

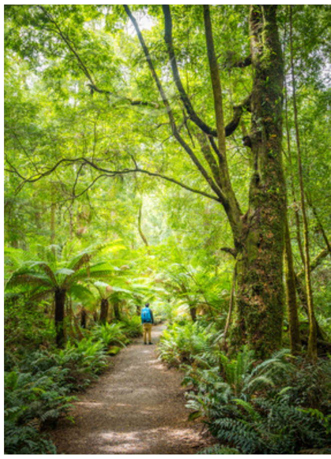

Managing
cumulative risks through
model-based processes

2017

MODSIM

Abstracts

EDITORS: Syme, G., Hatton MacDonald, D., Fulton, B. and Piantadosi, J.

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3–8 December
TASMANIA
AUSTRALIA

22nd International Congress on Modelling and Simulation

25th National Conference of the Australian Society for Operations Research — ASOR 2017

DST Group led Defence Operations Research Symposium — DORS 2017

mssanz.org.au/modsim2017

When and where appropriate, authors are encouraged and are free to submit revised versions of their paper(s) to peer reviewed journals provided they acknowledge the original 22nd International Congress on Modelling and Simulation publication.

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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 21 MODSIM Congresses in Australasia.

The society represents modellers and managers with interests in using quantitative and qualitative methods to manage practical problems in industry, environment, science, societal and economics areas. It is affiliated with the International Association for Mathematics and Computers in Simulation. mssanz.org.au

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The Australian Society for Operations Research (ASOR) was founded in 1972 and has about 400 members nationwide. ASOR, like other national societies is affiliated to the International Federation of Operational Research Societies (IFORS).

ASOR serves the professional needs of OR analysts, managers, students and educators by publishing a National Bulletin and National and Chapter Newsletters. The society also serves as a focal point for operations researchers to communicate with each other and to reach out to other professional societies. www.asor.org.au.

About the DST Group led Defence Operations Research Symposium

The Defence Science and Technology Group Operations Research (OR) Hub provides a forum for the exchange of ideas and concepts in OR research efforts within Defence. The OR Hub runs the Defence Operations Research Symposium (DORS), an annual event, devoted to the practice of military operations research and analysis. The event covers a range of topics such as new OR techniques, novel approaches to the integration of techniques, and wargaming and simulation, presented in the form of OR case studies by a range of experts in the field.

About the 22nd International Congress on Modelling and Simulation (MODSIM2017)

MSSANZ, ASOR and DORS bring together a broad spectrum of scientists who apply various mathematical modelling, simulation, statistical, engineering, spatial and computer science methodologies and skills to solving practical problems coming from a wide range of endeavours. For them, the practical matter under investigation and the available data are the driving forces behind the methodology chosen for the task, or in developing techniques required to analyse new models.

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2	August 1976	Monash University, Melbourne, VIC
3	September 1978	Australian National University, Canberra, ACT
4	August 1980	The University of Queensland, Brisbane, QLD
5	May 1982	The University of New England, Armidale, NSW
6	August 1984	Adelaide University, Adelaide, SA
7	May 1987	Royal Melbourne Institute of Technology, Melbourne, VIC
8	September 1989	Australian National University, Canberra, ACT
9	December 1991	Greenmount Resort Hotel, Gold Coast, QLD
10	December 1993	The University of Western Australia, Perth, WA
11	November 1995	The University of Newcastle, Newcastle, NSW
12	December 1997	University of Tasmania, Hobart, TAS
13	December 1999	University of Waikato, New Zealand
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15	July 2003	Jupiters Hotel and Casino, Townsville, QLD
16	December 2005	Melbourne University, Melbourne, VIC
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18	July 2009	Cairns Convention Centre, Cairns, QLD
19	December 2011	Perth Convention and Exhibition Centre, Perth, WA
20	December 2013	Adelaide Convention Centre, Adelaide, SA
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Contents

Plenary Speakers

Plenary Abstracts

Keynote Papers

Applied and computational mathematics

Stream leaders: Barry Croke and Roger Braddock

A1. Model identifiability and uncertainty methods: including sensitivity analysis, response surface methods, model emulation, active subspace and pseudo Monte Carlo methods

Session Organisers: Barry Croke, Tony Jakeman and Steve Roberts

A2. Spatial predictive modelling: model selection, accuracy assessment and predictive uncertainty quantification

Session Organiser: Jin Li

A4. Industrial modelling and simulation

Session Organisers: Bob Anderssen and Julia Piantadosi

A5. Time series applications

Session Organiser: Gurudeo Tularam

Biological systems

Stream leaders: Malcolm McPhee and David Mayer

B1. Agricultural systems

Session Organisers: Malcolm McPhee and Aroon Parshotam

B2. Advances in Agent-Based Modelling of complex biological, ecological and agricultural systems

Session Organisers: Mitchell Welch, Paul Kwan and Timothy Schaerf

B3. Modelling complexity in agricultural or environmental systems

Session Organisers: Neil Huth, Peter Thorburn, Val Snow and Dean Holzworth

B4. Mathematical modelling and image analysis for plant phenotyping

Session Organisers: Hamid Laga, Jinhai Cai and Pankaj Kumar

Computer science and engineering

Stream leaders: Peter Fitch and Tim Peterson

C1. Modelling, Simulation and Optimization in Engineering

Session Organisers: Amer Farhan Rafique and Qasim Zeeshan

C2. Provenance models and systems

Session Organiser: Nicholas Car

C3. Scientific research as a workflow: opportunities and case studies

Session Organiser: Paul Cleary

C6. Advances in Neural Networks, Soft Computing, Machine Learning and Big Data in biological, environmental and social systems

Session Organiser: Sandhya Samarasinghe

DORS – Defence and homeland security modelling

Stream leaders: Jim Smelt, Elizabeth Murphy and Arvind Chandran

D1. Simulation experimentation and wargaming

Session Organiser: Fred Bowden

D2. Systems Analysis

Session Organiser: Steve Harrison

D3. Mathematical sciences

Session Organiser: Richard Taylor

D4. Organisational management, behavioural and social sciences

Session Organiser: Brandon Pincombe

D5. Fleet management

Session Organiser: Stephen Baker

Economics and finance

Stream leaders: Michael McAleer and Chia-Lin Chang

E1. Modelling international business finance and financial markets in Asia

Session Organiser: Zhaoyong Zhang

E2. Technology and innovation

Session Organiser: Chia-Lin Chang

E3. Quantitative and computational finance

Session Organisers: Chia-Lin Chang and Michael McAleer

E4. Financial risk management

Session Organiser: Michael McAleer

E5. Combining information in socio-economic modelling and forecasting

Session Organiser: Felix Chan

Energy, integrated infrastructure and urban planning

Stream leaders: John Boland and Pascal Perez

F1. Recent advances in urban modelling for urban planning

Session Organisers: Nicole Ronald, Pascal Perez and Arnaud Banos

F2. Energy sources and networks modelling and assessment

Session Organisers: Sergei Schreider, Lynne McArthur, John Boland and Adrian Grantham

Environment and ecology

Stream leaders: Andre Zerger, Brett Bryan and Grant Hamilton

G1. Hybrid modelling and innovative analysis for integrated environmental decision support

Session Organisers: Marina Erechtchoukova and Peter Khaiter

G4. Recognising realism, pragmatism and dimensionality in ecohydrological modelling

Session Organisers: Willem Vervoort, Federico Maggi, Edoardo Daly and Sjoerd van der Zee

G6. Assessing impacts of resource developments on ecosystems

Session Organisers: Becky Schmidt, Brent Henderson and Steve Lewis

G8. GIS and environmental modelling

Session Organiser: Shawn Laffan

G9. Remote sensing applications in land and water management across scales

Session Organisers: Justin Costelloe, Fuqin Li and Dongryeol Ryu

Global change and natural hazards

Stream leaders: Jason Evans and Albert van Dijk

H1. Flood mapping, prediction, and management

Session Organisers: Stefania Grimaldi, Yuan Li and Jeffrey Walker

H3. Advances in forecasting flood and flood hazards

Session Organisers: Dongryeol Ryu, Rory Nathan and Valentijn Pauwels

H4. Urban flooding and geo-hazard

Session Organisers: Huili Gong, Pietro Teatini, Lin Zhu, Luigi Tosi and Tao Wang

H5. Data assimilation for energy and water cycle modelling

Session Organisers: Luigi Renzullo and Albert van Dijk

H6. Observations for climate and water modelling: data availability from point to continental scale

Session Organisers: Marta Yebra and Chris Rudiger

H7. Detecting and attributing changes in Australian climatic extremes

Session Organisers: Seth Westra, Fiona Johnson and Anthony Kiem

H8. New thoughts and approaches to environmental and natural resources modelling in the Big Data era

Session Organisers: Tingbao Xu and Yun Chen

H9. Satellite-based spatio-temporal monitoring of global/regional changes and natural hazards

Session Organisers: Yun Chen, Tingbao Xu and Chang Huang

H10. Modelling of bushfire dynamics, fire weather, impact and risk

Session Organisers: Jason Sharples and Bob Cechet

H11. Projections of regional climate change: from modelling to applications

Session Organiser: Jason Evans

H13. Remote sensing for land surface monitoring and prediction

Session Organisers: Jeffrey Walker, Xiaoling Wu and Ying Gao

Health informatics

Stream leader: Irene Hudson

I1. Modeling cancer and chronic disease data in translational and clinical research

Session Organisers: Sejong Bae, Karan P Singh and Alfred A Bartolucci

I2. Health analytics and informatics

Session Organisers: Irene Hudson, Garth Tarr, Sidra Zafar, Joanne Thandrayen and James Brown

I3. Healthcare Decision Support – methods, applications, and challenges

Session Organisers: Louise Freebairn, Jo-An Atkinson, Geoff McDonnell, Shaowen Qin and Ante Prodan

ASOR – Operations research

Stream leaders: Hussein Abbass and Simon Dunstall

J2. OR in mining/natural resources

Session Organiser: Louis Caccetta

J3. Service operations management

Session Organisers: Babak Abbasi, Gerardo Berbeglia and Zahra Hosseinifard

J4. Data analytics and OR in medicine and healthcare

Session Organisers: Babak Abassi and Vicky Mak

J5. Transport and supply chain

Session Organisers: Rodolfo Garcia-Flores, Tommaso Urli and Phil Kilby

J6. Optimal decisions under uncertainty

Session Organisers: Zili Zhu, Fabricio Oilviera, Monica Chen and Nicolas Langrene

J7. Fire and OR

Session Organiser: John Hearne

J8. OR methods and novel applications

Session Organiser: Simon Dunstall

Participatory decision making and modelling social systems

Stream leaders: Sondoss Elsawah and Susan Cuddy

K1. Evacuation Modelling: Technical and participatory advances

Session Organiser: Leorey Marquez

K2. Handling uncertainty, trust and model accuracy to resolve contested decisions

Session Organisers: Joseph Guillaume, Sondoss Elsawah, Baihua Fu, Tony Jakeman and Holger Maier

K3. Behavioural Operations Research

Session Organisers: Leon Young and Fred Bowden

K4. Integrated participatory systems approach for modelling socio-ecological systems

Session Organisers: Russell Richards, Oz Sahin and Sondoss Elsawah

K5. Integrative frameworks for assessing risks and opportunities from socio-economic and environmental change

Session Organisers: Serena Hamilton, Lilly Lim Camacho, Wendy Merritt and Uday Nidumolu

K7. Evaluating the incorporation of science and other forms of knowledge in decision making and practice

Session Organisers: Greg Summerell, Louise Goggin, Jenifer Ticehurst, Sondoss Elsawah and Keith Matthews

K8. Considering gender in the context of modelling

Session Organisers: Susan Cuddy and Joyce Wu

Water resources

Stream leaders: Francis Chiew and Jai Vaze

L1. Water data information: challenges, use and applications

Session Organisers: Francis Chiew and Jai Vaze

L2. The role of water data and information to better prepare for water security and future challenges

Session Organisers: Amgad Elmahdi and Ulrike Bende-Michl

L3. Statistical and Artificial Intelligence methods in hydrology and water engineering

Session Organisers: Monzur Imteaz and Jahangir Alam

L4. Evapotranspiration observation, modelling, and remote sensing

Session Organisers: Huade Guan, Yongqiang Zhang and Tanya Doody

L5. Innovations in water engineering: The role of data-based techniques

Session Organiser: Sivakumar Bellie

L6. Modelling and water management: Evolution of the role of modelling in water management

Session Organisers: Kumar Savadamuthu and Matt Gibbs

L7. Current state of hydrological modelling: Need for a new approach?

Session Organiser: Santosh Aryal

L8. Advances in large scale hydrological modelling to improve predictions and assessments of water availability and accounting

Session Organisers: Jai Vaze, David Post, Barry Croke and Dushmanta Dutta

L9. Process-based distributed hydrologic modelling for water resources management

Session Organisers: Jahangir Alam, Dushmanta Dutta and Srikantha Herath

L10. River System Modelling for water accounting, planning, management and forecasting

Session Organisers: Dushmanta Dutta, Jai Vaze, Justin Hughes and Shaun Kim

L11. Hydrodynamic modelling of floodplain/marine hydraulics, hydrological connectivity sediment transport and water quality

Session Organiser: Fazlul Karim

L12. Advances in flood inundation modelling

Session Organisers: Jin Teng, Stephen Roberts, Jai Vaze, Dushmanta Dutta and Fazlul Karim

L13. Flood frequency, variability and trend analysis

Session Organisers: Ataur Rahman and Fazlul Karim

L14. Floods and droughts under climate change

Session Organisers: Fubao Sun, Yanjun Shen, Yongqiang Zhang, Francis Chiew and Yaning Chen

L15. Hydroclimate projections in support for impacts and resilience research

Session Organisers: Bree Bennett, Dewi Kirono, Michael Grose and Seth Westra

L16. Hydrological prediction under change

Session Organisers: Francis Chiew, Jai Vaze, Lu Zhang and David Post

L17. Water resources management under changing environment

Session Organisers: Pan Liu, Lu Zhang, Kairong Lin and Lei Cheng

L18. Water planning and management: Issues, challenges, and solutions

Session Organiser: Sivakumar Bellie

L19. Hydrological forecasts and applications

Session Organisers: Andrew Schepen, James Bennett, Fiona Johnson, Dmitri Kavetski, Lucy Marshall, David Robertson and Mark Thyer

L20. Regional and global water and energy fluxes

Session Organisers: Yongqiang Zhang, Francis Chiew, Jorge Peña Arancibia and Fubao Sun

L21. Advances in water quality modelling

Session Organisers: Andrew Western, Susan Cuddy, Sandy Elliott, Tony Weber and Anna Lintern

L22. Recent advances in modelling in the Great Barrier Reef Region

Session Organisers: Dave Waters, Mark Silburn and Stephen Lewis

L23. Modelling water quality in rivers and lakes

Session Organisers: Freeman Cook and Aroon Parshotam

Plenary Speakers

Dr Beth Fulton

CSIRO Oceans and Atmosphere, Australia

Tackling the kraken – modelling cumulative risk in the oceans

Dr Beth Fulton is a Principal Research Scientist with CSIRO Oceans and Atmosphere where she leads the Marine Ecosystem Modelling and Risk Assessment Group. Beth is also an Adjunct Professor at the Centre of Marine Socioecology, a collaboration between University of Tasmania, CSIRO and the Australian Antarctic Division. Beth has been with the CSIRO for the past 15 years, where she has developed various system modelling tools for looking at marine ecosystems and sustainability. The best known tool is the Atlantis modelling framework, which has been applied in more than 30 marine ecosystems around the world. The models developed by Beth's team are some of the first to give equal attention to biophysical and human components of marine and coastal ecosystems. They underpin CSIRO's research into sustainably managing potentially competing uses of marine environments and adaptation to global change and have been used to consider effective means of conserving and monitoring marine ecosystems.

Beth received a BSc Hons I, majoring in Marine Biology and Mathematics, from James Cook University, Townsville (1997) and a PhD on ecosystem model complexity from the University of Tasmania (2001). She has more than 80 publications. She was a contributing author to the latest IPCC WG2 report and a review editor for IPBES Deliverable 3c. Her contribution to marine resource management and science have been recognised with numerous awards, including Ecological Society of America Sustainability Science Award (2011); a Pew Marine Conservation Fellowship (2010-2014); and the 2007 Australian Science Minister’s Prize for Life Scientist of the Year.

Associate Professor Jan Kwakkel

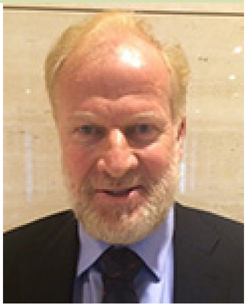
Delft University of Technology, The Netherlands

Advances in exploratory modeling for assessing uncertain cumulative impacts

Jan Kwakkel is an Associate Professor at Delft University of Technology. His research focusses on model based approaches to support decision making in complex uncertain systems. He is an expert in many objective robust decision making, and the use of adaptation pathways. He has applied his research in a variety of domains including fresh water supply, flood risk, air transport, sea transport, global logistics, and national safety and security. He is the vice president for the society for decision making under deep uncertainty. He is the lead developer of the exploratory modelling workbench, which is an open source library for applying a variety of model-based scenario techniques.

Professor Tom Smith

Macquarie University, Australia



Environmental finance: A research agenda for interdisciplinary finance research

Frank Finn Professor of Finance Tom Smith is ranked as number one Finance Academic in Australia and New Zealand and in the top 100 worldwide in the past fifty years in terms of Tier 1 Publications since graduation. Tom's research interests are in the areas of Environmental Finance, Asset Pricing Theory and Tests; Design of Markets - Market Microstructure; and Derivatives. His articles have appeared in leading journals including the Journal of Financial Economics, Journal of Finance, Review of Financial Studies, Journal of Financial and Quantitative Analysis, Journal of Business, Journal of Law and Economics, Journal of Accounting Research, Journal of Empirical Finance, Journal of Futures Markets, Journal of Fixed Income and Journal of Portfolio Management. Tom is particularly proud of all of his PhD students and the fact that they have more than 50 tier 1 publications.

Professor Martina Linnenluecke

Macquarie University, Australia

Environmental finance: A research agenda for interdisciplinary finance research

Professor Martina Linnenluecke researches the impacts of corporate adaptation and resilience to climate change impacts. Her expertise in the field has been demonstrated through a number of prestigious awards, such as the Peter Brownell Manuscript Award as well as the Carolyn Dexter Best International Paper Award at the Academy of Management Conference, – the leading conference in the field. Her research is published in high-ranked business and interdisciplinary journals, and she is the author of the book The Climate Resilient Organization.

Martina has secured significant funding for her group – most recently, a five-year, $500,000 Australian Research Council (ARC) Discovery Grant to study Australia's Clean Tech Revolution. The grant has resulted in a stream of new research changing the way in which climate change is factored into business and financial decisions. Martina has extensive experience in working with government and industry related to organisational climate adaptation strategies, assessments, and planning.

Professor Leonid Churilov

The University of Melbourne and RMIT University, Australia

The Art, Science, and Joy of Healthcare Modelling: being an important part of the effort to combat the world's third biggest killer

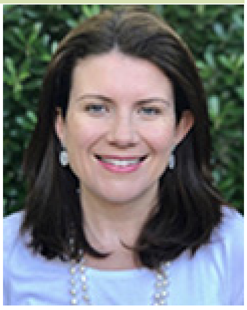
Professor Leonid Churilov is the Head, Statistics and Decision Analysis, Florey Institute of Neuroscience and Mental Health, Honorary Professor at Florey Department of Neuroscience and Mental Health (The University of Melbourne) and Adjunct Professor, School of Science (Mathematical Sciences) at RMIT University.

Professor Churilov is an internationally recognized leader in the applications of Operations Research to health and clinical care systems. He has co-authored over 200 peer-reviewed publications in the area of modelling methodology and health care applications, including those published in the Journal of Operations Management, New England Journal of Medicine, The Lancet, and Nature Biotechnology; a research monograph on Value-Focused Process Engineering; and an edited volume on simulation modelling for management decision making. He is a recipient of numerous ARC and NHMRC grants, and a Victoria Fellowship from the State Government of Victoria. Professor Churilov has supervised numerous PhD students and taught OR, statistics, and decision modelling at undergraduate and postgraduate levels. Professor Churilov is an Associate Editor of Operations Research for Health Care and an editorial board member for five other journals. He is a board member of ORAHS-EURO Working Group in Applications of Operations Research to Health Systems and a co-founding member of Cumberland.au - The Australian Health Care Modelling and Systems Design Collaboration.

The impact of modelling work by Professor Churilov is recognized by awards from ASOR, the Operations Research Society of Japan, and by the INFORMS Decision Analysis Society Practice Finalist Award. The results of his work featured in the international media, and were used in stroke public awareness campaigns by the Australian Stroke Foundation and in the USA by the American Heart Association and American Stroke Association. Professor Churilov has contributed OR and statistical modelling expertise to the development of an implantable Strentrode device for a bionic spine.

Professor Churilov was awarded the Ren Potts Medal of the Australian Society for Operations Research in 2016, awarded to individuals who have made outstanding contributions to theory or practice of OR in Australia.

Associate Professor Lucy Marshall



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

Uncertainty, creativity, and automated model building in the hydrologic sciences

Associate Professor Lucy Marshall is an ARC Future Fellow and Deputy Director of the Water Research Centre in the School of Civil and Environmental Engineering at the University of New South Wales (UNSW). Lucy completed her undergraduate, Master's and PhD degrees at UNSW before moving to Montana State University in 2006, where she worked at the interface of engineering and environmental science in quantifying uncertainty in hydrologic and environmental systems. She returned to UNSW as an ARC Future Fellow in 2013 where her research has involved new conceptualizations of hydrologic processes, improving catchment forecasts, and methods for hydrologic model diagnostics and uncertainty analysis (especially via Bayesian statistics and multi-model methods).

Associate Professor Shawn Laffan

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

Biodiversity modelling for all

Shawn Laffan is an Associate Professor in the Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, at the University of New South Wales. Shawn has a BSc(Hons) and PhD from the ANU. He has held lecturing positions at both ANU and UNSW, and is currently Asia-Pacific editor for the International Journal of Geographical Information Science. His research interests lie in the field of geospatial analysis, particularly the development of modelling and analysis tools, with a general applications focus on biophysical and biodiversity related processes.

The Art, Science, and Joy of Healthcare Modelling: being an important part of the effort to combat the world's third biggest killer

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Abstract: Decision sciences have made major contributions in improving systems and services in many fields of human activity. Healthcare – with the need to evaluate treatments and screening programmes, to allocate resources, to support individual clinical decisions, to redesign care processes and to improve quality of life - is a uniquely rich and stimulating field for the modelling profession to use our knowledge and skills.

In this plenary talk I will present a broad perspective on past, present, and potential future of healthcare modelling acquired from both ends of the "academic divide" over the last twenty-plus years. Special focus will be on the modelling work performed while contributing to the effort of combatting the world's third biggest killer: stroke. From the first ever model to evaluate long-term benefits of earlier access to thrombolytic treatment to working with paediatricians to create a new "brain attack" clinical pathways for children; from using the elegance and power of analytics to understand benefits and risks of early stroke rehabilitation to supporting the decision-making of an international roundtable of stroke clinicians in setting out major priorities in the area – modelling of stroke care systems not only requires the rigor of science and, often, the elegance of art, but also is capable of bringing an immense sense of joy and satisfaction from the ability to apply analytic modelling expertise to improve human life.

Keywords: *Healthcare systems, decision modelling, process modelling, analytics, model use*

Tackling the kraken – modelling cumulative risk in the oceans

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Abstract: The 21st century has seen a growing list of sectors expand into the ocean, with new industries added to the historical ones of fishing, transport and tourism. Activities once thought of as primarily terrestrial are growing in their marine footprint – energy generation, mining and infrastructure construction (floating platforms for ports and housing). In addition, seascapes are being influenced by modified water flows, run-off and pollutants. Things are further complicated by the non-stationary influence of climate drivers and the changing frequency of extreme events (which globally now cause billions of dollars of damage annually). This increasingly complex array of uses and stressors lays a growing burden and technical challenge at the feet of those tasked with understanding the risks and opportunities associated with the blue economy.

Low chance (but potentially high impact) events can no longer be ignored and this has led to demand for new risk assessment and modelling methods. To date foresighting is still the most widely used approach for complex risk assessment situations, as it is a rapid method that can cross scales and cope with vagary. While such exercises can be immensely insightful, particularly if they draw on a diversity of knowledge types that have a deep knowledge of the system, they tend to under-estimate variability, bifurcation points or the consequences of non-linear interactions of multiple variable types (whose alignment may see step changes in behaviour).

The next most commonly used marine risk tools are exposure, usage and vulnerability maps. Planners and other groups interested in marine and coastal issues find such maps an intuitive way of visualising the problem and potential solutions. Unfortunately, mapping currently struggles to move beyond additive layering of the pressures and system attributes. Uncertainty is also particularly difficult to incorporate comprehensively and consistently.

Presently tackling non-linearity and uncertainty in a consistent way has typically been achieved via a range of modelling tools, including: qualitative models that bring together diverse data sources and analyse the system using signed diagraphs and matrix algebra; Bayesian networks which can be used to explore probabilistic outcomes of perturbations and cascading effects; statistical approaches that use well understood relationships between variables to explore combined pressures, changing distributions or zones of influence; and process models applied across entire life cycles or socioecological systems. Common features of these tools are that they can (i) encompass multiple stressors, scales and their interconnections; and (ii) have the capacity to express multiple potential endpoints or system structures. Using a range of approaches also provides a means of handling model structural uncertainty, one of the key but often unacknowledged sources of uncertainty.

The value of all of these tools can be maximised by using a staged approach to match the complexity of the assessment method with the complexity of the question. A staged approach screens scope (temporal and spatial scales), the number, nature and connectedness of components and thereby identifies relevant methods and complexity. Many questions can be tackled straightforwardly using existing approaches - e.g. single risks with clear flow-on effects or even the accumulation of multiple low risk activities that cumulatively build risk to more worrying levels (Figure 1). Integrated models can be used to tackle more complicated situations where there are multiple interacting activities in one location or mixes of uses and stressors changing through time. These later approaches can be resource intensive exercises and rapid coherent alternative methods for assessing risks resulting from non-linear interactions of activities represent a gap in the toolbox. Addressing this hole represents a great opportunity for quantitatively skilled scientists to help society make sure the blue economy proves to be more sustainable and with less pitfalls than its terrestrial counterparts.

Keywords: *Cumulative impacts, risk*

Advances in exploratory modeling for assessing uncertain cumulative impacts

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Abstract: Many of the challenges society is facing involve a network of actors with different resources and heterogeneous power relations that has to coordinate their actions, while the system relating decision alternatives to consequences is both complex and subject to uncertainty. The complexity is due to non-linear cross-scale interactions among various sub-systems. Uncertainty exists about the current state of the system, the possible ways in which the future might unfold and how this affects the system. Moreover, the various actors often have diverging understandings of the system and the uncertainties, while also disagreeing on the relevant values that should be considered in decision-making. Examples of such decision problems can be found in many domains such as energy transitions, flood risk management, infrastructure planning, supply chain management, and climate adaptation. These decision problems have been described as wicked, as ill-structured, or as societal messes.

Offering model-based support for decision-making on societal challenges entails coming to grips with the multi-actor character of decision making, as well as the intrinsic uncertainty and complexity of the system. Over the last decade, under the label of decision-making under deep uncertainty, a novel paradigm for developing and using models has emerged in response to the perceived failure of existing approaches in offering meaningful model-based decision support on uncertain complex multi-actor decision problems. This paradigm entails a shift from using models to try to predict the future, towards using models to explore thousands of scenarios. In evaluating the performance of candidate strategies, rather than using some decision analytic approach for aggregating the various outcomes of interest into a single measure of goodness, this paradigm places a strong emphasis on Pareto optimality. Focusing on Pareto optimality allows doing justice to the plurality of values actually at stake in decision-making on societal challenges.

The uncertainty, complexity, and multiplicity of values intrinsic to decision-making on societal challenges preclude the possibility of developing a single true representation of the system of interest. Instead, analysts have to develop and use a set of models that encompasses the uncertainty, while being constrained by available data and knowledge. A single model drawn from the set is not a prediction. Rather, it is a computational experiment that reveals how the real world system would behave if the assumptions made in the experiment about the various uncertainties were correct. Such a what-if experiment in isolation is typically not that informative, other than suggesting the plausibility of its outcomes. Instead, exploratory modeling aims to support reasoning and decision-making on the basis of large sets of computational experiments. Thus exploratory modeling involves searching through the space of possible experiments using many-objective optimization algorithms, and sampling over the space using design of experiments and global sensitivity analysis techniques.

In this talk, I will introduce a general taxonomy of exploratory modeling approaches, illustrate this taxonomy using a stylized toy case, and demonstrate it with an in depth real-world case focused on the resilience of the multi-modal transport model of Bangladesh to natural hazards.

Keywords: *Exploratory modeling and analysis, uncertainty, decision-making, multi-modal transport model*

Biodiversity modelling for all

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Abstract: We are entering the sixth mass extinction event in Earth's history, making it ever more important that we understand the spatial distribution of Earth's biodiversity. Such an understanding is crucial to determine the allocation of scarce conservation resources. It is also integral to efforts to comprehend the evolutionary and environmental processes that shape past, current and future biodiversity distributions.

Online and freely accessible databases now make available enormous and ever increasing amounts of data describing and documenting species occurrences and related attributes. Spatial data can be obtained from sources such as the Atlas of Living Australia (http://www.ala.org.au; >70,000,000 observation records) and the Global Biodiversity Information Facility (http://www.gbif.org; >700,000,000 observation records). Other non-spatial data such as phylogenetic trees and genetic data can be obtained from sources such as Treebase (www.treebase.org) and Genbank (www.ncbi.nlm.nih.gov/genbank/). There is also an increasing wealth of environmental layers at regional to global extents, representing for example climate, edaphic and terrain variables.

There is a clear need for modelling and analytical tools to enable the easy integration of these considerable resources. This is especially the case for the many researchers who have a deep understanding of their specialist areas (e.g. organisms or ecosystems), but who lack the technical know-how and sufficiently powerful hardware to implement potentially complex modelling processes for large data sets.

The Biodiversity and Climate Change Virtual Laboratory (BCCVL; http://bccvl.org.au) has been developed for this purpose. The BCCVL provides a "one-stop modelling shop" to simplify biodiversity and climate change modelling.

The BCCVL provides tools to generate distribution models for any number of species using any or all of 17 different SDM algorithms. While use of such models is standard practice in many fields, typically no more than two such algorithms are run using a researcher's own systems, and then commonly with little to no experimentation with parameter settings. The further advantage and novelty of the BCCVL is in the "value adding" — model outputs can be used in subsequent experiments to (1) identify potential impacts of climate change under nine different potential emissions scenarios, (2) aggregate indices to identify hotspots of endemic species, and (3) use ensemble analyses to combine SDM results from different algorithms.

More recent developments in the BCCVL have expanded the nature of the data sets that can be used by researchers. (1) Users can move beyond the grid cell and develop SDMs of freshwater aquatic systems, leveraging the stream segments and catchments provided by the Bureau of Meteorology's Geofabric data set. (2) There is support for migratory species SDMs, enabling the analysis of distributions that can change rapidly over time. Migratory species can often have part of their distribution in highly threatened environments, so gaining an understanding of where these occur is of vital importance. (3) The response of species traits, a current hot topic in ecology, can be modelled in relation to the environment. This allows the prediction of how the spatial distribution of traits such as leaf size, or potentially CO_2 uptake, will change under future climate projections.

The BCCVL is a major collaborative project between researchers across multiple universities, with funding from NECTAR, ANDS and RDS. The code base is free and open source, and accessible through GitHub (https://github.com/BCCVL/). The web interface is freely accessible to any researcher, with access for Australian researchers enabled through the Australian Access Federation.

An aspiration of many modellers is to get their models into practical use beyond the academy. The BCCVL provides a clear example of how this can be done, a process relevant across the modelling spectrum.

Keywords: *Biodiversity, species distribution modelling, climate change, BCCVL*

Environmental Finance: A Research Agenda for Interdisciplinary Finance Research

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Abstract: Environmental Finance is an emerging and rapidly growing interdisciplinary field of research, concerned with the financial implications of environmental change for industries and firms, and the need to transition to a sustainable economy. The field brings together research in finance and the natural sciences to develop financial and market solutions to some of humanity's most pressing concerns; namely, climate change and shifts in other Earth system processes. Firms need to adjust to these environmental changes, which offer many opportunities for wealth and growth. There are various historical examples of technological breakthroughs over the history of modern markets that have driven growth and wealth; such as, railways, electricity, automobiles, radio, microelectronics, personal computers, biotechnology, and the internet. The 2015 Paris Climate Agreement has given the green light to clean technology firms worldwide to start commercializing their patents. This will create the next technological breakthrough – a clean tech revolution that will drive growth and wealth in the same way as earlier breakthroughs. This article summarizes the state of this newly formed interdisciplinary field and sets out avenues for future research.

Keywords: *Environmental finance, asset impairment, adaptation to climate change, volatility, real options*

Uncertainty, Creativity, and Automated Model Building in the Hydrologic Sciences

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Abstract: Hydrologic modeling has advanced considerably over the last 50 years, evolving from simple mathematical representations of dominant rainfall-runoff processes, through the advent of Freeze and Harlan's (1969) blueprint for physically based models, to the complex and integrated modeling platforms that exist today. Currently, modeling approaches allow the rapid formulation and deployment of hydrologic predictions across the full range of potential applications and in response to prospective hazards. Despite this advancement, no model is perfect for any given modeling exercise. Significant effort has thus been put into the development and refinement of uncertainty frameworks that attempt to quantify and convey the imperfections in our models, and reconcile them with our observations of hydrologic systems.

One way to address model uncertainty is via the use of multi-model platforms that attempt to simplify and automate the process of model building. It can be argued that these platforms have transformed the modeler's ability to effectively develop competing hypotheses about hydrologic systems, and have unified modelers by providing a common template for previously disparate model structures. However, do they inhibit or enhance creativity and innovation in hydrologic science?

This presentation will discuss the importance of creativity in hydrologic model building, and how it might be enhanced using field observations, expert knowledge, and current or future modeling tools. Using a suite of case study catchments from the US and Australia, the lecture will consider the use of multi-model approaches for improved uncertainty analysis and understanding of model performance. We will demonstrate how field experiments can challenge the traditional conceptualization of a catchment, and how this information may be incorporated into existing uncertainty frameworks. An iterative modeling framework (where we propose, test and refine our models) remains critical to further understanding of hydrologic systems, and this presentation will demonstrate how we must challenge the necessary bounds of automated modeling platforms to propose new (creative) solutions to scenarios where our models fail.

Keywords: *Hydrologic modeling, multi-model ensembles, uncertainty quantification*

Opportunities for workflow tools to improve translation of research into impact

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Abstract: There are many obstacles to the translation of research activities and research software into distributable and commercialisable applications. This is important for improving the transfer of research into economically useful outcomes and an important path to impact that can justify funding for such research. Usage of research outcomes and research software can be highly valuable to the right customers if it is deployed to them fit for purpose and easy to use in a timely and cost effective way. Typically research IP is initially developed to target specific research outcomes (most commonly with the aim of publication) and wider opportunities for translation are only identified well after the form of the IP has been set, for example after a project has been completed. It is also common for the use of the IP to involve manual and semi-manual steps, particularly relating to the preparation of inputs and the analysis and/or preparation of outputs, often requiring intimate knowledge of the underlying technology. These represent substantial barriers to entry, as customers generally deem this knowledge overly costly to obtain and its loss too high a risk to their business processes. Large amounts of capability developed within research and many commercial organisations, which we term Stranded IP, have varying combinations of such translation obstacles. This Stranded IP cannot, therefore, be easily exploited for opportunities beyond the original research focus.

For Australia, which has a large gap between research inputs and economic outcomes, understanding where and in what form the IP generated resides represents a significant opportunity. Aside from publication outputs (which are usually the primary measure of research excellence) and registerable IP (patents etc) which form only a small amount of the IP generated, there is significant development of enabling tools and data. Some may be provided in the form of open source software or curated data, but often this is not considered to be externally valuable. However, such stranded IP can often have value to third parties if these opportunities can be identified, the IP put in a usable form and then provided to them for use.

It is useful to consider research IP usage as a workflow process, composed of a series of unit operations linked in a network manner with input-output relationships and execution order dependencies. Typically some or many of these operations or steps will use software components (often including proprietary or open third party sources). The intervening manual steps present strong hurdles to the automation of these semi-manual workflows which inhibit reproducibility and allows errors in the IPs use to be introduced. Some basic integration of such software components can be achieved by using scripting languages such as Python to automate them. A more complete solution is to convert all steps into workflow unit operations with a dedicated workflow platform to facilitate the interoperability of the software components and best expose the required inputs and outputs to the less technically-minded end user.

In this paper, we will describe one specific workflow engine, Workspace, which has been developed to provide relatively low cost pathways for the translation of Stranded IP into useful applications for use by third parties. This can provide commercialisation opportunities for valuable IP whose market sizes range from large to ones that are sufficiently small so as to prevent cost-effective exploitation by more traditional software development processes. Key attributes of the workflow engine that support this include the ability to

- easily add a Graphical User Interface (GUI) layer over a workflow, including complex data visualisation options,
- create closed source compiled products with installers,
- easily convert pre-existing software into workflow compatible operations,
- arbitrarily inter-connect unit operations and to be able to adapt, customise and evolve both the workflow and GUI layers, and
- extensively re-use IP once it is within the platform framework.

These attributes provide a comparatively low cost pathway for commercialisation of both existing and new IP and software.

Keywords: *Workspace, commercialisation, stranded IP, translation of IP, workflow*

Scheduling a Production Line Using Heuristics and Constraint Programming

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Abstract: Sequencing and scheduling are activities that are of paramount importance in the man-ufacturing industries. In today's economic environment, the efficiency gains produced by effective scheduling represent not only a competitive advantage, but also are crucial to keep customers happy through adequate service levels and to ensure adequate use of resources. In this paper, we minimise the makespan in a single-machine environment with release dates and sequence-dependent setup times, or a $1|s_{jk}, r_j|C_{max}$ scheduling problem in the notation introduced by Lawler et al. [1982]. This problem is based on a deodorant manufacturing facility where a number of products are produced, and a sequence must be determined such that the costs of switching from one family of products to another are minimised, subject to raw material availability and delivery dates. Schedules must be produced for a horizon of two weeks, which normally requires planning the production of around forty products (from a total of around three hundred) which may belong to any one of nine product families. The major component of the cost associated with changing from one family of products to another is due to cleaning the line when products from different families are produced in sequence. We present results obtained with two solution methodologies: first, we use the common strategy of producing a good initial solution via dispatching rules and then refining this solution through Tabu Search, and second, we develop a Constraint Programming model. Our results show that finely-tuned heuristic and Constraint Programming models can produce a satisfactory result with realistic data sets in a short execution time.

Keywords: *Production scheduling, constraint programming, Tabu search, dispatching rules*

U.S. Navy Risk Reduction through Modeling and Simulation Enterprise Tools

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Abstract: The United States Navy has developed an extensive portfolio of Modeling and Simulation (M&S) Enterprise tools, which when used in conjunction with the full spectrum of Test and Evaluation greatly reduces risk of operation, enhances safety, and increases effectiveness. Intensive use of M&S beginning with pure digital models, progressing to integrated models combined with production hardware, then to integration laboratories with aircraft and simulation in the loop, and finally M&S integrated into flight operations has proven to be a cost effective risk reduction technique and an extremely effective Test and Evaluation Methodology.

A common portfolio of Enterprise tools contributes to the success of these efforts. Independent model development in disparate labs, often to accomplish the same ends via different means is not cost effective, and either precludes the distribution of models across the Naval Aviation Enterprise, or makes the reuse by non-developers difficult, requiring adaptation by the receiving labs to their own schema.

The Naval Air Systems Command portfolio includes: The Next Generation Threat System (NGTS), the Architecture Management Integration Environment (AMIE), and the Joint Integrated Mission Level Model (JIMM).

An example of the utilization of such tools from Digital Systems Models to flight test is the Ground Based Sense And Avoid (GBSAA) program. The use of Unmanned Air Vehicles in the conduct of military operations has been a reality for decades. The integration of such systems into civilian airspace teeming with commercial and private traffic, however, remains a daunting task. The portfolio tools were used to generate realistic traffic based on parametric and statistical history, and then seamlessly integrate actual vehicle tracks into the GBSAA system.

The United States Navy Naval Air Systems Command (NAVAIR) has successfully deployed the United States first such Federal Aviation Administration (FAA) approved system for UAS operations in the national airspace system. The use of a portfolio of modeling and simulation tools was critical in driving the risk of integrated operations to an extremely low level.

The use of Portfolio tools is also central to the success of the Royal Australian Air Force (RAAF) F/A-18 A/B/E/F, EA-18G, and P-8A training systems. Each of these systems utilize NGTS and AMIE to provide realistic synthetic representations of both threat and friendly air, land, and surface platforms, and their corresponding weapons and subsystems. NGTS accurately stimulates the avionics models in these training systems using data driven models and authoritative data.

Ms. Markowich's remarks will focus on the reduction of risk with Navy Enterprise tools using the real-world examples cited above.

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Keywords: *Unmanned Aircraft System, Ground-Based Sense and Avoid, simulation tools, NAVAIR*

Delivering more than the “Sum of the Parts”: using Quantitative Storytelling to address the challenges of conducting science for policy in the EU land, water and energy nexus

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Abstract: This paper introduces an EU Horizon 2020 project (MAGIC) being conducted between 2016 and 2020 to better understand how EU water, food, energy and biodiversity policies are linked together and to EU climate and sustainability goals. The research is thus another instance of a nexus study in which various forms of research-derived and other knowledge are combined to evaluate and improve policy and other decision-making. The project is shaped by insights on the conduct and evaluation of inter- and transdisciplinary research for policy support reported through the MODSIM and iEMSs conferences in recent years. MAGIC brings together, from multiple centres, expertise in biophysical, computational, economic and social sciences underpinned by theories of transdisciplinary science-for-governance. These MAGIC consortium partners also have experience of treading the fine line between challenging policies (which may be defended by vested interests) and supporting processes of policy reform (whose impetus and legitimacy rely on generating communities of interest). The key challenges for MAGIC are whether this breadth and depth of expertise can be combined in ways that are theoretically rigorous, practical within the resources available and deliver more than the sum of its parts, that is, with discernible impact beyond the science-policy interface (i.e. outwith academia).

The integrative core of the project is Quantitative Story Telling (QST), a process of making quality tests of the narratives that underlie or justify key policy positions. The qualities of the policy narratives assessed are their feasibility (within biophysical limits), viability (within the existing institutional context) and desirability (reflecting distributional and acceptability issues); using uses reformulations of existing statistical datasets and simple empirical transformations. The analysis is framed using a societal metabolism metaphor. That is, it focuses on the funds of land and human time needed to create the flows of materials, energy and money that reproduce and maintain the identity of the system of interest (e.g. current patterns and trajectories of consumption). The analysis is conducted simultaneously across scales (geographical or classificatory) to highlight key externalisation effects and dependencies that may undermine long-term security.

This quantitative testing of narratives is preceded and shaped by critical choices made by both policy stakeholders and the research team. Which narratives should we focus on? How should we explore these with our social metabolism analysis? Different stakeholders and team members may all have different preferences and epistemological positions. Failure to acknowledge, and where possible resolve, such fundamental differences could limit potential for impact by ensuring that researchers and policy makers have no shared issue framing. For MAGIC, there is thus a strong focus on, and investment in, using social science methods to understand the actors, framing and institutional context within which the QST is conducted and any outputs are used. Deliberative and inclusive processes (undertaking the research in mixed-teams of researchers and stakeholders) are being used to legitimise the process of analysis and ensure that the outputs of QST are salient and credible. The paper concludes by reflecting on how well the expertise developed by the authors in conducting policy support translates from the particular context of Scotland into the structures, processes and procedures of the EU.

Keywords: *Nexus, policy, Europe, science for governance, transdisciplinary*

The Waroona fire: extreme fire behaviour and simulations with a coupled fire-atmosphere model

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Abstract: The Waroona fire burnt over 68,000 ha and destroyed more than 160 homes in southwest Western Australia in January 2016. On the second evening of the fire, there were two fatalities when the fire made an unexpected run and produced a destructive ember storm over the town of Yarloop.

During the first two days of the fire, there were four episodes of extreme fire behaviour. Two separate pyrocumulonimbus events developed; both produced anomalously fast runs in the prevailing winds, with one pyrocumulonimbus igniting new fires downwind. The other pyrocumulonimbus event occurred at a time that is outside the normal diurnal timing of thunderstorms. Two evening ember storms occurred; the first impacted the town of Waroona and the second caused the devastation at Yarloop. The ember storms were driven by fire plumes interacting with local downslope winds; resulting in a turbulent horizontal transport mechanism for lofting and transport of numerous firebrands.

The processes that occurred at the Waroona fire were driven by three dimensional fire-atmosphere interactions. The detail of such processes can be examined using a coupled fire-atmosphere model.

The Australian Community Climate and Earth-System Simulator (ACCESS) Numerical Weather Prediction model has been coupled to a fire spread prediction model. The coupled model can be used to simulate large fires with full coupling to the atmosphere. The code has been developed and tested by Monash University (publications in preparation). The fire spread code is implemented by a level set solver and includes a number of fire spread formulae including McArthur, Rothermel and Vesta. SRTM topography is used and fuel maps can be included as available. The ACCESS model can be run at resolutions of hundreds of meters and the required resolution to resolve dynamic feedback processes will be explored as the project evolves.

