inflow forecasts. From this standpoint the QG proves a simple, promising technique to be further assessed.

Keywords: *Water resources systems, rolling horizon technique, inflow forecasts, timeliness of forecasts*

Towards operational forecasting of agricultural soil water in Australia

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Abstract: Australia has large and diverse agricultural industries, in addition to a highly variable climate. Recent government policy has focussed on increasing farm productivity. One of the challenges for achieving this, especially for rain-fed agriculture, is improving local-scale information on current and forecast future soil water status. Reliable soil water forecasts will allow users to better predict likely future water availability and make better informed farming decisions over timescales from days to seasons. This paper explores the state-of-the-art of the components that need to be brought together to transition our research knowledge into operational soil water forecasts, and the challenges that lie therein.

Achieving operational agricultural soil water forecasts requires bringing together a diverse range of components, including:

Long-term soil water monitoring – high quality profile soil water monitoring datasets extend to 10 years for some sites, while remote sensing data for surface (<5cm) soil water extends to fifteen years and beyond. These provide fundamental data against which soil water simulation 'hindcasts' and forecasting methods can be developed and tested.

Remote sensing and data assimilation – the resolution, frequency, quantity, and inter-product consistency of remote observations relevant to modelling of soil water is increasing. This includes dedicated satellites for soil water. Current technology, techniques, and infrastructure provide the capability to assimilate such data into soil water models on an ongoing operational basis. These datasets can improve both forecasting methods, by bounding hindcast predictions, and operational forecasts, by providing good initial conditions for predictions.

Rainfall and temperature forecasts – multi-week to multi-season climate forecasts are a critical driver of soil water forecasts. These are currently produced weekly as daily ensemble (probabilistic) forecasts over a 250 km grid out to 270 days ahead, with significantly diminishing skill (accuracy) beyond about 3 months. Limited research to increase the resolution and skill of these forecasts is underway, with a focus on agricultural applications. Operational improvements, including increased spatial resolution, will occur in the near future.

Soil water modelling – Operational earth system forecasting models and crop growth models are both capable of producing soil water as outputs. Each operates at extremes of the global spatial scale (landscape versus point-scale). Their skill to produce explicit probabilistic soil water forecasts as ensembles has yet to be fully evaluated. There is also a challenge to determine the best approaches to take advantage of, and integrate, rainfall forecasts, remote observations, and local scale soil and management information.

Local scale inputs – The ability of soil to store water and make it available to plants varies widely. Local information on soil type and properties, soil water observations, and crop management increases the relevance of forecasts. They can also increase forecast accuracy by tuning the down-scaling of broad-scale forecasts to local conditions. Farm-scale monitoring and communication technologies have now matured to the point where they offer significant potential as a key input to the localisation of forecasts.

Integrating and maturing these components in a structured and strategic manner is required for us to achieve the goal of useful operational seasonal forecasting of agricultural soil water in Australia.

Keywords: *Soil water forecasting, seasonal climate outlook, soil water modelling*

On the predictability of SSTA indices from CMIP5 decadal experiments

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Abstract: Information from improved near-term climate predictions (from 1 year to several decades into the future) can help shape decisions for various societal applications, whilst adapting for regional climate change. Following this, several modelling groups have set up decadal retrospective forecast experiments as part of the Phase Five of the Coupled Model Intercomparison Project (CMIP5). Originally, the CMIP5 coordinated decadal predictability experiment involved a series of 10-year hindcasts, initialized every five years starting around 1960. However recent studies about bias adjustment, amongst many others, have highlighted the need of more start dates for a reliable estimate of the skill of the CMIP5 decadal experiments, which has led to start dates every year becoming a recommendation of CMIP5. This study aims at identifying the sampling biases in sea surface temperature (SST) predictions from experiments initialized every five years and those initialized every year. The effect of a recommended drift correction method on the two sets of prediction experiments is also analyzed. Our results show that the differences are mostly noticeable for SST predictions over tropical Pacific, especially for anomaly initialized models, and negligible for global average SSTs. These are further analyzed by considering sea surface temperature anomaly based climate indices and the discrepancies are attributed to the El Niño Southern Oscillation (ENSO). The recommended drift correction approach leads to spurious trends over the Pacific in case of start dates every five years and negligible improvements in the case of start dates every year. The study also asserts the need to reanalyze any skill assessment over the tropical Pacific using the recommended drift correction method.

Sea surface temperature anomaly (SSTA) climate indices in the tropical Pacific and Indian Oceans are statistically significant predictors of seasonal rainfall in the Indo-Pacific region. On this basis, this study also evaluates the predictability of nine such indices, at interannual timescales, from the decadal hindcast experiments of four General Circulation Models (GCMs). A Monte Carlo (MC) scheme is applied to define the periods of enhanced predictability for the indices. The effect of a recommended drift correction technique and the models' capabilities in simulating two specific El Niño and La Niña events are also examined. The results indicate that the improvement from drift correction is noticeable primarily in the full-field initialized models. Models show skillful predictability at timescales up to maximum a year for most indices, with indices in the tropical Pacific and the western Indian Ocean having longer *predictability horizons* than other indices. The multi model ensemble mean (MME) shows the highest predictability for the Indian Ocean west pole index (WPI) at 25 months. Models simulate the observed peaks during the El Niño and La Niña events in the Niño 3.4 index with limited success beyond timescales of a year, as expected from the predictability horizons. However, our study of a small number of events and models shows full-field initialized models outperforming anomaly initialized ones in simulating these events at annual timescales.

Keywords: *General Circulation Models, SSTA indices, Predictability, Indo-Pacific, CMIP5 decadal hindcasts*

Getting it right: the roles of research, stakeholders, and delivery for a seasonal streamflow forecasting service across Australia

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Abstract: The Bureau of Meteorology (Bureau) provides an operational seasonal streamflow forecasting service that, each month, issues three month ahead forecasts of total water volumes at about 200 locations across Australia (http://www.bom.gov.au/water/ssf/). Development of this service began in 2009, it became operational in 2010, and continues to be user driven, because it must ultimately influence decision making that results in improvements to water resource management.

Service development has been led by the Extended Hydrological Prediction (EHP) section within the Bureau, and research and development support from the following partners has been critical. These partners include the Water Information Research and Development Alliance (WIRADA, a research collaboration between the Bureau and CSIRO), the Research and Development Branch within the Bureau, and the university sector. Modelling approaches developed through these collaborations form the basis of the service. Forecasts are provided to the public using a statistical modelling approach based on relationships derived directly from observed streamflow data and derived climate (predictor) indices. Forecasts based on rainfall-runoff modelling forced by downscaled rainfall forecasts (dynamic approach) are currently being released to and evaluated by registered users. This approach takes advantage of outputs from the Bureau's operational seasonal climate model. Current work is underway to combine forecasts from the statistical and dynamic approaches to provide merged forecasts that capture the strengths of each approach, thereby providing forecasts with greater accuracy and reliability.

Delivery, and continued development of the seasonal streamflow forecast service, requires attention to a wide variety of tasks. It requires cooperation with internal and external stakeholders, along with a comprehensive understanding of user needs, research and development support, robust operational modelling tools and web-based service delivery systems, a communication and adoption strategy and an implementation plan.

For example, the forecasting service relies on good quality historical and near real-time climate and hydrological data, especially streamflow. The service relies heavily on the Australian Water Resources Information System (AWRIS) for hydrological and related geospatial data, with the seasonal streamflow forecasting service being the first operational service utilising AWRIS. Assessing and controlling the quality of observed data used for forecasting is a core process that enhances forecast quality.