This paper will describe key features of the extreme fire behaviour of the Waroona fire, introduce the coupled fire-atmosphere model ACCESS-Fire and report on progress simulating the Waroona event with the coupled model.

Figure 1. Pyrocumulonimbus above the Waroona fire. Image provided by Neil Bennet, Bureau of Meteorology.

Keywords: *Waroona fire, pyrocumulonimbus, ember storm, coupled fire-atmosphere model, ACCESS-Fire*

Progress towards generating accurate and reliable 7-day ensemble streamflow forecasts for Australia

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Abstract: Streamflow forecasts for lead times of up to 10 days are valuable for a wide variety of applications. Forecasts of potential flood conditions enable emergency services and water managers to plan mitigation and community responses. Forecasts of within-bank streamflow allow water managers to optimize water distribution and environmental benefits in regulated streams. Streamflow forecasts are generated by initializing a calibrated hydrological model using observed precipitation and evapotranspiration, then forcing the hydrological model with weather forecasts derived from numerical weather prediction (NWP) models. There are many potential sources of error in streamflow forecasts. Hydrological and NWP models are simplified representations of real-world processes and therefore result in prediction errors. Imperfect observational data introduce errors into model parameterizations and the initial conditions of the models used to generate forecasts. These errors mean that streamflow forecasts are fundamentally uncertain. Ensemble methods that combine statistical techniques and process-based models provide a robust approach for characterizing forecast uncertainties. International experience suggests that formal estimates of forecast uncertainty can lead to better and more robust decision making.

For ensemble forecasts to be valuable to users, they need to be as accurate as possible and the ensemble spread should reliably quantify remaining uncertainty (i.e. to ensure the spread is not too wide or too narrow), which is a formidably difficult task. CSIRO, in partnership with the Bureau of Meteorology, have been working to overcome barriers to the development of an ensemble 7-day streamflow forecasting service for Australia. This presentation describes progress towards generating accurate and reliable ensemble streamflow forecasts for lead times of up to 10 days, to support emergency and water resources management applications. Advanced methods are used to estimate historical and real-time sub-catchment rainfall from rain gauge records. These interpolation methods allow for incomplete gauge records, explicitly characterize the effects of covariates, such as elevation, and quantify the uncertainty of rainfall estimates. Statistical post-processing is used to obtain sub-catchment precipitation forecasts from NWP model output, and in the process reduce biases and generate reliable estimates of forecast uncertainty. Semi-distributed hydrological modelling is implemented in computationally efficient software designed for ensemble forecasting. Residual errors in hydrological predictions are reduced and represented using a staged hydrological error model. At each stage the error model reduces uncertainty of hydrological predictions by removing a systematic component of residual errors. The final stage of the error model is used to refine the distribution of residual errors to ensure uncertainty estimates are reliable. Each component of the forecasting system that quantifies forecast uncertainty is able to handle data heteroscedasticity with data transformation, and treats the mixed discrete-continuous distribution of precipitation and streamflow in intermittent streams using continuous distributions and data censoring. We show that the accuracy of streamflow forecasts generated using the integrated system is dependent on catchment area and hydrological characteristics, and that the ensemble forecasts are statistically reliable. We conclude the presentation by highlighting opportunities to further improve forecast accuracy and to support the use of these forecasts to improve operational water management in Australia.

Keywords: *Ensemble forecasts, forecast reliability, hydrological prediction, uncertainty, forecast verification*

What is "sufficient" complexity when modelling urine patches in grazed pastures?

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Abstract: It is well-known that urine patches are the primary source of N leaching from intensively grazed pastures. Grazing ruminants regularly harvest N in pasture from the whole paddock but then deposit the majority of that ingested N into small areas or patches with high N loadings – perhaps of 200 to 2000 kg N /ha covering only 2 to 5% of the paddock area. Such loadings are far in excess of the ability of plants to use the N within a growing season and this is the major driver of leaching in grazed systems. Despite this knowledge, most simulation models ignore the patch nature of urine N returns to pastures and assume a uniform paddock-wide application of urinary N – primarily because of the increased simulation runtime that a patchy return would bring to models. New technology in the simulation model APSIM now allows routine simulation of within-paddock heterogeneity of soil carbon and nitrogen and this can be used to represent individual urine patches. This new technology also opens up questions as to what degree of complexity is necessary. Here we use some new data of individual urine patch load and wetted area that was measured from six dairy herds with a variety of physiological states for six hours a day over seven days (Figure 1). The data shows very high variability and we combined it with the new technology to understand if the complexity of individual urine patch characteristics should be used, or if it is sufficient to include urine patches with average size and load.

Simulations were set up in contrasting environments for ~1200 individual urine patches deposited over a 24-hour period in either March or September and various outputs, but primarily leaching, examined for 24 months after deposition. Simulations with the full complexity of individually varying load and varying area (VL-VA), as shown below, were contrasted with equivalent simulations using the fixed average load and area (FL-FA).

Although the VL-VA simulations had soil mineral amounts that were highly spatially variable, the flow-on effect to whole-paddock pasture production and leaching were minimal. Using this data set alone (Figure 1) we would conclude that consideration of individual patch characteristics is not necessary but with the caveats that we have not yet considered whether this finding holds for the sequential or repeated grazing and deposition events. Also, given that the data shown in Figure 1 are not generally available, it would be prudent to repeat the analysis to investigate if correlation between urine patch load and area might change this conclusion.

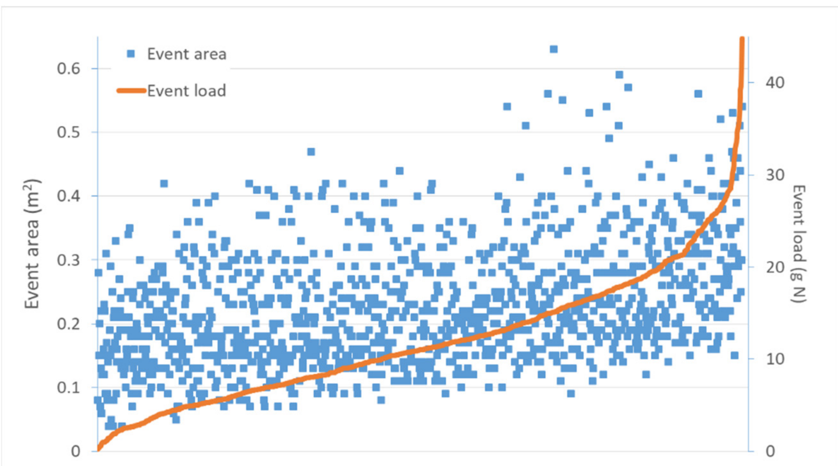

Figure 1. Individual urine patch area (blue symbols, left axis) and N load (orange line, right axis) from the experimental measurements showing the data sorted in order of increasing event load.

Keywords: *Pastoral farming systems, APSIM, process-based modelling, leaching*

Small Area Coupling of Synthetic Census and Spatial Micro-simulation Applied to Mortgage Taxation in Australia

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Abstract: Socially disaggregated and spatially explicit models, like spatial micro-simulation or agent-based modelling, allow for flexible testing of policy interventions at household level and analyzing of their consequences at relevant levels of socio-economic or spatial aggregation. However, the approach requires demographic data both at household and small area levels, information that is not publicly available in Australia. The authors propose to use a synthetic census to generate this information and couple it with a spatial micro-simulator. This paper describes the approach and provides an example of application to taxation in Australia. The application examines the impact of making mortgage interest payments tax deductible, similar to the way that investment property mortgage payments are tax deductible.

Results show that, overall, the proposed change in taxation regime was nearly cost neutral by increasing tax rates for top income earners. The impact of this change is looked at by family type, household income decile and the area that the person is living in. the model shows that this housing policy benefits low income households most, and the impact is relatively similar across all Australian States and Territories. Households with a household head aged 16 – 44 benefit more than those with an older household head, although households who lose most have a household head aged 35 – 44. Single parents with dependent children win most, and couples with dependent children lose most.

These results also show that households in regional and remote areas were mainly in the middle of the distribution in terms of losses, but experienced significant gains due to the rental policy change. Most households in richer areas lost, while households in poorer areas won, due to a mix of lower incomes and greater benefits from being able to claim mortgage payments as a deduction against their income.

From a modelling perspective, the study shows that bringing together a synthetic census and a spatial micro-simulation model is possible using direct linking of the household ID, as long as the two models use the same base dataset. Where this is not the case, then other methods can be used. However, these methods will not provide the same amount of variability as a direct linking.

Keywords: *Synthetic population, micro-simulation, mortgage, small area estimation*

An N-player Trust game: comparison of replicator and logit dynamics

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Abstract: Trust and trustworthiness are fundamental aspects of society. Trust acts as the glue which holds a social system together. The greater the levels of trust, the greater the stability of the society. Further, trust acts as a simplifying heuristic or complexity reduction mechanism. Once trust is established between members of a society it makes possible certain types of exchanges which were not before or greatly simplifies mechanics of existing transactions.

The phenomenon of trust is often studied in a game-theoretic environment known as the trust game or investment game. In this work we consider a variant of the trust game played by N players where N is sufficiently large such that the population of players can be modelled as a continuous quantity. Players may choose the role of trustor, honest trustee, or dishonest trustee continuously throughout the game and earn the associated pay-offs. Decisions are made via two different strategy revision functions: replicator and logit dynamics.

We show that when players base their strategy decisions upon mimicking the successful strategies of players they encounter (replicator dynamics) there is no stable equilibrium in the model with non-zero population proportion of trustors. In contrast, when players choose the strategy with the greatest pay-off in their current situation, but in an environment without perfect knowledge of what is best, a stable equilibrium with trusting players exists.

This work has application in the area of trusted autonomy. Trusted Autonomy refers to two or more interacting and self-governed autonomous intelligent systems (including humans) where one side of the interaction is willing to delegate a task that will make it vulnerable to other parties in the interaction who are willing to accept and can autonomously perform the task. As such these results could inform design decisions of these autonomous systems.

Keywords: *Game theory, trusted autonomy, trust game, investment game, logit dynamics*

A comparative analysis of precipitation estimation methods for streamflow prediction

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Abstract: Surface hydrologic models are widely used for streamflow prediction, forecasting and for understanding hydrologic processes. They are also an important tool for contributing to the resolution of wider resource and environmental issues, providing information to support policies and decisions for water resource management. Precipitation is a key input to hydrologic models and is however also the major source of predictive uncertainty. Whilst station-based observed precipitation data can be adequate for hydrologic modelling in small catchments, they may not be sufficient for large catchments, in particular for large catchments with a mountainous terrain. Areal estimation of precipitation is a potential option to provide more precise precipitation input to models for large catchments. Conventionally, for areal precipitation estimation, station-based precipitation data are interpolated across the model domain using various methods, including Spline fitting, Inverse Distance Weighting (IDW) and the classical Thiessen Polygon, which are among the more popular and commonly used methods. Different precipitation interpolation methods will affect the spatial and temporal variability of areal precipitation inputs, resulting in different uncertainties when used to help calibrate a surface hydrologic model. This paper investigates the effect of the above three types of precipitation interpolation methods (ANUSPLIN surface, IDW surface and Thiessen polygon) on streamflow predictions. The Chaohe basin located in northern China is selected as the study area. It is an important headwater of the Miyun Reservoir which provides drinking water to Beijing and surrounding townships. Three lumped, surface hydrologic models (GR4J, IHACRES and Sacramento) are selected to study the accuracy and predictive uncertainty of these three types of precipitation interpolation on daily streamflow. The models were calibrated separately using discharge observations from three gauges in the basin. The results show that the ANUSPLIN surface interpolation performs the best overall under various combinations of conditions. The IDW surface also performs well in the upper and middle basin but the Thiessen polygon is inferior to the other two methods. The comparison of the three hydrologic models shows that IHACRES and Sacramento perform better than GR4J. The best combination is areal rainfall estimated using the ANUSPLIN derived surface with the IHACRES model in the case study catchments, though the Sacramento model is a close second.

Keywords: *Areal precipitation, ANUSPLIN, IDW, Thiessen polygon, hydrologic prediction*

Sensitivity Analysis to Configuration Option Settings in a Selection of Species Distribution Modelling Algorithms

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Abstract: In pursuit of a more robust provenance in the field of species distribution modelling, an extensive literature search was undertaken to find the typical default values, and the range of values, for configuration settings of a number of the most commonly used statistical algorithms available for constructing species distribution models (SDM), as implemented in the R script packages (such as Dismo and Biomod2) or other species distribution modelling programs like Maxent. We found that documentation of SDM algorithm configuration option settings in the SDM literature is very uncommon, and the justifications for these settings were minimal, when present. Such settings were often the R default values, or were the result of trial and error. This is potentially concerning for a number of reasons; it detracts from the robustness of the provenance for such SDM studies; a lack of documentation of configuration option settings in a paper prevents the replication of an experiment, which contravenes one of the main tenets of the scientific method. Inappropriate or uninformed configuration option settings are particularly concerning if they represent a poorly understood ecological variable or process, and if the algorithm is sensitive to such settings; this could result in erroneous and/or unrealistic SDMs.

We test the sensitivity of two commonly used SDM algorithms to variation in configuration options settings: Random Forests and Boosted Regression Trees. A process of expert elicitation was used to derive a range of appropriate values with which to test the sensitivity of our algorithms. We chose to use species occurrence records for the Koala (*Phascolartos cinereus*) for our sensitivity tests, since the species has a well known distribution. Results were assessed by comparing the geospatial distribution from each sensitivity test (i.e. altered-settings) SDM for differences compared to the control SDM (i.e. default settings), using geographical information systems (QGIS). In addition, two performance measures were used to compare differences among the altered-setting SDMs to the control. The aim of our study was to be able to draw conclusions as to how reliable reported SDM results may be in light of the sensitivity of their algorithms to certain settings, given the often arbitrary nature of such settings, and the lack of awareness of, and/or attendance to this issue in most of the published SDM literature. Our results indicate that all two algorithms tested showed sensitivity to alternate values for some of their settings. Therefore this study has showed that the choice of configuration option settings in Random Forests and Boosted Regression Trees has an impact on the results, and that assigning suitable values for these settings is a relevant consideration and as such should be always published along with the model.

Keywords: *Configuration option settings, provenance, transparency, koala, boosted regression trees*

Estimating model structure errors when observational error variances are known

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Abstract: A new method is proposed to estimate model structure errors in memory-carrying time series models assuming the error models of observational data are known. The method is based on Bayesian uncertainty analysis and relies on the understanding that no model structure is perfect at representing every complex environmental response. This misrepresentation not only causes some immediate error in the simulated response but, due to the inaccurate estimation of the model states, causes further deterioration in following time steps. With the aim to develop a new robust method for estimating model structure error that takes account of potential interactions between all time steps, a new approach is proposed that explores the notion that model structure errors arise from mis-approximations of the model states. The method, therefore, allows for the potential reduction of error propagation problems. The proposed approach is unique to typical state uncertainty estimation approaches since the uncertainty over the whole time series is assessed simultaneously, rather than one time step at a time, as in for example, the Kalman filter.

The current study utilises the Adaptive Metropolis algorithm. The main distinction in the implementation of the current study compared to typical uncertainty analyses is that instead of model parameters being sampled, it is the state and input error values and the initial states (all three lumped into the vector: $\mathbf{x}_i$). Assuming that the forcing data (rainfall) error population mean (μ_{ε_p}) and variance ($\sigma^2_{\varepsilon_p}$) are known, as well as the response data (streamflow) error population mean (μ_{ε_q}) and variance ($\sigma^2_{\varepsilon_q}$), the likelihood function is given by:

$$P\left(\mu_{\varepsilon_p}, \mu_{\varepsilon_q}, \sigma^2_{\varepsilon_p}, \sigma^2_{\varepsilon_q} | \mathbf{x}_i\right) = P\left(\mu_{\varepsilon_p} | \overline{x}_{\varepsilon_p,i}, \sigma^2_{\varepsilon_p}, n_t\right) P\left(\mu_{\varepsilon_q} | \overline{x}_{\varepsilon_q,i}, \sigma^2_{\varepsilon_q}, n_t\right) P\left(\sigma^2_{\varepsilon_p} | s^2_{\varepsilon_p,i}, n_t\right) P\left(\sigma^2_{\varepsilon_q} | s^2_{\varepsilon_q,i}, n_t\right), \quad (1)$$

where $\overline{x}$ and s^2 represent the sample mean and variance, respectively. Note, i indicates that the attached variable is computed during the sampling procedure, and μ_{ε_p} and μ_{ε_q} is set to zero in this study.

The method was tested in synthetic studies using combinations of different rainfall-runoff models, qualities of data, lengths of time series and state error sizes. Results showed that the simpler model provided narrower and more accurate state error posterior distributions than the more complicated model, as did configurations with higher quality data and longer time series (Figure 1).

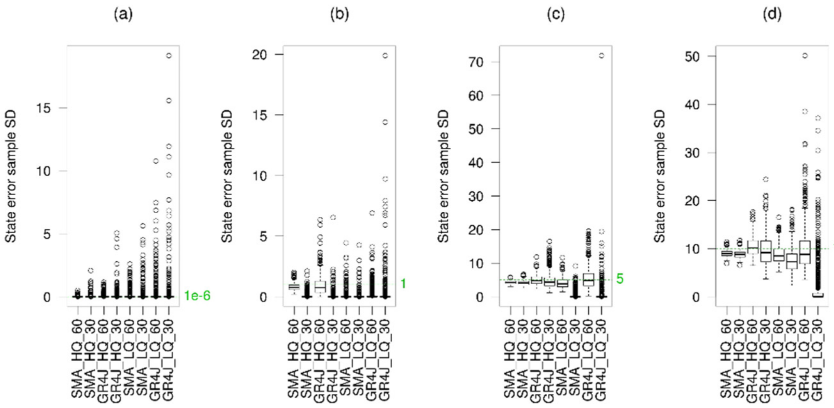

Figure 1. Boxplots of state error sample standard deviations (SD) using state error population SD of (a) 10^{-6}, (b) 1, (c) 5 and (d) 10. Note, SMA: simple model, GR4J: complicated model, HQ: high quality observational data, LQ: low quality observational data, 60: 60 time steps simulations, 30: 30 time steps simulations.

It was found that sampling of a state error scaling factor was required in order to accurately estimate very small state errors. This, however, came with its own artefacts, namely, strong biases towards small state errors, particularly when observational data quality was poor, number of time steps were short and model was complicated. The method has been tested with independent and identically distributed observational data errors. Future research will involve more realistic trials, for example, cases with heteroscedastic errors.

Keywords: *State uncertainty, model structure uncertainty, MCMC, Bayesian uncertainty analysis, error propagation*

Comparison of variance-based and derivative-based sensitivity analyses in terms of computational efficiency and accuracy

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Abstract: Sensitivity analysis (SA) is a useful tool for understanding the behaviour of a model and as a precursor to uncertainty analysis. Global sensitivity analysis (GSA) investigates the entire model parameter space, varying all parameters simultaneously (i.e. all-at-a-time). However, variance-based GSA methods such as the Sobol' method are typically computationally expensive to achieve reasonable convergence. To conduct a sensitivity analysis, a modeller has to make many decisions that meet the purpose of their modelling application. One of the decisions is the selection of an appropriate sampling scheme (including sampling strategy and design).

Many SA methods sample the given parameter space by selecting a suitable sampling technique. The simplest procedure is random sampling by Monte Carlo (MC) which is effective for high-dimensional integrations and does not depend on the dimensionality, however the price for its robustness is long runtimes. Latin hypercube sampling (LHS) is also commonly used. LHS uses a stratified sampling method to ensure full coverage of model parameter space with uniform density and helps reduce the number of sampling runs required. Quasi-Monte Carlo (QMC), also known as low-discrepancy sequences (e.g. Sobol' sequences), can potentially provide even faster convergence.

The preferred characteristics of a GSA are efficiency of sampling of parameter space and accuracy of the sensitivity estimated, especially for parameters that are not highly sensitive and insensitive. Each sampling technique has its own strengths and characteristics and it is worthwhile comparing each of these sampling strategies using practical applications to determine the computational efficiency and accuracy of the sensitivity metrics that they yield. This study examines these issues using a simple rainfall-runoff model. It compares the variance-based Sobol' and the derivative-based active subspaces (AS) methods in terms of the aforementioned preferred characteristics of GSA. The sampling methods considered are MC, LHS, and QMC, with each combination of GSA and sampling method investigated using a number of sample sizes. Firstly, we estimated so-called "true" sensitivity metrics based on $10 * 2^{15}$ samples for the two SA methods and the three sampling schemes. Subsequently, each sample size experiment was replicated 50 times to estimate the confidence achieved and check for convergence. The parameter sensitivity, convergence rate and accuracy are monitored based on a comparison with the "true" sensitivity metrics.

In terms of convergence rate, it was found that all three metrics of AS (first eigenvector, activity score and total sensitivity index) have approximately 10 times faster convergence than the Sobol' metrics, i.e. total sensitivity index (TSI) and first-order sensitivity index (FSI). For the Sobol' metrics, both LHS and QMC showed better convergence rate than MC, with LHS converging slightly faster than QMC for both TSI and FSI (for each sampling method, both indices converged at comparable rates). For all three metrics of AS, QMC showed the fastest convergence rate, whereas LHS and MC had similar convergence unlike the experiments using the Sobol' method. The first eigenvector had the fastest converge rate and is followed by the activity score, and then the total sensitivity index of AS, which corresponds to Sobol' TSI. Using the "true" sensitivity values to estimate accuracy, QMC sampling produced a higher accuracy for all experiments regardless of the type of metric invoked. The metrics of AS showed similar accuracy when using LHS and MC, but MC returned notably higher errors than LHS for Sobol' indices. The study delivers information that helps practitioners to choose a suitable GSA method and an efficient sampling scheme, as well as distilling the advantages of the AS method.

Keywords: *Sensitivity analysis, Sobol' method, active subspaces, sampling method*

A comparison of global sensitivity techniques and sampling method

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Abstract: Inspired by Tarantola et al. (2012), we extend their analysis to include the Latin hypercube and Random sampling methods. In their paper, they compared Sobol' quasi-Monte Carlo and Latin supercube sampling methods by using a V-function and variance-based sensitivity analysis. In our case we compare the convergence rate and average error between Sobol', Latin hypercube, and Random sampling methods from the Chaospy library, keeping everything else the same as in their paper. We added the Random sampling method to test if the other two sampling methods are indeed superior. The results from our code confirm the results of their paper, where Sobol' has better performance than Latin hypercube sampling in most cases, whilst they both have higher efficiency than is achieved with Random sampling.

In addition we compared the explicit forms of 'Jansen 1999' total effects estimator used in Tarantola et al. (2012) with the 'Sobol' 2007' estimator, again keeping sample sizes and the test function the same. Results confirm that the 'Jansen 1999' estimator is more efficient than 'Sobol' 2007'. The presentation will also include the Morris sampling method and other test functions to further test efficiency among all the sampling methods on different cases.

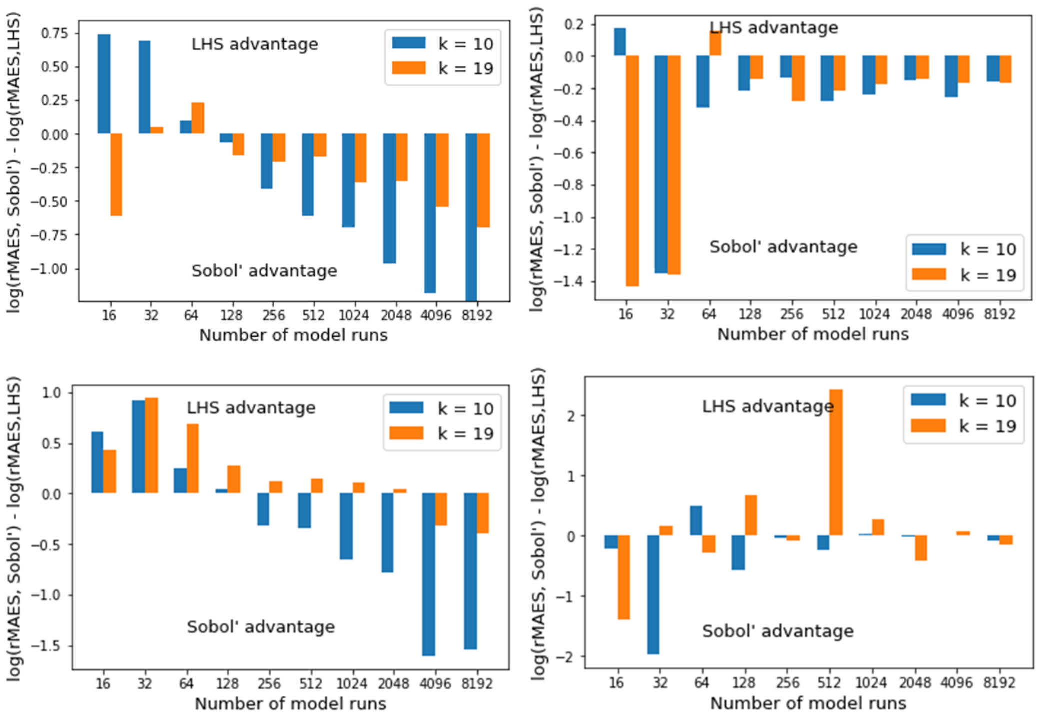

Figure 1. Comparison of rMAES value for Sobol' and Latin Hypercube. Top left is for type A1-1, top right is for type A2, bottom left is for type B, and bottom right is for type C.

Keywords: *Sobol', Latin hypercube, Random sampling, global sensitivity analysis, variance based, total effects estimator*

Accuracy Analysis of the Brownian Motion Approach for the Ballistic Resistance Estimation : Comparison of Numerical and Experimental Distributions

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Abstract: The ballistic resistance assessment is an active research field that deals with the estimation of the perforation probability of a given protection/bullet combination. The modelling challenge is to increase accuracy and precision of estimates based on a small sample of hidden penetration processes (limitation of experimental measurement tools due to the complexity of dynamic impact phenomenon). Actually, existing methods make use of the impacting bullet initial velocity and the protection response coded in a binary outcome (0 if perforation takes place and 1 if not). Recently, a Brownian motion approach has been proposed using the numerical integration of stochastic differential equations. This contribution analysis the sensitivity of the ballistic resistance estimations regarding the model parameters. To fulfil the desired goal, the numerical and experimental distribution of the estimates are compared. Available database allows the computation of a point estimation of the perforation probability at a given impact velocity. Statistical Bootstrap is performed to obtain the experimental distribution of the perforation probability in order to avoid costly experiments. In the other side, the model parameters uncertainty is propagated to the model estimations using Monte Carlo simulations. The resulted numerical distribution encompass the inherent stochastic model randomness and the model parameters uncertainty effect. Furthermore, the numerical experiments are generated as the experimental observations in the interest of a fair comparison. First, the numerical and experimental distributions are compared regarding the optimum values of the model parameters and randomly selected values over the tolerance intervals. It is concluded that the model presents a low sensitivity to the parameters estimation. Next, the experimental and numerical variance of the perforation probabilities are investigated. It is observed that the model estimations are in good agreement with the experimental one. Finally, the distribution of the mean difference between the numerical and experimental distributions is analysed as a function of the bullet impact velocity. Again, the model appears to have a low sensitivity to its parameters estimation uncertainty. Further-more, it is showed that the model performance depends on the bullet initial impact velocity. Therefore, it is suggested to further investigate the functional form of the stochastic differential equation coefficient in order to better estimate the perforation probability as a function of the initial impact velocity.

Keywords: *Stochastic model, Brownian motion, ballistic resistance, model sensitivity, perforation probability*

Graphical diagnostics for classification trees using asymmetric penalties on misclassification

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Abstract: Classification trees are powerful modelling tools, which are widely applied in several disciplines. Despite their popularity, there are few diagnostic methods available for evaluating their performance. Many extensions have focused on improvements of predictive performance by combining many models via model averaging, such as boosting and bagging.

Boosting is widely used to improve the performance of many algorithms. It consists of learning several weak classifiers to build a final strong classifier. Another popular method, used to improve performance, is bootstrap aggregating, also known as bagging, which is another special case of model averaging. In bagging, several training data sets are randomly sampled from the data with replacement, and for each of those sets, the same classifier is applied. The prediction of new data is obtained by averaging predictions from individual models. Model averaging approaches like this perform well for prediction but not so for interpretation, as they do not provide a single model that can be used to explain the relationships among variables. Here, we consider graphical diagnostics to support selection of one single model for explanatory purposes.

In addition, predictive performance of a single model typically presumes that all kinds of misclassification are equal. In our example, misclassifying pest presence could be devastating when the aim is early detection. In contrast, misclassifying pest absence would be problematic if aiming to claim that an area is free of a pest. Of particular interest in the motivating case study, is how to improve the model by applying different penalties for misclassification of each class. This work proposes a new set of diagnostics, specifically for evaluating classification trees, their predictive performance and sensitivity to misclassification penalties. Such diagnostics can only be applied when the algorithm for fitting a classification tree adopts criteria that allow asymmetric misclassification penalties. One example is recursive partitioning with penalties ("loss" matrix) implemented in `rpart` in `R`.

The use of penalties in constructing classification tree models appears to be a feature that is little used in practice. We suspect it is because there are no diagnostics readily available to examine sensitivity to value assigned to those penalties. In contrast, the use of graphical diagnostics for sensitivity analysis is a common practice in many types of analysis, such as cluster and factor analysis. Here we develop and present a new graphical approach for diagnostics of a single classification tree fitted using recursive partitioning, where both the goodness-of-fit criteria and the threshold for classification are weighted by penalties for misclassifying each class.

Our method exploits detailed information provided with the results from fitting a tree: node height and change in height, which represent the amount of information added to the model and improvement in fit gained by each split, respectively. We also define new measures of fit that are of particular interest when penalising classes, which measure how well classes are separated, and the number and size of 'pure' nodes that perfectly predict each class.

In this paper we demonstrate how to use these new graphical diagnostics, for a plant biosecurity case study to describe potential distribution model for a pest, the Russian Wheat Aphid (RWA). We show that these new graphical diagnostics for tree reveal insights that would not be evident otherwise. Using a high penalty on false negative misclassification, it was possible to identify factors (such as precipitation in July, and Temperature seasonality) that corresponded to large groups of reported absences (pure nodes on the tree). Using the diagnostic, we were able to evaluate sensitivity to the magnitude of the penalty. With small penalties, only a few pure absence nodes were identified. With larger penalties, the fit deteriorated.

Keywords: *Classification trees, graphical diagnostics, error rates, penalty for misclassification, cost-sensitivity*

Induced seismicity in producing hydrocarbon reservoir: a Bayesian approach

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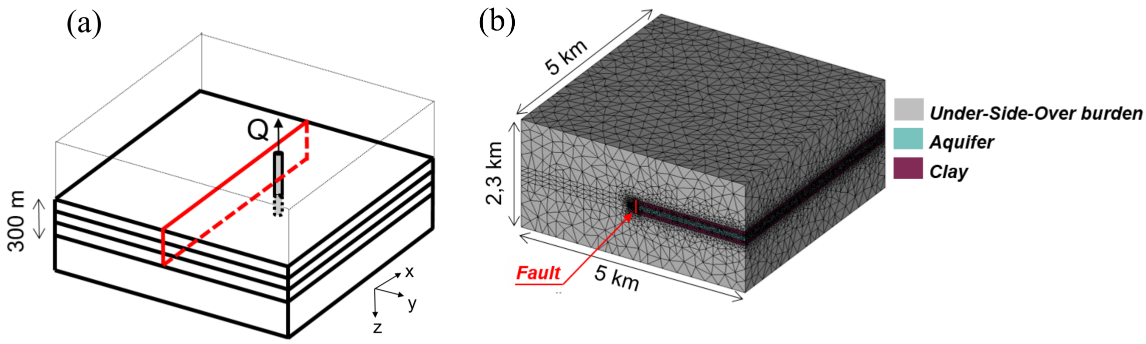
Abstract: Induced and/or triggered seismicity is becoming extremely important within the general geomechanical modeling framework of ground response to subsurface resources exploitation. The variation of loading conditions due to injection and/or extraction of fluids may cause the faults re-activation and the opening of new fractures that may generate (micro)seismic events. The aim of this work is at developing a mathematical framework to quantify and possibly reduce the model uncertainties by assimilation of seismic data. The fault mechanics is simulated by a Finite Element (FE) numerical model, where the discontinuous displacements between the fault surfaces are suitably considered using appropriate Interface Elements (IEs) by means of a Lagrangian approach. A global sensitivity analysis based on the computation of the Sobol' indices is first carried out to characterize the influence of each model input and their combinations on the model solution. In particular, the effect of the Mohr-Coulomb parameters, i.e., the fault cohesion and the friction angle, and the initial stress regime described in terms of principal stresses are considered. The indices are computed based on the surrogate solution of the forward model using the generalized Polynomial Chaos Expansion (gPCE). Then, an inverse problem is solved to constrain the model parameters with seismic data, e.g., magnitude, collected over the reservoirs by appropriate seismic networks using a Markov Chain Monte Carlo (MCMC) sampling technique based on the gPCE surrogate solution. A 3D synthetic case (see the figure below) of fluid withdrawal at 1100 m depth is employed to investigate the effectiveness of the proposed methodology. The results appear to be promising as the updating approach is capable to reduce the prior information on the parameters around their true reference values. The outcome from the Bayesian update underlines that records of seismic magnitude are likely to infer information on the initial state of stress rather than on the cohesion coefficient and the friction angle.



(a) Schematic representation of the synthetic test case with the location of the extracting well and (b) axonometric view of the 3D FE grid. The vertical fault is highlighted with a red solid line.

Keywords: *Induced/triggered seismicity, geomechanical modeling, uncertainty quantification, polynomial chaos expansion*

Estimation of direction of increase of gold mineralisation using pair-copulas

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Abstract: The case study is based on a gold deposit in western Ghana. One thousand five hundred surface soils samples are available on an area of 7810 hectares. The distribution of the grade appears to be a realization of a non-stationary anisotropic random process. The objectives of the analysis are to model the gold grade and to extrapolate into the near surrounding area to determine regions of highest gold value for a future drilling campaign. In the analysis we compare possible transformations of the data to reduce the influence of outliers, and in the case of copulas achieving a marginal uniform distribution. The anisotropy of the gold grades is described with empirical copula density plots for each distance class and for two orthogonal (135° and 45°) directions. The non-stationarity is modelled by regression methods including periodic variation if appropriate. The residuals from the regression are modelled with spatial pair copulas. An investigation of the possible benefits of increasing the number of nearby locations modeled in the spatial pair copula construction is utilized. Predictions are done for unknown sample locations to the North-East (NE) and South-West (SW) of the main field. The different approaches of increasing the nearby points are compared in terms of minimum, maximum and average predicted grade at all unknown sampling locations outside the main field.

Keywords: *Copula, geostatistical modelling, pair-copula, kriging*

Bayesian Gaussian models for interpolating large-dimensional data at misaligned areal units

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Abstract: Areal level spatial data are often large, sparse and may appear with geographical shapes that are regular (e.g., grid based climate model output) or irregular (e.g., postcode). Moreover, sometimes it is important to obtain predictive inference in regular or irregular areal shapes that is misaligned with the observed spatial areal geographical boundary. For example, in a survey the respondents were asked about their postcode, however for policy making purposes, researchers are often interested to obtain information at the statistical area level 2 (SA2) – a geographical area defined by the Australian Bureau of Statistics (ABS). This level of geography is the lowest for which the ABS outputs population projections and migration data, and is used as the basis for much of the spatial analysis undertaken in Australia. The statistical challenge is to obtain spatial prediction at the SA2s, where the SA2s may have overlapped geographical boundaries with postcodes.

The study is motivated by a practical survey data obtained from the Australian National University (ANU) Poll. Here the main research question is to understand respondents' satisfaction level with the way Australia is heading. The data are observed at 1,944 postcodes among the 2,516 available postcodes across Australia, and prediction is obtained at the 2,196 SA2s. This paper develops a modelling approach to address the issue with prediction or spatial interpolation at the SA2s, where postcodes and SA2s have geographical boundaries that overlaps.

The proposed method also explored through a grid-based simulation study, where data have been observed in a regular grid and spatial prediction has been done in a regular grid that has a misaligned geographical boundary with the first regular grid-set. The real-life example with ANU Poll data addresses the situation of irregular geographical boundaries that are misaligned, i.e., model fitted with postcode data and hence obtained prediction at the SA2. A comparison study is also performed to validate the proposed method.

In this paper, a Gaussian model is constructed under Bayesian hierarchy. The novelty lies in the development of the basis function that can address spatial sparsity and localised spatial structure. It can also address the large-dimensional spatial data modelling problem by constructing knot based reduced-dimensional basis functions.

Keywords: *Bayesian spatial models, basis functions, misaligned areal units*

Assessment of the effects of the inclusion of poor quality sediment samples on spatial predictions of seabed sediments in the Australian marine margin

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Abstract: Spatial predictions of seabed sediments based on samples in the Australian Marine Samples (MARS) database provide environmental baseline information used in the management of Australia's marine jurisdiction, offshore resource development, and marine protected areas. Interpolations of seabed samples are often required for understanding target regions between collection sites. Data quality in the MARS database varies, with data quality control resulting in the exclusion of over 7,000 samples, most of which were dredged samples. Dredged samples are thought to lower the accuracy of the spatial predictions produced from the database. In this study we examined whether these excluded dredged samples should be used for spatial predictions by assessing whether the dredged samples decreased or increased the accuracy of the resulting spatial predictions of seabed mud content, and whether the dredging method used altered the accuracy of the resulting prediction.

We confined our analyses to two contrasting areas in the Australian Exclusive Economic Zone (AEEZ): the Southwest Region (407 total samples; 150 dredged) and Petrel Region (534 total samples; 297 dredged). We compared the accuracy of interpolated surfaces of mud content generated from quality controlled (QCed) samples with surfaces generated with samples from different dredge types (benthic, pipe, chain bag and unspecified). In the Southwest region samples included 73 benthic, 19 pipe, 41 chain bag, and 17 unspecified dredged samples. In the Petrel region samples included 46 pipe and 251 unspecified dredged samples. Spatial predictions of seabed mud content were made using Inverse Distance Weighting (IDW) and Ordinary Kriging (OK). Predictive errors were assessed based on leave-one-out cross-validation in terms of relative mean absolute error (RMAE). The effects of the dredged samples on the predictive error were analysed using paired Mann-Whitney tests.

For sediment samples in the Southwest region, including benthic dredge samples in the prediction reduced the accuracy of IDW by 1.79% in terms of RMAE. Including chain bag dredge samples increased the accuracy of IDW with a small difference in RMAE of 0.47%. The difference in accuracy of IDW was insignificant for the unspecified type samples, all dredged sample types and pipe dredged samples. Including samples with all-dredged type and unspecified type dredge samples improved the accuracy of the OK predictions over the QCed samples in the Southwest region with a small effect on RMAE of 0.68% for all-dredged samples and 0.65% for unspecified type dredged samples. The difference in accuracy of OK was insignificant for benthic dredged, pipe dredged and chain bag dredged samples in the Southwest region. No significant effects on the accuracy of IDW in the Petrel region were found for all the tested dredged sample types (unspecified type, pipe dredged samples, and all-dredged samples). The difference in accuracy of OK in the Petrel Region for samples with all dredged and with unspecified dredged samples was insignificant. Including pipe dredged samples increased the accuracy of OK in the Petrel with a negligible effect on RMAE of 0.02%.

In summary, the inclusion of dredged samples produced minimal effects on the accuracy of spatial predictive models. Effects were not consistent across region or dredge type, but findings showed dredged samples had surprisingly little effect on the accuracy of the predictions. Including the dredged samples would require reprocessing the spatial predictions for the AEEZ based on the MARS database, so as the findings are only based on mud sediment data from two regions, caution should be taken to generalise these findings to other sediment types and to the entire Australian marine margin. Further testing is required to verify these findings for other methods, regions and sediment types and identify whether future spatial predictions can include some of this extra data without a loss in accuracy.

Keywords: *Spatial interpolation, inverse distance weighting, ordinary kriging, seabed sediment samples, dredge sampling types*

Incorporating an operational satellite-derived leaf area index into a computationally efficient semi-distributed hydrologic modelling application (SMART)

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Abstract: The Soil Moisture and Runoff simulation Toolkit (SMART) is a GIS-based semi-distributed hydrologic modelling framework designed for large catchment scale simulations. Computational efficiency in SMART is achieved by formulating topologically connected Hydrologic Response Units (HRUs) and series of equivalent cross sections (ECSs) delineated by weighting topographic and physiographic properties of a part or an entire first-order sub-basin. The current version of SMART adopts the Unsaturated Soil Moisture Movement Model (U3M-2D) to solve the 2-dimensional Richards' equation using spatially distributed climate, land cover and soil type information. To incorporate the impact of vegetation dynamics on catchment hydrology, U3M-2D adjusts the user defined monthly Leaf Area Index (LAI) climatology data for different land cover types using monthly mean rainfall. The scaled monthly LAI is finally used for adjusting potential evapotranspiration input for the hydrologic simulation.

This study aims to investigate possibility of using operational satellite-derived LAI data to directly incorporate changes in evapotranspiration caused by vegetation growth stage in the hydrologic simulation. For the investigation, we selected two ecohydrologically contrasted catchments from the Australian Hydrologic Reference Stations (HRS) dataset. The HRS catchments have relatively long-term records of high quality stream flow data which are not impacted by anthropogenic factors such as river flow regulation and land use change. Although the two catchments, with station numbers 215002 (1382 km^2) and 412028 (2630 km^2), have almost similar percentages of vegetation cover classes, the dynamics of LAI against precipitation are different. Therefore, they are classified as two different ecohydrological catchment classes, one being water limited (412028) and the other is nutrient/light limited (215002).

We performed 16 years of model simulations based on availability of MODIS LAI product to assess the impact of incorporating vegetation dynamics on simulated runoff and soil moisture. Preliminary results suggest that the degree of sensitivity of hydrologic simulations to vegetation dynamics in ecohydrologically contrasted catchments is different between the two simulation scenarios in the studied catchments. Further investigations will be performed to assess model performance against in-situ and satellite based observations.

Keywords: *Soil Moisture and Runoff simulation Toolkit (SMART), Semi-distributed hydrologic modelling, Hydrologic Response Units, Unsaturated Soil Moisture Movement Model (U3M-2D), Leaf Area Index (LAI)*

Selecting predictors to form the most accurate predictive model for count data

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Abstract: Spatial predictive models have been increasingly employed to generate spatial predictions for environmental management and conservation. The accuracy of predictive models and their predictions is essential to support evidence-based decision making with high-quality information. However, the development of predictive models with high predictive accuracy can be challenging in environmental sciences because causal predictors are often unavailable and proxy predictors are used instead. Therefore, it is essential to select a subset from a set of potential proxy predictors to form a predictive model with high predictive accuracy. In this study, we use a dataset from a marine conservation area in northern Australia containing 77 samples with sponge species richness (SSR) as the response variable and 49 seabed biophysical variables (i.e., proxy predictors). We use random forests (RF), generalised linear models (GLM), lasso and elastic-net regularized GLM (glmnet) and their hybrid methods with geostatistical techniques (i.e. ordinary kriging (OK) and inverse distance weighting (IDW)). For RF, five feature selection methods were used: 1) averaged variable importance (AVI); 2) Boruta; 3) knowledge informed AVI (KIAVI); 4) recursive feature selection (rfe), and; 5) variable selection using RF (VSURF). For GLM, six variable selection (i.e., model selection in statistics) methods were employed to select GLM predictive models: 1) stepAIC; 2) dropterm; 3) anova; 4) regsubsets; 5) bestglm and; 6) RF. The accuracy of predictive models was validated based on 10-fold cross validation in terms of VEcv (i.e., variance explained for predictive models based on cross-validation). In this paper, we discuss the research findings in relation to: 1) feature selection methods; 2) the influence of initial input predictors and highly correlated predictors for RF; 3) variable selection methods for GLM and glmnet; 4) goodness of fit and predictive models for GLM and; 5) the hybrid methods for count data. The case study provides an example of predicting the spatial distribution of count data using RF, RFOK and RFIDW, and offers guidelines for selecting predictors for RF, GLM and glmnet predictive models based on predictive accuracy instead of parsimoniousness. This study also provides important environmental baseline information with improved accuracy for the informed monitoring of ecosystem health within the Oceanic Shoals Commonwealth Marine Reserve, northern Australia.

Keywords: *Machine learning, feature selection, model selection, predictive accuracy, spatial predictive model, spatial prediction*

DoTRules: a novel method for calibrating land-use/cover change models using a Dictionary of Trusted Rules

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Abstract: Predictive models such as cellular automata are beneficial in understanding the dynamic processes of land-use/cover change (LUCC) and supporting policy and management decision making. Here, we simulated LUCC using a new method, DoTRules—a dictionary of trusted rules—combined with a cellular automata model. DoTRules is introduced as a predictive LUCC simulation approach as a simple alternative to more complicated machine-learning algorithms for calculating transition rules for simulating LUCC in cellular automata. DoTRules is designed for prediction when a large amount of categorical/discrete data are involved. It is similar to the random forest method insofar as rule sets are used to select the mode response among every available potential response variable. However, instead of generating random trees, DoTRules operates by constructing many rules from a training dataset, with land-use assigned to the most frequently occurring land-use class. Shannon entropy is also calculated to assess the reliability of each rule. Following our method formulation the lower the entropy values indicate to the higher reliability of transition rules. We applied DoTRules in simulating LUCC in the Ahvaz region in Iran, and mapped the accuracy of LUCC projections based on the entropy intervals. To this end, three sets of Landsat image for the years 1985, 1991, 2000 along with the target year of 2006 were used. Three groups of independent predictors including time sequence (TS= 3 variables), neighbourhood values (NV= 15 variables) and suitability values (SV = 6 variables) along with one target variable were extracted from the main data sources for LUCC simulation. Training sample size also influences the predictive ability of transition rules; hence, we assessed the effect of sample sizes of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% in the derivation of transition rules for LUCC simulation, with the remaining cells used for accuracy assessment. The overall accuracy of automata-based LUCC simulations using the DoTRules approach was lower than those calibrated with the established random forest method at small sample sizes, but higher at larger sample sizes. In addition, the method enables the spatial mapping of prediction accuracies. We believe this novel approach can be applied more generally to similar predictive land-use modelling problems, which deal with dynamics in discrete or categorical data.