Current development of the service is focussed on site expansion, in order to provide forecasts to many more end users across Australia. Reaching these potential users has always been a challenge. In recent years, the Bureau has diversified its communication channels by organising regular briefings to key stakeholders (e.g. National and Climate Water Briefing) and by moving into social media, embracing Facebook, twitter, and YouTube, on top of its usual delivery channel - the standard Bureau web pages. This provides an avenue for water forecasts, in the context of climate information, to reach many more users in a clear way that is easily understandable, and that can ultimately enhance decision making.

This paper discusses evolution of the seasonal streamflow forecasting service in Australia, including some of the challenges faced, and examines how the many collaborative partnerships in areas of research, stakeholders and delivery, have enabled it to develop.

Keywords: *Seasonal water availability prediction, hydrological modelling, water forecasting, seasonal streamflow forecasting*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Using hydroclimatic forecasts to improve water resources management – how to determine what is important and useful?

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Abstract: Seasonal to interannual hydroclimatic forecasts have the potential to improve water resources management and enable more informed approaches to ensuring water security and resilience under the impacts of climate variability and change. However, two major challenges exist: (1) the development of skillful and reliable seasonal to interannual hydroclimatic forecasts that account for the impacts and non-stationarities associated with climate variability and change and (2) ensuring the hydroclimatic forecasts are practically useful for application in real world water system operation and hydrological disaster management. This study demonstrates, via a case study in the major water supply catchment for Newcastle, Australia, a novel method for objectively identifying the large-scale ocean-atmospheric drivers (e.g. El Niño/Southern Oscillation (ENSO)) of climate variability that are most influential for different locations and seasons. The method accounts for the inherent non-linear nature of the links between the large-scale ocean-atmospheric drivers and Australian hydroclimatic variability while also identifying when and where combinations of drivers are important. The predictive skill and reliability associated with each of the identified relationships is quantified and the utility of this information is tested using Grahamstown Reservoir, the main source of potable water for the Newcastle region. It is shown when skillful and reliable forecasts are available the Grahamstown Reservoir can be run in a more efficient manner and the chance of reaching critical storage levels or reservoir over flow is reduced. However, existing forecasts are only skillful and reliable in some seasons and some climate states. These findings are useful as they provide a set of metrics against which existing statistical and dynamical forecasting schemes can be tested. The results also give an indication of the existing and potential costs and benefits of using hydroclimatic forecasts in water resources management and the areas requiring further research (i.e. where and when do seasonal forecasts need improving and to what level? how can insights available from climate science be better implemented into practical challenges facing water resources managers?).

Keywords: *Water resource management, uncertainty, climate scenarios, flood, drought*

Evaluating a prototype ensemble water quantity and quality forecasting system for the Fitzroy River Basin

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Abstract: The eReefs initiative is developing a series of marine hydrodynamic and biogeochemical models that will model and provide forecasts of rainfall and flooding impacts on the Great Barrier Reef. These models require real-time predictions and forecasts of riverine inflows and associated concentrations of fine sediments, speciated nutrients and carbon at each time step. This paper describes and evaluates one possible approach to the generation of water quantity and quality predictions and forecasts by linking ensemble streamflow forecasts and empirical Generalised Additive Models (GAMs). Forecasts of daily sediment and nutrient concentrations are generated by forcing GAMs with hourly streamflow forecasts that have been aggregated to daily totals. The streamflow and water quality forecasts are evaluated for over a 24-month period concluding in December 2013. The ensemble streamflow forecasts have considerably lower errors than simple persistence, which is used as input for the prototype marine models in forecasting mode. This suggests that marine modellers can potentially improve their simulations by using the streamflow forecasts in place of simple persistence. The ensemble forecasts of nutrient concentrations however display large errors, often significantly overestimating the observed values, which may limit their value for marine modelling. Errors in sediment and nutrient concentration forecasts, and the forecast uncertainties tend to be largest when the GAMS are extrapolating beyond the range of observations used to fit the GAMS model. Therefore improvements in the performance of sediment and nutrient concentration forecasts are most likely to be realised by fitting the GAMS to a larger set of either modelled or observed data.

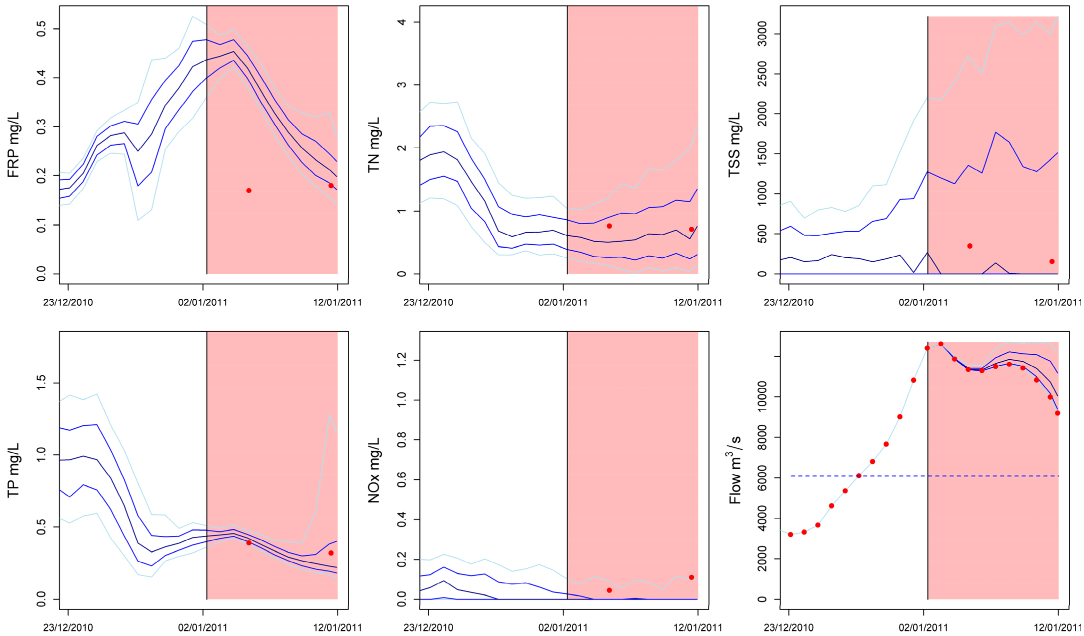

Figure 1. Forecasts of streamflow, sediment (TSS) and nutrient concentrations for Fitzroy River at The Gap issued at 2100 UTC on 02/01/2011, corresponding to a period of high streamflow flow. The 10 day forecast period is shaded, while the unshaded area are the predictions made using observed streamflows in the 10 days prior to issue of the forecast. The black line is the prediction/forecast median, mid blue lines and pale blue lines represent the [0.25,0.75] and [0.05,0.95] predictions/forecasts quantile ranges, respectively. Red points represent the observations. The dashed blue line on the flow plot is the maximum streamflow used in fitting the GAMs.

Keywords: *Short term flood forecasting, ensemble forecasting, general additive models, water quality*

SWIFT2: High performance software for short-medium term ensemble streamflow forecasting research and operations

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Abstract: The second version of the Short-term Water Information and Forecasting Tools (SWIFT2) is a suite of tools for flood and short-term streamflow forecasting, consisting of a collection of hydrologic model components and utilities. It is currently developed within the Water Information Research and Development Alliance, with a requirement to address both research and operational modelling needs. Catchments are modelled using a traditional approach for semi-distributed models: conceptual subareas and a node-link structure for channel routing. SWIFT2 comprises modules for calibration, model state updating, ensemble runs, output error correction and data assimilation. While applicable to simpler modelling tasks, SWIFT2 is designed from the ground up to tackle computationally intensive problems in probabilistic forecasting research, with sub-daily time steps over decades, and ensemble sizes in the thousands. Typical retrospective ensemble simulation outputs can reach hundreds of gigabytes, and projected runtimes can reach days if not parallelized. SWIFT2 simulations are safe for in-memory copy and parallel executions, can make effective use of multi-core personal computers or high-performance compute clusters to address computationally demanding research or operational requirements. SWIFT2 is written in modern C++ and is platform-agnostic. SWIFT2 is architected to offer several options for user interfaces. Driven by the needs of current users, it is seamlessly accessible from high-level interactive languages including R, Python and MATLAB (Figure 1). To achieve this, the SWIFT API (Application Programming Interface) offers a controlled yet fully fledged access to core modelling features and concepts. The time series handling is performed in a separate library for reuse outside of SWIFT2, using advanced C++ templates, similar to the Boost libraries. Users have access via concise commands in their interactive language of choice to high level modelling concepts, such as simulations, parameterizers, state initializers and objective calculators. SWIFT2 already offers sophisticated features for calibration such as composability of parameter sets, definition of meta-parameters and non-trivial hard constraints on parameter feasibility. This permits the formulation of modelling goals, e.g. calibration, for use in conjunction with state of the art third-party model analysis tools such as metaheuristics frameworks. While the robustness and correctness of SWIFT2 are the primary development goals, runtime performance and parallel scalability are important. Initial measures and usages already show amply adequate operation in calibration mode on multi-core computers, with a very good multi-threaded parallel scalability on larger catchment models. Known performance tuning strategies have been investigated and will further enhance the raw computational performance.

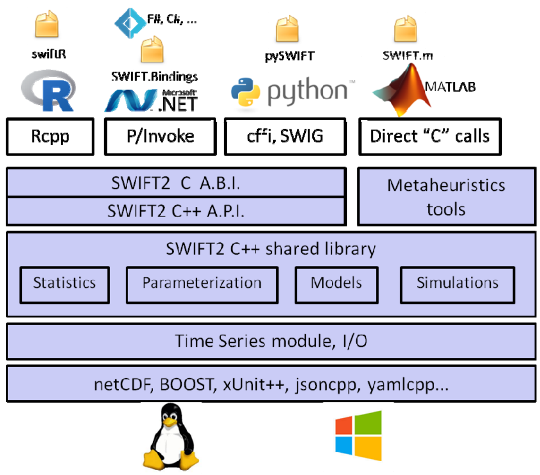

Figure 1. SWIFT software stack

Keywords: *Ensemble streamflow forecasting, high-performance computing, semi-distributed model*

An overview of Hydro Tasmania's dynamic real-time inflow prediction and flood forecasting system

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Abstract: Hydro Tasmania manages 30 hydro-electric power stations fed from 45 major lakes across Tasmania, 13,500GL of water is managed annually. Forecasts play an important role in optimising the operation of the system, assisting in minimising spill, ensuring lakes operate at economic levels and that flood and environmental risks are managed. These forecasts are generated by Hydro Tasmania's Dynamic Real-time Inflow Prediction (DRIP) system which produces 7 day forecasts for 61 locations across Tasmania, 21 of which are then used by lake level prediction models.

In 2014 Hydro Tasmania initiated a project to upgrade this system with the aim of improving forecasts and gaining a better understanding of the forecast uncertainty. The project involves: implementation of gridded rainfall forecasts, a GIS based model rebuild and auto calibration. For the forecast points, the system now provides an improved best estimate forecast and, based on analysis of the rainfall forecast uncertainty, a high and low forecast.

This paper discusses how these forecasts are used to inform operational decisions, gives an overview of the model development process, operational implementation, and reflects on the strengths and weaknesses of the system.

Keywords: *Decision support system, short term forecasting*

Post-processing of GCM rainfall and temperature forecasts for agriculture and water management

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Abstract: Australian agriculturalists and water managers require quality forecasts of seasonal rainfall, temperature and insolation for use as inputs to cropping models and hydrological models. Quality forecasts guide decision making and inform planning processes. For mainly pragmatic reasons, statistical models are most commonly used to generate seasonal climate forecasts for use in water and agriculture. However, most seasonal climate forecasting centres around the world, including in Australia, are now issuing forecasts from physics-based general circulation models (GCMs). However, GCM forecasts are generally biased, unreliable in ensemble spread, and still of low skill. Post-processing GCM forecasts to resolve the bias and reliability issues and boost forecast skill will aid the adoption of GCM forecasts for water and agriculture applications.

A calibration, bridging and merging (CBaM) method has been developed to statistically post-process seasonal climate forecasts from general circulation models (GCMs). The CBaM method is designed to extract as much skill as possible from the GCM and yield forecasts that are reliable in ensemble spread. Firstly, multiple forecasts are produced using different GCM output fields, such as rainfall, temperature and sea surface temperatures, as predictors. These forecasts are then merged based on evidence of skill in hindcasts. Calibration refers to direct post-processing of the target variable — rainfall for example. Bridging refers to indirect forecasting of the target variable — forecasting rainfall with the GCM's Nino3.4 forecast for example. Previously, CBaM has been found to improve overall skill and reliability of GCM rainfall forecasts in Australia.

In this study, CBaM is applied to post-process POAMA forecasts of seasonal minimum and maximum temperatures across Australia. POAMA is the Predictive Ocean-Atmosphere Model for Australia; a coupled ocean-atmosphere GCM operated by the Bureau of Meteorology. CBaM effectively corrects biases and produces temperature forecasts that are reliable in ensemble spread. Calibration and bridging have unique strengths. Calibration yields the most skilful forecasts of maximum temperature. Bridging yields the most skilful forecasts of minimum temperature. Merged forecasts yield the overall most skilful forecasts of minimum and maximum temperature. CBaM has previously only been applied to post-process climate variables individually. CBaM is also tested here for joint calibration of rainfall and temperature. CBaM produces post-processed GCM forecasts that are suitable for use in water and agriculture.

Keywords: *Seasonal, forecasting, temperature, water, post-processing, GCM, calibration, bridging, merging*

Improved water resources management using seasonal ensemble streamflow forecasts: factors affecting performance in reservoir operations

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Abstract: Water storage reservoirs benefit society in a variety of ways, including ensuring sustainable water supply, producing clean electricity, providing amenity and protecting downstream communities against damaging floods. Irrespective of the function, the value of the reservoir depends on how well it is operated. Water managers must decide how much water to release, and when to release it, in order to maximise the net benefits of the reservoir through its design life. A major problem that operators face is uncertainty pertaining to future reservoir inflows, and any information that can reduce that uncertainty is potentially valuable. Various case studies have shown that probabilistic seasonal forecasts of streamflow can improve simulated reservoir operating performance. Yet we find no generalised study that shows how the potential value of applying probabilistic seasonal forecasts varies as a function of reservoir specifications and objectives. We suspect this information would be of interest to meteorological agencies seeking to encourage water management authorities to acquire and apply their forecast products. A general theory of where forecasts add most value would also serve the broader scientific community and could help water managers decide whether to invest in new models for incorporating forecasts into their operations.

This study seeks to develop relationships between reservoir characteristics and forecast value as measured by quantifiable improvements in operating performance. We begin with a set of 30-year, monthly reservoir inflow records and corresponding 1000-member ensemble inflow hindcasts for five catchments distributed across Australia. The hindcasts are produced using the Forecast Guided Stochastic Scenarios (FoGSS) model, which generates forecasts of monthly inflow totals out to 12 months. As forecast skill decreases with lead time, the forecasts regress to stochastic realisations of the inflow process. For each inflow record we devise a range of hypothetical reservoirs, which vary in the following specifications: storage (defined by the storage ratio, or ratio of storage to mean inflow); demand (defined by the draft ratio, or ratio of required yield to mean inflow); operating objective (water supply / hydropower generation / amenity); and objective function (e.g., loss exponent applied to delivery shortages in water supply operation). We then optimize the online operating policy for each reservoir using Sampling Stochastic Dynamic Programming. The operating performance gains made available by the skilled forecasts are found by simulating the optimized policies through the observed inflow record and then benchmarking against two alternatives: online operation with climatology forecasts and offline operation using the characteristics of the recorded flow data. We also compare results with the upper-bound optimal operation, found by assuming known future flows and using deterministic dynamic programming. The study demonstrates the importance of reservoir characteristics in controlling the added-value of applying seasonal forecasts in operation.