Keywords: *DoTRules, Land-use/cover change, Shannon entropy, Accuracy map*

A Fuzzy Optimisation Model with Applications to Air Pollution Exposure Mitigation

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Abstract: Exposure to air pollution has been extensively associated with adverse health effects, including cardiovascular illness and premature mortality. To reduce the risk of exposure, Australian state governments develop candidate mitigation strategies outlining specific actions and interventions to reduce emissions of, and exposure to, air pollutants. However, a common challenge in air quality management lies in selecting the optimal control strategies from a potentially broad range of candidate strategies to mitigate exposure whilst adhering to budgetary requirements and national air quality standards. The complexity of this challenge is further compounded by the many different, incomparable types of uncertainty inherent to air quality analyses.

To this end, optimisation models have been a commonly used tool in air quality management. However the majority of optimisation models presently available in the literature typically focus on minimising implementation costs alone, with limited consideration of uncertainty in model parameters.

In this paper, a theoretical optimisation model is formulated and solved to accommodate for uncertainty to some extent in model parameters and the optimal solution. The developed model is applied in an air pollution context to identify cost-effective strategies to potentially reduce pollution exposure, with the objective of maximising the estimated societal health benefits, rather than implementation costs alone, under uncertainty. Within the model, the inherent spatiotemporal uncertainty of emission analyses can be represented, to an extent, through the combination of traditional linear programming techniques with the principles of fuzzy logic. This is an attractive modelling approach as fuzzy logic allows for imprecise model parameters.

The developed model is solved using a fuzzy linear complementary problem approach with Lemke's pivoting algorithm. The numeric model output is complemented with maps of the model results, including health impact maps showing the expected number of adverse health episodes potentially avoided through the implementation of the optimal solution. These maps allow for simple, quick interpretation of the model results and easy identification of areas with the greatest, and least, potential for health impact.

The use and format of model results are demonstrated through an application to Adelaide, South Australia, under sample emission scenarios. The performance of the developed fuzzy model is evaluated through a comparison against the corresponding 'crisp' model wherein all model parameters are assumed to be precisely defined. The results indicate that the fuzzy model is able to identify a cost-effective control strategy, or combination of strategies, to potentially reduce pollution exposure within the limited context of the sample application. Results are consistent between the developed fuzzy model and the corresponding crisp model however the fuzzy model has the additional advantageous feature of representing parameter uncertainty to some extent through the provision of upper and lower limits on the model results.

There are complex processes beyond the scope of the developed theoretical model which impact on emission analyses. However the developed optimisation model is a step towards an accountable framework for air quality managers to aid the selection of cost-effective mitigation strategies that maximise the health benefits to society while accommodating, to an extent, for the associated uncertainty.

Keywords: *Air pollution, optimisation, fuzzy logic, exposure mitigation*

Effects of Spatial Reference Systems on the Accuracy of Spatial Predictive Modelling along a Latitudinal Gradient

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Abstract: Spatial predictive information is essential for applications such as modelling, planning, risk assessment and decision making. Previous studies have examined the complex factors that affect the performance of various spatial interpolation methods including sampling density, data variation, spatial structure of data, spatial distribution of samples, data quality, secondary variables and interaction among these factors. Another potential source of error is the Spatial Reference System (SRS) according to which the spatial information is stored. All SRSs generate spatial distortions of reality in some form, and this may impact on the accuracy of spatial predictions. Preliminary investigations into this issue found negligible differences in the predictive errors using different SRSs. However, these studies have tested regions restricted to the latitude extents of the Australian continent. The latitudinal gradient needs to be investigated for its effect on SRSs and any resulting impact on interpolation performance.

This study examines the effects of ten different SRSs on spatial predictions using three datasets in regions spanning a long latitudinal gradient from approximately 10°S to 70°S. The study areas are located off the northern coast of Australia, southern coast of Tasmania, and on a section of the Antarctic coast. The tested SRSs consist of two geographic coordinate systems (i.e., WGS84 and GDA94), six map projections selected for minimal spatial distortion for datasets located in Australia (i.e., Equal-Area Azimuthal, Equidistant Azimuthal, Stereographic Conformal Azimuthal, Albers Equal-Area Conic, Equidistant Conic and Lambert Conformal Conic), and two map projections selected for minimal spatial distortion for datasets located in Antarctica (i.e., Australian Antarctic Lambert and Australian Antarctic Polar Stereographic). Continuous spatial predictions of seabed sand sediment information were built in the SRSs using two interpolation methods: inverse distance weighting (IDW) and ordinary kriging (OK). Prediction accuracy was measured using leave-one-out cross validation, and assessed in a number of error measures including relative mean absolute error and paired Mann-Whitney tests.

The results show insignificant differences in predictive errors between all tested SRSs over the studied latitudinal gradient. This is the case for comparisons between WGS84 and GDA94, geographic coordinate systems and map projections, and map projection classifications. Insignificant difference was also observed between the map projections selected for Australia compared to the map projections selected for Antarctica, even when the Australian map projections were tested on the Antarctic study area and vice versa. There was a high level of variation in map distortion occurring between SRSs, but this did not equate to variation in interpolation error. It is argued that this is due to the nature of projecting data; distortion is applied consistently to all data points and thus the spatial relationship between data points is preserved in terms of their relative distance within the study area, resulting in similar prediction errors.

The negligible levels of variation between SRSs in terms of predictive error suggest that WGS84 is sufficient for spatial predictive modelling. This removes the need for extensive projection selection and the associated transformation tasks, improving modelling efficiency.

Keywords: *Spatial Reference System (SRS), map projection, spatial predictive modelling, inverse distance weighting (IDW), ordinary kriging (OK), predictive accuracy*

A numerical modeling of natural gas using multistage membrane permeation

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Abstract: In this paper, a mathematical model is presented that has been developed using membrane permeation for the recovery of helium from natural gas in hollow fiber modules. Recovery of helium from natural gas is an important process, so investigating a robust and accurate numerical model is of great significance for membrane gas separation industry. The numerical approach described in this paper illustrates the correct separation of helium by a membrane module with minimal computational effort. The model has also been applied for multi-stage membrane permeation to check its flexibility at various operating conditions. To our knowledge, this is the first reliable numerical investigation for the recovery of helium from a gas mixture, consists of six components by using multistage membrane permeation with countercurrent flow pattern. The mathematical modeling comprising six components is a complex and demanding research task in terms of the computational programming required for its solution. Broyden's method and Paterson approximation are used in this paper to deal with the computational complexities of the numerical model. Membrane stem structures and operating conditions are easy to improve with this numerical model because of its algebraic nature and simplicity.

Keywords: *Numerical modeling, membrane gas separation, countercurrent, multistage permeation*

A multi-criteria approach to academic workload allocation: A case study

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Abstract: Allocating academic staff to the teaching and chairing of units (subjects) is a highly complex decision making task for university management. There are a number of factors (goals) to be considered in the decision making process, subject to possibly even more factors that restrict the decision search space. In this paper, we discuss our decision support system that can cut days or weeks of manual planning time down to just minutes of computation time. With the complex and tedious tasks handled by a computer, school management can then make higher level decisions, resulting in significant improvement to the decision making process and more importantly, the decision outcome.

At the end of each year, all academics are given the opportunity to list and rank 5 units (from 1 to 5) that they would prefer to teach. These preferences will then be considered by the school's management when making decision on the unit/staff allocation. Afterwards, the workload (in units of hours) for each staff will be calculated, and many rounds of revision will be carried out. These are all performed manually, and takes a long time. By the beginning of the following year, all academics will receive a workload spreadsheet that details the units they are allocated to teach and chair, and the number of hours of teaching and service-related work that are associated with these units: such as academic student support, online resource management, unit campus coordination, class delivery, online seminar, and so on. Staff may or may not agree to these allocations, and then many rounds of discussions, negotiations, and revisions of workload will be needed by the management. Sometimes the change of allocation for one unit will trigger a sequence of changes for many other units, hence making the workload decision process incredibly sophisticated and tedious.

To automate the most complex part of the decision process, which is the allocation of staff to units and unit chairs, we developed a decision support system that is based on an integer programming (IP) model for solving the allocation problem with a number of possible objectives for management to consider. In the IP model, we use a binary decision variable $x_{u,t}^{c,s}$ to decide whether an academic s is to teach a unit u at a particular campus c in a particular trimester t, and a binary decision variable $z_{u,t}^{s}$ to decide whether a staff that is teaching Unit u in Trimester t will be the chair of the unit. We also use continuous variables ϵ_t^s and σ_t^s to measure the excess or slackness in workload Staff s will be performing in Trimester t respectively.

We use constraints to make sure that no more than one academic is allocated to teach a unit at a particular campus in a particular trimester, and the role of unit chair will be allocated to exactly one staff member who is teaching the unit in one of the campuses. We then use two constraints each for measuring the excess or slackness in the workload of each staff member. We also add constraints that will ensure a staff member is not teaching more than a particular number of units in a particular trimester (this number is by negotiation with management and is an input parameter).

There are several objectives to this optimisation problem: 1) to minimize the number of unallocated units; 2) to minimize the total excess workload $\sum_s \sum_t \epsilon_t^s$; 3) to minimize the total slackness in workload $\sum_s \sum_t \tau_t^s$, and 4) to maximize staff preference using their ranking score $\sum_s \sum_t \sum_c \sum_u \mathcal{P}_{u,t}^s x_{u,t}^{c,s}$, for $\mathcal{P}_t^s$ Staff s's preference score for teaching Unit u in Trimester t. We experiment with a number of approaches. 1) To use a weighted objective function. 2) To use a lexicographical approach, and by optimising the first objective function, the school's management will have early knowledge of extra teaching staff required to fill all teaching roles, with subsequent objectives be considered one by one, with the optimal values of the earlier objectives added to the IP as a constraint. E.g., when optimising with respect to the third objective function, the constraint $\sum_s \sum_t \epsilon_t^s \geq z_2^* - \delta$ can be added, for z_2^* the optimal value obtained in the previous round for the second objective function, and $\delta > 0$ a tolerance. 3) To find the Pareto set for management to consider.

Keywords: *Workload allocation*

The Optimal Location of Ambulance Stations in a Regional Area: The Case of Mackay

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Abstract: The provision of efficient and effective emergency service such as ambulance service is a task faced by most cities and major regional centres. The emergency medical service is very necessary and plays a vital role in reducing death or serious complication from life threatening health incident. Over the years, there have been several major initiatives to improve the access to and quality of emergency care in Queensland. In 2009-2010, public hospital Emergency Departments (ED) in Australia covered about 7.4 million emergency cases of which there were over 3 million ambulance incidents.

Mackay is a regional city in Queensland, Australia's east coast. The Mackay Metropolitan which comprises of 24 suburbs is prone to natural disasters such as cyclones and flood. The Mackay region depends highly on emergency services especially during disasters. The current ambulance locations in the Mackay Local Ambulance Service Network (LASN) are significantly underperforming with regard to not meeting the target response time according to Queensland 2014 ambulance report. Early response to emergency calls is important and crucial for human survival. The response time is a function of the distance between the emergency facility and emergency demand. It is therefore important to locate emergency facility such that the distance to be travelled by an ambulance in response to emergency call is minimized.

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 objective of this study is to discuss the importance of the application of the *p*-median model to locate emergency stations. We compare existing ambulance stations with the optimal solutions proposed by the *p*-median location models in the Mackay region. We determine the cost of assessing the facilities that are located using the *p*-median model and showed the cost saving of the model when optimal locations are compared with locations when facilities are added to the existing ambulance locations optimally.

Keywords: *Optimal, emergency, ambulance, cost*

Genetic linkage to explain genetic variation

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Abstract: Population genetics theory has been used to develop models to inform biodiversity conservation. The implementation of these models for the decision-making, monitoring and evaluating conservation efforts has improved their efficacy. Many of these models are based on neutral loci, which are assumed to not have any effect on the survival or reproduction of organisms. However, when neutral loci are linked to loci that are under selection, they do not follow the expectations predicted by theoretical neutral models. The term linked selection has been used to refer to this phenomenon.

Linked selection might accelerate the rate of loss of genetic diversity, with respect expectations under neutral models. This acceleration is typically expected to occur under two different scenarios: selective sweeps and background selection. A selective sweep occurs when an advantageous allele is spread across the population along with the alleles that are linked to it. Conversely, background selection occurs when a deleterious allele is eliminated from the population along with the alleles linked to it. A third scenario of linked selection has been hypothesised to occur in small populations: associative overdominance. This scenario rather than an acceleration involves a retardation of the loss rate of genetic diversity. The proposed mechanism in operation is a type of natural selection that maintains two or more alleles in the population (*i.e.* balancing selection). Ultimately, linked selection will bias the conclusions obtained by neutral models.

To investigate the mechanisms by which linked selection alters genetic diversity, we built a population genetics model incorporating the main factors involved in the occurrence of linked selection. We modelled the following factors: recombination/linkage disequilibrium, fitness/selection, population size and dominance. Our overall aims are twofold:

- Build a model that serves as a base to develop more complex models to test competing hypotheses of linked selection.
- Implement the model in a programming language and validate it against theoretical expectations

The model was implemented in the programing language R and was extensively tested. The program produces outputs that are consistent with predictions from population genetics theory. By using this model as a starting point, we will be able to investigate potential mechanisms by which linked selection affects genetic diversity and its derived consequences. Our research may highlight the importance of the need to adjust neutral models.

Keywords: *Associative overdominance, population genetics, linkage disequilibrium, linked selection*

Lattice models of habitat destruction in a prey-predator system

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Abstract: In recent decades, species extinction has become one of the most important issues in ecology and conservation biology. Such extinctions are mainly caused by habitat destruction. The destruction has no possibility of recovery for endangered species unless the destroyed habitat is restored. Furthermore, even if the destruction is restricted to a local area, its accumulation increases the risk of extinction. Habitat destruction not only reduces the habitat area but also fragments the habitat. In the present article, we introduce three types of destruction models. i) Bond destruction: the fragmentation occurs, but habitat area is never reduced. ii) Random site destruction: both fragmentation and area loss occur. iii) Rectangular site destruction: the habitat area is reduced, but fragmentation never occurs. We apply a lattice system composed of prey and predator, and compare the effects of the three types of habitat destructions. Simulations reveal that outcomes entirely differ for the different models. The density of prey or predator undergo complicated changes by destructions. The habitat fragmentation is much more serious for species extinction than the area loss of habitat. In our simulation, extinction only occurs for fragmentation models. For the random site destruction, we universally obtain a "40% criterion": when the proportion of destroyed sites exceed percolation transition (40%), the risk of species extinction suddenly increases. Moreover, we find an asymmetric effects on predator and prey. In all destruction models, the steady-state density of predator tends to decrease with the increase of the magnitude (D) of the destruction. In contrast, the effect on prey is rather opposite: prey density usually increases with increasing D.

Keywords: *Stochastic cellular automaton, area loss of habitat, habitat fragmentation, prey and predator, percolation transition*

Analysis of the activated sludge process in a reactor configuration employing three reactors

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Abstract: The activated sludge process is the most widely used process for the biological treatment of do-mestic and industrial wastewaters. Wastewater treatment plants based on the activated sludge process are in widespread use in developed and developing countries. The activated sludge model number 1 is an interna-tionally accepted standard for activated sludge modeling. It describes nitrogen and chemical oxygen demand within suspended-growth treatment processes, including mechanisms for nitrification and denitrification.

We analyse the biological treatment of a wastewater when a cascade of three reactors is used. Operating conditions are investigated in which all three reactors are aerated, only the last two reactors is aerated, and only the final reactor is aerated. The process configuration includes one settling unit and two recycle units. The settling unit is placed after the third reactor and its recycle stream is fed into the second reactor. The recycle units recycle from the second reactor the first reactor and from the third reactor to the second reactor.

A combination of direct numerical integration and continuation methods are used to investigate the steady-state behaviour of the system. We take the hydraulic retention time (HRT) as the bifurcation parameter, allowing it to vary over the range $0 <$ HRT (days) ≤ 1. We investigate how the nitrogen concentration in the effluent stream depends upon the operation of the settling unit and the recycle units. We identify conditions for effective nitrification and denitrification to occur in the reactor.

A sample of our results is summarised as follows.

1. In the absence of a settling unit and recycle units there is negligible nitrogen removal (of the order 2%). The 'best' reactor configuration has no aeration in the first two reactors. For such a reactor configuration the performance is maximised at a HRT of one day.
2. When a settling unit is deployed in the absence of recycle units the maximum nitrogen removal is approximately 44%. This is obtained in reactor configurations having either aeration in all three reactors or no aeration in the first reactor. In both of these cases the nitrogen–HRT operating curve contains two local minimia. In both cases the maximum nitrogen removal occurs at a HRT of just under 0.2 days.
3. When a settling unit is deployed in conjunction with a recycle unit operating from the second to first reactors the maximum nitrogen removal is found to depend upon the value of the recycle ratio (R_{21}). When $R_{21} = 1$ or $R_{21} = 2$ the maximum nitrogen removal is approximately 60%. The best reactor configuration is that in which there is no aeration in the first reactor, when the performance is maximimised at a HRT of one day. There is a higher local minimia at a HRT of approximately 0.2 days.
4. When a settling unit is deployed in conjunction with a recycle unit operating from the third to second reactors the maximum nitrogen removal is found to be insensitive to the value of the recycle ratio (R_{32}). The behaviour of the system is very similar to that without a recycle unit, with a maximum nitrogen removal of approximately 44%.

In addition to identifying operating conditions which minimise the total nitrogen in the effluent stream we conclude that continuation methods provide the right tool to investigate how changes in process parameters effect outputs in a systematic manner.

Keywords: *Activated sludge, modelling, wastewater*

Invasive species in a confined environment: Reindeer population in the Pribilof Islands

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Abstract: The plight of the reindeer population on the Pribilof Islands, Bering Sea, is an interesting example of resource depletion and population collapse. To U.S. government officials, the abundance of lichen on the Pribilof Islands, together with the absence of large grazing animals, and the lack of natural predators appeared ideal conditions for the introduction of reindeer in 1911. Once introduced, the reindeer population grew rapidly followed by a precipitous decline, with very few remaining by 1951. It is generally believed that grazing pressure by the reindeer in combination with markedly warmer and drier climatic conditions caused a rapid and sustained reduction of lichen. We use a variant of the Lotka-Volterra model and apply it to available data to model the reindeer population in response to changes in the availability of lichen.

Keywords: *Invasive species, predator-prey model, population dynamics*

Mathematical modeling, computation and analysis for heat and sweat transport in porous textile materials

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Abstract: Mathematical and numerical study of multiphase and multi-component flow in porous media attracts considerable attention since it can be found in a wide range of industrial and engineering do-mains, such as food industry, paper materials, building construction and more recently, textile industry. Here we focus on clothing assemblies. In this application, heat, air and moisture transfer are coupled in rather complicated mechanisms. The air and vapor gas mixture moves through a clothing assembly by convection and diffusion which are induced by the pressure gradient and concentration gradient. Heat is transferred by convection in gas and by conduction in all phases (liquid, fiber and gas). Phase changes occur in the form of evaporation/condensation and fiber absorbs vapor due to its chemical/physical na-ture. The physical process can be viewed as a non-isothermal, multi-component and multi-phase flow in a fibrous porous medium with condensation/evaporation and fiber absorption and governed by a system of nonlinear, degenerate and strongly coupled parabolic equations.

In recent work, we present more realistic formulations of the multi-component and multi-phase model. A reasonable combination of all the three parts in the batting area, heat capacities of gas (C_g), fiber (C_f) and water (C_w), with C_g being proportional to the density of gas, is more realistic. A truncated Hertz-Knudsen equation may be introduced to describe the condensation/evaporation for the general dry-wet case in clothing assemblies. We describe the fiber absorption by an evolution equation along the fiber radius with a Robin type boundary condition, with which the absorption on the fiber surface is always smaller than the saturation absorption before the steady state is reached. In addition, many fiber materials in clothing assemblies are approximately transversally isotropic. The mathematical equations of the model can be described with certain nondimensionaliztion by

$$\frac{\partial \epsilon\rho c}{\partial t} + \nabla\cdot(\boldsymbol{u}_v \epsilon\rho c) - \nabla\cdot(d_g \epsilon\rho\nabla c) = -\Gamma \tag{1}$$

$$\frac{\partial \epsilon\rho \widetilde{c}}{\partial t} + \nabla\cdot(\boldsymbol{u}_a \epsilon\rho \widetilde{c}) - \nabla\cdot(d_g \epsilon\rho\nabla \widetilde{c}) = 0 \tag{2}$$

$$\frac{(\partial\rho\theta + \sigma\theta)}{\partial t} + \nabla\cdot(\boldsymbol{u}_g \epsilon\rho\theta) - \nabla\cdot(\kappa\nabla\theta) + \lambda\Gamma \tag{3}$$

$$\frac{\partial w}{\partial t} = M\Gamma_{ce}\,. \tag{4}$$

Here the generalized Fick's law has been used for the binary multi-component gas mixture (vapor and air) and the vapor-air mixture velocity (volumetric discharge) is given by the Darcy's law

$$\boldsymbol{u}_i = -\frac{k k_{ri}}{\mu_i}\nabla P, \quad i = a, g, v\,. \tag{5}$$

c and $\widetilde{c}$ denote the water vapor and air concentrations, respectively, w the liquid water content, θ the temperature and d_g the molecular diffusion coefficient over the tortuosity of the air-vapor diffusion. In the wet zone, λ is the latent heat of evaporation/condensation, while in the frozen zone, it represents the latent heat of sublimation.

An uncoupled numerical scheme with finite element approximations was proposed for solving the system of nonlinear and degenerate parabolic equations. At each time step, one can solve these physical compo-nents in parallel. We present our numerical simulations in several practical cases, including human-sweat, firefighter-jacket and 3D clothing assemblies. Qualitative comparison between the numerical results and the experimental measurements are also given.

Keywords: *Heat and sweat transport, textile materials, mathematical modeling, numerical simulation*

Propagation of travelling waves in a complex system modelling fire spread

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Abstract: A system of coupled partial differential equations which models a complex system of a solid fuel, endothermically pyrolysing to a combustible gas, which in turn exothermically reacts with oxygen, is studied. We use a numerical method based on the Crank-Nicholson finite difference scheme to solve the governing equations in order to investigate the dynamics of this model. It has previously been shown that there exist solutions to the model which exhibit oscillatory propagating combustion waves. In this work, we extend the original study to explore the parameter space to locate regions where both steady propagating waves (single valued wave speed) and also pulsating waves exist. Parameter space where no propagating waves are possible (extinction region) is also determined.

Keywords: *Combustion, exothermic, endothermic, pyrolysis, travelling waves, instability, bifurcation*

Population response to environmental change: A model with an alternate stable state

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Abstract: In ecology, the theory of alternative stable states predicts that ecosystems can exist under multiple "states". Ecosystems may transition from one stable state to another, in what is known as a state shift. Typically such shifts are considered as instantaneous and isolated non-interacting events resulting from environmental shocks, whose dynamics resemble the dynamics of a ball in a "potential well". More often however, ecological systems are subject to continuous variation due to environmental drivers such as rainfall, temperature, among others, and these interact with the ecosystem dynamics to alter the potential well. Such drivers are known to impact intra-species interactions.

We explore a single species population model with logistic-like growth and a variable crowding parameter that measures the strength of the intra-species interaction. The crowding parameter is treated as a state-variable whose dynamics is described via a potential function subject to external environmental drivers.

Keywords: *Population dynamics, alternative stable state*

Assessing long-term crop yield trends and yield variability using a time series analysis approach

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Abstract: Long-term yield data (> 50 years) from fertilization experiments provide highly valuable data for quantifying the effects of fertilization and meteorological conditions on crop yield trends and variability. However, yields result from non-stationary and often highly nonlinear processes. Moreover, most fertilization experiments have been designed without the use of replications, thus, their analysis with current statistical methods is restricted. Mixed effect models have been suggested to derive trends and to disentangle the effects of various factors on crop yields. Such models are largely based on subjective assumptions on dominant factors and prescribed functions for describing the underlying physical processes. Thus, their use for understanding and modeling effects of a priori unknown processes and interactions on yield variability is limited. Contrastingly, time series data decomposition techniques allow for deriving trends based on intrinsic data characteristics. Thus, they might provide useful objective tools for understanding yield variability and for deriving long-term trends. We here present an approach which is based on the combined application of different adaptive time series decomposition techniques (EMD and SSA) and process-based modeling to disentangle the effects of crop variety, fertilization and meteorological conditions on long-term yield trends. The approach is demonstrated using yield data of four different crops obtained at a fertilization experiment established in 1904 at the Dikopshof research site (Germany). An established process-based model (SIMPLACE<LINTUL5>: Scientific Impact assessment and Modeling PLatform for Advanced Crop and Ecosystem management) is used for understanding the signals in the multiple time series and trends derived from time series decomposition and for understanding the underlying processes at different time scales. SIMPLACE is a modeling platform which contains submodels for the major processes affecting crop growth including crop phenology and development, root growth, crop water demand, and soil water dynamics. Time series decomposition revealed that the effect meteorological anomalies on crop yield anomalies was highly dependent on the long-term fertilization treatment and allowed for the identification of major breaks and changes in crop management. However, the application of a process-based crop model was critical for estimating the crop phenological phases which explained much of the yield variability. Our results highlight the potential of using time series analyses tools for understanding long-term yield data and, in consequence, for improving the predictive ability of process-based models.

Keywords: *Crop yield, time series decomposition, crop model*

Impacts of cultural risk factors on project success in the UAE construction industry

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Abstract: Industrial risk management is an area of interest in business and management research. Construction is a risky and dynamic industry that is particularly prone to a variety of risks and uncertainties. The nature of these risks may depend on particular projects and can significantly vary from country to country. Therefore, the essential goal of research in identifying and characterising risks in construction is two-fold, involving (1) the identification and characterisation of any general trends, risks and mitigating strategies that are common in different countries and extend over a variety of construction projects in one or more countries; and (2) the identification and characterisation of any particular construction risk in a given country or even for a given project and understanding any variability of risks for different projects or countries. The detailed analysis of risks and risk factors associated with both these aims is essential for the successful development of the construction industries that constitute a significant part of the world economy.

The major focus of this paper is the analysis and characterization of cultural risks in the construction industry in the United Arab Emirates (UAE). The unprecedented construction boom in the UAE since 1971 has caused rapid and extensive growth in its construction industry. However, this rapid growth and its sustainability are threatened by a variety of factors including significant cultural issues associated with the traditional Arabic culture and the unprecedented diversity of the workforce in the UAE, as more than 80% of workers are expatriates from different parts of the world. This creates a unique business environment in the country whose successful development largely underpins the economic progress in the Middle East and elsewhere.

The analysis of cultural risks in the UAE construction industry was conducted using a specially designed and validated survey instrument. There were 237 participants of the study, all holding senior engineering or managerial positions in companies associated with the construction industry in the UAE. The analysis was based on the identification and quantitative characterization of the constructs associated with the cultural risk factors and generalized structural equation modelling to characterize the direct and indirect effects of these constructs on the success of construction projects. All outcomes were adjusted to socioeconomic and company variables.

Among the mediating constructs, External Risks (involving corruption, government regulations, market demand and differences between stakeholders) and Communication (involving communication issues between the parties to the contract, employers and employees) dominated Internal Risks, which were generally perceived as less important. The cultural factors produced significant impacts on these mediating constructs that, in turn, affected project success.

Only two UAE cultural aspects were found to have positive impact on project success. These were differences in educational backgrounds and a more stringent attitude to time among Emiratis that people from Western countries. All other specific cultural aspects were found to have significant negative impacts.

The two different constructs associated with the existing cultural aspects in UAE were identified as UAE Culture and Cultural Diversity. Both of these constructs were shown to have significant impacts on project success, but only through the mediation of the other three constructs of Internal Risks, External Risks and Communication. In particular, it was demonstrated that the cultural diversity issues have twice as strong an impact on the success of construction projects in UAE than the general cultural issues in UAE. Therefore, the issues of cultural diversity should be given priority in any attempts to mediate construction risks and improve productivity in the industry.

Keywords: *Construction industry in the UAE, construction risks, cultural risks, UAE culture, cultural diversity*

Empirical Mode Decomposition and the two-tone separation problem in the presence of noise

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Abstract: The Empirical Mode Decomposition (EMD) is a decomposition method that provides an alternative way to analyse nonlinear and non-stationary time series. Since its inception in the late 1990s, EMD has been applied in a number of areas, including bio-medicine, neuroscience, epidemiology, chemical engineering, finance, at-mospheric turbulence, seismology and ocean dynamics. The EMD process decomposes a signal into intrinsic mode functions (IMFs); each IMF can have variable amplitude and tends to occupy a narrow spectral band-width, rather than having a single frequency. The question of how the EMD copes with time series with high spectral density therefore naturally arises, but has only attracted limited attention in the literature. A time series with high spectral density is one comprised of multiple signals each with very similar frequencies.

In this study we consider fundamental cases of synthetic time series composed of two sinusoidal signals with prescribed differences in their frequencies. Separating the two component signals from the input data is known as the 'two-tone separation problem'. We investigate the ability of the EMD method to successfully identify the two component signals as IMFs for each time series, and heuristic bounds on the utility of the EMD applied to high spectral density data are discussed.

In this study we consider two-tone signals without noise and find results similar to those already reported in the literature. We also consider noisy two-tone input signals and consider the ability of ensemble EMD (EEMD) to resolve the two component signals. This work appears to be the first to consider the two-tone separation problem in the presence of noise. Somewhat unsurprisingly, the addition of noise to the input data diminishes the ability of the EEMD method to identify and separate the two component signals. However, our results indicate that the presence of noise has a more prominent effect of the ability of EEMD to separate the two component signals than it does on its ability to distinguish the two-tone signal from a single waveform.

Expressing the results in terms of the ratio of the frequencies of the two component signals f, it was found that in the absence of noise EMD cannot distinguish a two-tone signal from a single waveform when $f > 0.71$, and could only reliably separate the two component signals when $f < 0.5$ approximately. These figures are in good agreement with those found in previous studies. For a noisy two-tone signal, it was found that EEMD was not able to distinguish the two-tone signal from a single waveform when $f > 0.7$ and could only separate the two component signals when $f < 0.4$ approximately.

In this initial study the effects of varying the amplitude of one component signal relative to the other was not considered. This would be an interesting extension of the research.

Keywords: *Empirical mode decomposition, time series analysis, two-tone separation, frequency resolution*

Smoothing Ensemble Empirical Mode Decomposition

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Abstract: The Ensemble Empirical Mode Decomposition (EEMD) is a data-adaptive method that decomposes data into a number of constituent components called intrinsic mode functions. EEMD relies on an interpolation method to interpolate the local extrema. In the original version of EEMD, cubic splines were used to interpolate the extrema. However, there remain a number of questions about the sensitivity of EEMD to different underpinning interpolation methods and there is a need to identify interpolation methods that improve the robustness of EEMD in applications. In this study, we present evidence that supports the use of smoothing splines in implementing EEMD. In particular, EEMD based on smoothing splines, applied to synthetic data, produce far more robust and accurate results. We refer to smoothing spline based EEMD as 'Smoothing EEMD' (SEEMD).

To test the efficacy of SEEMD compared to EEMD using linear and cubic interpolation methods, we constructed two three-component signals with noise, consisting of two sinusoidal components, a trend component and Gaussian noise. In the first signal a linear trend was used and in the second a quadratic trend was used. The various EEMD procedures, each using 3000 ensemble members, where then employed to recover the trend components of the two noisy signals. Figure 1 shows the actual trend components in black overlaid with the trend components extracted using EEMD, along with 95% confidence intervals (shaded). The confidence intervals in Figure 1a indicate that there is a considerable degree of variability in the linear trends determined in each of linear EEMD ensemble runs. This figure shows that traditional (cubic) EEMD also produced a fairly wide spread of linear trend estimates. In contrast, the confidence intervals associated with SEEMD were very small, indicating greater consistency in the trend components produced over the 3000 smoothing EMD ensemble runs. Figure 1b shows similar results – even though SEEMD was lightly less accurate near the boundaries of the domain, when compared with cubic EEMD, the confidence intervals suggest that SEEMD is able to produce more robust estimates of the trend. This means that SEEMD can be run with far fewer ensemble members, hence saving on computational cost, with little effect of performance. We note that similar results were found using logarithmic and Gaussian trend components (not shown).

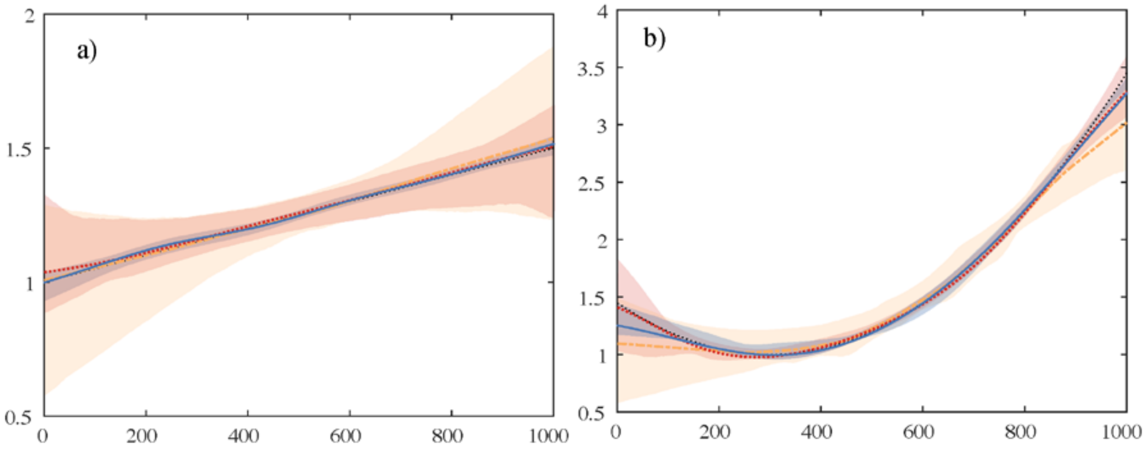

Figure 1. Results of EEMD with linear (yellow), cubic (red) and smoothing (blue) interpolation. The extracted trend and 95% confidence limits (shaded) are shown.

It should be noted that the SEEMD method requires selection of a smoothing parameter, which adds a degree of freedom to the procedure. Initial work has shown that the smoothing parameter can be adjusted to improve accuracy in obtaining higher or lower frequency components. Ongoing work is directed at optimizing the choice of smoothing parameter so that sufficiently accurate SEEMD results can be obtained across all the relevant time scales.

Keywords: *Empirical mode decomposition, smoothing splines, interpolation, time series analysis*

Impact of rainfall fluctuations and temperature variations on people movement in Sub-Saharan Africa: A Time Series Analysis of data from Somalia and Ethiopia

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Abstract: Water is highly critical for the existence of humans and other living organisms as well as for all sorts of life. Agriculture needs water to produce crops and manufacturing industries need it for producing products and services. Water is immensely critical for energy production and needed in the balance and sustainability of ecosystem. There has been a considerable rainfall variations that impacted water availability in Somalia and Ethiopia. Equally, temperature variations have also played a major role in the everyday life of Somalis and Ethiopians. Together the rainfall fluctuations and temperature variations have been attributed to climate change. The effects of these issues on people movements away from rural to urban have had little attention in recent times. This paper addresses the impact of climate change variables on rural - urban migration in both Somalia and Ethiopia. More specifically, we use time series analysis to examine the interactions between the rural-urban migration, rainfall and temperature. We model the multivariate data using ARIMA and VAR models; this is to first conduct univariate analyses for the purpose of predictions, and secondly to understand the nature of interactions and dependencies by conducting multivariate VAR analysis. This study determines the most appropriate ARIMA models of rural migration, urban migration rainfall and temperature of Somalia and Ethiopia as presented in Table 2. Both ARIMA and VAR analyses have produced relatively good models that are statistically significant and perform well in making short term predictions; a 10 year period of annual forecast of rural and urban migration as well as rainfall and temperature of Somalia and Ethiopia were carried out. Then univariate and multivariate analyses have showed that climate change factors such as "rainfall" and "temperature" variations have a combined granger effect on people migration in both rural and urban areas in both countries; in fact temperature variations have a significant impact (5% and 10%) on urban and rural migrations respectively. Climate change effects appear to be driving the migration from rural to urban. This is also compounding the international migration out of the African continent that is noted in Europe, Asia and even Australia.

Keywords: *Sub-Saharan Africa, water security, rural-urban migration, climate change, time series*

Time series regression relates soil microbial DNA concentration to enzymatic glucose neo-generation

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Abstract: Understanding how microbial DNA from root zone (rhizosphere) soil relates to key metabolic enzymes used by rhizosphere microbes was investigated using time series regression. We aimed to define the influence of these enzymes on DNA concentrations. This objective was achieved using phosphorescent measurement of both enzyme activities and DNA concentrations. Rhizosphere samples from three strains of canola genetically modified (GM) for herbicide resistance (HR) to atrazine, imidazolinone, and glyphosate respectively together with the isoline to the transgenic glyphosate-resistant variety were grown in a greenhouse in pH-neutral Vertisol soil. Analyses were carried out at days 7, 21, 42, and 56 growth representing germination, early growth, maturity, and seed formation-senescence. Enzymes represented key soil microbial metabolic processes and included leucine aminopeptidase (LAP), alkaline phosphatase (PHOS), cellobiose dehydrogenase (CELL), beta-glucosidase (BGL), and aryl sulphatase (SUL). The experiment employed a randomized complete block design with four blocks of eight pots, each pot containing two plants of identical genotype, and each cultivar randomly distributed within each block. Enzyme measurements were taken before substrate addition and again after incubating at 25 degrees Celsius for one hour. DNA concentrations were measured using the Pico Green technique. Mean increases in enzyme activities for each lifespan stage were correlated with DNA concentrations using time series regression. A highly significant relationship ($p = 0.001$) between DNA concentration and beta-glucosidase activity emerged. No other enzyme significantly influenced DNA. The implications of this finding are that during times in the plant lifecycle when microbial-root biochemical interaction are increased (flowering and seed formation), the soil must have adequate SOM available to the microorganisms. It is now known that commensal relationships exist between rhizosphere soil microorganisms and the roots within that soil. The importance of microorganisms in breaking down decaying organic material from plant residues is reflected in contemporary measurement of soil fertility which recognizes that a matrix of physical, chemical, and biological parameters together are required for an adequate assessment. This is because when organically-bound carbon biomass is subjected to transformation, other nutrients like Nitrogen (*N)*, Phosphorus *(P)*, and Sulphur (*S)* are released for mineralization by roots. The results reinforce the importance of soil organic matter (SOM) as a component of soil fertility and sustainable soil health.

Keywords: *Rhizosphere, enzymes, soil, DNA, time series regression*

Combing high-frequency surrogate measurements and data-driven models to early warn water quality anomalies

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Abstract: It is critical for surface water management systems to provide early warnings of abrupt, large variations in water quality. Anomalous water quality levels may be due to a variety of factors, such as natural accidents, uncertain point sources, and the intentional injection of contaminants. Although water quality monitoring systems generate data continuously using automatic sensors, the full benefits of online monitoring data cannot be obtained without real-time analysis. Smart anomaly detection systems (ADSs) based on real-time monitoring data are in high demand.

Many key water quality indexes, such as total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), etc., cannot be monitored at a high temporal resolution, and some may not be detected by a sensor in real time. Surrogate relationships can be used to estimate water quality concentrations at a much higher temporal resolution. Data-driven models such as artificial neural networks (ANN) and wavelet artificial neural networks (wavelet-ANN) can be used to describe these variations at a high resolution.

In this study, a combined approach integrating wavelet-ANN model and high-frequency surrogate measurements is proposed as a method of water quality anomaly detection and warning provision. High-frequency time series of major water quality indexes (TN, TP, COD, etc.) were produced via a regression-based surrogate model. After wavelet decomposition and denoising, a low-frequency signal was imported into a back-propagation neural network for one-step prediction to identify the major features of water quality variations.

The precisely trained site-specific wavelet-ANN outputs the time series of residual errors. A warning is triggered when the actual residual error exceeds a given threshold, i.e., baseline pattern, estimated based on long-term water quality variations.

A case study based on the monitoring program applied to the Potomac River Basin in Virginia, USA, was conducted. The integrated approach successfully identified two anomaly events of TP variations at a 15-minute scale from high-frequency online sensors. A storm event and point source inputs likely accounted for these events. Compared to the ANN prediction method, the wavelet-ANN method was more sensitive to sudden water quality anomaly events and avoided the effects of false positive events in many cases. ROC tests based on two hypothetic scenarios yielded a detection accuracy of up to 0.98. Analyses of the performance at different stations and over different periods illustrated the stability of the proposed method.

By combining monitoring instruments and surrogate measures, the presented approach can support timely anomaly identification and be applied to urban aquatic environments for watershed management.

We live in the age of big data, and intelligent and precise environmental management is essential. The data-driven method proposed can serve as a state-of-the-art alternative for safeguarding water quality, improving urban and aquatic environmental management, controlling non-point and point source pollution, and enhancing watershed management.

Keywords: *Water quality, surrogate parameters, anomaly detection, wavelet denoising, artificial neural networks*

Nonstationary nonparametric and regularised time series analysis of observed atmospheric dynamics

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Abstract: Principal Component (PC) or Empirical Orthogonal Function (EOF) analysis is a standard tool in atmospheric science to reduce the data to a few leading modes of variability. While a useful tool for dimension reduction, it is important to bear in mind that, whereas the leading PC/EOF modes may often have readily interpretable physical behaviours, often the higher order modes do not correspond by themselves to observable coherent features, rather a combination of modes can be required to characterise a physical dynamical mode.

When pre-filtering has been performed, intrinsic variability on timescales shorter than the averaging period is removed and causal connections are affected. Analysis based solely on methods where the dimensionality is reduced such that only the leading few modes are retained, often justified in terms of projection onto an arbitrarily determined slow manifold, can also be interpreted as a form of pre-filtering. Where scale separation is absent, arbitrary filtering and truncation of the underlying data, common to many studies of low frequency climate variability, can lead to the misrepresentation of the relative importance of the drivers of variability at given spatio-temporal scales. In general, more sophisticated stochastic approaches to mode reduction must be applied and, in particular, where some form of parameterization of the unresolved scales is incorporated. Determining the parameters of the optimal stochastic model in the relatively short timeseries of the available (atmospheric reanalysis) data represents a challenge.

For many atmospheric phenomena, low frequency variability manifests as transitions between quasi- stationary states or regimes, often initiated by weak stochastic forcing of the large scale slow modes by the fast-noisy small scales, or through the organised amplification of initially small disturbances via the inverse energy cascade such as occurs in quasi-two dimensional geophysical flows. In multi-scale systems time dependence of the model parameters can be induced by the influence of the unresolved scales leading to large scale regime transitions between quasi-stationary states.

Here, we apply a data-driven multiscale method that allows for approximation to non- stationary dynamical processes, including parameterization of subgrid scales by stochastic forcing. This work applies the finite element, bounded variation, vector autoregressive method (FEM-BV-VARX), to fit a non-stationary stochastic model to the data and then apply information theoretic criteria to determine the optimal set of time evolving free model parameters. Specifically, we examine the full three-dimensional (3-D) structure of the troposphere. The severe computational challenge requires dimension reduction in order to avoid ill-conditioning. Our focus is on the consequences of various dimension reduction strategies. We show that a careful and systematic approach to the problem can in fact lead to a deeper insight into the major atmospheric circulation modes and progress toward a more unified approach to analysing observational data.

Keywords: *Nonparametric time series analysis, atmospheric dynamics, information theory*

An analysis of the relationships between ownership structure and capital structure of the global water industry

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Abstract: It is unfortunate but people over the world are living without regular access to safe drinking water. Currently, around 20% of the world's population (1.1 billion people) have about 7% of its water. Water industry continues to suffer from global shortages, rising consumption levels and importantly, an aging infrastructure). Since water investment has been a challenging sector for making money, water markets across the globe are extending and seeking new opportunities. It is noted that the global water market is worth between US$400 and US$500 billion, including US$175 billion for municipal and industrial water and wastewater capital expenditure. There is an acute need for money and investment in water. Hence, the private sector participation is needed in the water sector but to join the investing in the water industry, private companies need to improve their capital structure. There is however little research regarding the relationships between ownership structure and capital structure of the water industry. This study examines the relationships between ownership structure and capital structure of 72 water companies that comprise the 4 water indices (WOWAX, S-NET, S&P and MSCI ACWI) over the period 2004-2014 using unbalanced panel (random effects) regression model. The findings of his study shows that investors (foreign and institutional) play an important role to effect the capital structure and investment performance. Foreign ownership affects the leverage and short term debt to asset at the 10% and 1% level of significance. However, the Institutional ownership factor does not seem to affect the leverage (LEV) and short term debt to asset (STDA). There are a number of implications for financial managers; types of financial strategies to undertake and thus, determine the optimal capital structure for ownership structure. Individual water investor can cogitate both capital structure and ownership structure when making investment decisions in water industry.