Keywords: *Reservoir operation, stochastic optimization, streamflow forecasting, dynamic programming*

Model development for prediction of alum dosing for treatment of domestic wastewater for recycling purposes

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Abstract: Removal of algae present in domestic wastewaters of stabilization ponds can be a significant challenge in the supply of recycle water for re-use purposes. Algae can be present in high numbers, especially in warm to hot summer and autumn months diminishing water quality when most needed for reuse purposes. Consequently further treatment of wastewaters may be needed for removal of turbidity and algae, prior to recycled water supply. A large recycle water treatment plant in South Australia – the Bolivar DAFF plant utilizes alum as primary coagulant for algal and suspended solids removal. Alum dosing varies significantly throughout the year, depending on source water (from stabilization ponds) quality. Algae can be present at bloom levels (>10^6 cells per mL) and the water can be at very high pH (~ 10); and with high alkalinity, very high doses of alum may then be required. With this high variation in source water quality, adjustment of coagulant dosing is continually needed to be performed by operators, at times diurnally. This is done on the basis of meeting target treated water quality (of low turbidity) and minimizing costs of chemical use. Coagulant use at the plant has been highly variable, and with consideration that dosing at times, may not be at optimum. As part of continual process improvement, research was instigated to determine if model development could be achieved for prediction of coagulant dose requirements.

Data available was sourced from documented treatment plant operations over a number of years where wastewater quality varied seasonally, and from laboratory investigations incorporating jar tests and water quality analyses. These water quality parameters included untreated water algae, pH, turbidity, ambient temperature and treatment plant daily processing volumes.

The model developed is based on apparent relationships between each of the source water qualities with alum dose rates applied at the treatment plant. Data was highly scattered for most parameters and model development was in context that error was potentially in operational dose application, as well as in model fitting i.e. that actual dosing data was not presumed to be 'true' or optima, and general trend equations might best reflect the optima. From general trend relationships and fitted algorithms of each, a model was built where the outputs of each sub-model is averaged to provide a fitted or predicted value. Model options include selection of input variables (e.g. pH, turbidity, algal number) and weighting of importance to each parameter. Treatment plant operators have accepted the model as an additional tool for decision making. In this paper the need for and the design of the model are discussed.

Keywords: *Algae, modeling, Dissolved Air Flotation (DAFF), recycle water*

Modelling THM formation potential based on the character of organics – in catchments and drinking water sources

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Abstract: Problems caused by dissolved organic matter (DOM) present in drinking water include its constituent compounds being precursors in the formation of disinfection by-products that pose risks to human health. The prediction of trihalomethanes (THM) formation is highly challenging due to a wide range of impacting factors, including the concentration and character of DOM, pH, temperature and the presence of halide anions (Cl^-, Br^-) in drinking water. The aim of the research reported here was to develop model(s) for prediction of THM formation potential (THMFP) including the four compounds, chloroform, bromodichloromethane, chlorodibromomethane and bromoform, based on the character of precursor organics sourced from discrete catchments of a drinking water reservoir.

Water samples were collected from six discrete zero-order catchments (ZOCs) of the Myponga reservoir-catchment, South Australia under three land management practices (Australian native vegetation, pine plantation, grasslands) with varying soil textures. Water samples were also collected from the main stream (Myponga River) and the Myponga Reservoir. Water samples from the ZOCs were collected at both the surface and subsurface (~60 cm depth) and were treated by alum coagulation under laboratory conditions to simulate conventional treatment for removal of organic compounds. Samples were analyzed for dissolved organic carbon (DOC) and UV-visible absorbance to measure and characterize the DOM. Raw and alum treated waters were then tested for THMFP under standardized laboratory conditions.

Mathematical models were developed to predict THMFP and abundances of constituent compounds from the DOM concentration and character, and bromide (Br) ion concentration (to ~0.5 mg/L), based on regression analysis. A linear model ($R^2 = 0.97$, T-test = 0.92 and standard error: SE = 32.9 µg/L) was developed to describe the relationship between THMFP and the character of DOM in terms of aromatic and non-aromatic compounds. Similarly, a linear model ($R^2 = 0.95$, T-test = 0.89 and SE = 33.9 µg/L) was fitted to describe the relationship between chloroform ($CHCl_3$) concentration and DOM character. For modelling of the formation of constituent THM compounds, the percentage formation (%) of $CHCl_3$ was predicted by using the same independent variables (DOC, UV absorbance at 254 nm (UV_{254}) and Br), ($R^2 = 0.85$, T-test = 0.99 and SE = 8.8%). Using the relative abundance of chloroform to THMFP, the percentages of bromodichloromethane and chlorodibromomethane were estimated using a power function equation ($R^2 = 0.99$) for bromodichloromethane and an exponential function equation ($R^2 = 0.98$) for chlorodibromomethane. From previous models, the concentration of each individual THM compound can be estimated. From this study, it was found that data of the character of DOM and Br present in waters of catchments with discrete land use can be related to THMFP and abundances of constituent compounds.

Keywords: *Catchment runoff, sub-surface flow, trihalomethane formation potential (THMFP), organic character*

A model for prediction of overtopping at berm breakwaters

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Abstract: Reliable prediction of wave overtopping rate is a key task in the design and safety assessment of coastal structures. The overtopping rates must be lower than the allowable rate both in normal operating and extreme conditions to guarantee the safety of both people and assets on and behind the breakwaters. The sea level rise caused by climate change and its effects on wave climate enhance the overtopping rate and make the existing coastal structures more vulnerable to the overtopping.

In the past decades, several approaches have been developed for prediction of overtopping rate in different structures, including empirical formulae, numerical models, and soft-computing methods. The most commonly used models are empirical ones. Typically, these models are developed by fitting dimensionless parameters to experimental data obtained from physical model tests. The most popular empirical formulae proposed for berm breakwaters are the formulae of Van der Meer and Janssen (1995) and EurOtop (Pullen et al. 2007). However, the applicability of these formulae is limited to specific structures and wave conditions for which the models were developed. Hence, a more comprehensive dataset which includes multiple tests with different structural and hydraulic conditions would enhance the robustness and reliability of the developed models.

As a part of the European CLASH project framework, two different ANN models for various types of coastal structures are developed. These models can also be used for the prediction of wave overtopping rate at rubble mound breakwaters with berms. However, using ANN models may not always be desirable, because, they have complicated structures and are not as transparent and understandable as empirical models. On the other hand, practical applications of these models need engineers to have some data mining knowledge which is not always the case.

In this study, a new formula for the prediction of wave overtopping rate at non-reshaping berm breakwaters is presented. In order to derive the new formula, extracted experimental data from the CLASH database is implemented and the effects of the most important governing parameters are considered. Several models were developed using various dimensionless parameters that seemed to be influential and the model which outperformed the other ones was selected. The final model considers the effects of dimensionless crest freeboard, dimensionless crest width and average angle of the structure slopes. The new formula's performance is then compared with those of previous empirical ones for prediction of overtopping rate. Statistical indicators such as Root Mean Square Error, *RMSE* show that the new formula outperforms the previous empirical ones.

Keywords: *Non-reshaping berm breakwater, wave overtopping, CLASH database*

Assessment of water quality in Hawkesbury-Nepean River in Sydney using water quality index and multivariate analysis

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Abstract: This study has assessed the water quality status of the Hawkesbury-Nepean River (HNR) in Sydney, Australia. It is based on the collected data of 12 water quality parameters at four monitoring stations along the river. HNR is one of the most important rivers in Australia which supplies over 90% of Sydney's potable water for more than 4.8 million people. Canadian Water Quality Index (CWQI) is adopted in this study to summarise the water quality status at the individual stations by categorising the water quality in five divisions; poor, marginal, fair, good and excellent. In addition, water quality parameters are regressed with the calculated CWQI to identify the significant parameters. Based on the calculated CWQI, only one station is found to fall in 'fair' category, two in 'marginal' and one in 'poor' water quality categories. No significant trend is observed in the CWQI for the stations during the period of data collection; however, one station shows slight trend of decreasing water quality. The preliminary results of the regression analysis demonstrate that not all the water quality parameters are significant in explaining the CWQI at the stations. The results of this study are expected to provide useful information for water quality management, and to form the basis for further investigation.

Keywords: *Multiple linear regression, Hawkesbury-Nepean River, water quality index, Australia*

Modelling of Chloramine in water distribution networks – Challenges and limitations

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Abstract: Chloramine is the second most popular secondary disinfectant used in the world. Unlike chlorine, which is traditionally used for disinfection of water, chloramines produces less harmful byproducts and persists in the water supply system for longer periods. This is a major advantage in preserving the high microbiological quality of water supplies that travel over long distances. Apart from the hydraulic challenges in the distribution network (flow, pressure and leaks), a primary concern of utility managers is to prevent microbial contamination of water in long distribution networks. This is because the network itself provides a habitat for microorganisms, which are sustained by organic and inorganic nutrients present on the pipes and in the conveyed water. Modelling of chloramine in water distribution networks is useful for utility managers to understand the water quality in the system with various operational and environmental conditions.

The purpose of this study is to identify necessary data for a comprehensive modelling of chloramine in the distribution network and to identify the weightage of each factor for the accuracy of the model. The required data may include water quality data (such as total chlorine, ammonia, nitrite, and temperature), distribution network data (such as pipe material, pipe size, valves, loops and bypass), operational and maintenance data (such as flow rates, service connections, pipe flushing and use of corrosion inhibitors) and reservoir data (such as reservoir levels, reservoir volume and tablet dosing). Available chloramine decay models will be analysed using Sydney Water (selected portion) data to quantify the impact of each data on the model accuracy. The results of this study will identify the key data to be incorporate within chloramine modelling to get reasonable outcome.

Keywords: *Water distribution, drinking water disinfection, chloramine, chloramine modelling*

The value of stochastic modelling for the characterisation of maturation pond performance and health risk assessment of effluent reuse options

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Abstract: Treated wastewater from Waste Stabilisation Ponds (WSPs) is a potential resource, especially in regional and remote areas facing water shortages. As the ultimate goal of reusing treated wastewater is ensuring that it is fit-for-purpose, the comprehensive assessment, management and communication of potential health risks are a necessity. Although not mandated by policy in Australia, Quantitative Microbial Risk Assessment (QMRA) is recommended in the Australian Guidelines for Water Recycling (AGWR) as a methodology for estimating the potential levels of health risk associated with exposures to microbial pathogens. With the rapid uptake of QMRA modelling in the water sector in Australia, it is necessary to explore the sensitivity of QMRA models to underlying assumptions.

This stochastic modelling study investigated the impacts of uncertainty in key input parameters underpinning QMRA and evaluated the sensitivity of a QMRA model to a range of underlying assumptions. This was conducted using the @Risk software program within the Palisade Decision Suite and operational monitoring data from a pond-based, Waste Water Treatment Plant (WWTP) in regional New South Wales, Australia.

This study was conducted in two phases. The first addressed two research questions regarding: 1: The impact of assumed sampling regimes (weekly, fortnightly or monthly), and 2: The impact of seasonal variability in characterising pond performance as measured by Log Reduction Values (LRVs). The fortnightly and monthly datasets were compiled from the weekly monitoring data collected from both the inlet and outlet of the 3 maturation-pond system within the overall treatment system. The weekly data were also stratified by season for investigation of potential seasonal patterns. The distributions of these LRVs were generated through Monte Carlo simulations and impacts of temporal variation investigated statistically. The second phase focused on estimating potential health risks associated with the hypothetical scenario of irrigating lettuce with pond effluent using QMRA. The results from the first phase were used as input data in the QMRA stochastic modelling. The QMRA incorporated the four steps: hazard identification, dose-response, exposure assessment and risk characterisation. Monte Carlo simulation was used to generate a probabilistic distribution of health risk estimates, and the built-in sensitivity analysis functions in @Risk were used to rank the input parameters by their effect on the estimated risk levels.

The results from the first phase revealed no significant difference between how weekly, fortnightly or monthly datasets characterised the microbial water quality from the maturation pond system in terms of LRVs. This suggests that the frequency of monitoring at the WWTP could be reduced without compromising the information value of the dataset. This would, in turn, reduce expenses. Seasonality, however, does appear to have a significant impact on pond performance as measured by LRVs. A pair-wise comparison of the weekly data by season revealed statistically significant differences between all seasons, except for winter and autumn. Summer provided the best performance and spring provided the worst. The results from the health risk assessment (second phase) suggested the microbial quality of the pond effluent would not be suitable for the proposed reuse scenario of irrigating lettuce eaten raw; however alternative, less risky reuse scenarios would be within the scope of the state guidelines. This phase of the research also opened up a broader range of issues such as how guidelines are interpreted and how different modelling approaches (*e.g.,* deterministic versus stochastic) can yield disparate results. The stochastic methods provide more conservative estimates and therefore engender greater assurance in both regulators and the community that safety standards are being met. Overall, this research highlights that stochastic modelling is a powerful tool for risk communication and risk management for the water industry, the community and regulators.

Keywords: *Stochastic modelling, pond effluent reuse, pathogen log reduction values, quantitative microbial risk assessment*

Improving hydrodynamic performance of waste stabilisation ponds using three-dimensional numerical models

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Abstract: Waste stabilisation ponds (WSPs) are widely used for wastewater treatment throughout the world. They are shallow constructed basins, typically located at the end of a treatment plant, that use natural microbiological, photosynthetic, biochemical, physico-chemical and hydrodynamic processes to generate a reduction of organic matters and pathogenic organisms in wastewater (Watters et al., 1973). They require little technical attention during operation, and are less demanding in terms of construction cost and energy consumption than other engineered wastewater treatment systems.

Practical experience and research over the past few decades have established that hydrodynamics is one of the crucial factors determining WSP's overall treatment performance. The Department of Environment and Planning (1992) in the state of Tasmania surveyed 39 wastewater treatment systems and reported that 74% of the pond systems failed to achieve the discharge requirements, and it is due to the hydraulic problems including short-circuiting, stratification in hot Australian climates, and stagnant fluid in dead zones. Therefore, it is of primary importance that WSP's hydrodynamic performance be improved before WSP treatment efficiency can be guaranteed.

A substantial number of numerical modelling studies have been undertaken to look into WSP hydrodynamics, both two-dimensionally and three-dimensionally. It is the ultimate goal of this study to use numerical modelling techniques to investigate measures to improve WSP hydrodynamic performance, consequently to propose retrofitting design. A validated three-dimensional numerical model using MIKE 3 by DHI (Danish Hydraulic Institute) was developed to study a typical pond with a dimension of 50 m (length) by 20 m (width) by 1.5 m (depth). The retrofitting scheme was proposed by placing baffles in the pond with different geometric ratios: the ratio of baffle length L_b to the width of the pond W: L_b/W, and the ratio of baffle spacing Δ_b to the length of the pond L: Δ_b/L. For generalised design guidance, baffles positively contribute to the hydraulic efficiency for ponds with a relatively small L/W ratio. Placing 8 baffles in a pond with $L/W = 1.6$ results in a λ (hydraulic efficiency) = 0.83 as oppose to $\lambda = 0.23$ if the pond is not baffled. However, ponds do not benefit from retrofitting baffles if their L/W ratios are large.