Keywords: *Global water market, water industry, foreign ownership, institutional ownership, capital structure*

Change-Point Detection in Time Series Data via the Cross-Entropy Method

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Abstract: In many applications data are collected over time and very often the statistical properties, such as mean or variance, of the data will change along data. In recent years, there has been an increasing interest to the problem, which is known as a change-point problem, where it is necessary to detect the number and locations of change-points of time series processes. The change-point detection problem, which may also be called a segmentation or break-point problem, can be found in a wide range of applications, such as financial time series analysis (e.g. changing volatility), signal processing (e.g. structural analysis of EEG signals), geology data analysis (e.g. analysis of volcanic eruption series) and environmental applications (e.g. detecting changes in ecological systems due to climatic conditions crossing some critical thresholds). For example, many macroeconomic variables such as inflation may be subject to changes in government policy that may cause structural breaks in the data and make highly persistent impacts. An awareness of those changes can assist people to eliminate and manage unnecessary risk and further improve the decision-making.

The main concern of change-point problem is the complexity to build a flexible and effective model to estimate the unknown number and locations of break points in time series. In this paper, we develop an innovative methodology to tackle this problem. We compare the statistical performance of a number of computational methods for estimating unknown parameters of autoregressive data with structural breaks. Specifically, we consider the Cross Entropy method for modelling break points using minimum description length (MDL) information criterion to estimate change-points as well as parameters of the process on each segment. Numerical experiments illustrate the robustness of this approach. We obtain estimates for the locations of change-points in artificially generated sequences and compare the accuracy of these estimates to those obtained with other methods. Finally, we use the proposed method to detect the potential location of change-points in the Australian annual inflation rate data from 1960 to 2016.

Keywords: *Change-point detection, autoregressive time series process, cross-entropy method, minimum description length*

Electricity consumption, Peak load and GDP in Saudi Arabia: A time series analysis

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Abstract: Energy is one of the most important resources of the national economy, which plays an important role in economic production and life more generally. Given its significance, this paper formulates prediction models for electricity consumption (EC), peak load (PL) and gross domestic product (GDP) in Saudi Arabia by employing the Autoregressive Integrated Moving Average (ARIMA) model; using time series data from 1990–2015. It also examines the relationships between EC, PL and GDP through a vector auto-regression (VAR) analysis, which includes Granger causality (GC) testing, impulse response, and forecast error variance decompositions (FEVD). The results show that ARIMA (1, 1, 1), ARIMA (0, 1, 0) and ARIMA (0, 1, 0) were the most appropriate univariate models of EC, PL and GDP, respectively, based on the Akaike information criterion. The results also revealed significant unidirectional granger causality from PL to EC and PL to GDP. The variance decomposition reveals that in the case of EC, the major changes arise from its own innovation and the contribution from GDP at the 1%.

Keywords: *Electricity consumption, peak load, GDP, ARIMA model, VAR model*

Time series forecasts with wavelet transforms: a critical revisiting of validation methods

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Abstract: Wavelet-based forecasts are now an established element of time series prediction in a number of disciplines, including such disparate subject areas as environmental studies, finance, electricity load, and the nuclear industry. In essence, the wavelet approach hopes to discover sufficient structure in a time series to enable a degree of self-forecasting in the absence of external information. This would apply, for example, if there were cyclic components in the data. However, concerns have been raised over the true forecast accuracy of such frameworks, which anomalously appears capable of extracting forecasts from time series without any structure.

With such anomalies in mind, we outline a mechanism by which wavelet-based time series forecasts could be inadvertently formulated from an incorrect methodology. This results in validations indicating falsely enhanced forecasting accuracy (Fig. 1), or even suggesting that a sequence of random numbers has some ability to self-forecast.

The source of potential error in validation lies in introducing some dependency between calibration and validation data segments. Such dependency might be introduced through the apparently innocuous step of data pre-processing being undertaken prior to partitioning the time series concerned into calibration and validation segments. We also shed a light on a more subtle way by which problems might arise with validation of wavelet-based time series forecasts when an ordered structure of time series is ignored and holdout cross-validation is utilized.

We provide a general result that if a decimated discrete wavelet-transform is used for pre-processing a time series then this generates an unavoidable requirement of having to know future data values which have not yet happened. Finally, we propose a new validation approach based on a Nash-Sutcliffe index, which avoids the possibility of indicating better forecasting ability than is actually the case.

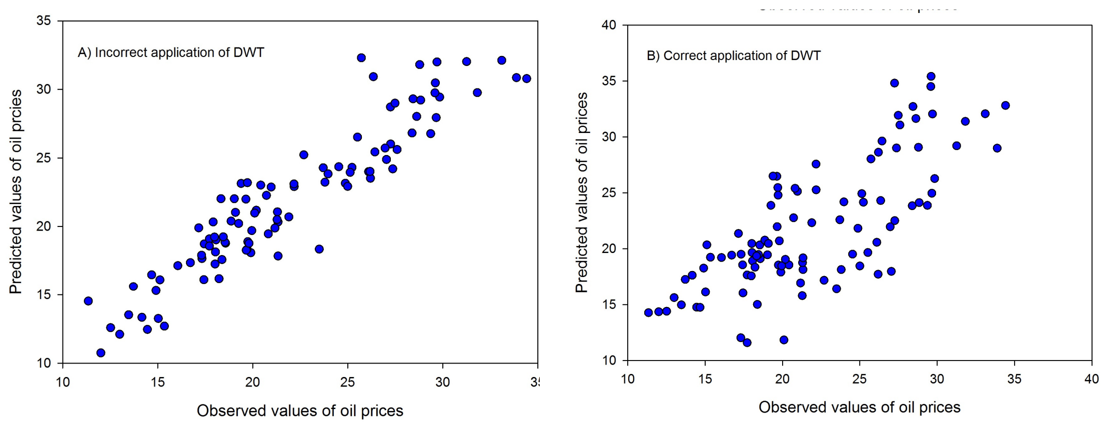

Figure 1. Wavelet-based forecasts of oil prices for a 4-month horizon: A) discrete wavelet transform applied to the entire time series prior to data splitting into calibration and validation portions; B) discrete wavelet transform applied after splitting into calibration and validation.

Keywords: *Wavelet, forecasting accuracy, calibration, validation, data pre-processing*

Modelling the spatial spread risk of plant pests and pathogens for strategic management decisions

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Abstract: Invasive pests and pathogens pose a grave and growing threat to agricultural systems, threatening food security and access to domestic and export trade, as well as having potentially serious environmental and social impacts. Management responses to pest or pathogen incursions include planning for conducting surveillance, implementing quarantine restrictions and treating infected farms. Smart and transparent decisions need to be made to control the spread of an incursion, often in the context of sparse information. Given the array of management options, modelling tools can help greatly in more targeted spatial prioritisation of surveillance and quarantine as the incursion response unfolds.

We constructed a simulation model to allow managers of incursions to explore the possible effects of their decisions. The model operates at the farm-level of spatial resolution, with risk pathways parameterised via flexible networks of connections between farms. It models growth of the pest organism within farms, its spread between farms by natural or human-assisted means, and its detection and control by land-owners or managers. Quarantine options within the model can range from isolation of an individual property to region-wide restrictions. Surveillance options range from straightforward ranking by estimated risk to more sophisticated search prioritisation algorithms. The model continually updates risk estimates from previous surveillance results and ongoing prevailing risk propagated through the connection pathways. Initial risk estimates can incorporate tracing data, wherein response managers have documented previous high-risk pathways connected to properties with known infections. Simulated surveillance results can be replaced by actual surveillance history data, if available.

Users such as biosecurity managers can explore model features and scenarios through the interactive model visualisation software "BIOSPARK". Whereas the model is underpinned by simulation of within-farm growth and between-farm spread of the invading organism, the output for response program managers is primarily presented as visualised expected risk to farms of unknown pest status, and their ranked risk levels, to aid in guiding surveillance decisions. Risk is visualised as heat maps overlaid on the landscape, and can be viewed over each time step of the analysis. Sites recommended for surveillance are presented as a ranked list, with their locations flagged on the landscape.

We have retained sufficient generality in the model, so that future developments can include considerations of different organisms, flexibility in number of risk networks to be entered, and application of the model to different jurisdictions. There is a need for model-based tools such as this to aid in framing, supporting and communicating agricultural management decisions in complex and challenging situations.

Keywords: *Biosecurity, invasive species, threatening processes, prioritisation, simulation*

Modelling Complex Insect Invasions: European House Borer as a case study

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Abstract: The European House Borer (EHB) is a serious insect pest of untreated dry softwood. The adult beetle lays its eggs into cracks and holes in the deadwood, with larvae subsequently hatching from the eggs and causing damage by feeding on the timber. Serious structural damage can occur when found in timber in buildings. Traditional optimisation models of invasions are of limited applicability for EHB because this pest not only infests the dead parts of pine trees in forests, it also infests buildings. Pine forests are the main habitat of EHB but the damage occurs mostly in residential areas. This means that knowledge of the extent of the invasion (infested area) does not provide enough information to describe the state of the system for management purposes. Another complication is that control of the invasion involves "packages" of actions. These actions cannot be easily related to reductions in area invaded as continuous variables.

A three-state variable model was developed to represent the problem. A number of parameters need to be estimated to represent the spread and management of the invasion, but the data needed for direct estimation are not available. We developed a numerical model that derives time trajectories of forest area, houses at risk and number of infested houses for any combination of parameter values and control packages. The four available control options within each package are building restrictions within restricted movement zones; early harvest of softwood plantations; forest hygiene activities; and fixed-cost activities associated with the EHB management programme. A full factorial design was used to test the effects of all possible combinations of control options. All the control packages result in a gradual reduction of the infestation. Under the base assumptions any form of control is preferred to no control. The present value of total cost is around $7 billion under no control and $800 million under full control.

The tool developed in this research may be used by biosecurity agencies to estimate plausible parameters sets based on their experience and considering the population dynamics of the EHB. The model can be used in an iterative approach to guide further data collection and should be applicable to other pests with similar spread and impact characteristics.

Keywords: *Biosecurity, European House Borer, dynamic models, model calibration, invasive species*

Simulated seasonal nitrogen fertilizer responses for diverse dairy regions of Australia

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Abstract: There is an ongoing challenge for Australian dairy farms to increase production, improve input resource efficiency and farm profitability in the face of climatic, price and regulatory requirements. The consumption of home-grown forage is widely recognized as a key metric to ensuring farm profitability. Optimal soil nitrogen (N) management is critical to improving quantity and quality of pasture produced on-farm. Reviews have highlighted that despite many years of field research, the production responses of pasture to varying rates of N fertilizer (kg dry matter/kg N applied) remains highly variable and uncertain for a range of contexts (i.e. soil, climate, and farming system (FS) interactions). Of the experimental data available, virtually all are from cutting studies. Such studies exclude N returns through the grazing animal, a critical component to the N cycle, thereby increasing the uncertainty in pasture responses to recommended rates of fertilizer. Biophysical modelling is considered an effective approach to assessing the complex interaction that exist between climatic, edaphic and management factors that influence pasture production response to varying N fertilizer rates within a FS.

Using a biophysical modelling (DairyMod) approach, we derived the pasture production responses to varying rates of N inputs using both a cutting and grazing simulation. These simulations were undertaken for two varying temperate locations. At both sites, N fertilizer was applied monthly, at incremental rates of 10kg N/ha.month, post-defoliation and were conducted for 18 years of climatic data (winter 1999 to autumn 2017 inclusive). Figure 1 shows the spring-time perennial ryegrass growth rate (kg DM/ha.day) at an irrigated site in NW Tasmania (a) and a rainfed site in SW Victoria (b) under cut and grazed conditions. At the irrigated site, there was disparity in average daily growth rates between the cut and grazed systems for rates up to 80kg N/ha.month. This difference highlights the impact on the soil-plant system of the animal sources of excretal N. In contrast at the rainfed site, the variation in daily growth rates between the cut and grazed system was minimal for rates above 40kg N/ha.month. The amount of N fertilizer required to achieve 90% of maximum pasture production under cutting conditions averaged ~ 75 and 50 kg N/ha.month at the irrigated and rainfed sites, respectively, reducing to an average of ~ 52 and 35 kg N/ha.month under grazing at the irrigated and rainfed sites, respectively. These results suggest that the grazing N fertilizer recommendation of between 20 and 50 kg N/ha is appropriate for both sites but does demonstrate that a greater level of N input is required for the NW Tasmanian site that the SW Victoria site, highlighting the importance of examining the complex interactions that exist in a grazing system. Also of note is the comparatively large interannual variation in the response at the rainfed site (Figure 1b) indicating that year to year N management should be adjusted according to current conditions. This information, along with assessments of N loss, will be used to validate and, where appropriate, update current dairy industry best management practices.

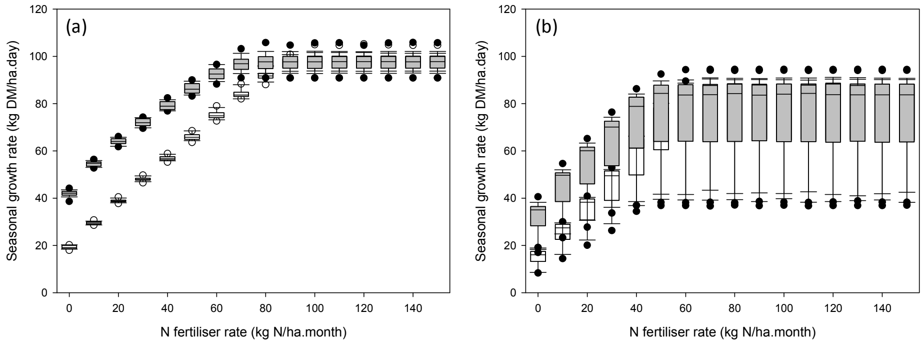

Fig 1. Average spring daily growth rate (kg DM/ha.day), at an irrigated site in NW Tasmania (a) and at a rainfed site in SW Victoria (b) under cut (open boxplots) and grazed (solid boxplots) conditions over 18 years.

Keywords: *Biophysical model, ryegrass, grazing, pastures, farming system*

Modelling Extreme Sugarcane Yields in the Wet Tropics

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Abstract: The Wet Tropics experiences one of the highest levels of climate variability in the world. These enormous swings in inter-annual climate patterns cause large fluctuations in crop size. Foreknowledge of the size of the crop can help marketers, millers and farmers plan for the coming season. In pursuit of simultaneously increasing industry competitiveness and improving environmental outcomes, the objectives of this research were to determine how early and how accurate yields can be forecasted and if it is plausible to forecast extreme yields.

Annual mill yields were predicted using a range of predictor variables. These predictor variables included yields from previous years, simulated biomass indices from the Agricultural Productions Systems Simulator (APSIM), cumulative rainfall, temperature and radiation. Seasonal climate forecasting indices like the Southern Oscillation Index and departures from average Sea Surface Temperatures in the central equatorial Pacific Ocean were needed to improve the accuracy of forecasts produced before the main growing season. Using these predictors, classification models forecasted if the crop was more likely to be above or below the observed median yield. Classification models were also deployed to calculate the probability of achieving an extremely high yield or an extremely low yield. An extremely high yield was defined to be a yield more than 20% above the observed mean yield, and an extremely low yield was defined to be a yield more than 20% below the observed mean yield. Forecasts were initiated on the 1st May in the year before harvest and updated until the 1st of November in the harvest year.

Using an optimised random forest classification it was possible to produce models with excellent skill on the 1st September (cross-validated correct classification rate = 0.864), 1st January (cross-validated correct classification rate = 0.955) and 1st March (cross-validated correct classification rate = 0.955). Extreme probability models demonstrated good skill at forecasting extremely low yields as early as 1st September (cross-validated relative operating characteristic score = 0.728) but was challenged to forecast extremely high yields.

We have identified that when La Niña conditions are present in the central equatorial Pacific Ocean in winter, in the year prior to harvest, there is a severe risk that the Wet Tropics regional yields will be extremely low. Accurate and early forecasts of crop yield potential are needed for industry to improve management routines. This project has at the regional level developed a skilful model for predicting yields. These predictions come early enough to influence farming, milling and marketing practices.

Keywords: *ENSO, seasonal climate forecasts, sugarcane*

Calibration and validation of AquaCrop for irrigated peanut (*Arachis hypogaea*) in lowland rice systems of southern Laos

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Abstract: There are opportunities to enhance rural household incomes and improve nutritional status through the diversification of smallholder agricultural systems from wet season rice monoculture to the dry-season field and horticultural crop production e.g. maize, mung bean, soybean and peanut. In the semi-arid, rice-growing lowlands of southern Laos, there are a number of physiochemical soil constraints that prevent the successful production of non-rice cultivars in these systems which are further exacerbated by limited water supply. As a first assessment of yield potential, crop modelling offers a relatively inexpensive alternative to time-consuming, and often costly, field trials. However, in less developed regions, modelling is often restricted by limited technical capacity and fragmented datasets; thus, the use of complex models that require equally complex datasets and skills may not be locally appropriate and/or available. Therefore, the primary objective of this study was to calibrate and test the ability of the FAO AquaCrop model, which has comparatively simple input requirements and is relatively easy to use, to simulate peanut (*Arachis hypogaea*) production in common lowland rice soils under different irrigation regimes. In 2015/16, a field trial was conducted at Phone Ngam Rice Research Centre at Pakse in Champasak province, southern Laos to collate a robust agronomic dataset that could be used to assess the use of AquaCrop as a tool to adequately model peanut production in these environments. Results showed that the model performance in soils commonly found in the rice-based lowland systems was good under well-watered conditions when simulating canopy cover (%) and aboveground biomass (t ha^{-1}) (*nRMSE* = 24.6 % and 30.6 t ha^{-1}, respectively). However, performance in water-limited conditions was moderate to poor (*nRMSE* = 27.0 % and 35.1 t ha^{-1}; and 44.2 % and 38.8 t ha^{-1}, respectively). Furthermore, the model was unable to simulate soil water with any degree of reliability given the limited lateral water distribution across the root zone, as evidenced by lack of soil water tension sensor response to irrigation and rainfall events, particularly once flowering had occurred. In addition to increased plant water use, the lack of lateral movement can be attributed to the physical characteristics of these hard-setting, sandy soils that are known to collapse soon after cultivation. Therefore, further work is required to thoroughly evaluate the use of AquaCrop to simulate soil water in relation to peanut production in the rice-growing lowland soils of the region. Subsequent experimentation to improve lateral water movement in the root zone, including: (i) the use of organic soil ameliorants; and (ii) irrigation system design may assist in the improved calibration of the soil water component of the model under these conditions. Lastly, as well as being the first assessment of peanut production in Laos, this paper also presents the first reported evaluation of AquaCrop used for the simulated production of peanut (*Arachis hypogaea*), more widely.

Keywords: *AquaCrop, peanut, Laos, lowlands, irrigation*

Modelling the impacts of climate change on major crops in southern New South Wales using a Regional Climate Model ensemble

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Abstract: Regional climate models (RCMs) can translate broad-scale representations of the climate from global climate models (GCMs) to fine spatial scales. Theoretically, they have advantages over statistical downscaling models in terms of realization of future climate projections. However, there are few studies that have used them to assess climate change impacts on cropping systems. In this study, we do this for the Riverina-Murray region of New South Wales, Australia by using output from an ensemble of 12 RCM simulations (4 GCMs × 3 RCMs) performed by the NSW and ACT Regional Climate Modelling (NARCliM) project to run the Agricultural Production Systems SIMulator (APSIM) model.

We consider four major crops, namely wheat, barley, canola and lupins, under various farm management practices. We evaluate the NARCliM simulations against observed (SILO patched point dataset) data for a historical period, hence enabling us to apply a secondary bias-correction (SBC) to the projected cropping responses systems. The post-SBC outputs of APSIM for two future periods (2020-2039 and 2060-2079) are compared to the historic period (1990-2009) to investigate impacts of climate change on cropping. Various crop residue and fertilizer applications are simulated for assessing adaptation options. Over the entire cropping area of the region, 406 SILO sites and 57 types of soils are involved in the spatial simulations. A total of more than 2 million simulations are conducted and outputs related to crop phenology, yields, evapotranspiration and water use efficiency are analysed.

Our results show that historical crop yields from the APSIM simulations forced with the RCM output tend to be less than the yields from the simulations forced with observed climate data. A comparison of the RCM simulations against SILO data for 406 sites for the historical period reveals some biases in the RCM simulations, especially for solar radiation and rainfall. In this study, although the post bias-corrected NARCliM simulation outputs are used, the radiation data are not bias-corrected due to a lack of suitable observations. Rainfall and temperature are bias-corrected, but towards a gridded observational dataset on a regular 0.05° by 0.05° grid and not towards site-based observations of the type used in our study. The differences between gridded and site data may partially contribute to the rainfall and temperature biases.

We attempt to remove the influence of the RCM biases on the crop model outputs by applying two simple "secondary" bias correction methods to the APSIM simulated outputs: one is to correct the mean biases only and another is to correct both the biases of the mean and year-to-year variability. In this presentation, we will show results from both the corrected and uncorrected crop model outputs and discuss the uncertainties arising from the RCM and APSIM simulations.

Keywords: *RCMs, farming system, climate change impact, APSIM, spatial modelling*

EXTENDED ABSTRACT ONLY

Evaluating agricultural productivity under varying water availability in northern Victoria using a phenologically-based horticulture model

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Abstract: Irrigated agriculture in northern Victoria is experiencing uncertain water allocations and future climates. The management and adaptation of farm irrigation demand under variable seasonal water allocations intrinsically depends on the availability of objective crop water demand estimates. Traditionally these estimates relied on published values of the coefficients that relate crop ET to weather (commonly derived from overseas studies). Historic measures of irrigation water use have also been used to gauge irrigation demand. Measures of historic water use are themselves dependent on seasonal weather conditions, water availability, and irrigation development within catchments, and are therefore inappropriate to the development of dynamic adaptive farm and regional water use strategies. As such, assessing options to increase irrigated agricultural production under varying water allocations required the development of a biophysical, phenologically-based framework to enable an evaluation of the balance between available water, crop water-use demands and crop yields.

The developed phenologically-based biophysical predictive model estimates soil-water-plant interactions in irrigated horticultural systems under varying water allocations. The model accounts for eight phenostages (bud development, leaf development, shoot development, emergence, flowering, fruit development, maturity of fruit and dormancy) which are influenced by a variety of different environmental controls. The phenological status determines the allocation of net primary production (NPP) to assimilate pools representing roots, stems, leaves and fruit. Plant tissue within each pool moves to a lesser grade pool (and ultimately to litter in the case of leaves) based on decay rate functions. Additionally, the modelling accounts for management interactions including pruning, thinning, harvesting and irrigation scheduling. The advances of the phenologically-based model over a more simple crop factor models include the capability to simulate: (1) carbon assimilation and allocation processes; (2) fruit development and yield; (3) fruit quality; and (4) biannual yields.

This paper details the conceptualisation and application of a horticulture phenological model. To evaluate the performance of the model, this study compared predicted crop water use and yield estimates with benchmark survey data from the Shepparton Irrigation District and the Mallee regions of northern Victoria. Satellite derived evapotranspiration and growth profile data was also used to assess the predictions of plant performance and phenological stage. Predictions of water use were similar to those derived using a crop-coefficient approach. The normalized root-mean-square error between evapotranspiration predictions derived using remote sensed data and the phenological model was less than 10 percent. An acceptable agreement between observed and predicted crop yield was also observed in which coefficients of determination (R^2) ranged between 0.76 and 0.85.

The results have been used to simulate fruit yield response to water (and other factors) for a limited range of irrigated systems, and develop water-yield production functions for incorporation into a bio-economic model to evaluate the trade-offs between meeting environmental flow obligations and maintaining agricultural profitability.

Keywords: *Horticulture model, phenological model, irrigated agriculture*

Misuse of coefficient of determination for empirical validation of models

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Abstract: The objective of this study was to demonstrate that the regression coefficient of determination (r^2) is misused when validating models. The deviance measures of mean square error of prediction (MSEP), the decomposition of MSEP (bias, slope, and random components), modelling efficiency, t-tests of bias and slope and the r^2 are all reported for 3 datasets.

On-farm data to evaluate BeefSpecs, a fat deposition model that predicts final P8 fat (mm) to assist producers meet market specifications, is the primary dataset used in this study [dataset 1 (n = 80)]. Datasets 2 (n = 80) and 3 (n = 80) were created from dataset 1. Three millimetres were added to the observed values of dataset 1 to create dataset 2 and for dataset 3 the observed and predicted values were rotated 90 degrees. For datasets 1, 2, and 3 respectively, the mean bias was 0.06, 3.06, and 0.06 mm, root-MSEP (RMSEP) was 1.72, 3.51 and 3.68 mm, bias was 0.1, 76, and 0%, slope was 6, 1.4, and 79%, random component was 94, 23, and 21%, modelling efficiency (MEF) was 0.39, -1.55, and -1.80 and the r^2 was 0.43, 0.43, and 0.43 and the percentage of data points within ± 1.5 mm of the control limits was 65, 14, and 31%.

This study strongly emphasizes that model validation should be conducted with the standard reporting of summary statistics of min, max, mean, standard deviation, mean bias, RMSEP followed by the decomposition of MSEP (bias, slope, and random components) along with the graphical display of observed vs predicted (Figure 1) and deviations with upper and lower control limits. The MEF is also recommended as an appropriate assessment of model evaluation in preference to r^2.

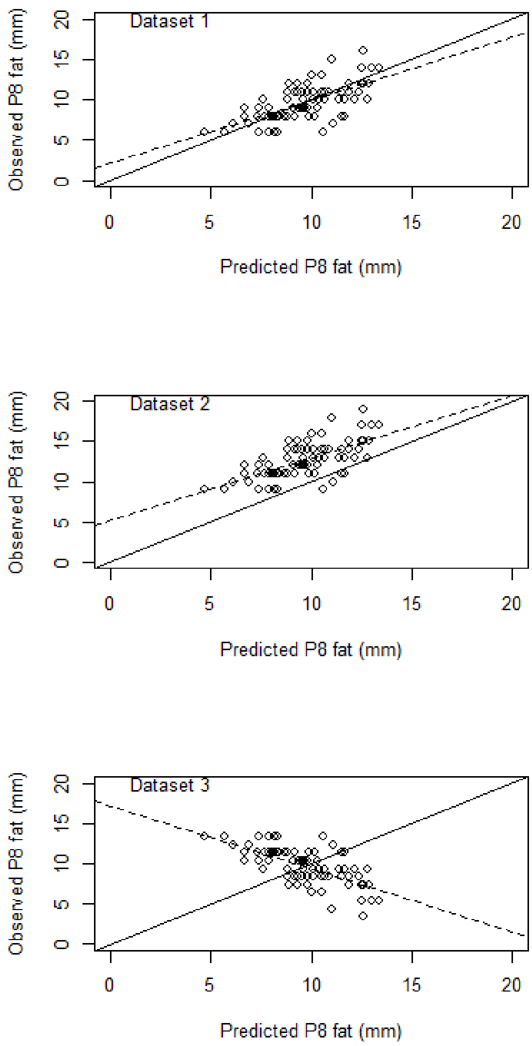

Figure 1. Datasets of the observed versus predicted P8 fat (mm) illustrating scenarios to demonstrate the misuse of regression for empirical validation of models. Dashed line is line of best fit.

Keywords: *Deviance measures, modelling efficiency, bias, slope, random*

Three-dimensional cameras to assess fat and muscle score on live cattle

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Abstract: The BeefSpecs fat calculator (http://beefspecs.agriculture .nsw.gov.au/) and the BeefSpecs drafting tool (Walmsley *et al.,* 2014; http://beefspecs.agriculture.nsw.gov.au/drafting) have been developed to assist producers manage cumulative risks associated with meeting market specifications [P8 fat (mm) and hot carcass weight (kg)]. This work began within the phenotypic prediction program of the Cooperative Research Centre (CRC) for Beef Genetic Technologies. It has been identified that if producers improve market compliance rates (i.e., improve meeting market specifications) it is worth over $51 million per year to producers and the processing sector of the beef industry, and more to producers through reduced feed costs.

Key inputs to the BeefSpecs tools are: weight (kg), frame score, muscle score and the initial P8 fat (mm). Development of a real-time system to assess these inputs was considered an important industry issue. A real-time, on-farm system for assessing live cattle also reduces variability between assessors and plays an important role in generating data that will assist the Beef industry make management decisions early in an animals' life that will impact profitability. This technology will also assist the industry and enhance the management and marketing of beef cattle.

A working relationship with the Centre for Autonomous Systems at the University of Technology, Sydney (UTS) was forged in 2009. The collaboration has grown between NSW DPI, UTS, and Meat and Livestock Australia (MLA) to conduct a 'proof of concept' using 3D cameras to assess P8 fat (mm) and muscle score (McPhee *et al.* 2017). Live animals are assessed using off-the-shelf Red Green Blue-Depth (RGB-D) Microsoft Kinect cameras.

The initial studies have been conducted on Angus cows and steers. Images from 2 cameras are converted into individual point cloud representations using a pinhole camera model. Surface curvature for each element of the point cloud are computed and encoded into a compact feature vector. Supervised learning then uses the feature vector to develop the relationship between the 3D images and the assessed traits. Figure 1 shows the rear end of a cow which has been fused into a single coherent 3D image using the point cloud. The results from this study found that there was a positive correlation between estimating hip height (cm) between the visually measured and the assessed 3D data from RGB-D cameras on cows and steers with correlation of 0.75 and 0.90, respectively. Supervised machine learning and global optimization approaches correctly classified muscle score [mean (±SD)] 80% (4.7) and 83% (6.6) for cows and steers, respectively. The root mean square of P8 fat (mm) was 1.54 and 1.00 mm for cows and steers, respectively. The results demonstrated the importance of capturing curvature as a form of representing body shape. Financial support from MLA is gratefully acknowledged.

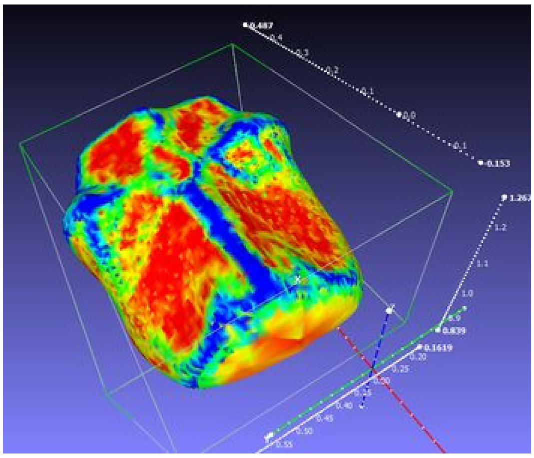

Figure 1. Point cloud, fused into a single coherent 3D image.

Keywords: *Red Green Blue-Depth (RGB-D), feature vector, supervised machine learning*

Modelling interventions for regional Ethiopian backyard poultry production systems

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Abstract: Livestock are a major component of rural economies in developing countries. They are a crucial asset and safety net for the poor, especially for women and provide an important source of nourishment for billions of rural and urban households. Livestock provide income and employment for approximately 1.3 billion producers in what are sometimes complex value chains. However, the productivity of livestock in the developing world is low relative to its potential. There are significant opportunities to increase productivity and profitability through improved technologies, policies and investments in farms and value chains. However until recently, the baseline data needed to adequately characterise livestock productivity levels in different parts of the developing world was either not available, nor at the level of disaggregation necessary to make informed decisions on the upscaling potential of key interventions and their impacts on productivity and household nutrition and income. Poultry keeping in smallholder backyard systems in rural households across regional Ethiopia plays an important role in poverty alleviation by generating income and food security. Improving the production of backyard poultry systems and thus reducing yield gaps can markedly contribute to income generation of small holder farmers. In this study we assessed the effects of interventions on backyard poultry systems across regional Ethiopia. Firstly by ascertaining current backyard poultry outputs, followed by modelling numerous interventions to identify both current yield gaps and potential opportunities for improvements in productivity. The efficacy of backyard poultry production is a function of nutrition, environment, management, diseases, and genetics, all of which interact in multiple ways, influencing productivity. The impact of interventions for a backyard poultry system can be explored by using simulation models such as Village Poultry Simulation Model (VIPOSIM). VIPOSIM integrates mortality, reproduction, egg production and bird offtake to assess various flock dynamic parameters. We report that a number of yield gaps currently exist within regional Ethiopian backyard poultry system and there exists potential to raise productivity outputs. We estimate that there is the capacity to raise the net aggregate egg and bird offtake rates above current production levels by 35 to 84% and 58 to 198% respectively. We also found that the financial returns from backyard poultry systems could potentially increase by 30 to 100% across Ethiopia dependent on the region. These potential increases in the productivity of backyard poultry producers result from better feeding practices, improved veterinary care leading to less diseases and lower mortalities from providing shelter and improving genetic stock. Secure markets and access to markets would also provide incentives to intensify. Our findings could be used to improve poultry husbandry and direct capacity building programs for those most in need of support, as well as to specify backyard poultry production structures that are most likely to perform efficiently in Ethiopia.

Keywords *Ethiopia, backyard poultry, VIPOSIM, modelling, interventions*

A functional-structural coral model

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Abstract: In biological systems, structural complexity is recognized as an important driver of coexistence and species diversity. This is particularly true for coral reefs, where some of the most biodiverse life on Earth coexists. A key contributor to reef structural complexity is the varied morphologies into which reef corals can grow. A large number of coral species of different forms can be found on a typical reef system, and, as well, individual species may show high plasticity in growth morphology in response to the local environmental conditions. As environmental conditions and disturbances regimes shift with climate change, future coral reef assemblages are in question.

Many corals respond to light in a comparable ways to plants, due to the presence of symbiotic algae in the cells of the animals that photosynthesise and it is well established that corals respond to their environment (e.g. light) by adjusting their morphology. Corals have very slow growth rates and field observations capturing growth and competition are therefore difficult. As such, a modelling approach provides a much needed opportunity to explore changes in coral structure and functioning. Here, we adapt a functional-structural plant modelling approach, commonly used in plant sciences, to represent coral colonies. Functional-structural modelling combines functional components, such as photosynthesis, growth rates, transport of resources and responses to environmental parameters, with a dynamic representation of the 3D structure or architecture of the modelled plant(s), or in this case, corals.

The aim was to create a 3D functional-structural model where structure, function and response to local environmental factors are specified by a set of 'morpho-functional' parameters, and determine whether this model could represent some of the major coral growth forms seen on coral reefs. Understanding the growth, competition and mortality of organisms at a three-dimensional (3D) level is important in understanding an organism's role as an engineering species and the mechanisms that lead to the maintenance of structural integrity.

The results show that the model can simulate corals with distinct morphologies by varying the simple set of morpho-functional parameters, including resources required for growth, self-avoidance and resource sharing. From varying these parameters, coral morphologies emerge that match with observed coral shapes in nature that are known to have different growth rates and structural fragility. These include hemispherical, encrusting, columnar and tabular forms.

The full diversity of morphologies is not yet captured, and further investigation into other parameters is required. There are many potential future applications of this functional-structural coral model, including matching model output at a coral community level to field measurements from a real coral community. If the model can represent real morphological assemblages for different environmental conditions it could be used to predict future assemblages under different climatic disturbance regimes.

Keywords: *Cellular automaton, coral reef, functional diversity, polyp, structural complexity*

EXTENDED ABSTRACT ONLY

Spatiotemporal modelling of a synthetic rangeland ecosystem to check ecological hypotheses and theories

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Abstract: The model presented allows the spatial dynamics stemming from the interactions between mobile agents (like herbivores) and their environment (like rangeland) to be simulated. This model thus features a herd grazing on a pasture. For the sake of sustainability a dynamical balance must be found between the grass consumption by the animals and the herbage growth. However, two behaviours may threaten this equilibrium: overgrazing, possibly leading to desertification; under-grazing, that may lead to excessive vegetation growth and the landscape "closure" by invasive shrubs. Both processes may lead the herd to extinction by starving.

This model's aim is not, actually, to mimic real specific rangelands but to offer a generic simple synthetic ecosystem to check ecological hypotheses and theories. Although deliberately naive, it has been parameterized with real rangeland and cattle values and implemented with the agent simulation platform NetLogo <ccl.northwestern.edu/netlogo>.

Simulations have been made to check variants of the ecosystem's structure and animal behaviours:

- Spatial distribution of vegetation and animals;
- Foraging strategies: staying or moving; local or global search;
- Animal ways of movement: directed vs. random walks, short vs. long step length;
- Heterogeneity vs. homogeneity among individual animals or land patches.

The main criteria of simulation assessment are the production of animal and vegetal biomasses, herd demography and landscape fragmentation.

In the simulations made, the most sustainable strategies are those emphasizing space occupation, local foraging, short walk steps and anticipating resource exhaustion.

Whereas the main focus to date has been put on the comparison of animal walk types, showing the strong importance of animal movement in the rangeland system's dynamics, the emphasis has been put, since then, on other uses of the model:

- Exploration of issues regarding ecosystem complexity (e.g. adding trophic levels), percolation of products through space, resilience in front of disturbances;
- Hypothesis testing: optimal foraging, ideal free distribution, marginal value theorem.

Without challenging the deliberately naive approach followed so far, for the sake of realism, some improvements have been (or are being) introduced into the model:

- Interactions among animals to reproduce herding behaviour or sexual mating, interaction among land patches to propagate the vegetation;
- Structuring landscape elements (e.g. water holes) or behavioural features (e.g. preference or aversion for some kinds of vegetation) influencing animal movement;
- Climatic characteristics and seasonality influencing animal behaviour or the herbage growth;
- Heterogeneity among individuals in the herd and land patches in the landscape;
- New relevant criteria and metrics for landscape assessment.

The main features of the model and simulations demonstrating its relevance to deal with hypothesis checking will be presented.

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

Developing a spatially explicit dynamic rural land use change model for the Tauranga Harbour catchment

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Abstract: Rural land use and land management practices have substantial impacts on the environment including water quality, carbon emissions, and ecological health and biodiversity. There is increasing focus on the need to understand how different rural land use scenarios affect the interplay between environmental and economic impacts.

In this work we present a novel model of rural land use change for the Tauranga Harbour catchment, in the Bay of Plenty region of New Zealand. The rural land use change model described here will be connected to an urban land use change model, a dynamic economic model, a pollutant transport model, a hydrodynamic model, and inter- and sub-tidal ecological models to form an Integrated Spatial Planning Tool (ISPT) as part of the MBIE-funded Oranga Taiao Oranga Tangāta research programme (MAUX 1502). The goal of the ISPT is to support co-management of the Tauranga Harbour by coupling the terrestrial and estuarine ecosystems, as well as showing how these ecosystems inter-connect to the Tauranga economy, land use and other environmental and management factors.

The rural land use change model is driven primarily by the return to land (profitability) of different land use options and land conversion costs, which come from a dynamic economic model for the Bay of Plenty region and the rest of NZ. Land use outside the Tauranga Harbour catchment is determined using an empirically determined aggregate land use decision model that incorporates economic conditions, as well as allowing for inertia and lag times, and is calibrated to historic data from the NZ context. Through our process for calibrating the model we identified some important datasets that are missing in the NZ context. In order to initialise our model, we developed a base year land use map using Random Forest machine learning techniques for classifying rural land uses from available national datasets. For land use change within the Tauranga Harbour catchment the aggregate land use decision model is paired with bottom-up (fine grained) spatial information about biophysical land properties, neighbourhood influences, zoning, and other restrictions on land use to determine land suitability and a probability of change for each land use cell. A key feature of the methodology is the two-way relationship between economics and land use; once land use supply is determined, this information feeds back into the economic model and imbalances between land use demands and supply produce flow-on adjustments in commodity and factor prices and thus land use profitabilities.

Our hybrid approach that couples a top-down dynamic economic model with a bottom-up spatially explicit land use change model within the Tauranga Harbour catchment enables investigations of the environmental and economic impacts of different policies or plausible futures (e.g. economic, climate). Furthermore, it enables users to consider individuals with different value sets on which land use change decisions are made, through being able to incorporate parameters relating to conversion hurdles, time horizons, or other (non-economic) factors.

Keywords: *Land use change, integrated modelling, individual-based models, economics, spatial planning tools*

Modelling the impact of trading biodiversity conservation requirements in tropical forests

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Abstract: Balancing economic development and ecological sustainability is a complex problem. One way to achieve both goals is by setting quotas and distributing permits for environmentally degrading activities. This method can be extended to allow permits to be traded between stakeholders. Quotas place a rigid, legal limit on the extent and magnitude on destructive economic activities with the aim of reducing the overall impact of, for example, fishing, hunting, greenhouse gas emissions, or deforestation. In areas with a significant threat of land-use change, Tradeable Development Rights (TDR) can be allocated to landowners, stipulating the proportion of their land that can legally be developed. Landholders must decide whether to meet their development allowance and conservation requirements on their property, or sell their development rights to other landholders.

While this policy mechanism may prevent native habitat area loss, the spatial pattern of reserved areas will shift, creating novel landscape patterns. The resulting altered fragmentation and connectivity of habitat will impact biodiversity. TDR may also allow landholders to earn rent on land they never intended on converting, resulting in additional deforestation elsewhere. Because of this spatial dependency, the ecological implications of TDR are not fully understood. Recent TDR research has focused on revisions to Brazil's Forest Code that allow for trading of existing legally-mandated development rights. Most conservation land in Brazil is on private property, so compliance with private land-use regulations drives conservation outcomes in Brazil.

We model the predicted native habitat and agriculture patterns resulting from these two policies, assessing outcomes with multiple graph-based landscape metrics. We incorporate potential agricultural profits into the model and assess the economic impact as the total agricultural income from the landscape. We compare outcomes under four different assumptions about the initial land-use patterns, from random initial land-use patterns to those predicted by economic value. We observe predicted land-use outcomes first in a heterogeneous landscape, then around a permanent conservation reserve, and finally with different levels of deforestation pressure.

When future deforestation was certain to occur, our individual compliance model resulted in a very diffuse landscape, which TDR counteracted resulting in a more connected landscape (up to 23 times higher mean probability of connectivity) with fewer and larger maximum fragment sizes (up to 9 times higher), and significant but small benefits for economic productivity and edge-to-area ratio. However, our model showed that a TDR is detrimental to a habitat type that exists only on land with the highest potential economic returns from agriculture. A TDR was also detrimental to biodiversity if deforestation is halted, and provides negligible benefit if deforestation is controlled according to our model.

Keywords: *Biodiversity conservation, economic incentive scheme, private land conservation, deforestation, habitat connectivity, graph theory*

Simulated evolution of phenotypic plasticity in a functional-structural plant root model

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Abstract: The aims of this study were 1) to develop a new computational functional-structural plant model (FSPM) to represent root development within a single growing season, with a focus on water uptake, and then 2) link the FSPM with an evolutionary algorithm in order to simulate evolution of plant populations over many generations. We wanted the model to allow for complex structures with any specified levels of branching orders. Even more importantly, we wanted the model to allow for plastic growth strategies, that is, growth strategies where growth and structure respond to local and global environments in different ways. We also wanted to include simple soil-water-root dynamics, including root-density-dependent water uptake and the possibility of water moving through the soil through bulk flow and diffusion. In order to link it with the evolutionary algorithm, we needed the model to be flexible, in the sense that it needed to be able to represent a very wide range of different root growth strategies with varying levels and types of plasticity, and it needed to do this by simply varying model parameters that represent functional plant traits. Finally, we wanted the model to be simple enough that large plant populations could be simulated quickly and efficiently. This ability to simulate large populations is essential for the model to be successfully linked with the evolutionary algorithm and conduct evolutionary simulations that represent changing populations with large numbers of individuals in each of many generations. It is also important because it allows us to fully investigate and account for stochasticity, and also to apply the model to simulate plant communities with large numbers of individuals of the same or different species interacting in a single environment.

We describe how we developed a new FSPM to meet the requirements outlined above. We also explain how the model was linked with an evolutionary algorithm in order to explore how, through the processes of evolution, plants develop effective and efficient strategies to acquire water in a water-limited environment. Evolution was simulated in four different environments, which varied in terms of higher or lower rainfall frequency and soil being either homogenous in water holding capacity or heterogeneous with small patches of higher water holding capacity. Replicate evolutionary simulations were conducted in parallel for each different environment. Our results show that populations evolved over time to increase the average fitness of the population, as measured by total biomass achieved at the end of the growing season. Different strategies evolved in different environments. Many of the flexible model parameters representing evolvable traits shifted in systematic ways as evolution proceeded and fitness increased; these shifts in functional traits could be understood in terms of ecological strategies that would increase the fitness of the plant in the conditions in which it was evolving. Evolutionary trajectories and rates of evolution were also found to vary considerably between parallel evolutionary runs in identical conditions. Our results highlight how the combination of FSPM with evolutionary algorithms can be used to explore fundamental ecological questions, such as the evolutionary advantages and disadvantages of phenotypic plasticity and its relationships with soil and rainfall patterns, the repeatability or uniqueness of evolutionary trajectories, evolution within diverse plant communities, and the processes of speciation.