Ultimately, this study is to provide regulators, decision makers, water managers and operators with information and tools to best operate and manage WSPs, to protect public and environmental health and optimise uses of the treated water.

Keywords: *Waste stabilisation ponds, three-dimensional, hydraulic efficiency, retrofitting baffles*

Simulating nitrogen long-term fate and transport processes at a regional scale with a surface and subsurface fully-coupled watershed model

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Abstract: Examining the watershed-inherent nitrogen loads and their reaction kinetics is important to understand past, present and future perspectives of water pollution. This study describes a recently developed watershed modeling tool for simulating fate and transport of nitrogen coupled with biogeochemical reaction kinetics. The tool was integrated into the distributed physics-based, surface and subsurface fully-coupled fluids flow code GETFLOWS (Tosaka et al., 2000). It allows to consider an arbitral number of multiple chemical species (i.e. ammonium nitrogen, nitrate nitrogen, etc.) and their interactions of reaction kinetics caused by microbial activities. Point and non-point source nitrogen loads can be traced to estimate the exchange of contaminated water in surface and subsurface via the land-surface interaction.

The developed tool considers the following major processes which are often required for an integrated watershed modeling:

- Meteorological forcing (rainfall, snowfall, air temperature, etc.)
- Evapotranspiraton
- Snowmelt
- Rainfall interception by vegetation covers
- Surface and subsurface fully-coupled water flow
- Air and water two phase, compressible fluid flow in geological porous media
- Reactive solute transport (advection, turbulence diffusion and hydrodynamic dispersion)
- Multiple biogeochemical reactions
- Point and non-point contaminant loads
- Sorption and desorption (generalized mass transfer processes between different phases)

The governing equations of these multiple processes are developed and then discretized by using an integral finite difference method in spatially and a fully implicit method in temporally. The developed tool was applied to the actual field named Lake Kasumigaura basin in Japan. The long-term observations over the past several decades showed that the nitrogen concentration had been gently increasing in the most of inflowing rivers. This tendency is supposed to be maintained by the inflowing contaminated groundwater from river and lake floors. To examine this (i.e., possible source and pathways of nitrogen contamination), we aim to analyze reactive nitrogen dynamics discharged within the entire region of watershed and to assess the impact of nitrogen load on the lake Kasumigaura through the inflowing river water and groundwater.

Simulation of nitrogen concentrations in tributary rivers of the lake Kasumigaura and in the subsurface water matched closely well with the multiple measured data (e.g., water discharge of rivers, groundwater level and nitrogen concentration). The computed nitrogen discharge from subsurface water to the rivers and the reservoir are reasonably examined, and it is clearly showed that nitrogen concentration in the most of rivers and lake water are maintained by nitrogen discharge from subsurface for long period.

This study presents the brief overview of the governing equations, the solution procedure and the practicable usage of the developed tool for contributing to a sustainable water resources management. The results obtained on the Lake Kasumigaura basin indicate that the developed tool is effective to simulate long-term nitrogen behavior for surface and subsurface coupled watershed environment.

Keywords: *Watershed modeling, water quality, nitrification, denitrification, GETFLOWS*

An exploratory water quality analysis of the Hawkesbury-Nepean River catchment

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Abstract: Water is a vital resource for the survival of all living organisms. This important resource should be protected by ensuring that *anthropogenic* activities do not impact adversely the sustainability of water resources. Therefore, monitoring and assessment of rivers is required to inform planning regulations in order to safeguard community and stakeholders' requirements in terms of water quality. Due to the high rate of population growth, development, increased agricultural use of land and industrialization, water quality in urban and peri-urban rivers has deteriorated over the last three decades.

This paper explores the water quality of the Hawkesbury-Nepean River (HNR) in New South Wales (NSW), Australia. The relevance of this lies in the fact that there have been audits in Australia that have found dramatic deterioration in some rivers' health due to its surrounding land-use activities. In the past, there have also been incidents in the Sydney region where the water quality deteriorated to a critical state triggering public dissatisfaction and subsequent changes in water management authorities.

This paper examines water quality at four different monitoring stations along the HNR using about sixteen years of data (2000 to 2015). This covers six water quality parameters, which are algae, E. coli, total nitrogen, total phosphorus, conductivity and turbidity. The results indicate that stations which are located near the urban areas have higher pollution levels; however, further study is needed to confirm this initial finding.

Keywords: *Hawkesbury-Nepean River, water quality, land use, pollutant, urban runoff*

Modelling the Impacts of Rainwater Tanks on Sanitary Sewer Overflows

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Abstract: Recent studies have demonstrated that the Water Sensitive Urban Design (WSUD) strategies are sustainable, innovative and cost-effective approaches for managing stormwater runoff in urban developments. Such runoff from excessive rainfall can cause sewer system overflows. It is well established that intense rainfall increases flow into the sewer system and this increased flow is called rainfall-derived infiltration and inflow (RDII). RDII is the increased portion of sewer flows which enter the sewer network as inflow due to flooding of yard gully taps, roof downpipes illegally connected to the sanitary sewers, broken manhole covers and cross-connections between stormwater and sewer pipes. These excessive flows can also enter the sewer network as infiltration, where stormwater runoff filters through the soil and then enters the sewer pipes via damaged pipes, leaky joints and defective manhole walls. Intense rainfall events (especially of short duration) are becoming more frequent and intense in recent years. Increasing intensity will lead to more RDII. This in turn will lead to more frequent occurrences of sanitary sewer overflows (SSOs).

According to various studies, there are different types of WSUD approaches available, which include rainwater tanks, rain gardens, bio-retention cells, infiltration trenches, porous pavements and vegetative swales. These WSUD approaches can reduce sewer overflows by managing excess stormwater runoff that enters the sewer network during intense storm events. However, few studies have analyzed the role of WSUD approaches on reducing sewer overflows. Therefore, rainwater tank as one of the popular WSUD approaches has been used for this study. This paper presents a detailed hydraulic modelling with rainwater tanks to quantify the impacts of WSUD approaches for SSO reduction. Rainwater tank captures roof runoff which reduces surface stormwater runoff during a storm event. Thus, it reduces the amount of RDII into the sewer networks.

In this study, four different rainwater tank capacities are considered: 500L, 1000L, 1200L and 1500L. In addition, the impact of drain time on the sewer overflow volumes and peak overflow rates is also investigated. Drain time (*T*) is the time required to drain out the depth of the stored water in the rainwater tank. A residential area in Glenroy, Melbourne, has been taken as the case study to illustrate the rainwater tank modelling results. The analysis indicates that rainwater tanks can reduce SSO volumes by a maximum of 31% and can reduce peak overflow rates by 30% (for the 1500L tank with a drain time of 36 hours). This study has also evaluated the cost efficiency of the rainwater tanks based only on the capital cost of rainwater tanks. Thus, the approach used in this study will help water professionals to consider rainwater tanks as a mitigation strategy for controlling SSOs.

Keywords: *SSO reduction, RDII, water sensitive urban design (WSUD), rainwater tank*

Water quality issues and challenges in mixing recycled water with stormwater

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Abstract: Fresh water is a finite natural resource. Prolonged drought, record low inflows, population increase and climate change have increased the pressure on water authorities and conventional water supply systems. Additional measures such as demand management and the use of alternative water resources (e.g. recycled water and stormwater) have been considered by water authorities to ease pressure on the conventional water supply systems. Projects utilising both recycled water and treated stormwater in an integrated system have the potential to increase the security of supply and to improve water efficiency by using water supplies and water storages more effectively. This study aims to investigate the water quality issues and challenges of a novel approach of using combined recycled water and stormwater where treated stormwater is injected into the 'third' pipe, which carries recycled water. In this new approach, the mixing of two types of water takes place inside the recycled water pipe, compared to the current approach of using combined recycled water and stormwater treated/mixed at the source and delivered through the third pipe.