Keywords: *Functional-structural plant model, evolutionary algorithm, ecological fitness, simulation model, rooting strategies*

The advantages of being big and a little bit noisy – the effects of variable location information on the honeybee nest site selection process

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Abstract: As part of their reproductive cycle, colonies of the cavity nesting honeybee *Apis mellifera* issue swarms. These swarms initially settle close to the location of the original colony, from which they search their surroundings for a suitable new nesting location. Such locations must be found quickly, as a swarm is unable to store food and is exposed to the elements. Aspects of the complex process used by *Apis mellifera* swarms to select a new nest-site are relatively well understood due to a century of scientific research founded on the works of Karl von Frisch and Martin Lindauer. Scouts travel from the swarm to explore the surrounding landscape (up to distances of 10 km); if a scout finds a suitable cavity then she returns to the swarm and reports the location and perceived quality of the potential home to other bees via stylised behaviour referred to as a waggle dance. Some of the bees that observe a waggle dance then decide to investigate the corresponding site and independently assess its quality. If these scouts also think that the site is viable, then they too will perform waggle dances on their return to the swarm, effectively seeking more recruits to examine the site. If sufficient bees visit a particular site at the same time, then the colony chooses that site as a collective. Often the process used by honeybees to select a new home is portrayed as being very clean and clear, whereas the reality is that there is considerable variability in the behaviour of individual bees, including the communication of locations using waggle dances. Here we will examine how variability in the location information communicated via waggle dances can affect the overall decision-making ability of honeybee swarms using a discrete time individual-based model framework originally developed by Kevin Passino and Thomas Seeley. Agents within the model represent the female workers engaged in the nest-site selection process (the scouts), with agent states connected to different tasks performed by the scouts (resting, seeking information about potential nest-sites from other bees on the swarm, independently exploring the landscape around the swarm, assessing potential nest-sites and communicating the location of acceptable sites to other swarm members). The landscape surrounding the swarm is modelled explicitly on a two-dimensional grid, with possible nest-sites randomly dispersed across the grid. Interestingly, it appears that some noise in dance communication can be beneficial in terms of choosing the best available home (out of many possible choices), and we will examine why this is the case.

Keywords: Apis mellifera, *nest-site selection, decision-making, dance precision, individual-based model*

Agent-based modelling approach to simulate the impact of irrigation expansion on the region and support effective decision-making

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Abstract: Investment in irrigation infrastructure in Tasmania prompts the need for highest and best returns in the use of land and water resources. The complexity of decision-making on irrigation expansion to optimise the benefit of regional agricultural land points to a modelling approach that includes not only spatial and agronomic considerations but also captures human judgment and the role of agents in regards to decision making. This research proposes Spatial Agent-Based Modelling (ABM) as a powerful modelling approach to simulate the farmers' behavioural rules under different agricultural scenarios and assesses their influence on the regional agricultural development and economic return from irrigation. It also outlines the steps by which the farmer behavioural rules were captured and incorporated into Geographic Information Systems (GIS). This spatial ABM simulates the regional land use and crops pattern based on a set of macro-level (regional scale), and micro-level (farm scale) rules via GIS layers. The individual farmer is the subject of the model who is a decision maker, and the agricultural land parcel is the object of the model that includes the geographic information and interactively changes over time based on farmers' decision.

Crop GIS-ABM is a spatial ABM developed in Agent Analyst toolbox (developed by ESRIArcGIS) that simulates a vector polygon (Block) agent interactions with a generic human agent (Farmer) to determine the changes in patterns of alternative crops over time. A Block agent includes available resources of the spatial and environmental dataset, and a Farmer agent contains human decisions criteria and social networks. The spatial interactions among farmers and the region depend on the place of the land farm and its relation to the irrigation districts. Farmers (generic agents) interact with each other and with their environment in each time step and the make choices to produce a different type of crops (e.g. ryegrass, poppy and hemp). The Block (vector polygon agents) are changed upon the farmers' decision based on the parameters and interaction with the neighbours land. As a result, the region's crop pattern emerges based on farmers' decisions and interaction. Using this approach, the behaviour of farmer agents and their interaction with Block agents and their environment can be simulated under different scenarios such as (proximity to the processing plant, irrigation availability, and neighbour's decision to adopt alternative crops).

The model presents complex dynamic interdependencies between farmers' decisions and regional land-use and crop pattern change. The strength of Crop GIS-ABM (by utilising both ABM and GIS) lies in the opportunity to visualise the land parcels' interactions and represent the changing pattern of alternative crops over time. The Crop GIS-ABM facilitates the human-environment interaction visualisation in GIS as well as flexible cross-scale simulation of farmers' micro behaviours to the macro emergent pattern. The validity of the model is ascertained by comparing the simulation output with different stakeholders' responses about the future of agriculture in the region. This Spatial ABM could be applied with appropriate modifications on similar regions to simulate the stakeholders' decision-making processes on agricultural land and water use.

Keywords: *Spatial ABM, polygon agent, Agent Analyst*

Modelling the integrated management of organic waste at a territory scale

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Abstract: Modelling integrated management of organic waste at a farm level is still a key challenge, but one can find several works in the literature. However, the shift to a larger (*e.g* area, district or county) scale is even more complex. Consequently, associated modelling work is still considerably under-developed. Here we use the UPUTUC model (french acronym of Production Unit, Transformation Unit, Consumption Unit) to examine fluxes of organic matter residues within the Territoire de la Côte Ouest (TCO), on the west of Réunion Island.

UPUTUC is an agent-based model and is developed using the AnyLogic platform. This platform is a multi-method modeling environment and allows for the combination of discrete event models, agent-based models and system dynamics models. It also provides spatial features in order to use information coming from GIS. UPUTUC uses three agents. These agents are: (i) *production units* that produces organic matter or waste (for example: pork, poultry breeding and sludge produced by a wastewater treatment plant), (ii) *transformation units* that produces compost or fertilizer with organic matter coming from the production unit, and (iii) *consumption units* that uses transformed organic matter from the transformation unit or organic matter coming directly from the production unit (for example: a sugar cane field, a market gardening and a grassland). State variables of *production units* are a production rate, a stock, and all times and distances to the *transformation units* and *consumption units* in the model. State variables of *transformation units* are a production rate, equations the transform organic matter into compost or fertilizer, a transformation time, a stock, capacity of trucks that delivers products to consumption units, and finally, all times and distances to *consumption units* in the model. State variables of *consumption units* are an area, compatible fertilizers with the unit, fertilizer requirements, and periods during which fertilization is possible. In addition, the agents are spatially situated based on GIS information. The French Land Parcel Identification System (LPIS) and the Farmers' block from the European Common Agricultural Policy provide this information. Moreover, as Réunion Island is a volcanic island, the roads are very rough and consequently the logistic dimension is crucial in the model. Therefore, as the dynamic of logistic characteristics of the associated road network is not simulated (for example, the time for a vehicle to transport organic matter from a production unit to a transformation unit) these variables are pre-computed off line in a previous step and are considered as parameters. In UPUTUC, there are 51 *production unit* agents, 2272 *consumption unit* agents and, finally, only 4 *transformation unit* agents. Several scenarios are tested. First, the current situation in order to check how the model behave. Second, the introduction into the first scenario of a new *transformation unit* (called UT1) that takes as inputs only litter, manure and crushed green wastes and combines them into a specific compost used by all the *consumption units*. Third, the introduction into the second scenario of two new *transformation units*: the first one (called UT2) takes as inputs only poultry dropping, vinasse and crushed green wastes and combines them into a specific compost, and the second one takes as input compost from UT1 and UT2 and produces granulates with them.

Keywords: *Agent based model, GIS, AnyLogic, organic waste management, Réunion Island*

EXTENDED ABSTRACT ONLY

Impacts of marine closures on catch rate standardizations – simulation testing

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Abstract: Marine spatial closures implemented in Australian waters have aimed to (i) generate a comprehensive, adequate and representative system of marine protected areas, (ii) contribute to the long term ecological viability of marine and estuarine systems, (iii) maintain ecological processes and systems and (iv) protect Australia's biological diversity at all levels. They may also help reduce fishing pressure on stocks, allow juvenile fish to grow, protect spawning/breeding areas and protect marine habitats or particular resident species.

If marine closures aim to reduce fishing pressure in particular areas and are sufficiently large, they may affect fishery dependent catch-per-unit-effort (CPUE) data. Also, if CPUE is influential in single species stock assessments, then such closures could affect how the population status of a species is perceived. Commercial fisheries CPUE indices are used to index population abundance for most Australian fisheries. As such, it is important to determine to what extent marine closures affect CPUE indices in their ability to proxy species abundance. CPUE may change following the introduction of closures if the areas closed are important fishing locations for a particular fish species, or if fishers alter where and when they fish in response to closures excluding them from preferred and/or 'high yield' locations.

An agent based simulation model was employed to determine the effect of marine closures on standardized CPUE, in the context of different fisher behaviour types and resource (fish) movement dynamics. Resource movement types are based on a generic platycephalid (i.e. tiger flathead) frequently occurring in the Southern and Eastern Scalefish and Shark Fishery (SESSF). Generated CPUE data were standardized using generalized linear models (GLIMs), and these CPUE indices then analysed with true abundance to examine the effect that marine closures have on the CPUE-abundance relationship. Standardizations were performed across a range of resource movements, in an attempt to ascertain to what extent the resultant CPUE indices represent trends in resource abundance for selected fisher behaviour scenarios with and without marine closures.

Linearity between CPUE and abundance is desired for CPUE to adequately index abundance. Significant improvements (in terms of linearity) over unstandardized indices for most resource/fisher scenarios were obtained which support the use of standardized CPUE estimates as proxies for abundance with or without closures. Overall, improvements towards linearity were greatest under particular fisher behaviour scenarios with or without marine closures. Additional key findings and recommendations will be further discussed.

Keywords: *Agent based model, fisher behaviour, CPUE, marine closures*

Modeling rhizosphere carbon and nitrogen cycling in Eucalyptus plantation soil

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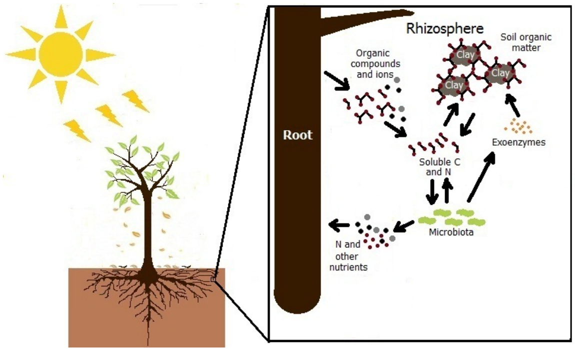

Figure 1. Illustration of rhizosphere C and N cycling processes in the ForPRAN model

Abstract: The model 'Forest Plantation Rhizospheric Available Nitrogen' (ForPRAN) is based on the laws of conservation of matter and energy and on the principle that systems seek self-organization as a strategy of self-preservation. One of these strategies is cooperation between organisms for mutual benefit (mutualism). In this case, trees release organic compounds that modulate rhizospheric microbial processes. The release of organic compounds into the rhizosphere provides energy and labile nutrients - factors in abundance for it and scarce for microbes - and receives in return a higher amount of mineralized N and other nutrients from soil organic matter. This symbiosis involves three components of the ecosystem - *Eucalyptus*, microbes and soil – which may have evolved to ensure nitrogen and energy fluxes in the forest ecosystem were maintained. The process is schematically summarized in Fig. 1. The objective of this work was to propose and evaluate a mechanistic model for predicting rhizospheric C and N cycling in *Eucalyptus* plantations. The process-based model predicts the change in rhizosphere C and N cycling resulting from root growth, and it consists of two modules: (1) fine root growth, and (2) C and N rhizosphere cycling. The model describes a series of soil biological processes: root growth, rhizodeposition, microbial uptake, enzymatic synthesis, depolymerization of soil organic matter, respiration, mineralization, immobilization, death, microbial emigration and immigration, SOM formation. Despite uncertainties in modeling root growth, the model is relatively simple and has an $R^2 = 0.75$ for a linear regression of predicted versus observed fine root biomass. The model also satisfactorily simulated microbial biomass across the range of observed data ($R^2 = 0.91$, Nash Sutcliffe efficiency (NSE) = 0.90, Mean Error (ME) = 0.02 μg C/g, and Mean Absolute Error (MAE) = 1.77 μg C/g). These last two indexes indicate that the error associated with predictions was low considering the range of the observed values of 19.7-38.2 μg C/g. Root Mean Square Error to Standard Deviation Ratio (RSR) was 0.32, which is low considering that values of RSR below 0.6 indicate good to very good performance. The qualitative evaluation of the model showed that as carbon availability increases, biomass increases, which is directly proportional to increased exo-enzyme production and respiration. In-turn, when microbial biomass increases there is a tendency for reduced total organic N of the soil, which indicates decomposition of soil organic matter (SOM) surpasses the formation of new SOM. Finally, we used the ForPRAN model to simulate a published experiment with the following treatments: water, water+C and water+C+N. Results were in accordance with expected responses in microbial metabolism, i.e. microbial growth was higher in the presence of C+N, followed by only water+C and water alone. Considering the high carbon investment in roots by *Eucalyptus* trees, the rhizosphere cycling model should be considered for adaptation to other forestry and agricultural production models where the inclusion of such processes offers the potential for improved performance model.

***Keywords**: Fine roots, rhizodeposition, microorganisms, mineralization, nutrient availability*

Using Pattern-Oriented Modelling to Parameterise Functional-Structural Plant Models

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Abstract: Functional-structural plant (FSP) models have been widely used to understand the complex interactions between plant architecture and underlying processes driving plant growth for over two decades. FSP models can be identified as agent-based models (ABMs), if the organs of a plant are considered as autonomous entities that have certain behaviours. FSPs use simple rules to represent these behaviours, the interactions among them in a branching structure, and the interactions between them and their abiotic environment. However, parameterisation of such models is a challenging task due to the high variability of plant growth and the complexity of interacting physical and biological processes. Therefore, it can be very difficult or impossible to collect all of data needed to allow models to be developed. Even if it is possible to collect required data, it relies heavily on a large number of field or lab experiments to estimate the appropriate values.

To address these issues, our study adopts the pattern-oriented modelling (POM) strategy to parameterise FSP models. A pattern refers to any observation that is beyond random variation and thus contains information about underlying mechanisms. In pattern-oriented parameterization, we use multiple patterns as filters for rejecting unrealistic parameter combinations, which is also known as inverse modelling. Our overall objective therefore is to demonstrate how POM can make the parameterisation of FSP models more systematic, efficient, and powerful.

Specifically, we used POM to parameterise an existing FSP model (avocado architecture model). We used five patterns, all of them scalar metrics characterizing structural features of the avocado annual growth module. Our model, which has six unknown parameters, was successfully parameterised manually before, so that we could check whether POM parameterisation would converge to the same results. To keep the number of parameter sets manageable, sub-sampling techniques from parameter space such as Latin Hypercube Sampling (LHS) was used. Then, each of the verification patterns was used as a filter to discard parameter sets leading to results violating this pattern. For this, we specified target confidence intervals around the observed values of our verification patterns.

The resulting values of pattern-oriented parameterisation shows a good agreement with the values of manual calibration. The existing avocado architecture model fitting with the resulting values of pattern-oriented parameterization, did not only reproduce all five verification patterns, but also predict the validation patterns. Our study thus suggests that FSP models can be parameterised using POM in a more systematic and efficient way. In our case, POM parameterization led to specific values for each parameter, which indicates that the processes underlying those parameters do not interact strongly, which is an important addition insight. In most existing POM parameterizations, interaction between parameters was high so that in the parameter sets passing all patterns, or filters, most individual parameters varied over a large range so that only the entire parameter set could be used for model applications. We conclude that the pattern-oriented calibration approach allows FSP models to be developed in a timely manner without relying heavily on field or lab experiments.

Keywords: *Pattern-oriented modelling, agent-based modelling, individual-based modelling, parameter estimation, parameter calibration, Latin Hypercube Sampling (LHS)*

Sensitivity of simulated yield of dryland wheat to uncertainty in estimated plant-available water capacity

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Abstract: Water availability, which is determined by rainfall and also by the plant available water holding capacity (PAWC) of soils, is a key determinant of crop yield in the Mediterranean farming systems of the Western Australian wheatbelt. While unlike rainfall data, soil parameters (DUL: drained upper limit, CLL: crop lower limit and RD: rooting depth) affecting PAWC at a field scale rarely exist and the values required by crop simulation models (e.g. APSIM) have to be inferred from nearby soil surveys or local knowledge. The estimation of these soil parameters unavoidably creates uncertainty in PAWC, which results in uncertainty in simulated crop yield. There may also be interactive effects on simulated crop yield between biased estimate of PAWC, rainfall and nitrogen (N) supply. However, the sensitivity and uncertainty of simulated crop yield to errors in estimated PAWC under variable rainfall and fertilizer applications have not been well researched. This study performed a sensitivity analysis, using the APSIM model, to quantify the influence of the uncertainties in PAWC on estimation of wheat yield in a rain-fed Mediterranean type environment with one typical soil and four N treatments. Simulation results showed that, for any given amount of N, the changes in the three parameters (DUL, CLL and RD) that resulted in the same changes in PAWC would result in the same changes in wheat yield, i.e. PAWC is the key factor to affect simulated yield. When PAWC was biasedly estimated by a small amount (< ± 20mm), the impact on simulated wheat yield was marginal (0-200 kg/ha) under all N treatments. However, when changes in PAWC were larger (>±20mm), its biased estimation had assymetric effects on simulated rainfed wheat yields: on average the underestimation of PAWC would cause greater deviation in simulated wheat yield compared to its overestimation regardless of N treatment. For example, when PAWC was underestimated by 40 mm, wheat yield was reduced by 80, 170, 320 and 440 kg/ha under zero, low, medium and high N treatments, respectively. In contrast when PAWC was increased by 40 mm, simulated yield increased by 30, 70, 140 and 240 kg/ha under the four N treatments, respectively. There was an interactive effect on simulated wheat yield between PAWC, N supply and seasonal rainfall, i.e. the simulated yield bias was larger when PAWC was estimated with bias in situations with more rainfall and more fertilizer N. Ideally simulations should be based on accurately measured soil water parameters. However, in the absence of measured data an overestimation of the true PAWC will result in less error in simulated yields than and underestimation, irrespective of rainfall condition and soil N supply.

Keywords: *APSIM, PAWC, wheat, soil parameters*

Determination of BMPs to Reduce Soil and Water Pollution in Tile-Drained Watersheds in Southern Ontario, Canada under Changing Climate

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Abstract: Best Management Practices (BMPs) can be implemented on agricultural landscapes to manage water flows and reduce nonpoint source pollution. However, given the specificity of each landscape, there are presently no credible methods of determining, *a priori*, which BMP would work best under a given situation and, more importantly, where in the watershed should it be located. Furthermore, climate change in Ontario, Canada is going to cause non-uniform spatial and temporal distribution of precipitation, thereby causing and aggravating flooding, drought, and pollution problems. Hydrological simulation models are useful tools to understand how a change in global climate could affect the availability and variability of regional water resources. This research addresses this important issue in two different watersheds in Ontario. The main goal of this study is to develop an agricultural landscape assessment tool by simultaneously considering physical, chemical, and biological landscape parameters and carry out a holistic analysis of the agricultural and environmental state of the landscape.

Our research team has developed SWATDRAIN, a watershed scale model for subsurface-drained agricultural landscapes, by fully integrating SWAT and DRAINMOD models. While the SWAT model has been used extensively around the world to simulate surface hydrology of watersheds, it leaves much to be desired when it comes to subsurface hydrology, specially for tile-drained landscapes. Therefore, DRAINMOD was fully incorporated into the SWAT model's subsurface hydrology module as an alternative method for simulating tile drainage, water table depth, and soil water status. The newly developed SWATDRAIN model is based on the DRAINMOD subsurface hydrology simulation and the SWAT surface hydrology simulation. SWATDRAIN computes the soil water balance for each HRU (Hydrologic Response Unit) in every sub-basin on a daily basis.

In this paper, the impact of controlled drainage on watershed hydrology and sediment loadings will be presented. The effects of climate change on annual and seasonal water budgets, sediment loads will also be reported.

Keywords: *Best Management Practices (BMPs), SWATDRAIN, climate change*

Evaluating Orchard Light Interception with a High Performance Light Simulator

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Abstract: Light interception plays a vital role in plant productivity. The quantity and quality of a plant's yield are highly dependent on the amount of light energy it can capture. For a single fruit tree, techniques such as training, pruning and selective breeding can improve its architecture, to produce less leaf overlapping and consequently more efficient light capture. At the orchard scale, the overall light interception is also influenced by planting density, row orientation and terrain location. Therefore, the optimal productivity requires a comprehensive solution to cover as many of these factors as possible. Nevertheless, using real-world experiments can take years and even decades, making it expensive for both horticultural research and industry. To narrow the range of orchard experiments, functional-structural plant modelling (FSPM) and light simulation have been applied to horticultural investigations. However, for a long time, most of these applications have been serial programs (using only one CPU regardless of how many cores a computer has), which does not make good use of modern computing architecture and sacrifices implementation efficiency to gain simulation accuracy or vice versa. Some researchers try to simplify the representation of the plant and light environment (e.g. using voxel hulls and turbid medium) for fast simulation, while others prefer to address the complex details (e.g. using explicit 3D architectures and light ray tracing) for accurate results. As part of Queensland's Small Tree High Productivity Initiative, we have developed a high-performance version of a quasi Monte Carlo light simulator (known as QuasiMC) aiming at both efficiency and accuracy for virtual experiments. In our first-stage experiments, this new version of light simulator was used to shoot 32 million explicit rays for simulating light distribution in two virtual macadamia orchards (one unhedged, with 562,488 leaves; the other hedged, with 197,520 leaves) incorporated with 24 virtual sensors. Producing the same results as the serial version, the new light simulator speeds up with an efficiency ($\frac{T_1}{p \cdot T_p}$, where T_1 is the running time of the old serial version, T_p is the running time of the high-performance version, and p is the number of processors) of 0.81 and 0.9 respectively for the two cases, demonstrating good performance in both scalability and accuracy. Our work in the near future will be to deploy this high-performance simulator onto a supercomputer with thousands of cores, by which the execution time of a fine-scale experiment at orchard level could be reduced from hours to seconds. This could significantly accelerate industry-oriented studies on orchard system design and management.

Keywords: *Functional-structural plant modelling, high performance computing, ray tracing, Quasi Monte Carlo, virtual plants*

From data to decisions: using real-time climate forecasts in biophysical models in a cloud-based online platform for agricultural decision-makers

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Abstract: The Tasmanian Institute of Agriculture, Sense-T, University of Tasmania, CSIRO and Dairy Australia have developed a free online framework and mobile app comprising several new livestock system tools for agricultural decision makers. The cloud-based Sense-T data platform supporting the framework ingests real-time climate data and nine-month weather forecasts from the global climate model POAMA at various Australian locations. The platform allows users to develop their own applications that use real-time climate feeds and/or other measured sensor data to provide new data streams. The data streams are produced by a combination of biophysical models that are either freely available (DairyMod) or that have been programmed in R and/or Python. The framework producing the data streams includes code for the scheduling of model runs, allowing regular updates of biophysical outputs with new climate data and POAMA forecasts.

The data streams are displayed online in a free dashboard called the 'Pasture Predictor' and as 'My Pasture App' via the 'HockeyApp' as a free subscription from the Tasmanian Institute of Agriculture. One of the functions of the dashboard is to output both hindcast and forecast pasture growth rates. On My Pasture App there are several other tools, including (1) forecasts of climate indices showing real-time evolution of pasture stress as determined by limitation of water, temperature or light, (2) a model that predicts leaf-appearance rates of perennial ryegrass, (3) a nitrogen calculator for estimating the optimal nitrogen application in terms of fertiliser cost relative to estimated dry matter production, and (4), a tool for decisions regarding on-farm livestock rotation between paddocks. The models for pasture growth rates and climate indices use historical data from longpaddock.qld.gov.au/silo/ppd/index.php as inputs and output biophysical data up to the present; models then use each of the 33 constituents of the POAMA ensemble to provide percentile data streams of three-month forecasts. Both current climate data and POAMA inputs are regularly updated via separate code for scheduling of model runs.

We are open to collaboration to develop other applications on My Pasture App and the Pasture Predictor, as well as improving the Pasture Predictor itself. We plan to continue to work with our dairy and red-meat partners to build further capability into the online dashboard that is currently available at http://dashboard.sense-t.org.au/. Some future updates may include (1) conversion of static tools (N calculator and leaf appearance rates) to a more dynamic approach utilising climate inputs, (2) development of machine-learning approaches of model algorithms that use input measurements and satellite data of pasture biomass, NDVI and soil water content, (3) growing degree-day predictions for maturation dates and phenology of different crop types, (4) market specifications of red-meat products and (5) NRM indicators such as nitrous oxide emissions and nitrate groundwater leaching. We also plan to transition from POAMA data feeds to improved climate model forecasts (e.g. ACCESS-S), providing better spatial and temporal resolution of climate forecasts to provide users with more timely and reliable information to aid business cost efficiency.

Keywords: *Big data, climate forecast, cloud computing, dynamic model, perennial ryegrass*

Maintaining the integrity of a complex model

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Abstract: Developing and testing complex models is difficult and time consuming so it is vital that once a model has reached an acceptable level of maturity it remains that way for the life of the model. This is particularly critical for models that are part of a large framework, share source code with the framework or other models, and the framework and models undergo continuous maintenance and improvement over an extended period of time. All too often, extensive effort is invested into model development and testing only to see the model performance drift over time, due to science and software enhancement in shared code. The APSIM Initiative have developed a methodology to help protect models in APSIM Next Generation against this possibility. Figure 1 graphically depicts this methodology.

1. Once a model developer has constructed a model that is sufficiently stable, even if it hasn't been completed, they can 'push' their model to the APSIM GitHub repository for testing and peer review.

2. This then automatically triggers a build and, if successful, a run against a suite of validation and sensibility tests. Statistics are calculated for all predicted versus observed values. If the statistics have changed unexpectedly, the run will be flagged as a fail. A freely available, off the shelf, continuous integration system (Jenkins) is used to perform the integration testing.

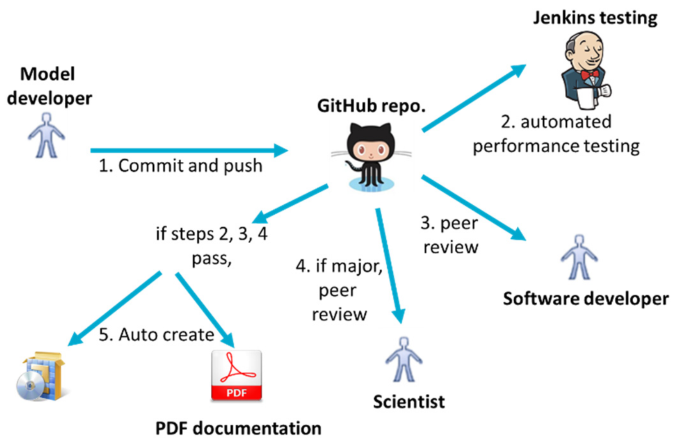

Figure 1. A graphical representation of a methodology to help maintain the integrity of a model.

3. At the same time as step 2 above, a software developer performs a peer-review of the model source code to ensure that it meets coding and model development standards and won't impact unduly on the user.
4. At the same time as step 2 and 3, a scientist will perform a detailed peer review of the model's performance, suggesting areas for improvement.
5. If the above steps 2, 3 and 4 pass, the change is accepted, a new release is automatically released to the users and model documentation is automatically generated from the validation tests and comments in the source code. The generated PDF files attempt to be of similar quality to a journal paper, complete with references and many figures. The advantage to auto-generating documentation is that there is a greater change the documentation will be kept up to date, solving a long standing problem in the modelling industry.

Much of the complexity of the methodology occurs at step 2 above. The APSIM Initiative have developed a web based performance portal that provides a whole of APSIM snapshot of the performance of all models in APSIM. This portal is responsible for detecting when the performance of a model (via comparison of predicted / observed statistics) changes unexpectedly as a result of a model developer or software engineer changing another part of APSIM. The portal also provides a high degree of transparency with respect to goodness of fit for all models, giving model users the ability to access the performance of any model. This can be used to drive model improvements, scientific investment and facilitates good governance. This methodology has been developed and refined over many years and is a work in progress. The current iteration of the methodology is working well for the APSIM Next Generation community.

Keywords: *APSIM, software process, software engineering, agricultural modelling*

Exploring drivers and tradeoffs for yield and nitrogen losses in oil palm plantations using sensitivity analysis

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Abstract: Oil palm cultivation has environmental impacts and so improved management practices to optimise yield and minimise N losses is critical. We identified key management and site parameters driving yield and N losses using Morris's sensitivity analysis of the APSIM-Oil palm model for three sites in Papua New Guinea (Sangara, Sagarai, Hargy). The Morris analysis included 12 parameters, 150 parameter trajectories, 10 planting years across three sites for 20 years of production corresponding to a total of 1,170,00 annual yield and N loss outputs. The influence of 12 parameters describing soil and management characteristics on crop yield and nitrogen losses depended on site characteristics, age of the palms, and climate.

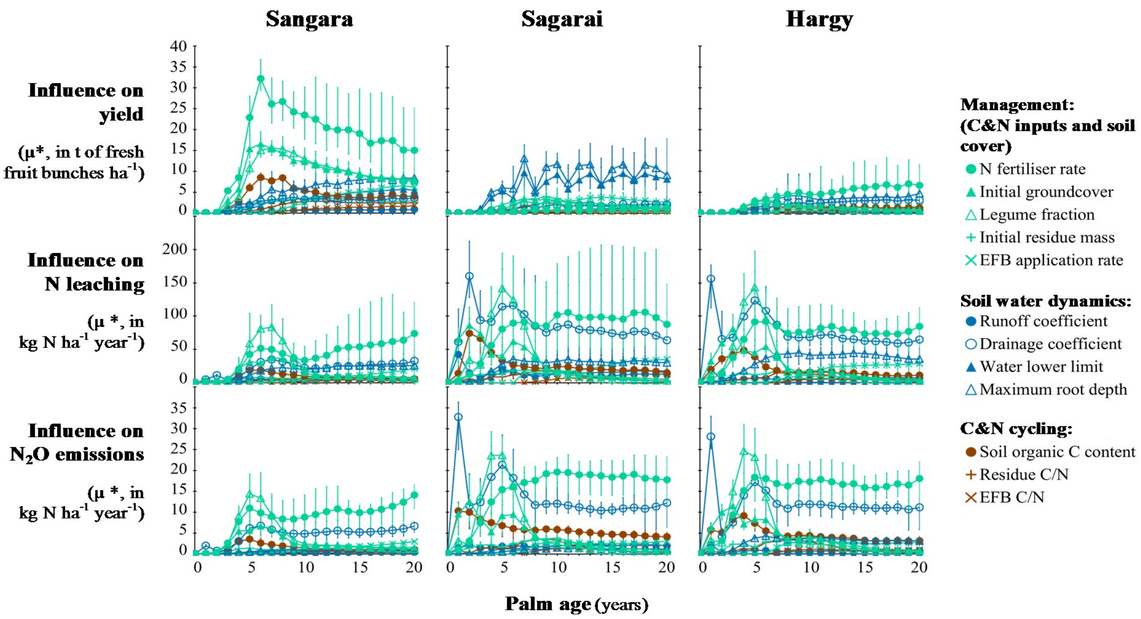

Figure 1. Effect of the age of palms and climate on the influence of the parameters listed on yield and N losses of oil palm plantations. μ* is the mean influence of the parameter on the chosen output. Error bars indicate the range in sensitivity caused by climate variability.

The most influential parameters for losses were those describing N fertiliser rate, site drainage and legume groundcover. N fertiliser was not a driver of yield at all sites, nor was it important in young plantations. Climate variability affected the influence of N fertiliser and drainage on N leaching at sites where rainfall was variable. The analysis suggests that such approaches can be a useful for assessing management options for yield and environmental outcomes in different environments. They also highlighted possible deficiencies in existing field studies where key drivers are currently not well understood. Therefore, the results may guide future measurements necessary to improve N loss estimates, models and risk indicators.

Keywords: *APSIM-Oil palm, Morris sensitivity analysis, perennial crop, environmental impact, nutrient use efficiency*

Stochastic sensitivity analysis of glyphosate biochemical degradation

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Abstract: A comprehensive numerical modelling of soil biogeochemical dynamics allowed us to explore uncertainties in the fate of the herbicide glyphosate (GLP) and its crucial byproduct aminomethylphosphonic acid (AMPA) in soil. GLP and AMPA are both toxic and have the potential to disrupt complex ecological and biogeochemical processes. This study aims at identifying the more influential sources of uncertainty in GLP biochemical degradation.

Microorganisms may evolve different strategies for scavenging nutrients and energy from anthropogenic molecules depending on the surrounding environmental conditions. GLP can be catabolized by soil bacteria along two pathways. One biotic pathway produces AMPA, which can be degraded biologically to non-toxic end products, while a second biotic pathway produces non-toxic byproducts. Recent studies have shown that GLP and AMPA can also undergo fast chemical degradation to non-toxic byproducts in the presence of birnessite mineral, in which Mn^{3+} and Mn^{4+} ions act as catalysts. Therefore, a comprehensive GLP degradation reaction network was tested numerically by means of the BRTSim solver to assess GLP and AMPA degradation potential within a network that integrates several biochemical processes. Chemical and biological processes were described by Michaelis-Menten (MM) kinetics and the Monod growth model, respectively. The biochemical reactions describing the reaction network and the corresponding kinetic parameters were retrieved from the literature.

In this numerical study, GLP was applied at typical rates in a soil control volume representing the top soil of an agricultural plot. GLP and AMPA concentrations were modelled over time as a function of both biological and chemical processes. A suite of sensitivity analyses on input Michaelis-Menten-Monod (MMM) parameters were run to assess the effect of biological parametric uncertainties and to quantify the influence of specific biological processes or specific group of MMM kinetic parameters to the overall model output. Parameter values were randomly chosen from a Gaussian distribution with mean equal to the corresponding experimentally-retrieved parameter value and standard deviation equal to 5, 10, 15, 20, 25, and 30% of that value.

We found that, in the lack of birnessite mineral, variability in the reaction rate constant increased GLP equilibrium concentration, while variability in the half-saturation concentration constant and the biomass yield decreased it. The action of birnessite mineral shrank output variability and decreased GLP concentrations by 5 times. Overall, the more GLP was biodegraded the more AMPA was produced, which accumulated due to its slow biodegradation.

Keywords: *Glyphosate, AMPA, bio-degradation, Stochastic, Birnessite, Monod*

Simplification of complex ecological networks – species aggregation in Antarctic food web models

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Abstract: Marine ecosystem models assist in understanding ecosystem changes resulting from fisheries and climate change, making them important tools for forecasting and guiding sustainable management decisions. One of the greatest challenges in formulating these models is determining their optimum scope that includes a suitable level of model complexity whilst still facilitating valid and robust predictions. For food web models this often involves reducing the system to a set of functional groups representative of the major components of the biological web. The process for choosing these functional groups varies considerably among modelling studies with many inferences made about the general structure of ecosystems.

In the Antarctic, food webs are taxonomically diverse, structurally complex and extremely variable in space and time, and our knowledge of the trophic linkages and energy flow is still fragmentary. This makes the development of ecosystem models for the Antarctic particularly challenging. Here we show that diet observations can provide a useful basis for justifying decisions regarding species aggregation in food web models. Using the Southern Ocean Dietary Database we investigated the trophic linkages present in the food web of the high latitude region of East Antarctica to create a simplified food web structure. Our aim was to determine an optimum level of aggregation whilst maintaining a high degree of realism in regards to the trophic interactions present in the web. Using results from these analyses we then made informed decisions, following best-practice guidelines, to assign species to functional groups for an Ecopath model of Prydz Bay and the southern Kerguelen Plateau region. We discuss our reasoning behind dealing with structural uncertainty in this manner, in particular our decisions regarding the formation of functional groups relevant to the system. We conclude by summarizing the implications of using dietary data to inform species aggregation in food web models and how transparency is an important concept during model formulation and documentation to ensure the development of robust ecosystem models.

Keywords: *Food webs, functional groups, structural uncertainty, Ecopath*

Two-dimensional tree-crop simulation complexities and progress in APSIM

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Abstract: Agroforestry systems of tree-crop mixtures are often promoted because the net effect of interactions between woody and herbaceous components is thought to be positive. These benefits can include improved nutrient cycling, less soil erosion, more food and fodder production, tree products (fuel, fodder, timber, fencing, fruit, and pharmaceuticals), increased resilience during climate change, and lifestyle or cultural benefits. However, the complexity of interactions leads to effects on food and wood production that range from positive to negative. A simulation capability could potentially assist in understanding tree-crop interactions and predicting outcomes. A two dimensional framework for modelling agroforestry interactions is under development using the Plant Modelling Framework in APSIM Next Generation that has focused initially on East African small-holder farmers, including interactions between *Gliricidia sepium* and maize (*Zea mays*) in Malawi and Kenya. Gliricidia is a nitrogen-fixing tree managed usually as a shrub by regular pruning and coppicing where prunings are used for fertiliser, fodder or fuel. These systems are complex, with many poorly-defined interactions. While model simplifications of processes are sought where possible, complexities cannot be avoided if many observed interactions are to be adequately simulated. Here we illustrate how the balance between simplification and complexity has been met so far using examples of light distribution, root development, tree dimensions, and uptake of water and nitrogen when trees are grown with crops or pasture. Test datasets of monocultures and mixtures are available or are developing across a range of contexts.

Spatial zones can be defined in the agroforestry model with different levels of crop and tree occupancy and influence. Usually this includes a tree-only zone, several adjacent zones of tree-crop interactions, and sometimes a crop-only zone at the greatest distance away from the tree. In each zone, light, water and N availability needs to reflect tree shading and root activity in order for a simulated crop in that zone to access these resources above- or below-ground. Initially we used a tree proxy with user-defined tree effects on resources in each zone (Smethurst et al 2017 Agricultural Systems 155:70–7), before developing a model that simulates gliricidia tree growth like other crops in APSIM based on data from Hawaii, Guadeloupe, and Malawi. Row (linear) or circular (single tree) geometries are simulated. In the proxy, tree root-length density is user-specified at all depths in all zones, and crop roots grow in each zone as already possible in APSIM.

Light availability in the proxy was user-specified as a shade percentage, but a simple shade model is being developed as a function of tree height and canopy characteristics. Water uptake from each zone by tree and crop roots is calculated using the APSIM arbitrator that had been used for carbon allocation to plant components. This calculation takes into account water availability, water demand by the tree and crop, and root-length density of each species. Water demand by the tree is user-specified when the proxy is used, but calculated in the simulation when the gliricidia model is used. Nitrogen uptake is simulated like water using the arbitrator, but additional complexity was needed to cater for ammonium and nitrate forms. Mass-flow and diffusive supply of both forms was calculated rather than assuming all mineral N in a soil volume would be available within a timestep. This necessitated use of concentrations in soil solution and solid-liquid phase partitioning that were integrated assuming a concentration of zero could be maintained at a root surface (zero-sink solution).

As predictions of tree and crop growth patterns adequately matched observations, we have not yet needed to develop more complex models for e.g. (1) shade that accounts for leaf clumping, angle, or sub-daily effects of sun position and row orientation (2) water that accounts for the water potential gradient between soil and leaves, or (3) nitrogen that accounts for variations in uptake kinetics along the root surface, uneven distribution of roots in a soil volume, or rhizosphere priming effects.

These examples are presented with reference to an appropriate level of process representation that is definable and useful, and an advanced sensitivity analysis method is available to guide priorities for future development.

Keywords: *Agroforestry, light, water, nutrients, gliricidia, maize*

Simulation of the progression of yellow spot on wheat using a functional-structural plant model (FSPM): Model concepts

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Abstract: Despite disease control management, each year part of crop harvest is lost due to plant diseases. Yellow spot is an important foliar wheat disease throughout the world. The fungus that causes the disease survives on wheat stubble and this is most commonly the source of primary infection (by ascospores) in a crop canopy in the next season. On infected leaves, lesions are formed, surrounded by yellow halos. After a latency period, conidia, the cause of secondary infection, are produced on lesions and are spread over long distances by wind. The secondary cycle can repeat several times through the season and results in the progression of the disease in the canopy. Weather conditions and the developmental stage of the crop play an important role in the progression and severity of disease in the crop canopy.

To study the interactions between pathogen, climatic conditions and growing host crop, we developed an epidemiological model of *Pyrenophora tritici-repentis*, the fungal pathogen that causes yellow spot, and coupled it with an existing functional-structural plant model (FSPM) for cereal crops. An FSPM simulates mutual interactions between plant architecture (structure) and physiological processes (function) in plants at a (sub)organ scale, affected by environmental conditions. In our model, light interception and temperature determine the development and the growth of the cereal crop. Temperature, rainfall, relative humidity and wind data control the development of yellow spot. The pathogen submodel predicts maturation of ascospores and simulates production and wind dispersal of conidia across the canopy. Conidia are transported inside a virtual cone starting from a sporulating lesion and with the axis following the wind direction.

Simulations demonstrated horizontal and vertical progression of the disease in the growing crop canopy. However, the upper leaves grew often away from the disease after the begin of stem elongation. In the future we will perform enhanced sensitivity analysis that should help us to identify the most (least) important parameters and so help in the process of model parameterisation. Epidemiological models coupled to models for plant architecture and growth under different climatic conditions are a promising tool to study the dynamics of plant-pathogen-environment interactions and their effect on crop yield. Furthermore, the coupled model can be used as a simulation tool to study the impact of different disease management approaches and lead to improved disease control. We will test the applicability of the model against field data on disease progression in spring wheat.

Keywords: *Functional-structural plant model (FSPM), disease progression, yellow spot, wheat, wind dispersal*

Soil water modelling using Richards' equation and cascade approach in texture contrast soils

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Abstract: Soil moisture is critical in agronomical, hydrological, ecological and environmental studies as it controls processes of evapotranspiration, runoff and infiltration. Models extensively used in the agricultural and environmental fields often solve the Richards' equation under variably saturated conditions, using common forms of soil water retention and hydraulic conductivity curves to model soil moisture (eg. SWIM, SWAP). Other simple field and regional scale process models use the conceptual "bucket or cascading" approach that apply the concept of field capacity and gravitational downward flow (eg. Howleaky-PERFECT, SoilWat, SWAT). Soil hydraulic parameters required for Richards' equation based soil water models are costly, laborious and time consuming to obtain. Thus, soil hydraulic parameters become the major source of uncertainty in soil water modelling at larger spatial scales and limits the usage of Richards' equation based models in situations where these models are necessary to predict convection/dispersion processes and/or connection with fluctuating bottom boundary conditions such as groundwater. The aim of this study was to evaluate the accuracy of soil moisture predictions derived using complex models with uncertain soil input parameters compared to those derived from simple models that use readily available dominant soil parameters. The performance of the two modelling approaches to estimate soil water in texture-contrast soils was evaluated by comparing the modelled daily soil water with the measured at two high rainfall grazed pasture sites in south west Victoria, Australia. The APSIM platform was used to simulate soil-water-plant interactions using either the SWIM3 module which simulates soil water dynamics based on solving the Richards' equation, or application of the SoilWat module which uses the cascading bucket approach. While SWIM3 solves the flow equation, the soil parameterisation within the APSIM framework requires the same readily obtainable soil parameters as SoilWat, including saturated soil hydraulic conductivity, saturated soil water content, field capacity, wilting point, and air dry. This functionality enables a comparison of soil water modelling approaches using one platform in which all other farming system processes are modelled similarly. In both cases pasture growth and pasture management was simulated using the AgPasture module with default parameters. Water uptake is estimated by AgPasture in APSIM-SoilWat whereas pasture water demand is represented as a sink term in the Richards' equation in APSIM-SWIM and solved simultaneously to estimate transpiration and soil water. The SCS runoff curve number technique was used to estimate runoff in both cases. Modelled (without calibration) daily soil water storage in 100 mm (top) and 1000 mm (root-zone) soil depth were compared with the measured at the two sites for varying time periods (2-8 years) that the measurements were undertaken.

Results demonstrated that both soil water modelling approaches perform similarly in terms of the statistical metrics examined. The Root Mean Square Error between soil water predictions using both approaches was < 8mm for top soils (representing sandy loam) and < 24mm for the root zone (medium clay). Simulations were more accurate at depth (1000 mm) compared to near surface (100 mm). Error differences in root-zone soil water predicted by the two approaches were within 6% of plant available water capacity. An acceptable agreement between observed and predicted daily soil water using both modelling approaches was also observed (Figure 1) in which regression coefficients ranged between 0.8 and 0.9. This study concludes that variations in soil water predictions derived using two soil water modelling approaches are negligible. The most appropriate soil water model depends on the processes to be modelled and available soil hydraulic parameterisation.

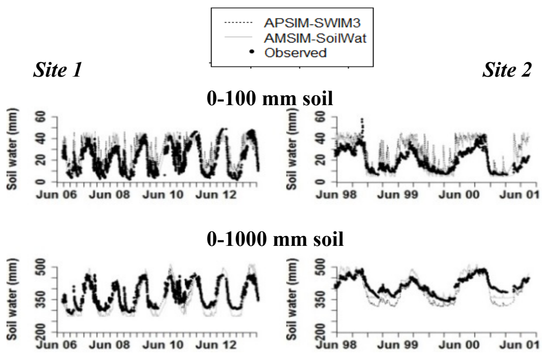

Figure 1. Soil water in 100 and 1000 mm soil for two sites.

Keywords: *Richards' equation, cascade soil water modelling, soil hydraulic properties*

A simulation model for exploring the effects of plant-soil feedbacks on the resilience of plant communities

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Abstract: Plant–soil feedbacks (PSFs) are plant-induced changes to the abiotic and/or biotic properties of soil that positively or negatively impact plant growth. Recently, PSFs have been shown to play a key role in both promoting and maintaining high levels of diversity within plant communities. There is mounting evidence that diversity loss leads to reduced resilience of a community, which can be defined as an ecosystem's ability to recover following disturbance, and/or its ability to resist the disturbance's effects completely. PSFs may also positively influence the resilience of a community by promoting diversity, however this relationship is poorly understood. This is largely due to the complex and uncertain nature of such processes in natural systems, which renders empirical experiments unfeasible. Therefore, we aimed to develop a model capable of capturing the most important processes involved in the interactions among PSFs, diversity and resilience in diverse plant communities undergoing disturbance, in order to investigate how PSFs may affect plant community resilience at a theoretical level.

We used a cellular automata simulation model to simulate plant community dynamics over 1000 years. In order to observe community resilience within this time, communities were subjected to a range of disturbance regimes that consisted of multiple disturbance events which occurred at different frequencies and intensities within a 60 year period. Resilience was then quantified by comparing the trajectories of the communities based on their diversity (using inverse Simpson's Diversity Index) over time and following disturbance. In particular, the degree of change from the pre-disturbance state to the state immediately following disturbance was used to quantify resistance, and the rate of return to the pre-disturbance state following disturbance was used to quantify recovery.

The model was tested using four well-known and highly studied PSF scenarios that are observed in natural systems i.e. negative, positive and 2 types of no/neutral conspecific PSF. We found the PSF scenario involving negative conspecific PSFs to be the most resilient when subjected to the majority of the disturbance regimes, with a neutral scenario of no PSF and a slow growth rate being more resilient under high frequency disturbance regimes. Communities with positive conspecific feedbacks experienced the greatest loss of diversity following disturbance, which generally deteriorated with increasing frequency of disturbance. Positive conspecific communities also did not recover following disturbance and instead became less diverse as time went on.

These results are consistent with expectations based on the literature, suggesting the model is appropriate for exploring the effects of PSFs on the resilience of plant communities. Such research promises to greatly contribute to our understanding of how resilience is built within communities, which in part may assist restoration efforts aiming to return degraded ecosystems back to resilience.

Keywords: *Cellular automata, community assembly, community resilience, disturbance, diversity*

Estimating uncertainty in crop model predictions: an overview

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Abstract: As for all prediction problems, estimating the uncertainty associated with crop model predictions is essential both for modelers and for users of crop model predictions. The recent use of multi-model ensembles has provided a powerful new tool for estimating uncertainty related to model structure; the variability between models is an indication of the level of this uncertainty. However, there are also uncertainties in model parameters and in input variables. Here we identify several of the challenges related to estimation of overall uncertainty. The discussion is largely based on a forthcoming special issue of European Journal of Agronomy devoted to uncertainty.

A rigorous treatment of this problem requires a clear definition of uncertainty. Here we focus on the mean squared error of prediction (MSEP) defined as the expectation of the square of model error, where the expectation is over both the range of conditions for which we want to predict (the "target population") and the model, which is treated as a random function because all of model structure, model parameters and model inputs have some probability distribution.

Model structure uncertainty can be estimated based on the variability between models in a multi-model ensemble study, but creating such ensembles is a practical challenge. A common approach is to solicit the participation of multiple modeling groups. Alternative methods of creating multi-model ensembles are to have a single group, often using a modeling platform, run multiple models, or to create a range of models starting from a single underlying model and changing only selected model routines. This last alternative is particularly interesting, since it allows one to target specific uncertainties in model structure.

Input uncertainty is particularly important for climate change impact studies. It is well-known that different GCMs give different results for future climate, with resulting uncertainty in crop model predictions. There is in addition the choice of spatial scale for climate data, with different choices leading to different inputs and in consequence different crop model predictions.

Given the large number of parameters in crop models, parameter uncertainty is likely to be an important aspect of prediction uncertainty. Bayesian methods are particularly adapted to providing uncertainty information, but frequentist methods can also provide such information.

For specific uses of crop models, other uncertainties can arise. In particular, when using models to estimate regional production, one can estimate point yields and then weight the points to obtain regional, national or global yields. The weighting introduces uncertainties beyond those inherent in model predictions. A different approach is to run a model at a limited number of well-characterised sites, then to interpolate the simulated yield to obtain values for all cells of a predefined grid using geostatistical methods, which involves different uncertainties.

Looking forward, we suggest that assessment of prediction uncertainty should be a standard part of any modelling project, in order that end-users be able to determine if the results are sufficiently reliable for their purpose. This will require a holistic view of uncertainty, where all major contributions to prediction uncertainty are identified and considered.

Keywords: *Crop model, total uncertainty, multi-model ensemble*

Plant segmentation and senescence analysis using stereo imaging in the field

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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. The task of ensuring sufficient grain is immensely challenging in the face of global environmental change. Plant breeders must be ever active in identifying new crop varieties that can meet the challenge. To assist in their efforts, new technologies must be developed to accurately, reliably, automatically and under high-throughput analyze phenotypic responses in order to understand the interactions between genes and the changing environments. An ideal tool for plant phenotyping is high-throughput automated imaging, which has become more advanced and more popular in recent years.

For image-based phenotyping under field conditions, the critical step is to segment plants or crop canopies from background, which includes the soil and objects such as weeds, mosses and dead plant matter. Currently most methods for plant segmentation are based on colour analysis. However, methods based on colour analysis have difficulty with differentiating green leaves of crop plants from mosses, which typically grow in dense green clumps or mats, and weeds. The methods also have difficulty with differentiating senesced parts of plants from some types of soil or dead plant matter from previous season, as their colours are very similar.

We propose to use stereo images for plant segmentation and colour analysis for plant senescence estimation. From stereo images, we can estimate digital surface models (DSMs), where DSMs in this study are the soil surface and plant canopy models. From DSMs, we can further estimate digital terrain models (DTMs), which are the soil surface models in this study. Now we can extract the 3D information of plants from DSMs and DTMs. With this 3D information of plants and DTMs, we can accurately segment plants from mosses, soil and other objects. We then employ colour based image analysis to estimate plant senescence. The proposed approach can fully exploit the advantages of colour analysis for plant phenotyping and avoid its weakness by using the 3D information of crop plants. Our experimental results demonstrate that the proposed approach can significantly improve the accuracy of plant segmentation and senescence analysis.

Conclusions: In this study, we obtain 3D information of plants from DSMs and DTMs, where DSMs and DTMs are estimated by stereo matching. The most important advantage of the proposed approach is the segmentation without using colour analysis, where segmentation based on colour analysis for plant senescence is error-prone. Our initial experimental results show that our approach is able to accurately estimate the canopy coverages of plants during their life spans, particularly after the starting of senescence. This allows us to study the effects of stresses on growth, senescence and the final yield of plants.

Keywords: *Plant segmentation, senescence analysis, stereo matching, digital terrain model, digital surface model*

Colour correction for image-based plant phenotyping in the field

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Abstract: The field of plant genomics has boomed recently, yet current techniques for phenotyping the wealth of information provided are not keeping up. As such there's been a recent shift from manual phenotyping to image-based phenotyping, in order to improve both throughput and accuracy. In the beginning, most image-based phenotyping was conducted in controlled environments and purpose-built systems. Since lighting and image setup are very consistent, experiments in controlled environments are more straightforward to analyse than those in the field. The major drawback of this approach is that those plants are not grown in their natural environments. The effects of competition for nutrients, for example, are not present in plants grown in individual pots. To further improve upon the legitimacy of phenomics there has been another shift in emphasis, this time within image-based phenotyping, to analyse experiments conducted in the field. However, the increase in throughput and volume of data offered from imaging field trials comes at a cost: new techniques are now required to accurately extract the same information from images.

One of the main challenges associated with image-based field phenotyping is the variability of illumination. During a single day's imaging session, or between different sessions on different days, the sun moves in and out of cloud cover and has varying intensity. How is one to know from consecutive images alone if a plant has become darker over time, or if the weather conditions have simply changed from clear to overcast? This is a crucial problem to address as, for a number of reasons, one of the most important pieces of information in such images is colour. First, the most well established methods for image segmentation in plant phenotyping are colour based. Second, many authors postulate a relationship between colour and traits such as yield, nitrogen content and grain protein content. Finally, distinguishing between senesced and healthy leaves and also the time that senescence begins, depends on accurate measurements of colour.

In this work we use an industry standard colour checker to balance the colour in images within and across every day of a wheat field trial conducted over five months in 2016. By ensuring that the colour checker is present in every image we are afforded a 'ground truth' to determine the illumination conditions of each image. We employ a least squares approach to fit a quadratic model for correcting the RGB values of the image in such a way that the observed values of the colour checker tiles align with their true values after the transformation. We demonstrate that a quadratic model provides a more accurate fit than the commonly employed linear model. We also show the effectiveness of colour correction during a single day with different illuminations and across multiple days. Compared with uncorrected images, the results show that images that underwent colour correction displayed more robust mean canopy colour values over time, allowing for colour to be used as a phenotypic trait with greater accuracy.

Keywords: *Phenomics, imaging, wheat*

Semi-supervised plant pixel detection for roots and shoots in digital images

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Abstract: Segmentation is an important pre-processing step for several plant phenotyping exercises by image analysis. Segmentation is used for plant growth analysis, estimation of cereal crop canopy coverage, 3D reconstruction of plants roots, and shoots, and in estimation and quantification of root phenotypes. Figure (a) shows an example of a plant image and (b) its segmentation in RGB colour space. Such images can be taken from a platform shown in Figure (c). Accurate segmentation is precursor for accurate and reliable phenotypic analysis. There are several segmentation methods, which have been innovated and experimented with in the past. Yet, there is definitely need for better, faster, robust, and reliable segmentation. In this paper we use an unsupervised clustering method to classify pixels in digital images of both roots and shoots, as either plant pixel or non-plant pixel. Our claim for innovation is that same method is being applied and evaluated for both root and shoot images. Clustering of the pixel feature vector in different colour spaces is carried out in an unsupervised manner using K-means clustering. However, the classification of the different clusters, represented by their cluster means, into different classes is done using user inputs, which is very simple compared to previous approaches. Hence we called our method as semi-supervised segmentation.

(a) (b) (c)

(a) Original image of an Arabidopsis plant imaged under controlled lighting condition. (b) Bilevel segmentation of the image in RGB colour space where plant pixels are white and background pixels are black. (c) Imaging platform

We analyse the quality of segmentation by experimenting with the representation of the pixel vector in different colour spaces. We employed five different colour spaces for clustering the pixel data: RGB, rgb, HSV, $YCbCr$ and $CIE-Lab$. These five form a good representation of a wide range of different colour spaces that are possible. An exhaustive study of all the possible colour spaces will be too voluminous. In our formulations we consider 3 dimensional pixel vectors as opposed to 2D or even scalar values considered in some of the previous approaches The 3 dimensions of a pixel comes from the 3 channels of each colour space. 2D pixel representation are just the colour channels lacking in the intensity information and the scale values are the colour indices. The motivation for studying different colour spaces is to decipher if plant pixel segmentation is qualitatively better in some specific colour space. We also experimented with different number of means in the K-means clustering algorithm. The method of segmentation is applied to shoot images taken under different lighting conditions. Root images were taken for roots grown in different growth conditions and imaged with different imaging hardware.

In results we obtained overall best segmentation of the plants in their images in the HSV colour space, which means that the separability of the plant pixel and background pixel is enhanced in this colour space compared to the other color spaces experimented with.

Keywords: *Plant phenotyping, segmentation, K-means, semi-supervised, colour spaces, roots, shoots.*

Quantification of root phenotypes under different tillage system using Micro X-ray Tomography

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Abstract: Quantification of root phenotypes is an important and well-established way to study root soil interaction and different amounts of organic carbon deposited into the soil by cereal plant roots. Root phenotypes are also affected by different genotypes of plants and there are various ways of observing and quantifying root phenotypes. However, in this paper we report an empirical study on the influence of different tillage practice on the root phenotypes of wheat plants. The roots are observed in their cores by high resolution computed tomography (CT) scanning of soil cores. An intact soil core of diameter 4 cm and height 20 cm, with a single plant is sampled from wheat fields with different tillage practices, at different growth stages of the plants, at 50, 110, and 180 days after sowing (DAS). Micro X-ray computed tomography (μXCT) was used to visualise the soil cores in 3D at a high-resolution scale of 20μm. The root regions were segmented from the soil and soil pores by manually seeding the root regions in the 3D volume imaged by μXCT. Two different tillage practices: No tillage (NT) and Conventional tillage (CT) with different loading rates of mulching treatment applied to NT (0 and 5 t ha-1). We report our observations of the root phenotypes : root length, root surface area, and root volume; and how they differ in different tillage practice and mulching treatments.

Different tillage practices have different influences on the physical properties of soil like moisture content, temperature, nutrient, soil compaction, and oxygen availability that certainly affects the root development and crop performance. Of the two tillage practices NT and CT which should be preferred or which is better? This is an important question and how can it be quantified for deciding which tillage practice to be used depending upon the time, location, and environment. Due to the short-term shift in tillage practice from NT to CT on a continuing no-till cropping system are expected to change the geometry of the soil pores and root phenotypes. The mechanical disturbance caused due to tillage shift have chances to create an unfavourable condition for root growth by limiting water, nutrient and increasing soil compaction which ultimately impacts the crop yield. Here we study how root growth of wheat plants differ under NT and CT pratices and try to conclude which of the two favours more carbon allocation into the ground.

The overall impact of tillage practices on root phenotypes are quite significant. Quantified root phenotypes when estimated from the image analysis of soil cores show that root volume was 9.6% higher in the top 20 cm of the soil where NT was applied compared to the root volume in the CT practice. The vertical distribution of roots evaluated through root architectural measurements indicated higher root length by 8.7% and higher root surface area by 2.6% under CT system compared to NT. These results indicate that NT provides soil structure, which could produce more root biomass in top 20 cm depth, possibly due to the increase in soil compaction by providing low disturbance to the soil structure. It may also be that presence of more soil pores helps the plant to have higher root length in CT than in NT as higher root lenghts where observed in CT plants. However due to higher root volume in plants grown in NT we concluded that NT favours more underground carbon allocation.

Keywords: *Root Phenotyping, micro x-ray tomography, tillage, mulch, underground carbon, time series*

Voice-based protocols for Mobile Ad Hoc Networks: Challenges, Design Principles, and Implementations

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Abstract: With the increasingly popularity of mobile devices (e.g. iPhones and iPads), Mobile Ad hoc Networks (MANETs) has emerged as one of the topical research areas in recent years. The special characteristics of MANETs (i.e. infrastructure-less and self-configuring) provide a flexible way of connecting mobile devices. Such implementation can provide the means of communications where telecommunication infrastructure is inattentive (Out-of-range, out of credit). Due to the inherent characteristics of MANETs (e.g. self-configuration of IP addresses), implementing Voice over IP (VoIP) services over MANETs remains an ongoing research challenge. In this paper, we highpoint the challenges of implementing VoIP, recommend design principles for such implementation and discuss some implementations. This research is based on an expert advice with over 15 years' experience in the area of computer network and around 10 years on intensive research in the area of adapting voice-based protocol for MANETs.

Keywords: *Mobile Ad hoc Networks (MANETs), Voice over IP (VoIP), voice-based protocol*

Process improvement based on an integrated approach of DMAIC and multi-method simulation

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Abstract: Many companies have used simulation techniques to improve their operations and generate process improvements for many years. Six Sigma has been developed as a disciplined approach and has introduced an alternative way of thinking about product or process improvement. The concept of combining the advantages of simulation techniques and Six Sigma's methodology has recently led companies and academics to investigate and implement this strategy. The Six Sigma method, composed by the Define, Measure, Analyze, Improve and Control stages, is a problem-solving method. However, it also identifies problems for which the approach may be ineffective. The objective of this study is to improve and control processes, reduce non-value-added activities and support decision-making by using Six Sigma's methodology alongside AnyLogic; using agent-based, discrete event, and system dynamics models. Moreover, the paper explores a multi-method simulation as a guided tool to assist organizations with the decision to implement a Six Sigma approach and pinpoints the strategies to be adjusted and monitor the process' parameters to be improved as well as reduce bottlenecks and weaknesses in the entire process by setting up management guidelines of such complex and dynamic process. This ensures that existing systems and proposed improvements account for any short and long-term outcomes. This paper begins with an overview of Six Sigma, followed by a description and the benefits of using the AnyLogic simulation package for implementing this methodology. This paper also shows the fundamental relationships between the Six Sigma methodology and AnyLogic simulation displaying a framework in which they can be integrated and a business case where this framework is used. The improvement and the strengths from this combination between Six Sigma and simulations are represented as preferable and capable enhancements to Six Sigma to deal with defects in many aspects.

Keywords: *Six Sigma, DMAIC methodology, agent based, discrete event, system dynamics*

A hybrid simulation model of individual and team performance in software project environment

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Abstract: Software development is a human- intensive effort, hence software project success heavily depends on performance of the members of its development team. A team member's performance can be influenced by many factors, such as level of technical skill, motivation, stress level as well as team culture and organizational environment. Understanding the impact of these factors on software project outcome can lead to better project management and human resource management decisions, and as a result improve project success rate. However, it is a non-trivial task to evaluate such impact, due to difficulties in quantifying human behaviour in a complex environment such as that of software project, hence little literature exists on this research topic. This study attempts to explore the impact of individual and team performance on software project outcome with a simulation model that introduces human factors to a virtual software project environment. The simulation model includes the interplay of three aspects typical of a software project environment, namely: a) individual behaviour of each developer and communication among team members; b) software development workflow of activities and project management practices; and c) organizational environment including culture and HR practices. A hybrid model that includes the application of agent-based, system dynamics and discrete event approaches has been developed. Agent-based modelling (ABM) is one of the most suitable techniques for investigating the complexity of agents' behaviour, actions, and interactions, thus allows us to observe the emergent behaviour of each individual agent; system dynamics (SD) modelling is suitable for observing, at an aggregated level, the cumulative and dynamic effect of varying conditions that influence the behaviours of model components; and discrete event simulation (DES) is suitable for capturing work flow under resource and/or other constraints. In our hybrid model, the agent-based component is developed as the core to simulate each team member's behaviour and states of each unit of work, the system dynamics component is used to capture the cumulative mood of each developer while working as a member of the project team, and the DES component is used to simulate the integration process. Various experiments ("what if" scenarios) can be conducted by changing model parameter values and observe the impact of such changes on project outcome. A sample application is provided to demonstrate the impact of team performance under different levels of requirement volatility on a relative scale.

This paper presents the design, development as well as a brief discussion on validation of such a hybrid simulation model. The research not only benefits those who are interested in understanding the impact of individual and team performance on software project outcome, but also those who are considering using hybrid simulation modelling approach to study human factors in other complex social-technical systems.

Keywords: *Hybrid simulation model, agent-based simulation, software project, human factor, team performance*

Development of a Real Time Runoff Analysis System for a Large Watershed using Distributed Model and Azure

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Abstract: The objective of this study is to develop high resolution rainfall-runoff system for a large watershed. Grid based Rainfall-runoff Model (GRM), physically based distributed rainfall-runoff model, was used to calculate runoff and Microsoft Azure was used to run the model. The developed technique was applied to Nakdonggang (Riv.) watershed (about 23,384 km^2) in Korea. The watershed was divided into 20 sub-watersheds. The GRM model was constructed in each sub-watershed, and the sub-watersheds were connected with each other along with the stream topology. Real time radar rainfall data from Ministry of Land, Infrastructure, and Transport, Korea were applied to the runoff simulation after fitting the area and the resolution of each sub-watershed.

The runoff modelling system was composed of real time radar rainfall data server, computation node (Azure), and web-based front end (personal computer). User could control runoff modelling (simulation start, simulation end, etc.), change model parameters, and review the simulation results of the sub-watersheds using the web front end.

High resolution runoff modelling for a large watershed using a distributed model consumes large computation time. Therefore, high performance computing resources and the techniques to use the machine are needed. This study used the Azure, Microsoft cloud computing and platform service, to run the runoff simulation system. F8S, F16S, and DS15v2 Azure virtual machine instances were applied and computation performances were tested by modelling times, the amount of memory used, and the disk I/O traffics. The modelling times could be reduced by using the higher performance instances which had the more CPU cores. Disk I/O traffic could cause modelling time delay when just one disk was used. The amounts of memory used were about 5.5GB, 4.0GB, and 5.9GB and the runtimes for 24 hours modellings were 2.13 minutes, 1.6 minutes, and 1.50 minutes when F8S, F16S, and DS15v2 were used respectively.

From this study, we found that the machine with higher core numbers and the disk I/O distribution (in this study C: and D: were used) were effective to reduce the model runtime. And the real time access of hydrological database by the runoff model was important part for the system stability and model runtime.

Keywords: *Distributed model, real time flood analysis system, cloud service, GRM, Azure*

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Hessian schemes for fourth order elliptic equations

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Abstract: Fourth order elliptic partial differential equations arise in various frame-works, such as structural engineering, thin plate theories of elasticity, thin beams, the biharmonic problem, the Stokes problem, in image processing, etc. A large number of schemes have been developed for the numerical approximation of these equations. Hessian schemes is a framework which enables the unified convergence analysis of many different methods such as finite elements (conforming, non-conforming) and fi-nite volumes methods for these equations. We here introduce the framework of Hes-sian schemes and use it for the approximation of fourth order linear elliptic problems. Hessian schemes are written in discrete weak formulation by replacing the continu-ous space, function, gradient and Hessian by their discrete ones, using the degrees of freedom. We show that three properties, namely coercivity, consistency and limit-conformity, are sufficient to prove the convergence of Hessian schemes for linear el-liptic problems. We also show that the schemes of the finite element family, finite volume family and the method based on gradient recovery operator are indeed Hes-sian schemes, which meets these three property. For non-linear problems, we need an additional property, namely compactness. The output of numerical experiments are presented. The framework of Hessian schemes enables us to develop one study that encompasses numerous classical methods (finite elements, finite volumes, etc.).

Keywords: *Hessian discretisation method, Hessian schemes, elliptic equations, numerical schemes*

Helicopter Risk Assessment Against Ground Based Rifle Shots Using Artificial Neural Network Agents

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Abstract: Defence Science and Technology (DST) Group has been conducting experiments to model the aiming error associated with small arms fire against a manoeuvring helicopter from spatially distributed positions. In general, it is difficult to conduct a large number of these experiments to gather consistent data for all firing positions in a prescribed area. It is therefore essential to develop a method to generalise the shooter aiming errors obtained from a relatively small number of firing positions to arbitrary firing positions. Such a generalisation offers several benefits including risk assessment posed by a small arms operator, and helicopter tactics analysis for risk minimisation.

This paper outlines a statistical approach to model a small arms operator's firing performance based on closest point of approach (CPA) for fired bullets. The CPA data collected in experiments are firstly pre-processed for data pruning and to estimate statistical parameters for the CPA (sample-averaged mean and covariance) in the 3D space for a limited number of shooter positions and under various helicopter manouevres and conditions such as day-time/night-time, and tracer or no tracer. The CPA data are modelled as multivariate Gaussian to simplify the analysis. With this modelling assumption, aiming errors at a given shooter position are fully characterised by a 3×1 mean vector $\boldsymbol{\mu}$ and 3×3 covariance matrix $\boldsymbol{\Sigma}$ for the CPA data.

Once the Gaussian statistics $\boldsymbol{\mu}$ and $\boldsymbol{\Sigma}$ are estimated for each shooter position using the experimental data, generalisation to any shooter position can be accomplished by function generalisation using an artificial neural network (ANN). To ensure that function generalisation produces *feasible* statistics with symmetric and positive-semi-definite covariance matrices, the task of generalisation is formulated in terms of the mean vector $\boldsymbol{\mu}$ and error ellipsoid for the covariance matrix $\boldsymbol{\Sigma}$. The error ellipsoids are described by their semi-axis lengths and angular rotation of semi-axes (Euler angles) about the principal x, y and z-axes. Using these parameters rather than covariance matrix entries ensures that the covariance matrix generated by the ANN agent will obey the properties of a covariance matrix. Therefore, for function generalisation purposes, the aiming errors are described by the following nine statistical parameters: $\boldsymbol{\mu}$, semi-axis lengths of error ellipsoid, and Euler angles for ellipsoid rotation.

The ANN agent for the shooter is computed using a single generalised regression neural network (GRNN) with an input consisting of shooter position relative to the helicopter at [0,0,0] heading North and helicopter speed, and a vector output comprising the nine statistical parameters that define the CPA error ellipsoid. It would be possible to implement multiple parallel ANNs for each of the output vector entries for the same input vector. However, this would drastically increase the computational complexity, which is an important consideration for helicopter tactics evaluation using Monte Carlo simulations. A GRNN is comprised of a radial basis layer followed by a linear layer. An important parameter of GRNN is the spread parameter for radial basis neurons. The larger the spread is the smoother the function approximation will be. An appropriate spread value to achieve satisfactory function approximation has been determined following numerical simulations. The ANN agent was trained using the experimental CPA data at 19 shooter positions spread over a semi-circle with radius 500 m, centred at the helicopter position.

An important consideration for helicopter vulnerability is the probability of hit in a given situation by a small arms operator on the ground. Trained ANN-based shooter agents have been simulated to ascertain how the probability of hit varies as the helicopter flies. The probability of hit information obtained from the ANN shooter agent can also be exploited to construct a probability of hit map to facilitate determination of helicopter flight trajectories that will minimise the probability of hit for the helicopter.

Keywords: *Closest point of approach, error ellipsoids, generalised regression neural networks, dynamic error probable*

A Virtual Element Model for the prediction of long-term salt marsh dynamics

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Abstract: Salt marshes are vulnerable environments hosting complex interactions between physical and biological processes. The prediction of long-term vertical dynamics, i.e., marsh growth and/or reduction, is crucial to estimate the potential impacts of different forcing scenarios on such systems. The most significant processes influencing the elevation of the salt-marsh platform are accretion, auto-compaction, and the variation rates of the relative sea level rise, i.e., land subsidence of the marsh basement and eustatic rise of the sea level. The accretion term considers the vertical sedimentation of organic and inorganic material over the marsh surface, whereas the compaction reflects the progressive consolidation of the porous medium under the increasing load of the overlying younger deposits. The present work describes a novel mathematical approach, based on the Virtual Element Method, for the long-term simulation of the salt marsh vertical dynamics. The Virtual Element approach is a grid-based variational technique for the numerical discretization of Partial Differential Equations allowing for the use of very irregular meshes consisting of a free combination of different polyhedral elements. The modelling approach provides the pore pressure evolution within a compacting/accreting vertical cross-section of the marsh, coupled to a geomechanical module based on Terzaghi's principle of effective inter-granular stress. The model takes into account the geometric non-linearity caused by the large salt marsh deformations by using a Lagrangian approach with an adaptive grid, where the domain geometry changes in time to follow the deposit consolidation and the new sedimentation. The use of Virtual Elements ensures a great flexibility in the element generation and management, avoiding the numerical issues often arising from strongly distorted meshes. The numerical model is developed, implemented and tested employing two different configurations of the sedimentation rate. The preliminary numerical results provide evidence of the flexibility of the proposed approach, which appears to be a promising computational tool for the accurate simulation of real-world applications.

Keywords: *Salt marshes, long-term dynamics, numerical modeling, virtual element method*

Interactive process simulation for industrial applications at the example of laser drilling

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Abstract: In long pulse laser drilling (µs – ms) of metals, it can be demonstrated that the ablation shape approaches an asymptotic shape such that it changes only slightly or not at all with further irradiation. These findings are already known from ultra short pulse (USP) ablation (fs – ps) of dielectric and semiconducting materials. The explanation for the occurrence of an asymptotic shape in long pulse drilling of metals is identified, a model for the description of the asymptotic hole shape numerically implemented, tested and clearly confirmed by comparison with experimental data. The numerical calculation requires much less in the way of resources, such that it can run on common desktop PCs, laptops or even smart devices. Against the background of an application in industrial environments the numerical implementation is equipped with a user-friendly GUI which allows an intuitive usage. Individual parameters can be adjusted using sliders while the simulation result appears immediately in an adjacent window. The software is called ***Asymptotic*****DRILL** and depicts the first example of a Customer Simulation Tool (CST) developed at Fraunhofer ILT. This new concept has been developed in order to facilitate and accelerate the transfer of scientific findings and expert knowledge to industrial usage. The CST concept is based on application-specific reductions of the underlying physical models separating those sub-processes with small influence from the dominant ones. In that way the complexity of the model can be reduced significantly while the essential properties are described with a small approximation error. The decreased complexity enables extremely fast simulations: *while time scales for drilling simulations presented in literature are in the range of hours (on common desktop PCs),* ***Asymp-totic*****DRILL** *calculates the resulting hole shape on a sub-second time scale (even on smart devices).* The CST concept opens a range of options for the industrial application: due to the low requirements of computation resources the industrial user becomes able to apply the process simulations directly in house and utilize the software in order to adjust processes or even to generate more process understanding.

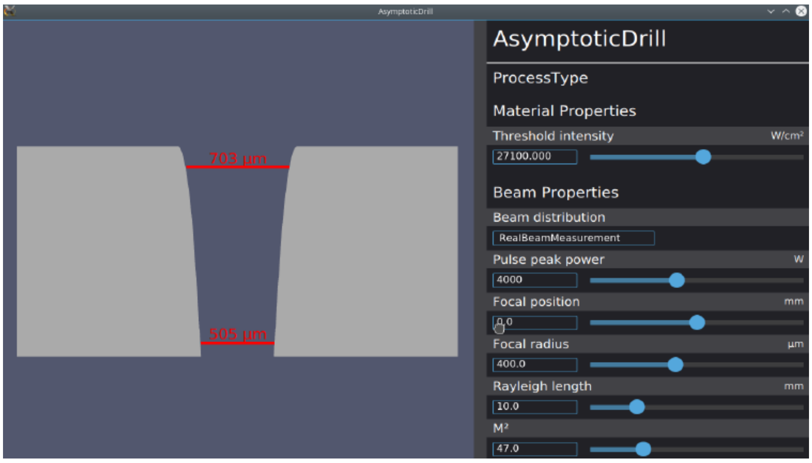

Figure 1. ***Asymptotic*****DRILL**. Customer Simulation Tool for calculation of the asymptotic hole shape in long pulse laser drilling of metals.

Keywords: *Laser drilling, cooling holes, asymptotic hole shape, reduced modeling, intensity threshold, Customer Simulation Tool*

Using Wind Shock-Waves and Turbulence as a Soft Attrition Capability against a Smart Adversary Team of UAVs

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Abstract: In this paper we propose a new soft-attrition capability: using wind shock-waves and turbulence against a smart adversary team of unmanned aerial vehicles (UAVs) within a confined space in an urban environment. A 3D UAV Simulator has been developed in Decision Sciences, JOAD, DST-Group, based on the theoretical foundation for controlling swarms of UAVs. A particular version of the simulator (used in this paper) was designed for indoor navigation of a team of UAVs with the objective to sustain their stable flight under wind turbulence conditions. The core of this indoor UAV simulator is a nonlinear, highly-robust, fuzzy-logic control based, smart individual collision-avoidance system for each UAV, which results in the flocking behavior of a whole team under threat. The simulator uses two types of sensors: radars-on-a-chip and sonars, 6 radars and 6 sonars per UAV, one radar and one sonar per side of the UAV's bounding box. The collision avoidance system was designed by combining (via logical And) the speed and distance fuzzy-logic If-Then rules of the form:

If an object is approaching from Front with *high speed* Then move Backward with *high speed*, And
If an external object is *very close* in Front, Then move Backward with *high speed*, etc.

To counteract this smart team of adversary UAVs, a new soft-attrition capability has been developed in the form of a wind shock-wave field (which develops into a tornado-type wind turbulence inside a confined space), defined by the Tanh-solution of the nonlinear Schrödinger equation. The wind shock-wave field represents a fast-traveling train of non-dissipating solitons (like a 1-dimensional train of neural impulses running down the neural fibre, or a 2-dimensional series of tsunamis caused by an underwater earthquake and fast-flowing along the ocean from one shore to the other). This non-dissipating wind wave depends on two parameters, amplitude and frequency, which can be changed at will. The qualitative analysis presented in this paper shows that even the smart team of bird-like UAVs with superb collision-avoidance system can be blown away by the wind shock-waves (with the amplitude that is many times higher than the thrust capabilities of the individual UAVs) and the tornado-like turbulence caused in the confined environment.

Keywords: *Smart UAVs, collision-avoidance system, wind shock-waves and turbulence, soft attrition*

Boundary Layer Approximation for Melt Film Dynamics in Laser Fusion Cutting

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Abstract: During laser fusion cutting of sheet metal parts, a focused laser beam is traversed relatively to the processed part. The material is molten due to the heat input of the laser beam and driven out of the cutting kerf by a gas jet aligned coaxially with the laser. The edges of the remaining cutting kerf show a striation pattern which affects the quality of the cut. The amplitude, wavelength and shape of these striations depend on the dynamics of the motion of the thin melt film inside the interaction zone.

Instabilities in the thickness of the melt film that emerge at the cutting front propagate to the sides and solidify to an irregular surface. Understanding effects that lead to the emergence and stirring up of instabilities is crucial to derive measures for high quality cuts with a drastically reduced striation depth.

To simulate the behavior of the thin melt film, the underlying incompressible Navier Stokes equations have to be solved with high accuracy using a well chosen set of boundary conditions. The surface of the melt film moves with a velocity of up to several meters per second from top to bottom side while the thickness of the melt film varies from a few to around one hundred micro meters perpendicular to the laser beam. These scales prevent the use of classical finite element or finite volume approaches to solve the mathematical problem numerically accurate without proper reduction techniques.

To develop a simulation that is able to depict the behavior of the melt film, the Navier Stokes equations are transformed to conformal coordinates and subjected to scaling analysis. A perturbation series expansion is performed and the equations are integrated in radial direction using a quadratic ansatz for the mass flux in azimuthal and axial direction. The resulting system of partial differential equations can be solved numerically and describes significant properties of the dynamics of the melt film with high temporal and spatial resolution. The physical mechanisms that lead to striation formation can be investigated by analysis of the model structure as individual physical phenomena can be selectively altered in the simulation.

The presented method leads to a simulation that provides support in the evaluation of measures to reduce the striation depth like modulation of laser power or beam shaping optics. The presented combination of model reduction techniques is adaptable to any boundary layer problem of similar type.

Keywords: *Boundary layer approximation, laser fusion cutting, incompressible Navier Stokes equation*

Optimising food waste diversion for GHG reduction in Melbourne, Victoria

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Abstract: The waste sector accounts for approximately two percent of the total greenhouse gas (GHG) emissions in Australia. The primary source of the waste-based GHG emissions is methane generated from uncontrolled degradation of organic wastes in landfills. Methane is a potent GHG considered 28 times greater than carbon dioxide over a 100 year time period. In Australia, most States have successfully set in place policies to divert residential and commercial garden organics from landfill to compost processors. The remaining food organics from residential and commercial premises have been targeted recently by some States for diversion from landfill to beneficial outcomes such as composting (soil amendments) and anaerobic digestion (energy recovery).

With a number of viable food waste processing options increasing in Australia for both larger offsite and smaller onsite applications, it is not clear to waste policy officers and sustainability managers which of these options provide the most effective GHG reduction outcome on a city scale. Optimisation modelling has been used by engineers in solving waste sector problems such as the selection of alternative waste technologies, the siting of waste facilities and the efficient routing of waste collection vehicles. For this study, six food waste diversion options including anaerobic digestion, composting (both onsite and offsite forms), vermiculture and the baseline landfill scenario have been modelled to determine their carbon footprint and their relationship to the avoided landfill GHG emissions.

An optimization model has been developed to explore the optimal allocation of technologies and collection systems to maximise diversion of post consumer food waste from the 31 metropolitan councils in Melbourne, Victoria. The general form of the objective function considers the minimisation of the difference between the GHG emissions reduced and GHG emissions generated from diverting food waste:

$$Minimise \sum_{t=1}^{T} (R_t - G_t)$$

where Rt = Reduction of CO_{2-eq} (tons) from soil sequestration, avoided landfill emissions and renewable energy generation at time, t, and Gt = Generation of CO_{2-eq} (tons) from transport emissions, biological emissions and operational emissions at time, t.

The decision variables were the tonnage of food waste transported between the following nodes: food waste sources, the existing landfills and the proposed five processing sites/technologies. To complete the optimisation, the following constraints to the allocation of food waste tonnages were: mass balance of the model, limitations of material flow between the nodes, available technology capacity and policy implementation settings. Sensitivity analysis on the major parameters has been performed.

Keywords: *Optimisation, linear programming, food waste, greenhouse emissions, Melbourne*

Dynamic modelling of complex systems under deep uncertainty using an exploratory multi-method approach

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Abstract: The decision making of complex systems is challenging because of the presence of non-linearities and time delays in their structure and their behaviour. This decision making over the system lifetime is also challenged by the presence of deep uncertainty in the future behaviour of systems and in their surrounding environment. Traditional modelling approaches are inclined to consolidate all facts into a single ultimate model and to take a deterministic, optimal and predictive approach in decision making. However, they proved to be inadequate for coping with complexity and uncertainty challenges. We argue that an exploratory multi-method approach to modelling is needed for making effective and robust decisions for complex systems; the decisions which remain valid under a diverse range of future conditions. This paper illustrates the combined use of multi-method modelling and exploratory analysis in the support of complex systems decision making, with an application to asset acquisition and management and using the case of aircraft fleet as an illustrative example. First, a framework is introduced for the implementation of this multi-method exploratory approach in practice, and the model structure, developed for the case of aircraft fleet, is explained. We then discuss how the use of our new approach can improve the robustness of decisions in asset acquisition and management. An initial exploratory analysis is performed on the model under deep uncertainty conditions and with three design strategies: High Acquisition – Low Maintenance, Low Acquisition – High Maintenance, and Medium Acquisition – Medium Maintenance. The analysis of the results shows that investing on the maintenance capacity of an aircraft fleet could result in more average flying hours compared to more acquisition of new aircraft. However, this could cause two side-effects: a higher total (acquisition and maintenance) costs and a wider uncertainty in the future performance of the system (in terms of average flying hours and total costs).

Keywords: *Robust decision making, exploratory modelling, system dynamics, multi-method modelling*

A new Benders decomposition acceleration procedure for large scale multiple allocation hub location problems

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Abstract: We consider the well-known uncapacitated multiple allocation hub location problem (UMAHLP). Hub location problems are widely used to model and solve problems that arise from network telecommunications, transport networks, and delivery systems. Due to the high complexity of hub location problems, different approaches have been employed to develop efficient algorithms. We apply a modified Benders decomposition method for solving large UMAHLP instances exactly. Since the derived subproblems possess an inherent high degeneracy, the implementation of Benders method for UMAHLP usually suffers from slow convergence. We adapt an existing state-of-the-art method in the literature, and apply a novel method of accelerating this approach. This is performed with a view to addressing the slow convergence issues. Our approach improves the current best results by more appropriately choosing parameters for the accelerated Benders method.

Furthermore, as observed in the literature, the exact solution of subproblems can add an extra complexity to the Benders approach for UMAHLP. We reformulate the subproblems and solve them more efficiently using a minimum cost network flow algorithm. Our computational results show that our acceleration procedures together with our different approach to solve subproblems are computationally efficient. According to our computational results, we are able to solve larger UMAHLP instances with up to 200 nodes in less than 2 hours. On average, our approach improves computational times of around two third of tested instances by 44% over current approaches. Also it requires around 10% fewer Benders iterations in our computational experiment.

Keywords: *Hub location problem, Benders decomposition methods, minimum cost network flow problem*

Computer modelling and simulation of the mechanical response of composite lattice structures

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Abstract: Composite lattice shells are highly efficient and extensively used in various structural applications, such as rocket interstages, payload adapters for spacecraft launchers, fuselage components for aerial vehicles, and components of the deployable space antennas. The aim of this paper is to present an analytical approach based on the finite element discrete modelling that is capable of predicting mechanical behaviour of composite lattice structures with sufficient accuracy and, at the same time, is affordable in terms of computational expenses. This allows the modelling approach proposed in this work to enable the efficient solution of relevant design and design optimisation problems.

Structural analyses reported in the literature have been conventionally performed for composite cylindrical lattice shells. The paper investigates buckling behaviour of anisogrid composite lattice cylindrical, conical, and parabolic shells. The lattice shells are modelled as three-dimensional frame structures composed of curvilinear ribs subjected to the tension/compression, bending in two planes and torsion. The specialised finite-element model generation procedure (model generator/design modeller) is developed to control the orientation of the beam elements allowing the original twisted geometry of the curvilinear ribs to be closely approximated.

The generation of discrete models are presented and explained in detail for cylindrical and conical lattice shells. Buckling analyses are performed for the cylindrical and conical shells subjected to axial compressive loading, and for the structure composed of parabolic lattice shell loaded by transverse concentrated external load.

The effects of varying the length of the shells, the number of helical ribs and the angles of their orientation on the buckling behaviour of lattice structures are investigated. Critical buckling loads and corresponding buckling mode shapes are determined based on the modelling approach proposed in this work. The effects of parameters of the lattice structure on the values of critical buckling loads, mode shapes are examined using parametric analyses. Based on the computations, the angles of orientation of helical ribs delivering maximum critical loads for a number of particular structural designs are identified.

The results of these studies indicate that the modelling approach presented in this work can be successfully applied to the solution of design problems formulated for composite lattice shells.

Keywords: *Composite lattice shells, finite-element modelling, spacecraft structures, buckling analysis, critical buckling loads*

Virtual Human Simulation on Memory Acquisition and Walking with the Memory

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Abstract: In virtual simulations, one of the most difficult tasks is how to model human behavior and how to validate the model by performing the simulations. Actually, many researchers have tried to model virtual humans for the behavior. Some researchers focused on how to decide the path for each person to move in a crowded situation. Others considered that human behavior cannot be generated with just one model, and the model should be categorized to some patterns such as individual, groups and crowd. Then, human actions are generated by applying each model according to the situation. In crowded situation, people might collide with each other if they move their own way without considering other person's path. Then, collision avoidance model was also investigated. In addition, there are some simulations considering real situations such as crowded train station or epidemics of infectious disease.

On the other hand, vision and memory are necessary for people to take actions so that some researchers proposed methods how to obtain the vision and construct the memory. In the real world, we memorize some landmark buildings at each intersection and build up our own map. With the help of the map, we can walk the same way several times and also can return to the original position. Furthermore, we sometimes intentionally change the way to find a new path. In this case, people decide the path by integrating the vision they are obtaining with their memory acquired until then.

Therefore, we have performed a simulation for virtual humans on how to acquire their memory and decide the direction by integrating the vision with the memory in order to investigate real human behavior. People memorize the information they have acquired by walking as a form of map, which is divided into two types as the following.

Route map: 1 dimensional information they have acquired along the walking path.

Survey map: 2 dimensional information they have reconstructed from the route map.

We have modeled how to construct the route map and transform the route map information into the survey map. The route map and the survey map include landmark images they have encountered at each intersection.

Then, we have performed two kinds of simulations as follows.

Same route walk simulation: simulation to check if people can walk the same path based on the survey map information they have constructed. People can recognize intersections with pattern matching for the scene they are looking and the landmark images stored in the survey map. If the recognition is correct, people can walk the same way, while people take a wrong way if the recognition is incorrect.

Different walk simulation: simulation to check if people can take the correct path even if they have started from another position different from the point they used when the route map was constructed. People can take the correct path if they correctly recognize the landmark they are looking, or they take a different direction if the landmark image does not correspond to the one they have in the survey map.

In the result of the simulations, a virtual human took the same path when he started to move at the same point. On the other hand, in the second simulation, there have been two kinds of results. One is that the virtual human took the correct path by the correct recognition of landmark images, and the other is that he did not take the correct path due to the incorrect recognition. This result reflects human behavior that people sometimes mistake the recognition of a street and move to a wrong direction.

Keywords: *Computer graphics, virtual human, memory acquisition, walking simulation with memory*

The application of Simulation (Virtual Reality) for Safety Training in the Context of Mining Industry

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Abstract: Virtual Reality (VR) technology has been used to train for various operations and dangerous circumstances where it is believed that training objectives cannot be achieved easily or the cost will prohibitive. Van Wyk and colleagues (2009) define VR-based training environments as "*real-time computer simulations of the real world, in which visual realism, object behavior and user interaction are essential elements*". The use of VR-based training environments assumes that Human-Machine interaction stimulates learning processes through better experiencing and improved memorization, leading to a more effective transfer of the learning outcomes into workplace environments. However, there are many human factors (internally and externally), which have impact on the quality of the training and learning process which need to be identified and investigated.

In this article, initially factors affecting the quality of the training and learning process for underground mine rescuers have been identified and then measured by using pre- and post-training questionnaires. Then statistical analyses have been performed to investigate the relationship among trainees' perceived realism, usefulness and success. Also, trainers' perception on 360-VR usefulness and success has been measured and compared with trainees. As the result of analysis indicated, trainees typically found the training sessions useful and perceived them to be successful; many felt that it was not really consistent with their real life experience. It would appear that perceived usefulness plays important role in forming the perception of success with high correlation and that the level of realism is not necessarily a deciding factor. Also, there was no significant difference between perceived usefulness and success between trainees and trainers. This research was conducted in collaboration with Mines Rescue Pty Ltd (a training provider for the coal mining industry in NSW, Australia) and was focused on training programs developed for mine rescue brigades. Data was collected from 94 mine rescue brigades (trainees) who attended a 360-VR training session over a twelve-month period and 25 trainers who run the training sessions.