The issues and challenges of two major exercises for establishment of water quality of the combination of recycled water and stormwater are considered in this paper. The first is to develop a guideline to define the water quality of the combination of recycled water and stormwater in the use of "third" pipe. The "third" pipe is becoming a standard practice in new developments to supply water for non-potable use. Secondly, the appropriateness of the mass balance approach to determine mixed water quality is investigated.

The two existing projects in Australia which use mixed recycled water and stormwater (i.e. the Mawsons Lake project in Adelaide and the Sydney Olympic Park project in Sydney) have established their own license agreements to manage water quality. However, the proposed project aims to establish a general guideline for the use of combined recycled water and stormwater for future projects. Three existing guidelines, namely the EPA Victoria guideline, the Australian guidelines for Water Recycling Phase 1 & Phase 2, and the Australian and New Zealand Guidelines for Fresh and Marine Water Quality were used to develop the proposed guideline. The quality of stormwater varies greatly and there are many obstacles in the use of stormwater to control risks of human health and environment. The proposed guideline sets the target quality of the mixed water from which the treatment measures required for raw stormwater and recycled water could be formulated. The selected set of parameters included in the guideline are made by reviewing the available literature to understand what parameters cause issues in the use of both types of water such as corrosion, colour, and odour that the end user may be subjected to.

Mass balance analysis is proposed to quantify the upper limits of the selected set of parameters. However, this theoretical approach needs to be validated by practical methods as the mix of two types of water may lead to produce different substances such as gases due to possible chemical reactions of two types of water. Testing of raw stormwater and recycled water before mixing and testing the mix of two types of water for pre-determined mix proportions is made to demonstrate the concentrations of the selected set of parameters in the proposed guideline. Using raw stormwater and recycled water quality results by laboratory experiments, mass balance analysis is carried out to calculate the concentrations of the selected set of parameters in the water mix. By comparison of the results of concentrations of the selected set of parameters in the mix, it is seen that the concentrations of the parameters in the water mix obtained by laboratory testing and the calculated concentrations of the same by mass balance analysis are similar to acceptable levels except for few parameters.

This paper presents the results of the investigations conducted on the above discussed issues and challenges.

Keywords: *Recycled water, stormwater, mixed water quality, mass balance equation*

Investigating environmental watering options using Source IMS: a case study – the River Murray, Australia

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Abstract: The integrated modelling tool Source IMS developed by eWater and its partner organisations provides a common modelling platform to investigate the increasingly complex nature of water resources management in Australia. This paper describes how a recently built model of the River Murray using Source IMS has incorporated the management, delivery and accounting of water recovered for the environment to achieve required hydrological behavior. The River Murray model in Source IMS is fundamentally different from previous models of the River Murray in that it is run completely on a daily timestep, and has the capacity to run both as a planning model for policy development, and also as a daily operational tool used by River Operators to manage the competing demands for water in this complex system.

In the last few decades, there has been significant reform of water resources management in the MDB to address declining environmental condition within the Basin, including an increased focus on delivering water to environmental sites along the river system to achieve specific environmental outcomes. This paper shows how the Source model has been developed to investigate various environmental watering options in river systems planning. One of the major projects to recover water for the environment is The Living Murray (TLM), a joint partnership between the States of the River Murray to recover an average annual volume of 500 GL, to be used to deliver environmental outcomes at nominated icon sites along the river (MDBA, 2011). Icon sites were chosen for the high environmental and ecological values. Specified ecological objectives at each site dictate water requirements: the timing, frequency and magnitude of environmental diversions to the site. Two of the TLM icon sites the Koondrook-Perricoota forest and Hattah Lakes have been presented in this paper.

The ordering of water to the icon sites is accomplished through a Source Plugin; a dynamic-link library exposing purpose-built functionality to the Source River Murray project. This plugin triggers environmental watering events at the icon sites based on need and the volume of water available to the TLM.

The Resources Assessment functionality in Source undertakes allocation of water to TLM held entitlements over the simulation period. Due to the entitlements being held in a number of different allocation systems, triggers have been developed in Source IMS that transfer the TLM's available water from the State allocation systems to a TLM system to determine the total available water to the TLM. Individual use at each icon site is tracked across the model simulation, and the total use of TLM water is then accounted for in the State allocation systems based on an assumed priority of use.

During a simulation, the model records watering events at each icon site, either by overbank flow or TLM intervention. Once the elapsed time since the last flood exceeds the optimal inter-flood period, the model identifies a watering need at the icon site. During subsequent months, the model attempts to operate the works opportunistically, without placing an order but using flow that is not necessary to meet downstream demands. If the site was able to operate opportunistically for the first month, then it places a demand for subsequent months to complete the intervention. This type of intervention is termed an opportunistic watering. If a site's dry spell passes the resilience inter-flood period without starting opportunistically, then it registers a demand and initiates a forced watering. When watering needs exist at multiple sites, they are ranked according to need by a rostering algorithm.

The paper demonstrates how Source IMS has been able to model the complexity surrounding environmental watering in the River Murray. Further confirmation of the model's ability to represent the hydrological states of the TLM sites should make the model a useful tool when undertaking future work in environmental water planning and delivery on the River Murray.

Keywords: *Environmental flow, water sharing, river operation, Source IMS, Murray-Darling Basin*

Companion Modelling for resilient water management: Stakeholders' perceptions of water dynamics and collective learning at catchment scale

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Abstract: The Mekong river region is facing rapid changes in land and water uses which involve unevenly distributed costs and benefits among various stakeholders, and raise the issue of the resilience of ecosystems and livelihoods in the Mekong river basin. In this region, the production of knowledge on water resource dynamics is mainly based on scientific hydraulic models which struggle to integrate ecological and social impacts of water dynamics at a river basin scale. Our work aims at taking into account a diversity of viewpoints and knowledge sources on water dynamics and their impacts, in order to promote dialogue among stakeholders. In this paper we propose a conceptual framework and a methodology to promote resilient water management, and present the first results of our work in the Nam Theun – Nam Kading (NT-NKD) River Basin, a Mekong river sub-basin located in Lao People's Democratic Republic.

Key basin stakeholders from the public and private sectors at multiple levels were brought together, including those from the hydropower industry, research and administration, as well as local government and villagers, into discussion arenas initiated through a participatory modelling process, called Companion Modelling (ComMod). In ComMod, participatory role-playing games (RPGs) associated with agent-based models (ABMs) are used within an iterative and evolving participatory process where stakeholders are involved in the co-construction of the common representation of the issue context and the co-design of the corresponding simulation tools. In the NT-NKD basin, the most pressing issue identified by stakeholders, and subsequently modelled, was river flood risk. The ComMod approach was implemented primarily through interactive field workshops. During these workshops, stakeholders were asked to co-design and use together a sub-basin model in the form of a RPG for land and water uses management, which includes up- and downstream interests and needs, multiple uses/managements and scales. Based on the same model as the RPG, an ABM was also developed, which made it possible to simulate longer periods, while allowing participants to understand its structure and simulation outcomes. The model is multi-scale, so that each participant considered management not only for his or her local interests but also at the whole catchment level and could link his or her activities, roles and responsibilities with the catchment context, as well as with other stakeholders. By actively playing roles in the participatory workshops, stakeholders could identify knowledge gaps and knowledge needs from other management levels, such as the farmers' level. This improved their understanding of flooding and enhanced their awareness of cross-scale interactions and of the need to collect multiple knowledge sources to approach such complex processes. Overall, the stakeholders had been receptive and were appreciative of ComMod and its modelling tools, because it afforded them the opportunity to engage in discussions of important issues regarding the catchment. This attitude contributes to a conducive environment for long term ComMod initiatives and other participatory processes.