Keywords: *Virtual Reality (VR), safety training, evaluation, mining industry*

Scheduling of Distributed Energy Resources as a Virtual Power Plant

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Abstract: A transactive energy system can provide an integral management scheme that facilitates power delivery with high efficiency and reliability. To close the gap between wholesale and retail markets, this paper presents a two-stage optimal scheduling model for distributed energy resources (DERs) in the form of a virtual power plant (VPP) participating in the day-ahead (DA) and real-time (RT) markets. In the first stage, the hourly scheduling strategy of the VPP is optimized, in order to maximize the total profit in the DA market. In the second stage, the outputs of the VPP are optimally adjusted, in order to minimize the imbalance cost in the RT market. The conditional-value-at-risk (CVaR) is used to assess the risk of profit variability due to the presence of uncertainties in renewable energy outputs, market prices and energy demands. The formulated two-stage models are solved by an enhanced particle swarm optimization algorithm (PSO) and the commercial solver AMPL/IPOPT 3.8.0. In the procedures of the enhanced PSO, two particles with the lowest and highest fitness values are used as the starting points, and then the interior point method will be employed to quickly locate local optima. The population size is set at 200, and the iteration number is set at 1000. Simulation results show that coordinated scheduling can effectively offset the renewable energy fluctuation and mitigate the impacts of uncertainties. With the two-level scheduling, the risk exposure can be mitigated, and the cost related to the risk aversion is also effectively reduced. The paper finds that coordinated two-level DERs scheduling is a flexible risk-hedging tool that can identify optimal operation, resulting in more affordable electricity prices for end users.

Keywords: *Virtual power plant, transactive energy, optimal scheduling and distributed energy resources*

On Wavelet Transform: An extension of Fractional Fourier Transform and its applications in optical signal processing

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Abstract: Wavelet theory is associated with building a model for a signal, system or processes with a set of special signals and is emerged as a powerful tool of signal de-noising. Earlier, the much celebrated fractional Fourier transform (FrFT) has been used to decompose the contaminated signals and obtain the desired signals on removing the noise. In optical data transmission, continuous signals are represented as functions of space or spatial frequency. Fractional Fourier transforms are closely related to chirp transforms, which in turn characterize and formulate optical transmission as the propagation in free space whereas fractional domains are the generalizations of conventional space and frequency domain. This leads to an interpretation of fractional Fourier or chirp transforms as wavelet transforms. The Wavelet Transform of one dimension has two parameters viz. scaling and shifting parameters. This makes possible to establish the correspondence between fractional Fourier transform and wavelet transform by choosing chirp function as the wavelet transform kernel.

In this paper, a strong relationship between wavelet transform with fractional Fourier transform has been exploited to develop a full-fledged analytical framework in tempered distributional settings, which can be viewed as the extension of the FrFT. This interpretation of wavelet transform in terms of fractional Fourier transform is then used in filtering and separation of undesired noise and distortion from optical signals.

The proposed model has far reaching applications especially in the field of signal processing and in particular, in the field of long range optical fiber transmission; which has been an active area of research ever since the introduction of multiresolution techniques in the fractal representation of modulated signals.

Experimental results have shown that the wavelet based models have better performance over the other transform techniques ever applied for signal processing.

Keywords: *Fractional Fourier transform, wavelet transform, signal processing, multiresolution*

Fuzzy network analysis of bi-serial and parallel servers linked to a common server

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Abstract: Queues or waiting lines arise when the demand for a service facility exceeds the capacity of the server, i.e. customers do not get service immediately upon request but wait or the service facilities stand idle. Queues or waiting lines help facilities or businesses provide service in an orderly fashion. Forming a queue being a social phenomenon, it is beneficial to the society if it can be managed so that both the unit that waits and the one that serves get the most benefit. Waiting lines are a part of everyday life. We wait in traffic jams or at toll booths; we wait on hold for an operator to pick up our telephone calls; we wait in line at supermarkets for check out; we wait in line at fast-food restaurants; and we wait in line at banks and post offices. The amount of time that a nation's population wastes by waiting in queues is a major factor in both the quality of life and the efficiency of nation's economy. Great inefficiencies also occur because of other kinds of waiting else than people standing in lines/queues. For example, making machines wait to be repaired may result in lost production. Airplanes waiting to take off or land may disturb later travel schedules. Delay in telecommunication transmissions due to saturated lines may cause data glitches causing manufacturing jobs to wait to be performed may disturb subsequent production and delaying service jobs beyond their due dates may result in loss of future business. Therefore, queuing theory is the study of waiting in all these situations with an aim to find formulas to optimize various queue characteristics including the average waiting that will occur under a variety of circumstances.

This paper is an attempt to introduce the concept of fuzziness, uncertainty or vagueness in analysis of network of queues in which a common server is linked in series with a system each of two bi-serial and parallel servers. The α - cut approach, fuzzy triangular membership function and various fuzzy arithmetic operations are used to estimate the uncertainty associated with input parameters. The model find its application in decision making, in process industry, in banking system, in super markets, in health care centers, in data communication and processing and in many administrative setups. A solution methodology is proposed to find mean queue length, mean arrival rate, average waiting time of jobs/customers for the proposed network of queues in fuzzy environment.

Keywords: *Fuzzy arrival rate, fuzzy service rate, bi-serial server, parallel servers, mean queue length*

Multistage Flowshop Scheduling with Sequence Dependent Setup Time in Fuzzy Environment

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Abstract: Flowshop scheduling problem involves scheduling a number of jobs on a number of machines in order to optimize a given set of criterions. The most of research problems assumes that the setup times are negligible or taken as a part of processing times. However these assumptions are invalid in real life situations. Generally, two types of problems exist, when setup time is considered independent of processing time. In the first, setup time depends only on the job to be processed, called sequence independent, and the second, setup time depends on both the jobs to be processed and on the previous job too, sequence dependent setup time. Flowshop scheduling problems with sequence dependent setup time is the mist typical case of scheduling problems. The practical situations may be considered as a paper bag factory where a setup time is needed for the machines to switch between the types of paper bags, and setup duration depends upon size and number of colour bags available. Similar, practical situations arise in chemical, pharmaceutical, food processing, metal processing and semiconductor industry etc.

It is usually assumed that the various processing times and setup times of jobs/tasks are exact. However, the real world is complex and the complexity is due to the uncertainty. To express this uncertainty, the concept of fuzziness is introduced in the scheduling models. Fuzzy sets theory provides a mathematical way to represent uncertainty, vagueness and fuzziness in humanistic systems. A fuzzy system can be thought of an attempt to understand a system for which no model exists, and it does so with the information that can be uncertain in a sense of being vague, or fuzzy, or imprecise, or altogether lacking. From this angle, fuzzy logic is a method to formalize the human capacity of imprecise reasoning. Such reasoning represents the human ability to reason approximately and judge under uncertainty. In fuzzy logic all truths are partial or approximate. In this sense the reasoning has also been termed interpolative reasoning, where the process of interpolating between the binary extremes of truth and false is represented by the ability of fuzzy logic to encapsulate partial truths. The objective is to schedule *n*-jobs on *m*-machines to minimize total elapsed time of jobs in a flow shop whenever the setup times on machines are sequence-dependent under fuzzy environment. A numerical example is also given to substantiate the algorithm.

Keywords: *Processing time, sequence dependent setup time, completion time, fuzzy processing time*

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 optimisation 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 optimises 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. A numerical illustration is carried out to illustrate the execution of proposed algorithm.

Keywords: *Fuzzy processing time, total tardiness, weighted flow time, weighted job, weighted shortest processing time*

Modelling a Single-Blade Wind Turbine using Computational Fluid Dynamics

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Abstract: Wind resource does not necessarily occur near areas of high population where the power it could generate can be readily used. It can therefore be uneconomic to site large-scale wind farms in the most suitable areas. New Zealand has a small population that is concentrated in areas that do not necessarily coincide with good wind resource. Transporting power is also a challenge in New Zealand as it is a long thin country with an ageing lines network. An alternative could be distributed household energy generation utilising wind resources at or near point of use (private properties or small community hubs such as schools). Requirements for such wind turbines are likely to differ from those for a commercial wind farm. The scale is reduced with a lower mast, a smaller power output and often a less than ideal site placement due to planning restrictions and other issues such as cost. These factors can lead to a domestic turbine having to utilise highly variable winds to generate power.

A unique one-blade downwind stall regulated horizontal axis wind turbine, Thinair 102, has been designed by PowerhouseWind and is in initial production in Dunedin, New Zealand. This turbine is designed for domestic use and to be efficient and effective in such highly variable winds. The turbine is designed to have a high real net output ratio. The turbine is limited to 3kW and has a shutoff at 345rpm. The blade is part of the NREL S series and was chosen for its soft stalling capabilities and high angle of attack. The airfoil section has the S835 at the root, S833 as the primary profile and S384 at the tip providing high lift. It has a rotor diameter of 3.6m and a rated rotation speed of 370rpm. The freely teetering hub is angled at approximately 7° (to the y axis) while operating normally. This mechanism allows the blade to change angle in response to variation in the wind speed and allows strong gusty winds to be used efficiently to generate power. In extreme wind conditions the blade swings into a safe horizontal position. The controller for the turbine adjusts the RPM of the blade to maximise the power output although in highly variable winds care has to be taken to avoid rapid changes as this has the potential to put unexpected structural load on the turbine hub. Understanding of the stall behaviour of the turbine therefore becomes important for optimum design of the controller software.

Computational Fluid Dynamics modelling has been used to model the stall behaviour of the turbine blade over a range of wind speeds and RPM in order to better understand the variations in power that can occur in variable winds. Comparison of the CFD simulation results with other commonly used models to calculate wind turbine power output was undertaken. When there was little or no stall on the blade the simpler models for power output gave adequate estimates. However they did not fully account for when stall occurs, giving either higher or lower power output estimates. CFD modeled stall more accurately as well as giving detailed three-dimensional visualisations of the flow over the blade. This allowed examination of the areas of the blade that were contributing to the power output and where stall was occurring over a range of wind speeds and RPM of the blade.

The value of using CFD for a small enterprise to further understand and develop their product was highlighted. By undertaking a specific project with well-defined boundaries PowerHouseWind gained valuable knowledge about their turbine that can be used in the future to further enhance their design and its capability. However it was essential to have a skilled analyst to undertake the work, spend sufficient time understanding the problem and use appropriate models and assumptions to ensure the results were applicable and accurate.

Keywords: *Computational Fluid Dynamics, wind turbine, stall behaviour*

Recommender system for high-level command and control using modelling and simulation

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Abstract: Autonomous vehicles are expected to be a force multiplier of Defence operations in the future. Currently multiple human operators are required for the command and control (C2) of a single vehicle. Reversing this so that a single human operator controls multiple vehicles places a significant cognitive burden on the operator and is not feasible using current control systems. As such, there is a growing need for high-level recommender systems to reduce the cognitive burden of controlling multiple autonomous systems.

To meet this challenge, we have developed a Recommender System to aid in the high-level C2 of multiple autonomous vehicles. Our system consists of an extensible, loosely coupled framework that allows multiple machine learning recommender agents to learn from (and control) various simulations. The architecture provides flexibility – allowing agents to learn on low-fidelity, rapid training simulations. Trained agents can later provide recommendations on other, related, simulations (even if these are more complex, higher fidelity or slower to run). Multiple different recommender agents can be plug and played into the architecture. Some early recommender agents that have been implemented include a Bayesian Bandit (BB) and Deep-Q Learning (DQL) agent.

The goal of the BB is to learn the distribution of red force locations to make search location recommendations. The BB uses Bayesian Inference and the Multi-Armed Bandit (MAB) formalism to balance exploration vs exploitation of the simulated world. The Bernoulli-Beta conjugate is used to update the belief of finding a red force at a specific location after each observation. The learnt probability distribution of red force locations can be overlaid onto a map to provide a heatmap for explainability and location recommendations using a probability threshold. Experiments were conducted with the following techniques; BB compared to an Upper Confidence Bound (UCB) Bandit, and a Multi-play Thompson Sampling (MP-TS) Bandit compared to a Multi-play Exponential 3 (MP-Exp3) Bandit. Results showed BB and MP-TS techniques have comparatively robust learning rates under high uncertainty.

A DQL agent, based on Google/Deepmind's algorithm, was also implemented to track suspects. The DQL receives updates on the state of the simulation and can choose from a number of actions, with a reward being calculated as a function of the end-state. Different action choices and reward/punishment models were implemented and compared. Successful tracking behaviour was achieved with all of the actions and reward models, however learning speed and stability was affected by choice of actions and reward, as well as by neural net learning parameters and the size of the experience replay memory. For instance, direct actions (such as "up, down, left, right") provided more rapid, stable learning than velocity-based (speed up, slow down, turn left/right) controls.

In general, we found that different recommender agent approaches have differing strengths and weaknesses that may complement one another if combined appropriately. We also found that exploring different problem formulations and simulation types (with different abstraction levels and run-speeds) can significantly speed up algorithm exploration and training.

Keywords: *Trusted Autonomous Systems (TAS), Deep-Q Learning, Bayesian Multi-Armed Bandit, Decision Support System (DSS), Human-on-the-loop*

Modelling causes for actions with the Decision and PROV ontologies

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Abstract: Provenance modelling systems such as PROV and its precursors, PML and OPM, do not have specific mechanics to deal with causes for actions. They can represent what information was used within processes and who did what, when, but not why. However, modelling human decision making to represent *why* has long been of interest to philosophers, politicians, mathematicians and, more recently, computer scientists and multiple decision modelling systems have been implemented over time. Aristotle in ancient Greece, codified representations of decision logic. The Marquis de Condorcet in 18th century France, proposed fair voting systems for elections. John Dewey in the early 20th centaury described logical step-wise decision-making processes. Computer models for aspects of decisions have existed as long as computers and recently, several standards groups have implementing specifications about how to record decisions such that knowledge of them may be shared and understood by others.

In this paper, we first demonstrate conceptually mapping part of a decision representation system, the Decision Ontology (DO), to the ontology version of PROV, PROV-O. We indicate that a complete mapping is not possible due to the DO modelling templates for possible future decision making and PROV-O only dealing with past actions such as decisions already made.

We deliver our DO/PROV-O mapping in a step-wise manner by first modelling a decision using DO, then extending the model to include extra concepts for agency and then re-modelling it as PROV-O. This exercise shows that some decisions modelled in depth using DO can be well understood using general PROV-O provenance terms.

Next, introduce a stand-alone ontology, DecPROV (http://promsns.org/def/decprov) which is a specialisation of PROV-O that captures the elements of DO we can map to it. We have chosen to implement a new ontology rather than creating a new version of DO due to the incompleteness of the mapping. We indicate why we have made certain modelling choices where they might be controversial. We also model our example decision in DecPROV.

In addition to showing that certain detailed decisions can be modelled in DO and PROV-O and thus DecPROV, we describe several common provenance scenarios and indicate causes for the generation of elements within them using a few DecPROV elements.

We conclude with a few thoughts about some of the aspects of decision modelling that the exercises related here have unveiled.

Keywords: *Decision theory, decision ontology, provenance, provenance ontology, ontology alignment*

Linking document-based metadata to provenance expressed in graphs

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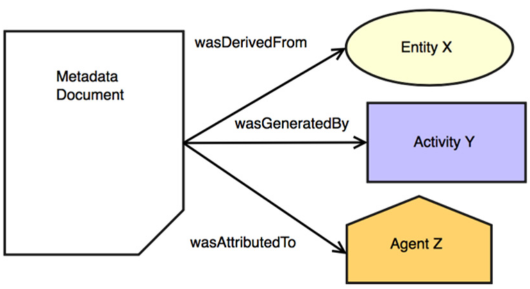
Abstract: Provenance of data – information about the entities, activities, and people involved in producing it – is of great interest as it can be used to form assessments about data's quality, reliability, or trustworthiness. The volume and complexity of digital data now generated requires sophisticated provenance handling and recently (last 5 years) new digital provenance representing standards have been established using graph structures. The graph implemented by the World Wide Web's PROV provenance standard can be extended with new data and specialized with new concepts while still adhering to a fundamental model allowing for some level of interoperability among different, specialized provenance data collections.

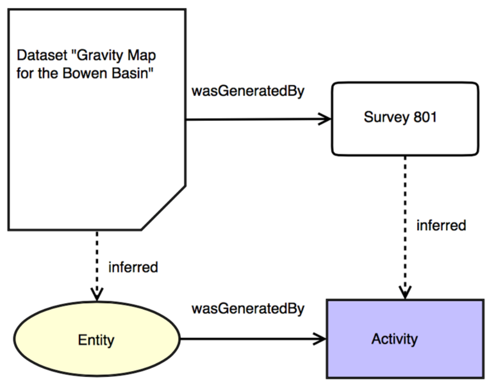
While PROV is clearly attractive to potential users given demonstrable interest in it, it is very different from the digital document-based metadata models that have been used for the past the, four or five decades. This poses a problem for the uptake of PROV since many catalogues of data using metadata documents in use cannot just adopt graph structures due to technical capacity or community metadata requirements.

Here we discuss "best practice" guidance about linking document-based metadata to provenance expressed in graphs. This is for implementers of document-based metadata catalogues and catalogue software producers. The work described here is done through the Research Data Alliance's *Provenance Patterns Working Group* (PPWG) which aims to assist the research data community's through a series of "provenance pattern" publications, of which this guidance is just one. Other patterns involve conventions for describing provenance scenarios within graphs and how to share provenance between institutions.

The best practice guidance discussed here does not recommend only one way of doing things as this is thought to not be realistic for implementers, given the great variability in implementer's capacities. Instead, an underlying principle for is given and several implementation patterns suggested. The principle here is that the item described in the document-based metadata should be categorised as one of the three basic classes of the PROV model – Entity, Activity, or Agent – and then conceptually PROV-compliant provenance recorded about it. This may not always translate to technical PROV compliance but optimally would. Of the three patterns recorded as of September 2017 "Linking directly with PROV relations", is represented graphically below. The generic pattern is given (left) as well as an example of use (right) at the author's agency. This pattern, and others available at the date of this conference, will be discussed in the presentation.



Pattern: Linking directly with PROV relations



This pattern and others are expressed in the PPPWG's database of provenance use cases and patterns online: http://patterns.promsns.org/pattern/12. It is expected that the patterns expressed here will evolve over the lifetime of the working group (September 2017 – March 2019), as feedback from members is acquired, with a final best practice recommendation published in 2019.

Keywords: *Provenance, lineage, metadata, graph, Linked Data*

PROV ontology supports alignment of observational data (models)

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Abstract: The W3C PROV ontology provides a flexible process-flow model that can capture many specific applications. A provenance trace is the retrospective view of a workflow, with specific instance data added. Thus it provides a basis for the description of any chain of activities which generate interesting outputs, such as observations, actuations, or acts of sampling. Furthermore, its relatively generic structure and naming allows it to be used as an alignment bridge with other ontologies that have previously challenged simple mappings. In this paper, we will show a harmonization of a number of important ontology patterns that can be linked through the PROV-O OWL implementation of PROV.

The alignments stack is as follows:

- PROV-O aligned to W3C OWL-Time
- PROV-O aligned to BFO
- W3C SSN/SOSA aligned to PROV-O
- OBOE, OBI and BCO (from the obo foundation) aligned to SOSA/SSN and thus PROV-O

Some of the alignments have been proposed previously, but the set described here both augments them and is larger in aggregate than previous work.

The availability of these alignments supports the fusion of data from a range of disciplines such as earth and environmental sciences, in particular observational data where the act of sampling and observation is understood in a provenance context.

Keywords: *Ontology alignment, observations, sensors, provenance*

Provenance in the next-generation spatial knowledge infrastructure

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Abstract: In quality evaluation of the piece of art its provenance (e.g. ownership over time) is often more important than the item itself. Considering that spatial data is rarely used and shared in its raw form, knowing its history (i.e. computation, transformation and other processes) may be decisive in evaluating the quality of spatial data (Buneman and Davidson, 2010). There are two concepts referring to the history of (spatial) resources on the web: lineage (defined by the International Organization for Standardization – ISO) and provenance (defined by the World Wide Web Consortium – W3C). In geospatial domain, these two concepts are widely understood and used as synonyms.

Lineage of a spatial resource (dataset or a service) is the standard term used in the spatial information domain, which is used to describe the history of a dataset and, in as much as is known, recount the life cycle of a dataset from collection and acquisition through processing, compilation and derivation to its current form (SA, 2015). Lineage metadata is only optional in the ISO-compliant standard metadata set, however, this element often appears in often sparsely populated spatial resources' metadata and, along with other metadata elements, serves as a potent vehicle for deciding on spatial resources' fitness for use. However, even in if lineage information might be present in its most exhaustive form, its main drawback for widespread automated use, is its standard data structure: more or less structured collection of the free-form text descriptions, a format unsuitable for the use in a geospatial (semantic) web.

Provenance is the standard term used in the context of the web and it is defined within a standard known as PROV as information about entities, activities, and people involved in producing a piece of data or a thing, which can be used to form assessments about its quality, reliability or trustworthiness (W3C, 2013a). PROV defines highly structured conceptual model for provenance encoding, enabling its interchange between systems and automated use on the web (W3C, 2013b).

With the aim of enabling spatial data on the web, there have been several attempts to align the standards for lineage and provenance, and these efforts demonstrate a strong convergence towards extending the current W3C provenance standard for geospatial resources. Enabling geospatial web services with provenance is paramount for reusability of spatial resources (data, information and services). In this context, there are two perspectives on provenance modelling:

- Modeling provenance of spatial resources for their discoverability and automated evaluation of spatial resources fitness for use, and
- Modeling provenance capture for automated data production and/or update.

In this paper, we review the state-of-the-art in using provenance and lineage in the spatial domain. We also demonstrate the importance and applicability of both perspectives with a use-case in which, at this point in time, we provide a partially complete solution, and look at what should be possible in current and next generation spatial knowledge infrastructure.

Keywords: *Lineage, provenance, spatial knowledge infrastructure, semantic web, fitness-for-use*

Documenting provenance of science in a state government agency

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Abstract: The South Australian Department of Environment Water and Natural Resources (DEWNR) has developed a comprehensive suite of standards, tools and guidelines to improve the quality and transparency of the science we produce. The approach is named MEK (Managing Environmental Knowledge). The MEK suite of resources supports the department's Information Management Framework and is aligned to South Australia's Digital by Default and Open Data agendas. DEWNRs Project Management Framework (PMF) does not currently address data management in projects. The MEK fills this gap by adding steps to the project phases which enable data supply chain management. This reminds projects of the importance of early data management planning and which standards or guidelines to refer to during the execution and delivery of a project. MEK tools support project managers and scientists to explicitly document data supply chains so that provenance of intermediate data outputs and publishable products is clear and accessible. The MEK aims to (a) improve the security, integrity and availability of data produced through projects (b) establish provenance, ensure transparency and enable re-use of data products and (c) enable effective use of existing enterprise information systems.

MEK resources are made available to employees through the department's intranet. The tools include (i) **data planning form** for estimating resources and broad needs of a project in relation to data management, (ii) **data charts** that provide a visual way of describing data supply chains and (iii) **data catalogue** for storing detailed metadata of each element in the data charts. The guidelines that underpin these tools include: **data storage** describing how to make use of the various corporate systems and applications, **evaluation** detailing the peer review procedures for major deliverables and evaluation guidelines for other project outputs, **data handling** describing information classification and sensitive data handling, and **publication** including proofing and publishing procedures.

Government agencies which rely on data to produce scientific outputs require a synergy of people, process and technologies to be effective and achieve strategic objectives. In DEWNR, an organisation which was recently formed as an amalgam of a number of departments, a disparate mix of platforms, applications and procedures have evolved over time. The result of this is that there is lack of consistency across the organisation in data management processes.

The South Australian Government's Digital by Default, Open Data and Data Sharing agendas have contributed to the need to better understand the provenance of DEWNR's science information. Simply printing a run of documents is no longer sufficient, we must openly provide intermediate datasets and products such as models, as well as communications material. Therefore, clear provenance is critical to ensure outputs provided to downstream users are evaluated and authorised. The MEK resources are enabling the department to improve its culture around data management, deliver improved science outputs and thereby enable evidence based decision making to support the management of our State's natural resources.

Keywords: *Knowledge management, data management, provenance*

Uchronia, a software module for efficient handling of multidimensional time series and use in ensemble forecasting

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Abstract: Ensemble prediction techniques have been shown to produce more accurate predictions than single prediction runs as well as being able to formally quantify prediction uncertainty in a range of scientific applications. Statistically meaningful quantification of uncertainty can require very large ensembles, with associated increases in computation and data storage, particularly for predictions in the form of time series. In addition, the verification of statistical properties of an ensemble, such as the reliability of the ensemble spread, requires very long retrospective verification periods. This presents logistical and conceptual challenges for researchers and practitioners still transitioning from simulations based on deterministic, single instance realisations. A software system for handling such ensemble time series has to address many needs, notably: (i) retrospective ensemble predictions can quickly require several hundred gigabytes of data, and may need to be accessible from workstations or high performance parallel compute clusters; (ii) users should still have an interactive, responsive experience when processing data, with little concern for on-disk logistics - a well-known principle that remains unsatisfactory in many implementations; and (iii) data infrastructure must promote strong data identity and versioning to help sustain a reproducible simulation outcome.

This paper presents an ensemble time series software infrastructure that has stemmed from needs in streamflow forecasting research, with potentially much wider applicability. The core entities of time series and ensembles are implemented in portable C++ code, using template metaprogramming. This permits a unified but versatile implementation for handling time series of various dimensional complexity. Time series elements can thus range from an atomic value, typically numeric, all the way up to a time series of ensemble forecasts. Object-oriented design patterns are used to allow for RAM caching of large data. A C API permits convenient data manipulation from a variety of interactive higher-level technical computing languages such as Python and R. Time series can be accessed via a time series library. Time series creation and retrieval relies on string identifiers and metadata, rather than paths to data files which are prevalent. The libraries can bring otherwise disparate data into a consistent data set for the simulation or analytical purposes. We envisage the time series library facilities as a solid basis for use in conjunction with federated data provenance infrastructure.

Keywords: *Ensemble streamflow forecasting, time series, interoperability*

Spotsizer–software package for quantitative genomics built on a general purpose workflow engine

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Abstract: In this paper we present Spotsizer – a software package that automates a scientific workflow to quantify microbial growth from photographic images of microbial colonies. Biologists grow colonies of microbes in multiple assays to study complex genetic interactions or the effects of chemical compounds. Although computational tools to acquire quantitative measurements of microbial colonies have been developed, their utility can be compromised by inflexible input image requirements, non-trivial installation procedures, the presence of manual steps, or complicated operations. We have chosen to develop Spotsizer using a general purpose workflow engine, CSIRO's Workspace, as it provides a wide range of preexisting building blocks and automated solutions for common development issues, including the ones mentioned above.

CSIRO's Workspace package (http://www.csiro.au/workspace) is a framework in which a user can construct workflows, user interfaces and complete applications quickly and easily. Workspace's flexible architecture allows users to connect their own specialized plug-ins to the framework thereby multiplying the number of available data transformations and tools. In addition to numerous built-in operations and widgets to visualize various data types, Workspace provides wizards and tools to easily wrap an existing library into a plug-in or create a full-fledged application complete with an installer, for Windows, MacOS and Linux.

At the core of Spotsizer lies a customized workflow developed by Data61's Quantitative Imaging Team, in collaboration with a team of geneticists from the University College London. This workflow links a number of data transformation steps that are applied to a photograph of microbial colonies robotically arrayed on a grid. The outputs of the workflow are an automatically generated file with locations and size measurements for each colony as well as the image of detected colonies. The Spotsizer workflow combines image analysis operations from an the Quantitative Imaging team's plug-in, Workspace's built-in operations and data types, and it uses Workspace's inline Javascript execution for custom computations within the workflow. It is possible to run the workflow from the command line or from within the Workspace graphical user interface (GUI), however, for the end user, we created a standalone application in order to further improve its ease of use.

Workspace provides a simple application generation wizard to create a basic application that connects a user's workflow and to a GUI created with Qt Designer, a GUI design tool included with Workspace. The GUI we designed for Spotsizer allows a user to choose a mode of operation (single image or batch processing), and a type of colony grid array, and then to review input and output images. One of the advantages of using Workspace is the ease of making modifications to an application – all the changes made to an underlying algorithm are applied to a workflow within the Workspace GUI, without a need to modify any code.

In literature, Spotsizer has been compared with a manually curated approach that uses a combination of automated steps and manual tasks. To its advantage, Spotsizer provides reproducibility, ease of use, robustness and versatility. The absence of manual tasks enables an efficient high-throughput analysis of images of growing microbes. Additionally, Spotsizer recognizes multiple colony grid types and image file formats. Spotsizer has been successfully used in finding differential growth phenotypes in yeast, with results published in Nature Genetics (http://doi.org/10.1038/ng.3215). We conclude that a general purpose workflow engine, such as Workspace, could be successfully used to facilitate development of automated tools and, consequently, advance quantitative research in this area.

Spotsizer can be downloaded freely for academic use from the CSIRO Data Access Portal (http://doi.org/10.4225/08/57315CD446E2C), together with an accompanying test data set. Spotsizer is distributed as a binary package for Windows, Linux and MacOS, and follows a standard installation procedure for each of these operating systems. From September 2015 there have been 140 downloads of Spotsizer.

Keywords: *General purpose workflow engine, image analysis, quantitative genomics*

Dive Mechanic: Bringing 3D virtual experimentation to elite level diving using the Workspace workflow engine

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Abstract: Dive Mechanic is a custom 3D software application for modelling elite level diving. It is designed to assist coaches, athletes and sports biomechanists in understanding, visualising and improving diving performance for both platform and springboard diving. This application was developed by research scientists within CSIRO Data61 and was built upon the Workspace workflow engine. Biomechanics algorithms were developed within this graphical workflow environment and an intuitive graphical user interface (GUI) was developed to make the software accessible to end users. Workspace also simplified the packaging of Dive Mechanic by providing an installer and access to software licensing controls. This paper outlines how the Workspace workflow engine assisted in the process of both developing scientific algorithms and encapsulating them within a commercial product offering.

Dive Mechanic was developed by CSIRO for use by Diving Australia as part of a larger project to investigate diving technique and injury risk. The aerial dynamics portion of the modelling was identified as sufficiently computationally-cheap to facilitate an interactive software solution. Dive Mechanic uses personalised body and motion data based on laser scans of the athletes and markerless motion digitisation from multiple camera video of the athletes performing dives. It employs a fast and detailed human biomechanics motion engine specifically developed for the application that allows diver technique to be modified interactively by coaches in order to explore technique or synchronisation improvements. Its GUI is powerful yet sufficiently simple and intuitive so as to provide a very positive user experience for non-IT diving experts. Dive Mechanic's virtual experimentation offers advantages over physical experimentation in that it can help avoid injury and having divers training possibly worse techniques whilst experimenting. Dive Mechanic was used by coaches of the Australian Olympic diving squad in preparation for the Rio 2016 Olympics.

The Workspace workflow engine was well suited to the development of Dive Mechanic. The first stage was to elicit requirements from Diving Australia and to formulate software specifications. Computational modelling of diving fits naturally within the workflow paradigm with the inputs of a physical diver model, diver technique and takeoff conditions being processed to output the complete diver aerial motion which feeds through to a visualisation workflow. From these specifications, the software architecture was determined in terms of functional blocks in a computational workflow and corresponding features in the user interface. Initial development involved creating the biomechanical file format readers, data structures, widgets and unit testing operations. Critical widgets for software usability including a kinematics modification widget and a simplified 3D OpenGL widget were then created. Next, the dynamics engine was developed and tested. Important features in the overall workflow were then connected with UI elements to produce the Dive Mechanic software. Incremental development of the workflow and the ability to easily inspect and interrogate data locally in the workflows using the same widgets used in the final product simplified software debugging and troubleshooting. Additionally the inherent modular nature of workflow operations maximised the reuse of existing operations and improved design of new reusable workflow operations by computational scientists.

Keywords: *Workflows, computational modelling, software engineering, diving, biomechanics*

Senaps: A platform for integrating time-series with modelling systems

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Abstract: Models of physical systems are the foundation of many scientific and decision support systems. These models rely heavily on observational data, typically collected from sensors. Increasingly this data comes from a wide range of sources. For example, agricultural models often require data from climate observations, soil conditions, on-farm equipment, seasonal forecasts, among others. Integration of these data with models is very time-consuming and often is repetitious across different models. Furthermore, automation of model runs is difficult due to the complexity of managing data dependencies.

We have developed a distributed system, Senaps, to support automation of sensor data retrieval and coupling with model execution in a scalable way. It has been developed over many years across scientific disciplines, including water management, agriculture, aquaculture, and related Information, Communication and Technologies areas. It has been used, and is in use, by a diverse range of projects, resulting in a flexible system that is not tied to a specific domain.

Senaps includes a publish-subscribe subsystem that handles ingestion of disparate time-series data. It supports stream processing, such as quality assurance and data checking, and automates data ingestion with monitoring and recovery. The storage and access subsystem is a scalable time-series backend with an Application Programming Interface (API) to allow third party developers to build on. It has a range of features including dynamic temporal aggregations; fine-grained access control to support data privacy and sharing (users can elect to share data between organisations); metadata for sensor data management; and controlled vocabularies.

The focus of this paper is the model integration subsystem, which provides the model integration and automation features. This system builds on developments in cloud and container-based computing to isolate a user submitted model's runtime environment and provide access to the data backend. APIs are provided to handle environment images (e.g. Linux with R), model definition, workflows (instances of a model), and running of model jobs.

We have successfully used this system to automate model runs and provide continuous results from a number of parameterised models. We have hosted a number of models on the platform, including a timber drying model and two agricultural prediction models. Being tied to a robust sensor-data backend ensures models are run on the most recent data and removes the need for model developers to continuously manage model execution. Results from the model are automatically available and can be easily shared between users and organisations. In this paper, we detail the technical challenges in implementation, provide example results from a running model, and describe our next research steps.

Keywords: *Sensor data platform, Internet of things, sensor model integration*

Using CSIRO's institutional data repository API through a Workspace plugin

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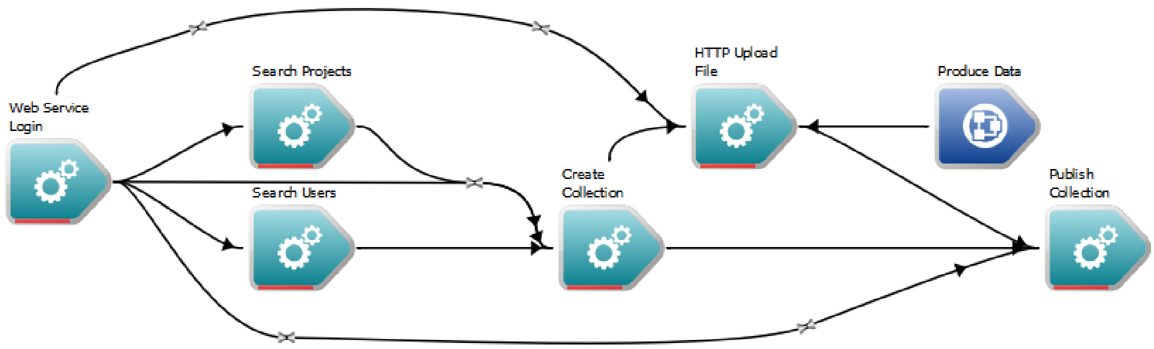
Abstract: Reproducible workflows are becoming increasingly relevant in academic publishing. Recently the journal Nature Neuroscience announced in an editorial (http://doi.org/10.1038/nn.4579) a project where "For the duration of the pilot, authors of papers accepted for publication in our pages will be asked to make the code that supports the generation of key figures in their manuscript available for review." The editorial goes on to say that "code review is a part of the full manuscript assessment process at several other journals, including Nature Methods and Nature Biotechnology." The scientific workflow platform Workspace (https://research.csiro.au/workspace/) allows such code to be run on multiple platforms with all dependencies provided, requiring minimal configuration on behalf of the end user.

We present the development of a prototype plugin for Workspace that allows both consumption of existing Data Access Portal (DAP – https://data.csiro.au) collections and production of new ones. Such a tool allows researchers to host or access reference or raw data in the DAP, process it in a workflow, then store both the outputs and the workflow itself in a new DAP collection. With the Workspace software itself hosted in the DAP, this provides a low-barrier-to-entry method of creating reproducible scientific workflows and outputs, meaning all required data and software is accessible to the end user through one repository. The DAP uses a RESTful API, which technically means all that is required is a suite of HTTP request operations to use in Workspace. Use at this basic level, however, requires familiarity with the DAP, the constructions of collections, and how they are accessed. The DAP Workspace plugin aims to abstract these features from the Workspace user, allowing them to use the operations catalogue as they would for any other task.



The operations provided by the DAP plugin for Workspace consist of:

- Create, Read, Update and Delete (CRUD) operations for creating DAP collections, uploading data, and publishing draft collections;
- Basic JSON and string operations for manipulating response data from the DAP API;
- Read API operations for searching and retrieving published DAP collections;

The development of this plugin has informed development of the DAP API itself, being one of the first practical uses of the recently developed CRUD endpoints, as well as assisting in the development of interfaces for other languages, such as DAP Python modules.

Keywords: *Web services, REST API, workflow software, institutional repositories, data management, data publication*

A computational model of arc welding – from a research tool to a software product

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Abstract: CSIRO has a long history of modelling arc plasma processes, including arc welding, plasma torches and plasma waste conversion. The models use the methods of computational fluid dynamics applied to viscous incompressible flows, extended to include an energy conservation equation, Maxwell's equations, and additional source terms to take into account plasma effects. The models have been used to gain a scientific understanding of arc plasma physics and chemistry and, as they have gained sophistication and accuracy, to improve and optimise industrial processes.

The computer codes that have been developed have, until recently, relied on expert users with familiarity with the detailed operation of the code, and access to a FORTRAN compiler. In a typical implementation, input parameters are provided using user-editable text files, progress towards convergence is monitored by viewing a continuously-updated text file, and the results of the calculations are written as text files and as data files readable by graphics programs. Input and output file handling is not automated; the user is required to rename files to avoid overwriting, and to ensure that all relevant files are stored together. The provision of an appropriate start-up file (for example, a solution obtained for a similar set of input parameters) has required the user to select the file; this relies on the user carefully documenting the input parameters for all solution files.

One of CSIRO's arc welding codes has now been packaged into a software product, ArcWeld, using CSIRO's Workspace workflow framework. This advance was motivated by a customer, General Motors, requesting that the code be easily usable by its welding engineers and technicians. The model is three-dimensional and treats the full arc welding process, with solid, liquid and plasma regions included in the computational domain. Despite these factors, physically-based simplifications are used to ensure that ArcWeld can be run under 64-bit Windows on standard desktop computers. A simple GUI is used for entry of input parameters, starting the computer code, displaying progress towards convergence, and access to graphical output. The most appropriate start-up file is automatically selected based on the input parameters. All input and output data are written to a user-selected directory.

This work has had important benefits. For the scientist, using a workflow platform means that common components and functionality are available as prewritten and pretested operations, so scientists can focus more on their core science and not as much on software development. For end users, the code can now be run by non-experts, who require only very basic training and access to a desktop computer. The input parameters are automatically stored with the output data, reducing the reliance on user documentation, and the user can easily visualise the results. These changes mean that the science can be advanced more quickly and the software can be used 'on the factory floor' to help optimise welding processes. More broadly, the software can easily be demonstrated to potential customers, and has greatly increased the attractiveness of our arc plasma modelling work to potential customers.

Keywords: *Arc welding, graphical user interface, CFD modelling, workflow, Workspace*

Heliosim: A Workspace-driven application for the optimisation of solar thermal power plants

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Abstract: Heliosim is a standalone application developed by the CSIRO that provides a graphical interface to an integrated computational model for the optimisation and simulation of central receiver Concentrating Solar Thermal (CST) power plant components. Central receiver concentrating solar thermal (CST) power involves using a field of independently controlled mirrors (heliostats) to concentrate solar radiation onto a centrally located heat transfer device (receiver) such as a falling curtain of solid particles or banks of pipes containing a fluid such as molten salt. The thermal energy can then be stored and used on-demand to drive electric turbines or industrial chemical processes. The core physical modelling in Heliosim consists of a GPU accelerated ray tracing optics model for simulating the concentrated solar radiation distribution on the receiver, and a finite volume heat transfer model for simulating the heat transfer of receivers consisting of banks of pipes containing a heat transfer fluid. This core modelling can be used to either evaluate the performance of a fully specified facility design, or used in an objective function for optimising the heliostat layout. The C++ API for Heliosim has been in development and usage at CSIRO for approximately 10 years. Previously, a calculation was performed by: 1) using a Python script to define the calculation as a series of 'jobs', each with its own XML input file, 2) running SConstruct to determine what executable to be used for each job and what order to run them in, 3) post-processing the results with Python scripts and viewing the results with a data visualisation package such as ParaView. Using Workspace, a scientific workflow and application development platform developed by the CSIRO, this manually coordinated and error prone workflow was converted into an easy to use standalone application. This was done by: 1) exposing parts of the API as a set of operations and datatypes in a Workspace plugin, 2) creating the workflow in the Workspace GUI by combining the functionality of the Heliosim plugin with that of other builtin plugins (e.g. data analysis, 3D rendering, Python scripting), and 3) connecting the inputs and outputs of the workflow to slots in a user interface (UI) created with QtDesigner and compiling the standalone application. A screenshot of Heliosim running on Ubuntu 16.04 is shown in Figure 1. A public version of the software with restricted functionality will be available for download from CSIRO's Data Access Portal, whilst the full version has been licensed as a commercial software package. By leveraging the large collection of built-in plugins and following a streamlined development process, the use of Workspace has allowed a powerful and easy to use application to be created in a relatively short amount of time.

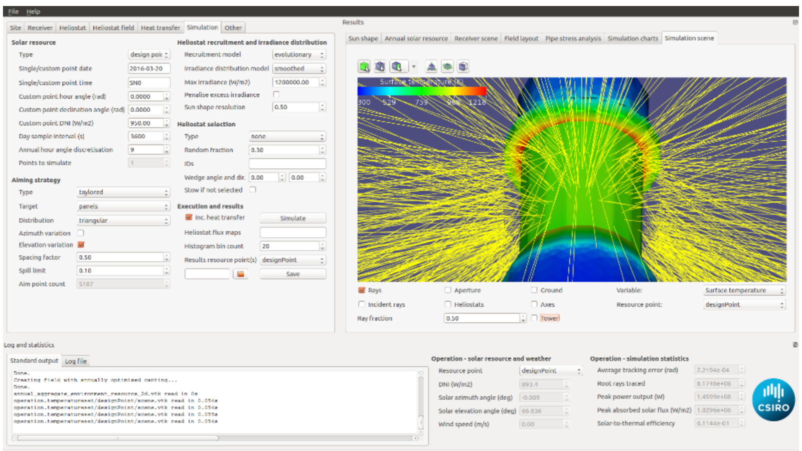

Figure 1. The Heliosim UI. The 3D scene shows reflected sunlight rays impacting on a cylindrical receiver.

Keywords: *Workspace, workflows, solar energy, optimisation*

The need for a unified framework for Natural Hazards Modelling and Analytics

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Abstract: Natural Hazards in general are large scale geospatial events occurring over multiple time scales. Accurate computational modelling of such events for the purposes of risk analysis, mitigation, adaptation and operational management requires multiple complex inputs from various sources including remotely sensed data, meteorological inputs and empirical data. Due to the uncertainty associated with the data inputs as well as the predictive models being used it is becoming increasingly essential to run multiple sets of these simulations to enable the quantification of uncertainties associated with the eventual spatio-temporal outputs. Visualising the outcomes of the simulations in a manner that is descriptive to a wide range of audience ranging from highly trained researchers to the community that is affected by the natural hazard is also significantly important. Finally key consumers of such predictive technology including emergency managers, local cities and planners are no longer just requiring outputs of the models in reports and map formats. They are also increasingly very keen on being able to interactively run scenarios themselves to further understand the consequences of decisions they might need to take action on as and when the need arises. To resolve these challenges we are developing a framework that is able to respond to a significant number of the above requirements utilising CSIRO's Workspace workflow platform.

Thus far the framework has been used to develop three key capabilities:

Spark: A toolkit for end-to-end processing, simulation and analysis of wildfires utilising high performance GPU based processing. Spark is able to be scaled up in an operational context for a range of fuel models and therefore allows its use in Australia and globally.

Amicus: A quick and easy to use expected fire behaviour calculator based on user defined inputs that allows a very rapid assessment of the prevailing local fire danger.

Swift: An integrated GPU based hydrodynamic (2D) and hydraulic (1D) flood modelling toolkit that is purpose built for urban inundation and includes the ability to assess combined coastal and catchment flooding.

The key features of Workspace that have enabled the rapid development of these capabilities include:

a. Tight integration with geospatial plugin GDAL,
b. Provenance support that allows tracking the history of simulations. This feature is critical for disaster management applications due to the need to revisit the origins of simulation outcomes for post disaster analysis,
c. Database support, essential for managing large geospatial and meteorological data inputs,
d. Integrated parallel and distributed computing supporting ensemble simulations and analytics.

Going forward our focus is on further extending these capabilities to include the following features:

Integration of Downscaled Climate Model outputs with bushfire and flood models – further differentiating our capability offering in the bushfire and urban flood spaces; *Evacuation modelling* – as a decision support system to simulate evacuation scenarios integrated with bushfire and flood models; *Surrogate models* – to overcome challenges associated with computational speed we are developing parametric and nonparametric surrogate models utilising training datasets from detailed physics based computational models.