At the end of this first ComMod cycle, the stakeholders requested to further integrate knowledge from many groups of stakeholders to feed the flood risk model. Integrating knowledge from diverse stakeholders first requires understanding of their worldviews about the river basin. The next ComMod cycle will therefore aim at collecting and confronting scientists', farmers' and decision-makers' views in order to highlight the diversity of perception levels and purposes assigned to the environment, allowing them to collectively analyse trade-offs between water and land uses, knowledge gaps, and potentially emerging collective purpose, and thus support discussion on river basin resilience and decision-making.

Keywords: *Resilience, vulnerability, companion modelling, role-playing games, agent-based modelling*

Building capacity in basin planning in South Asia – an Australian government investment in regional sustainable development

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Abstract: The Australian government, through its Sustainable Development Investment Portfolio (SDIP), has a goal of strengthening trans-boundary cooperation in South Asia in order to promote more inclusive, accelerated and resilient economic growth while improving livelihoods, especially of the disadvantaged. Water resource management has been identified as a key domain of change. CSIRO is engaged in three basin planning projects within the SDIP. The basins – the Koshi which spans Nepal, India and China; the Brahmani-Baitarni which spans three states in eastern India, and the Indus which spans Pakistan, India, Afghanistan and China – have very different water resource planning challenges – including lack of good quality data, poor quantification of water supply and demand, and complex water governance arrangements. Underpinning the water resource management objectives is the implementation of basin planning principles, with a fit-for-purpose approach in each of the three project areas. We have contributed Australian expertise (and water reform experience) as appropriate to inform the water management journey in each country. Central to each however has been the construction of a river system model to provide the underlaying repeatable evidence based on which to support future water policy decisions. This has involved substantial capacity building exercises with relevant ministries, stakeholders and agency collaborators in each country. Instilling good modelling practice has been a paramount consideration, requiring significant investment in building understanding of the social and planning contexts within each country, and improvement in our own practices. Within the Koshi project, the focus has been on working with ICIMOD (a SDIP partner) to evaluate the range of possible water-related development pathways that may lead to inclusive poverty reduction. Activities have included the development of an eWater Source river system model for parts of the Koshi, development of improved climate surfaces, and emerging complementary projects analyzing livelihood impacts, and linking ecological indicators (e.g. dolphins, riparian vegetation) to changes in river flow. Impact and return on investment will be measured by our ability to carry the work through to policy. The Brahmani-Baitarni project has focused on capacity building with central and regional water managers. Model prototypes have been built to serve as training and outreach material with sufficient capacity built over the past 18 months for our in-country colleagues to have commenced their own modelling journey. They are presently building their Baitarni model (using eWater Source as the platform), and working through how to build their knowledge base, how to deal with lack of detail (both spatially and temporally), and how to work together. They have recently been involved in a successful future scenarios workshop, which is assisting them shape their conceptualization of their system. The key challenge thus far in India has been in demonstrating how tools and methodologies developed in Australia can be applied in an Indian context. While the Indus project has also focused on capacity building, it has had a strong technical agenda and is assisting central and regional agencies in building their operational river system model of major reaches of the Indus. The project is focusing on modelling and linking understanding from field to basin as Pakistan has a strong dependency on the Indus river for food, energy, economic and environment security. Having a model of the river system that is agreed and trusted is seen to be a great asset for underpinning regional and trans-boundary dialogues. In the three projects, the key lesson for transferring Australian modelling expertise and experience into another country is that constant and honest engagement is needed to build and maintain capacity, build and harness momentum, and realise the Australian government's investment in better water management as a key livelihoods requirement.

Keywords: *Basin planning, basin planning models, river system models, livelihoods assessment, capacity building*

Hydrological modelling for water availability assessment in the Brahmani and Baitarni Basin, India

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Abstract: Water resources assessment is of great importance in basin planning. Owing to lack of ground observations, the available water in Brahmani and Baitami Basin is still not clear to the local management agencies, therefore makes it difficult to develop an integrative basin planning, which involves energy supply, food production, urbanization and environmental protection.

In this research, we aim to provide the long-term time series of daily streamflow using rainfall-runoff model for further water resources assessment and basin planning in the Brahmani and Baitarni Basin. Two hydrological models (i.e., Sacramento and GR4J) are selected for this purpose. The two models are firstly calibrated against observed monthly runoff from five unregulated catchments using two different schemes (regional calibration and individual calibration). In individual calibration scheme, the hydrological models are calibrated for each individual catchments, which means that each catchment would have a specific parameter set. Instead, in regional calibration, all catchments are assumed to share a same parameter set. The objective function of the calibration is the modified NSE (MNSE), which is the combination of Nash-Sutcliffe efficiency (NSE) and bias. In regional calibration, the objective function is the total MNSE of the catchments concerned. The SCE-UA optimization method is used for model calibration.

The results show that Sacramento outperforms GR4J in the region. The calibration MNSE of the Sacramento is around 0.5, with volumetric error <30%. Given the limited observed streamflow data set, the model calibration results are satisfactory. The results of individual calibration also show that parameter sets vary significantly among catchments, which makes it difficult for parameter regionalization to predict streamflow of the ungauged basins. While in regional calibration, though all catchments are assumed to share one identical parameter set, the performance of the model in all the gauged basins is comparable with the individual calibration. With the consideration of both the modelling efficiency and effectiveness, the parameter set derived from regional calibration is used to simulate streamflow across the Brahmani and Baitarni Basin at the spatial resolution of $0.5^{o}\times0.5^{o}$ for the period 1901 to 2013, where the climate forcing input is from the Princeton climate dataset. The availability of water resources is assessed for each grid cell with given probability.

Keywords: *Water resources, hydrological model, model calibration, Brahmani and Baitarni Basin*

Global high-resolution reference potential evaporation

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Abstract: The increasing pressure on water resources worldwide request for both global and local scale assessments of fresh water availability. Gridded global reference potential evaporation (PET) datasets derived from either satellite or re-analysis data already exist, yet their time-coverage is often limited. Moreover the spatial and/or temporal resolution does not match the local scale requirements or the ever increasing resolutions of global hydrological models. We here introduce a high-resolution gridded reference potential evaporation dataset covering a period of 34 years that can be used in data sparse regions and for global scale analysis.

The dataset is derived from the WATCH-Forcing-Data-ERA-Interim (WFDEI) dataset which has a resolution of 0.5◦ by 0.5◦. By basic oversampling of such coarse data large and systematic biases are introduced, particularly in areas with strong relief. By down-scaling based upon a high resolution DEM, the main variables for determining reference evaporation can be down-scaled and improved considerably for the complete period of the reanalysis based meteorological forcing.

Down-scaling 10x10 km resolution was performed by applying a lapse rate on temperature, an altitude correction on air pressure and incoming radiation and by taking the effect of aspect, slope and local shading on illumination into account. Subsequently we produced Penman-Monteith, Priestley-Taylor and Hargreaves reference evaporation estimates. We analysed the impact of the down-scaling methods on calculated reference evaporation by comparison with (1) reference potential evaporation estimates based upon the WorldClim datasets and (2) locally derived Hargreaves evaporation for the Australian Murrumbidgee basin.

The WFDEI based Hargreaves estimates show highest resemblance with the WorldClim estimates, the Priestley-Taylor estimates are closest to the ensemble mean of the three estimates. The Penman-Monteith equation results in relatively large biases for the Sahara, Amazon and desert region of Australia. This is in line with other comparisons of the different PET equations for arid climates.

The high resolution data and the down-scaling tools are made available through the eartH2Observe data portal at http://wci.earth2observe.eu and https://github.com/earth2observe/downscaling-tools.

Keywords: *Reference potential evaporation, eartH2Observe, WFDEI, high-resolution*

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