The flexibility, modularity and integration capabilities of Workspace has allowed us to rapidly develop capabilities. Future development will further test the flexibility of the workflow engine thereby enhancing its robustness at the same time as it supports us in our endeavors.

Keywords: *Natural hazards, modelling, analytics, integration, uncertainty, Workflow based framework*

Implementing best practices and a workflow for modelling the geospatial distribution of migratory species

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Abstract: Species distributions are mainly determined by abiotic conditions, other species with which they interact, and the potential for dispersal and colonisation. Most of these factors are dynamic and change over time. Species' responses are also dynamic and may vary from evolved ecological niches to geographical isolation and speciation, to extinction.

In the past, summarising evolutionary processes into mathematical models would result in problems which were too complex and analytically intractable. A simplified modelling technique was developed to estimate geospatial species distributions with computationally viable solutions. It combines species presence/absence data with the relevant environmental layers for its survival (e.g., temperature and rainfall), calculating the species probabilistic distribution by applying machine learning and statistical algorithms. The resulting model is the species potential niche distribution, which can be applied to determine potential geographical areas for conservation and sustainable use of the environment, and to evaluate impacts of climate change, among other relevant applications.

Nowadays, supercomputers, big data, and cloud computing can be used to improve ecological modelling, but the research community is only gradually understanding the potential of these technologies. Researchers often use their own modelling environment (e.g., R/R Studio) and ignore the potential outcomes that can be brought about by large-scale computing and data resources. Modelling the geospatial distribution of migratory species, for example, requires running several models for different periods of time along a year, depending on the species migratory patterns, so it is a clear case for applying these new technologies.

This paper introduces a workflow to run cloud-based migratory species modelling. It determines the required steps to produce reliable models and best practices to properly design, understand, and evaluate such models. The workflow was implemented in the Biodiversity and Climate Change Virtual Laboratory (BCCVL), which is available for the research community. Experiments with the monthly and seasonal distribution of the migratory species *Danaus plexippus* (Monarch Butterfly) were conducted to assess the workflow and the BCCVL implementation. The generated models were compatible to results available in the literature, and they also matched the corresponding species data available in the most relevant species data portals worldwide, such as the Global Biodiversity Information Facility and the Atlas of Living Australia.

This workflow is the first step in a series of dynamic features that can be proposed to improve the current state-of-art in species distribution modelling with the help of new technologies such as cloud computing, HPC (High Performance Computing), and IoT (Internet of Things). Combined, they have the potential to take ecological niche modelling to the next level in terms of usability, availability, scalability, performance, and accuracy of the generated models.

Keywords: *Migratory species distribution, cloud computing, workflow, HPC, IoT, species distribution modelling, BCCVL (Biodiversity and Climate Change Virtual Laboratory)*

Workspace - a Scientific Workflow System for enabling Research Impact

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Abstract: Scientific Workflow Systems (SWSs) have become an essential platform in many areas of research. Compared to writing research software from scratch, they provide a more accessible way to acquire data, customise inputs and combine algorithms in order to produce research outputs that are reproducible. Today there are a number of SWSs such as Apache Taverna, Galaxy, Kepler, KNIME, Pegasus and CSIRO's Workspace. Depending on your definition you may also consider environments such as MATLAB or programming languages with dedicated scientific support, such as Python with its SciPy and NumPy libraries, to be SWSs. All address different subsets of requirements, but generally attempt to address at least the following four to varying degrees: 1) improving researcher productivity, 2) providing the ability to create reproducible workflows, 3) enabling collaboration between different research teams, and 4) providing some aspect of portability and interoperability - either between different sciences or computing environments, or both. Most SWSs provide a generic set of capabilities such as a graphical tool to construct, save, load, and edit workflows, and a set of well proven functions, such as file I/O, and an execution environment.

Workspace is an SWS that has been under continuous development at CSIRO since 2005. Its development is guided by four core themes; Analyse, Collaborate, Commercialise and Everywhere. Three of these map to the SWS requirements:

- Analyse - improving researcher productivity and enabling reproducibility by enabling a higher level of reuse and sharing of software components
- Collaborate - enabling collaboration between different research teams by providing a common platform and interoperability between otherwise incompatible software elements
- Everywhere - the ability to build multiplatform applications leveraging a range of computing and communication platforms and to support transdisciplinary knowledge integration

Workspace's fourth core theme of Commercialise is a key differentiator to most other SWSs and one not usually at the forefront of a researcher's mind. Workspace has been developed with a goal to shorten the path from research to impact, which in many cases takes the form of translating research into usable, robust, standalone tools for research, industry and commercial partners.

Workspace provides significant productivity gains with a learning curve suited to a broad range of users, without requiring software engineering expertise. This is aided by an intuitive user interface and comprehensive help system, to produce workflows and applications. Key features include:

- Easily extendible plugin architecture which allows individuals and teams to easily add their own data types, algorithms and user interface components into the framework to use and share with others. This feature has been used to expose a number of popular scientific libraries (such as OpenCV, PCL and VTK) and languages (such as Python, R and MATLAB) in the framework.
- Flexible and powerful execution system enabling continuous, inline interaction with data throughout the workflow while it is running, facilitating rapid prototyping. Parallel and distributed execution of workflows is supported as are other execution models such as batch runs from a command line or embedding workflows as shared library calls from within other software.
- Highly optimised and customisable real time interactive 2D plotting and 3D visualisation, combined with strong point cloud, surface and volume geometry pre and post processing capabilities.
- Capability to package workflows along with plugins and user interfaces as distributable, standalone software applications. This represents a fast and cost-effective path to the commercialisation of research outputs.

This paper discusses SWSs and their requirements and then introduces Workspace. Finally a high level comparison of the more popular platforms is given.

Keywords: *Workspace, workflow, plug-in, visualisation, commercialisation, rapid prototyping*

Vegetation indices and their statistical associations in mapping burned areas using Earth Observation data: an integrated modelling approach

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Abstract: In this study, burned areas in Tasmanian World Heritage Wilderness Area from 2016 summer were mapped using pre and post-fire Earth Observation [EO] data. Landsat 8 and Sentinel-2 products were used in deriving the layers of vegetation and burned area indicators. The derived layers were visualised and examined for statistical association before making a decision to selecting them as input to machine learning environment. Open-source image segmentation algorithm was used in generating objects and mapping burned areas in different hierarchical levels. The results were validated using the ground truth data. This study demonstrates that automated approach based on EO data is cost effective and attractive against on ground mapping of bushfires in wild landscapes.

The importance of the study area recognised internationally by UNESCO for natural and cultural values and as world and national heritage under the Environment Protection and Biodiversity Conservation Act (1999) of the Commonwealth Government. The natural values include glaciated alpine landscapes where fire-sensitive Cretaceous palaeoendemics survive and marsupial carnivores thrive. The cultural values of the study area consist of artefacts, cave-sites, rock art and other evidence of the Aboriginal occupation of Tasmania, extending back over 40,000 years, including the most recent ice age.

In order to test the developed integrated modelling approach, we used a Landsat 8 image before the fire and a Sentinel-2 image after the fire event. These images were pre-processed and atmospherically corrected to ensure further spatial analysis and modelling were accurate. Sentinel-2 was used because Landsat 8 cloud-free images were not available. The Sentinel-2 Multispectral Instrument (MSI) acquires 13 spectral bands ranging from Visible and Near-Infrared (VNIR) to Shortwave Infrared (SWIR) wavelengths along a 290-km orbital swath. The MSI sensor data are complementary to data acquired by the U.S. Geological Survey (USGS) Landsat 8 Operational Land Imager (OLI) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+). Being complementary to Landsat 8 OLI, Sentinel-2 was used for comparison. The fire ground truth data was assembled from several sources & agencies (Tasmania Fire Service; Parks and Wildlife; Forestry Tasmania; Forico). The 'official' fire history is released in late July of each year. It is available on LISTmap (The State mapping authority of Tasmania) where the source and method of data capture for each polygon is provided.

The integrated modelling approach consisted of the functions developed in mapping the extent and severity of bush fires. All the functions were developed in R language environment. Furthermore, our approach considered the statistical associations among the vegetation and burn indices. Our approach took into account spatial-spectral-statistical aspects in mapping burned areas in native vegetation environment. The performance of this approach was assessed using Overall Accuracy; Balanced Accuracy; Cohen's Kappa; True Positive Rate (sensitivity); True Negative Rate (specificity); Positive Predictive Value; and Negative Predictive Value, all based on ground truthing and calculated for multi-sensor data. The contribution of this study is the development of a novel integrated machine learning process and its assessment in depicting bushfire extent and severity in the native vegetation environment.

Keywords: *Earth Observation, bushfires, Tasmania, Burned Area Map, R, GRASS*

Constrained Sampling of Markov Chains

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Abstract: Homogeneous Markov chains with discrete state-space and time are very straightforward to simulate, due to the memorylessness property. In this talk, we consider sampling from the normalised restriction of a Markov chains joint distribution to a subset defined by two kinds of constraints: univariate constraints, restricting individual chain variables to belong to certain sets, and multivariate constraints, restricting non-adjacent groups of chain variables to be unequal but equivalent under a predefined equivalence relation. The multivariate constraints, in particular, present some challenges. An efficient sampling method involving Metropolis-Hastings with some pre-tabulated distributions is described.

We demonstrate an application to text generation, and in particular the random generation of rhyming, scanning lyrics, as a component of an algorithmic songwriting project. In this setting, the states of the Markov chain are syllables (that know which words they are from, so that for instance the final syllables of perilous and marvellous are two different states). The univariate constraints enforce the metre of the text, by indicating which syllables must be stressed or unstressed (for correct scansion) and which syllables must be word-final (so that words do not straddle lines). The multivariate constraints enforce a rhyming scheme, by requiring certain groups of syllables to rhyme without being equal.

This work relies on the Carnegie Mellon Pronouncing Dictionary (CMUdict; Weide, 1998) and sample text. CMUdict contains over 130000 entries, comprising words, proper nouns et cetera as used in spoken American English. This dictionary indicates the phonemic and stress pronunciation of each entry.

A Markov chain including the entire dictionary would require over 330000 syllable states. We have used sample texts, both to reduce the state space, and to build a first-order Markov model of word sequence, or equivalently, syllable sequence. The problem of interest is to sample from the Markov chain, subject to the constraints imposed by a given rhyming scheme.

Our algorithm firstly samples the multivariately constrained chain variables. After location of a feasible subsequence of rhymed syllables, ratios of joint probabilities are calculated and compared in a Metropolis-Hastings algorithm, where each candidate arises from the incumbent by replacing one set of rhyming syllables with another drawn from a pre-tabulated distribution. After a burn-in period, the skeleton provided by the rhymed syllables is fleshed out by sampling the unrhymed syllables according to the Markov chain, subject to metrical and boundary conditions.

Keywords: *Constrained Markov chain, Metropolis, rhyme, text generation*

Comparison learning algorithms for artificial neural network model for flood forecasting, Chiang Mai, Thailand

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Abstract: Artificial neural network (ANN) has been widely used for flood forecasting, however, different learning algorithms may lead to different model performance. Therefore, this study investigated 10 learning algorithms; GDX (Variable Learning Rate Gradient Descent), BFG (BFGS Quasi-Newton), CGP (Polak-Ribiere Conjugate Gradient), BR (Bayesian Regularization), LM (Levenberg-Marquardt), OSS (One Step Secant), CGB (Conjugate Gradient with Powell/Beale Restarts, CGF (Fletcher-Powell Conjugate Gradient), SCG (Scaled Conjugate Gradient) and RP (Resilient Backpropagation).

This study area is located in the Upper Ping River Catchment, Chiang Mai, Thailand. There are two experiments for evaluating the learning algorithms performance. The first experiment is forecasting water level at P.1 station using water level and outflow from dam (7 input variables including: 5 variables of 3 water level stations ($P.67_t$, $P.67_{t-6}$, $P.75_t$, $P.75_{t-6}$ and $P.1_t$) and 2 variables of outflow from the upper dam ($Flow_t$ and $Flow_{t-6}$). In addition, the second experiment is forecasting water level at P.67 station with using dBz value of Doppler radar images of precipitation, water level of the upper station and outflow from the dam (16 input variables including: 12 variables from 6 pixels of dBz ($Z11_t$, $Z11_{t-6}$, $Z12_t$, $Z12_{t-6}$, …, $Z23_{t-6}$), 2 variables of water level ($P.75_t$, $P.75_{t-6}$) and 2 variables of outflow from the upper dam ($Flow_t$ and $Flow_{t-6}$).

For ANN model development, model architecture was set with 1 hidden layer and a number of hidden nodes from 1 to 2n+1 nodes (n is the number of input variables) and forecasting times are 6, 12 and 18 hours (t+6, t+12 and t+18). Available data for this study is only year 2005 with 5 flood events and the first flood event is for testing and other flood events are for training.

The results showed that increasing the number of hidden nodes did not affect the performance of the model excepted t+18. Where, the performance of the model using LM and BR was decreased by increasing the number of hidden nodes. For the model performance with different learning algorithms, at P.1 station, all learning algorithms presented similar results in hydrographs at t+6, 12 and 18 with CE: 0.02, 0.03-0.05, and 0.05-0.07 respectively. On the other hand, at P.67 station, all learning algorithms forecasted different hydrographs, BR and LM tended to be the best algorithm at t+6, 12 and 18 with CE: 0.37, 0.33 and 0.34/0.37 respectively, while GDX was the worst algorithm with CE: 0.44, 0.43 and 0.49 respectively. Therefore, it could be said that the recommend algorithm for flood forecasting at P.1 and P.67 is LM algorithm because LM is a fast learning algorithm while BR is a slow learning.

Keywords: *Artificial neural network, flood forecasting, learning algorithms, Thailand*

Robustness of artificial neural network and discrete choice modelling in presence of unobserved variables

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Abstract: Models are used to gain a better understanding of complex systems such as the evolution of a population, the transportation demand, the brain behaviour, elections outcome, the propagation of a disease,...

System models should be precise and parsimonious. However, the total variation of the system cannot be precisely captured by the observed variables as there can be unobserved ones influencing the system output. The unexplained variation caused by unobserved variables is, therefore, considered as a noise in the model. Different models handle that noise in a different way. For instance, a linear regression assumes that the noise follows a normal distribution and explicitly incorporates it into the model formulation. On the other hand, other models, such as a deterministic neural network, do not explicitly incorporate that noise. Several models can then be applied and the selection of the best one can be a challenging question.

This research aims to highlight the importance of the unobserved variables on the results of two types of simple yet widely used models: feedforward neural networks (FFNN) and logit discrete choice models (LDCM).

The first application consists in modelling the divorces in an agent-based microsimulation, the agents being the individuals of a given population. For each couple in the model, the divorce is predicted based on the characteristics of the couple (ex: length of the marriage, age of the individuals). In this application, it is shown that the LDCM outperforms the neural network due to the presence of - possibly many - unobserved variables.

The second example is a model defined to predict the level of interaction between groundwater and quarry extensions. In this application, the value of every relevant variable is assumed to be known, i.e. the noise from unobserved variables is minimum. In this case, it is shown that both approaches perform well, but FFNN perform slightly better than LDCM. We then investigate how the model performance evolves when the noise increases by removing variables from the models specification.

Finally, those two applications will allow us to conclude on the robustness of the discrete choice models and artificial neural network in presence of unobserved variables.

Keywords: *Discrete choice modelling, neural network, unobserved variables*

Score function of violations and best cutpoint to identify druggable molecules and associated disease targets

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Abstract: Predicting druggability and prioritising certain disease modifying targets is critical in drug discovery. Expanding the spectrum of disease-relevant targets to pharmacological manipulation is vital to reducing morbidity and mortality. We test a druggability rule, based on 10 molecular parameters (scores counting violations, denoted by score10), which uses cutpoints for each molecular parameter based on mixture clustering discriminant analysis (MC/DA) (Hudson et al., 2014). A total of 1279 small molecules from the DrugBank chem-informatics database (Knox et al., 2011), combining detailed drug (i.e. chemical, pharmacological and pharmaceutical) data with drug disease target information, were analysed and these were shown to be aligned with 173 targets. The score10 function comprised 4 traditional parameters of the rule of five (Ro5) (Lipinski, 2016), plus 5 extra parameters (polar surface area PSA, number of rotatable bonds, rings and halogens, N and O atoms) with an extra candidate of lipophicility, log D (the distribution coefficient) recently suggested by Bhal et al., 2007 as a possible preferable predictor for permeation (Zafar, Hudson et al., 2016, 2013;) to Lipinski's traditional partition coefficient, Log P, a predictor for permeation.

Multivariate skew normal (SN) (Lee and Mc Lachlan 2013) and Gaussian (MN) mixture clustering identified 5 molecule groups based on the 10 predictors, or 9 predictors when the number of halogen atoms was omitted. MN clusters were highly differentiable with 3 of the 5 clusters classified as poor druggable candidates, similarly the SN clusters. Logistic regression was used to determine the best cutpoint, C, for the total number of violations, score10 (< C versus greater or equal to C, for C= 3, 4 or 5) using predictor models containing the molecule's Ro5 status (if Ro5 compliant the molecule is druggable by Lipinski's rule), oral status, and poor vs good druggability grouping based on the clustering. We studied the performance of a support vector machine (SVM) and Recursive partitioning (RP) based on the 10 molecular descriptors, to classify compounds with high or low violator scores (defined by our optimal cutpoint, C). RP was applied to find simple hierarchical rules to classify the high score violators from the low (< C). PRoC analyses (Robin et al., 2011) and logit analyses showed that a cutpoint of 5 is best in partitioning chemo-space. For either partition of the score10 function, logistic models with the MN10 cluster predictor were superior to that of the (SN10). The best model was obtained for a cutpoint of 5 (AIC = 1403.79) and established that molecules with 5 or more violations tended to be non-oral candidates ($p < 0.00001$), MN10 poor ($p < 0.00001$) and be Ro5 violators ($p < 0.00001$), with a significant oral by cluster interaction ($P < 0.03$) found. The SVM classifier of the score10 partition (C=5) gave a Matthews coefficient C= 0.887. PROC analyses gave high values for the area under the curve (AUC) of 98.7%, with 95% CI (98.2%-99.3%), sensitivity (r) and specificity (s), 0.961 and 0.924, respectively for the training set. For the validation set SVM gave an AUC of 98.1%, 95% CI (97%-99.2%), r=0.927, s=0.983 and likewise a high C=0.818. The RP classification gave similar but slightly lower AUC and C values as the SVM. Specifically, the RP classifier for the score10 partition yielded an AUC of 95.1% with 95%CI (93.8%-96.4%), sensitivity of 0.918, specificity 0.936, and C= 0.845 for the training set; for the validation set an AUC of 95.3% with 95% CI (93.1%-97.5%), with r=0.924, s=0.886 and C=0.809. The RP rules to classify the high score violators from the low (< 5) confirmed the value of log D's inclusion in the scoring function and supported the original MC/DA cutpoints established for each molecular descriptor (Hudson et al., 2014). Our work illustrated that SVM used in combination with simple molecular descriptors can provide a reliable assessment of our simple scoring function of counts of violations partition. Moreover, molecules with score10 representing 5 or more violations were shown to be associated with specific disease targets, namely, Anti-Bacterial, Antineoplastic, Antihypertensive and Anti-allergic, within which most of the drugs have a non-oral delivery mode. Target drugs with a median score10 < 5 were Adrenergic, Dietary, Analgesics, Anti-infective, Anesthetics, Adjuvants, Anti-convulsants, Antimetabolites and Antidepressants, all of which, except Dietary and Anesthetics, were non-oral.

Keywords: *Druggability rules, Beyond the Rule of Five (bRo5), disease targets, machine learning*

Analysis of ligand binding to macromolecules using kinetic and polynomial approaches

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Abstract: One of the most interesting property exhibited by most of the proteins is its ligand binding and cooperative interaction ability. The cooperative interactions occur when ligand binding on one site alters the interactions at a distant ligand binding site of same protein. This cooperative and allosteric interactions are an important and interesting phenomenon, and they can be seen throughout biology. The first and probably the most studied cooperative molecule is Haemoglobin which was studied by Bohr, who showed that the binding curve of Hb-O_2 interaction is sigmoidal instead of hyperbolic. The process of cooperative binding and allosteric binding of ligands to the macromolecules or proteins adds complexity to the ligand binding process studies. To understand these functions we have to look beyond the scope of sequence of nucleotides encoding proteins required for a process and look into the network of interactive and interdependent regulatory networks as system which allows certain regulatory expressions to happen. The expression of these networks in the form of computer models that extracts the topology of events occurring in the systems representing it in a systematic way, makes the system easy to explain and predict. There are a number of ways in which a process or network can be modelled for easy explanations and understanding. In the current study we will be analysing ligand binding interactions using two different approaches (1) BP (Binding polynomial) approach; (2) Kinetic modelling approach.

The use of BP and kinetic modelling approach will be discussed in this study on two cooperative ligand binding proteins (1) TRAP (tryptophan RNA-binding Attenuation protein) and (2) CaM (Calmodulin). The BP approach has been used to analyse the cooperativity in the ligand binding sites in TRAP protein in *B. Subtilis* but it is new to be used on cooperative binding in CaM highlighting the possible use of this technique on the interaction analysis of cooperativity in Ca^{2+} – CaM system. The kinetic modelling approaches are more popular, and therefore have already been used on both TRAP and CaM analysis. In the current study we will explain and analyse these approaches in order to give an easier and detailed picture of the interaction to the readers, along with extracting useful insights from the models revealing better interaction properties and biological significances of different parameters and concentration values on the ligand binding process. The current study will not only help readers in getting detailed insight about the cooperative step-by-step binding on TRAP and CaM, but also help in getting an application based comparison of the two modelling approaches for analysing cooperativity.

Keywords: *Cooperativity, ligand binding, TRAP, CaM, computational biology, BP, ODEs*

Model estimation using overhead view images by image recognition

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Abstract: Every year, the performance of the camera improved and the price went down. Furthermore, it had become more compact, making it can possible to easily record highly accurate images. Particularly, as the camera became very small, the degree of freedom of shooting widened significantly. When you want to perform the system simulation, you often record your shooting with a camera to observe the target system. For example, suppose that you want to capture the entire object of simulation with this compact, high-performance camera. In this case, since the camera is small, it is easy to install in a high place. Even if a wide area is photographed from a high place with this camera, since it is a highly accurate image, it is easy to analyze the recorded image.

And image recognition technology has dramatically improved in recent years. At present, image recognition technology is mainstreaming machine learning and deep learning. In the case of using the machine learning technique in image recognition, a teacher image serving as a model for recognizing an image is prepared. At this time, the image is divided into a "positive image" that makes a correct judgment and a "negative image" which makes a wrong judgment. Then let the computer learn these images. With this, it becomes possible to automatically identify whether or not there is an image to be searched for a newly given image. So, in this research, we used a compact camera with a high degree of freedom to install, shoot bird's-eye view images where they can look over the entire system to be simulated and use images that are difficult to analyze by image recognition technology. By applying machine learning to these images, it is necessary to collect data such as the entry time and exit time of the car into the intersection, which is necessary to construct the automobile traffic simulation model.

Generally, modeling is necessary to perform system simulation. Therefore, it is necessary to investigate and analyze the target system. Then, modeling can be performed by formulas or logical expressions. However, investigation and analysis of the system to be simulated are very difficult. For example, conventionally, when conducting traffic simulation, observe and investigate actual car traffic situation. At that time, much labor was required, such as investigation of traffic volume at the worksite and grasp of the driving situation of the car by the car equipped with the measuring device.

However, in this research, it is possible to reduce the trouble of carrying out the traffic simulation by improving the miniaturization and high performance cameras and the image recognition technology. Furthermore, by increasing the photographing time and the number of times, it is possible to record the situation at the site in detail. As a result, the accuracy of the system simulation can be improved.

In this research, we propose a method to automatically construct the simulation model by automatically analyzing the car traffic around the intersection as research subject. It depends on the following procedure.

(1) Use the camera to shoot simulation targets (mainly intersections).
(2) Recognize movement of simulation element by image recognition technology.
(3) Identify the simulation model from the numerical data of the recognized movement.
(4) Execute the simulation.

In the system that we conducted experiments, we gave machine learning by giving thousands to ten thousand positive images and negative images as teacher images. As a result, it becomes possible to automatically extract elements necessary for model construction of automobile traffic simulation, such as the moving locus of automobiles, the number of vehicles passing through, the average staying time within the intersection, and the standard deviation.

Keywords: *Machine learning, traffic simulation, image recognition*

Modular Recurrent Neural Networks for molecular cell signalling networks – Study of system dynamics under changing parameters

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Abstract: Molecular cell signalling networks are networks of molecules within cells of living organisms. They perform all the functions that are required to keep the organism alive. These networks are characterised by complexity, high interconnectivity and cross talk, parallelism and lack of discernible boundaries, which make modelling these networks particularly challenging.

Many approaches have been used to model cell signaling networks and the most predominant has been the Ordinary Differential Equations (ODE) due to their ability to provide accurate continuous dynamics of the molecular system of interest. However, they require the knowledge of the model parameters (kinetic rate of all molecular reactions), a large number of which is currently unknown for many signalling networks, and the solution of a large system of equations. To address some of these limitations, we recently introduced a recurrent neural networks (RNN) approach that transforms an ODE system into a neural network. The advantage of the RNN is that it allows estimation of parameters from data and provide continuous dynamics more quickly. We demonstrated the method through application to an important aspect of the DNA damage response of cells (p53-Mdm2 system in mammalian cell cycle). Recently, we further extended the RNN to a Modular RNN approach to modularise larger molecular cell signalling networks and successfully applied it to a larger signaling network (G1/S checkpoint of mammalian cell cycle, where readiness of a cell for DNA replication is tested). Modular RNN combines a number of trained RNN models representing segments of the whole network into a single RNN system model. We analysed the behaviour of the modular RNN system and it was found comparable to that of the whole system ODE model. In the present study, we further investigated the RNN system behaviour within the multi-dimensional parameter space to further probe into the characteristics of the system behaviour under changing parameters. The results have assisted us to find regions of robust system behaviour.

Keywords: *Molecular cell signaling networks, Recurrent Neural Networks (RNN), ODE systems, robustness*

Efficient NetCDF processing for big datasets

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Abstract: NetCDF (Network Common Data Form) is a data format used commonly to store scientific array-oriented data. A number of software tools exist that can be used to process and view NetCDF data. In some cases though, the existing tools cannot do the processing required and thus, we have to write code for some of the data processing operations. One such case is when we have to merge two NetCDF files. Although the core library for read-write access to NetCDF files is written in C, interfaces to the C library are available in a number of languages including Python, C#, Perl, R and others. Python with the Numpy package is widely used in scientific computing where the Numpy package provides for fast and sophisticated handling of the arrays in Python. NetCDF being an array-oriented data format, Python/Numpy combination is a good candidate for NetCDF processing. But in terms of performance, Python is not as fast as C. So if we are looping over the NetCDF data, as is the case when we merge two files, then as the dimension size of the arrays increases, so does the computing time. And if we have to merge 1000's of such files, then we have to look for opportunities to speed up the process. The processing time can be shortened by extracting the 'looping' code out to a custom C module which can then be called from the Python code. The C 'looping' code can then further be parallelised using OpenMP. This gives us best of both worlds, ease of development in Python and fast execution time in C. Problem setup can also reduce processing time if the files are sorted in such a way that the adjoining files show increasing overlap in the dimensions. And if one has access to a cluster of machines, then exploiting the parallelism at a coarser level by running multiple merge processes simultaneously will expedite the process more so than just parallelizing the loop given that the number of machines available is more than the cores in a single machine.

There also exist other use cases like where you have to provide aggregations and averages for NetCDF data. Existing third party tools like NCO and CDO, which themselves are written in C, cannot handle all the scenarios, like leap years or have other undesirable effects on the NetCDF files, like renaming the dimensions. For these cases as well, custom code has to be written to provide a coherent, portable, extensible and fast solution. C/C++ again is a good choice for writing such code keeping in mind the performance benefits it provides for processing large datasets. Modern C++ specially with STL, lambda functions support and smart pointers makes a compelling case to be used over plain C as it does away with issues like dangling pointers and memory allocation for dynamic arrays. Lambda functions combined with STL result in very expressive and concise code unlike the procedural C code.

Keywords: *netCDF, Python, C, OpenMP, high performance computing*

An Improved Hybrid Algorithm for Multiple Change-point Detection in Array CGH Data

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Abstract: A human genome is highly structured. Usually, the structure forms regions having patterns of a specific property. It is well-known that analysis of biological sequences is often confronted with measurements for the gene expression levels. When these observations are ordered by their location on the genome, the values form clouds with different observed means, supposedly reflecting different mean levels. The statistical analysis of these sequences aims at finding chromosomal regions with "abnormal" (increased or decreased) mean levels. Therefore, identifying genomic regions associated with systematic aberrations provides insights into the initiation and progression of a disease, and improves the diagnosis, prognosis and therapy strategies.

In this paper, we present a further extension of our work, where we propose a two-staged hybrid algorithm to identify structural patterns in genomic sequences. At the first stage of the algorithm, an efficient sequential change-point detection procedure (for example, the Shiryaev-Roberts procedure or the cumulative sum control chart (CUSUM) procedure) is applied. Then the obtained locations of the change-points are used to initialize the Cross-Entropy (CE) algorithm, which is an evolutionary stochastic optimization method that estimates both the number of change-points and their corresponding locations. The first-stage of the algorithm is very sensitive for the thresholds selection, and the identification of optimal thresholds will increase the accuracy of the results and further improve the efficiency of the algorithm. In this study, we propose an improved hybrid algorithm for change-point detection, which uses optimal thresholds for the sequential change-point detection procedure and the CE method to obtain more precised estimates. In order to illustrate the usefulness of the algorithm, we have performed a comparison of the proposed hybrid algorithms for both artificially generated data and real aCGH experimental data. Our results show that the proposed methodologies are effective in detecting multiple change-points in biological sequences.

Keywords: *Change-point detection, aCGH microarray data, CNVs, DNA copy number, combinatorial optimization, Cross-Entropy method*

A local sensitivity analysis of Ca^{2+}-calmodulin binding and its influence over PP1 activity

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Abstract: Synapses are the site of signal transmission between neurons (neurotransmission). Long term synaptic plasticity refers to synaptic efficacy being modulated in response to neurotransmission events. This change can last from minutes to years. In postsynaptic excitatory synapses, increasing synaptic efficacy (known as long term potentiation (LTP)) is a molecular mechanism of memory formation, while decreasing efficacy (long term depression (LTD)) induces memory loss. Postsynaptic LTP and LTD are modulated when Ca^{2+} fluxes into postsynaptic neurons and binds to the signal transducer protein called calmodulin (CaM). Upon binding four Ca^{2+} ions, CaM becomes active (as CaM_4) and integrates the signal. That is, CaM_4 can bind and activate proteins that pertain LTP (kinases), and also protein phosphatases which induce LTD. The ratio of kinase: phosphatase activity determines the direction of synaptic plasticity. Interestingly, activity of the key LTD- inducing protein, "protein phosphatase 1" (PP1) is coordinated by other CaM_4- sensitive proteins. PP1 is inactive when bound to protein inhibitor 1 (i-1). Phosphorylation of i-1 prevents it from dissociating from PP1, thereby blocking its activity. At basal Ca^{2+}, i-1 is phosphorylated due to kinase activity, meaning PP1 activity gets blocked. Synaptic activity can then cause intracellular Ca^{2+} influx to the cell which alters the phosphorylation state of i-1. This is because Ca^{2+} binds CaM, then CaM_4 activates "protein kinase A" (PKA) and "protein phosphatase 2B" (PP2B) which phosphorylate and dephosphorylate i-1 respectively. These proteins thereby modulate PP1 activity by collectively controlling the phosphorylation status of i-1. When Ca^{2+} levels begin to rise, PP2B gets preferential activation due to having a faster CaM_4 binding rates than PKA, resulting in net dephosphorylation of i-1 and subsequent activation of PP1. If CaM_4 levels escalates further, more PKA gets activated which has greater catalytic activity than PP2B. This means increased phosphorylation of i-1 and subsequent suppression of PP1. PP1 activity can therefore be modelled as a function of CaM_4 formation, meaning its activation is affected by CaM binding to Ca^{2+}. CaM has two separate lobes (the N- and C-lobes) which have different mechanisms of binding cooperativity to Ca^{2+}. In the current study, mathematical modelling is used to determine to influence each of these CaM cooperativities/binding rates. Here, a detailed Ca^{2+}-CaM binding model based on Mass Action fed into simplified Hill equations of PKA/PP2B regulation over PP1 activity were used. To determine the influence of each lobe, Ca^{2+} binding/unbinding rates to CaM, a local sensitivity analysis (LSA) was performed over a range of Ca^{2+} concentrations. Since PP1 activity is dependent on CaM_4 formation, PP1 activation was used as an output for the LSA. From the analysis, it is evident that C-lobe has more stable binding than the N-lobe across all Ca^{2+} levels.

Keywords: *Calcium, Calmodulin, signal detection, computational biology, local sensitivity analysis*

Decision Intelligence in Public Health – DIONE

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Abstract: Public health surveillance is the ongoing systematic collection, analysis, interpretation, and dissemination of health data for the planning, implementation, and evaluation of public health action. To achieve effective public health interventions, it is pivotal to analyse and interpret the vast amounts of data collected by surveillance systems to enable good understanding of all factors having an impact on health.

For example, we can consider child protection, which is an important public health issue. Often relatively extensive data exist on families in official statistics, research reports, social services reports, school and medical records, etc. However, these data are dispersed and hard if not impossible to relate and compare. This leads to numerous interventions that are conducted without adequate knowledge of target families that are to benefit from these interventions. Inadequate knowledge also leads to lack of intervention where it is needed, such as undetected cases of child abuse. In many cases the basic data that are needed for intervention decisions exist, but are not available to decision makers due to inadequate communication and lack of data integration, analysis and interpretation.

Chronic condition management is another area where extensive disparate data exist from statistics and various health services and intervention agencies. In this area too there are numerous organizations offering services and a great need to better coordinate these services to achieve better outcomes for patients and also to reduce soaring costs of the healthcare system.

We propose DIONE (Decision Intelligence for Organizations in Networked Environments), a decision support system that uses a complex systems approach to offer a means to integrate and maximally exploit *all* available data to optimize intervention decisions. It will transform dispersed data into relevant information for decision makers. The proposed system has its place on top of existing research and data collection, rather than duplicating any existing research, and will optimize utilization of existing data and research results.

DIONE will enable more focussed health and social service interventions to encourage and help people to manage life stages and events, in view of achieving the best possible health and behaviour outcomes. The system will use data mining and analysis techniques such as predictive analytics, text analytics, data mining, machine learning, and Bayesian statistics to integrate and exploit all available quantitative and qualitative data from heterogeneous data sources, such as statistics, social services, schools, medical services, etc., to identify risk factors and people most at risk. This will enable more focussed health and behaviour interventions. The problem with risk factors for health outcomes is that they are in general hard or impossible to observe directly. The proposed data mining techniques will be calibrated with synthetic data, obtained from agent-based simulation or micro-simulation models of the populations to be studied. For a neural network, for example, this amounts to training it with the synthetic data. The trained neural network can then be applied to real observable data to predict the risk factors of interest for the population. Knowledge of these risk factors will constitute a significant contribution to decision making, for example on allocation of resources to specific areas or people with certain characteristics.

Keywords: *Public health, decision support system, complex systems, multi-agent simulation, Bayesian networks*

Modelling a multi agent system for dairy farms for integrated decision making

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Abstract: Currently, dairy farmers are using various software tools to enable them to make decisions on different aspects of farming such as pasture management, herd management, nutrient management and finance management. Some of the widely used software tools for dairy farming are as follows: Rapid Plate Meter, Overseer, Farm Enviro Walk, and Cash Manager. Each of these tools is used only for particular aspects of dairy farm management. For example, Overseer is used to check the nutrient levels present in the soil. Since these tools operate independently, farmers often find it difficult and time consuming when making integrated decisions relating to farm management. Often, they need to extract data from each of these tools, combine and integrate them and use another general purpose tool to perform analysis before making any decision. The complexity of the decision making is increased with the amount of information and, to make matters worse, information loss may occur during the integration.

The main objective of the proposed research is to model a multi agent system platform to automatically integrate data from the various software tools and perform a variety of analysis to support decision making on the farm. The proposed multi-agent system environment provides an interface in which farmers can enter queries related to farming which requires agents to communicate with the various tools in order to respond to these queries. This is possible as the agents possess special abilities such as autonomy, dynamism and intelligence. Each management activity has its own functions and outputs.

- Pasture management - deals with pasture related works.
- Nutrient management - performs tasks involving nutrient application.
- Herd management - perform tasks related to cattle health, herd cleaning and other herd related activities.
- Financial management - contains tasks like calculating revenue, stock maintenance and other related financial activities.

An individual agent is designed for each management aspect of dairy farming and co-ordination between them is managed by a coordinator agent to form a multi-agent system. Depending on the problem to be solved, different agents are invoked. Agents can communicate with other agents whenever necessary when making decisions in a multi agent system. The model consists of the following agents: interface agent, control agent, pasture management agent, herd management agent, nutrient management agent and finance management agent. The interface agent is the bridge between user and the multi agent system. The interface agent senses the environment and passes the user information to the control agent. The control agent is the controller who decides what action plans need to be executed based on the information received from interface agent. The control agent will trigger the appropriate actions based on the changes in the environment. All other agents deal with tasks related to the appropriate dairy farm management. For instance, the pasture management agent handles queries related to dairy pasture management. The main advantage of this integrated model is that farmers will be able to make farming decisions more efficiently and effectively without the hassle of having to work through the data from various data sources.

Keywords: *Software agents, Multi Agent System (MAS), integrated decision making, dairy farms*

Exploring the limits of automated species identification with convolutional neural networks

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Abstract: A traditional approach to species identification includes using DNA sequencing or key-based identification by an expert taxonomist. However, both these approaches require specialist expertise not available to the general public.

By way of alternative, there have been a considerable recent interest in automated image-based biological species identification. In particular, identifications based on deep convolutional neural networks (CNN) are gaining momentum. The advantage of a deep CNN-based approach is that relevant image features are extracted automatically as opposed to hand-crafted feature extraction. Automated feature extraction makes deep CNNs applicable to a wide variety of morphologically-distinct species, with no additional inputs from taxonomical expertise. However, a large number of images are required to train deep CNNs to a sufficient level of accuracy.

We will explore here two challenging scenarios from an on-going project of automated species identification with deep CNN.

The first scenario is multi-class classification of morphologically-similar (cryptic) species with only a small number of images (<30) across 17 classes are available for training (Fig. 1). In particular, we test different data augmentation methods and explore whether a network pre-trained on a significantly larger dataset of biological organisms enhances classification accuracy and helps to avoid overfitting.

The availability of a dataset with a sufficiently large number of images such as ImageNet allowed a breakthrough in general image classification tasks accuracy. However, the ImageNet dataset contains general categories of images (cars, cats, etc.) and features extracted from them might not be necessarily suitable for the task of biological organism classification considered here. We will therefore explore a transfer learning from a dataset based on iNaturalist (https://www.inaturalist.org/) which contains around 1.2 million images of 19000 species to significantly smaller datasets of plant images.

Secondly, we explore a one-class classification problem which mimics a biosecurity problem of invasive species identification. In this scenario, images of known species are the only ones available for training and the requirement is to detect a novel species. We will evaluate generative adversarial networks and stacked autoencoders to learn internal representation of the commonalities of the images from the target set. Once trained, their reconstruction error will be used to perform a one-class classification by deciding whether a new image belongs to the target group or to an outlier species. We will evaluate this scenario on a case-study of moth images from two countries – Costa Rica and Ecuador.

Figure 1. Leaves of cryptic plant genus Coprosma.

Keywords: *Convolutional neural networks, multi-class classification, anomaly detection, image recognition*

INVITED PAPER

EXTENDED ABSTRACT ONLY

In-field observation of rice grains using deep learning

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Abstract: Pre-harvest monitoring of grain qualities such as moisture content and infested grains is vital in rice production to ensure a high quality yield. Majority of methods employed to determine such grain qualities are labour intensive, time consuming and destructive. Remote sensing offers the basis to develop scalable, efficient and non-destructive methods to monitor some of these factors associated with grain quality. A foremost challenge to developing accurate indices and models that explain such parameters using imagery is separating grains from the complex background. Object based image segmentation has been widely used for similar tasks with some success. Recent advances in deep neural networks offer a unique opportunity to substantially increase the accuracy of image segmentation. In this study, we explored the applicability of deep neural networks to segment rice grains in imagery acquired over paddy fields.

The deep network architecture used in this study includes a VGG16 convolutional neural network as the encoder and an FCN8 architecture as the segmentation decoder. The encoder-decoder architecture is trained end-to-end using raw RGB images and binary annotation images (grain and background being two classes) as inputs. Input data covered several varieties of rice at various grain maturity stages. Early results are promising: we achieved an overall precision of 87% for the validation set after training the model with relatively a small training sample. Figure 1 illustrates an input image and the segmentation output.

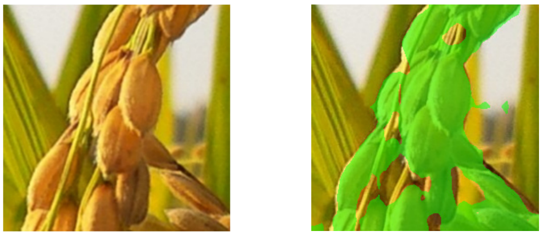

Figure 1. An input image and the corresponding semantic segmentation

We believe this work will lay the foundation required to develop accurate algorithms that link spectral and spatial information to grain qualities of interest such as the moisture content.

Keywords: *Rice, deep learning, semantic segmentation*

Projecting Australian Forest Cover Using Deep Neural Networks

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Abstract: As an indispensable natural resource for all humanity, global forests have been experiencing astonishing loss. Gaining a reliable vision on the spatiotemporal dynamics of forest cover and understanding critical factors that drive the dynamics are of great importance for forest managers to design policies and make investments to reduce forest loss and improve its sustainable management.

We developed a spatially explicit model of Australia's forest cover change using state-of-the-art deep learning methods and high-resolution (~1.1 km grid cells) spatiotemporal forest cover and environmental and socio-economic data. Using high-performance computing clusters we trained a fully connected Long Short-Term Memory (LSTM) network for each grid cell with data observed during the period 1988–2010. For model validation, forest cover estimates for the period 2011–2014 were tested with observed data and compared with the projections of a state-of-the-art spatial longitudinal econometric model. The relative importance of the factors associated with the observed spatiotemporal forest cover dynamics were also investigated.

We found that the proposed model outperformed the benchmark econometric model with respect to prediction accuracy by 10%, increasing from 85% to 95%. The LSTM model also estimated more accurately the location of forest cover change. This work demonstrates the power of deep learning methods in automatically identifying critical factors governing spatiotemporal dynamics of complex systems.

Keywords: *Long Short-Term Memory, deep learning, forest cover change, spatiotemporal data, projections*

Course of Action Analysis Wargaming for Assessing Operational Risk

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Abstract: 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)."

The operational planning doctrine of the U.S. Department of Defense (DoD) that is contained in Joint Publication 5-0 (JP 5-0, 2011) mandates that wargaming is used for course of action (COA) analysis. This type of wargaming is a specific yet unique application of analytic wargaming with an implicit requirement to build operational risk analysis into the wargame.

Specifically, JP 5-0 mandates that the commander develop multiple courses of action, and that each course of action must be assessed against the enemy's most likely and most dangerous COAs, with the implication that the enemy's most dangerous COA presents the greatest operational risk to the (friendly) COA being wargamed.

JP 5-0 specifies that each critical event within a COA should be wargamed using the action-reaction-counteraction method. While it states that this method can be applied to non-combat operations as well, this method clearly has a red versus blue construct to it. No mention is made of more complex operations, such as counterinsurgencies, where the planner must factor the population's reactions into the mix.

Risk Management: U.S. DoD adopted a "balanced scorecard" approach to measuring risk in the early 2000's. This method identified four main areas of risk: Institutional Risk, Force Management Risk, Operational Risk, and Future Challenges Risk. Each area of risk further identified 4-5 goals. Institutional and Force Management Risk are not appropriate for assessment using course of action analysis wargaming as it focuses on planning military operations. This paper will focus on the goals of both operational and future challenges risk that can be considered for assessment within the context of a COA analysis or planning wargame.

The four key goals of operational risk that may be assessed in COA analysis are planning and strategy execution, force readiness, force availability, and critical needs (systems, personnel, sustainment, and infrastructure (buy exception). The four key goals of Future Challenges risk that might be assessed in COA analysis are driving Joint Operations (CONOPS experiments), define and develop transformation capabilities, define future human skills and competencies, and developing more effective organizations.

Some of these goals will be fairly straightforward to assess in COA analysis, but others may be more challenging. We will address this in more detail in our presentation.

Keywords: *Wargaming, Course of Action (COA), planning, risk, Defense*

Using Combat Simulation and Sensitivity Analysis to Support Evaluation of Land Combat Vehicle Configurations

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Abstract: Combat simulations can be used to compare the operational effectiveness of alternative system configurations in a well-defined military context via an experimental layout. However, modelling complex warfighting is challenging as there are many parameters in high-fidelity combat simulations that can affect the outcome, particularly those relating to the environment and the implementation of tactical decision making, and some of these can be quite uncertain. Exploring all possible parameter combinations is often infeasible; therefore a well-designed experiment is required to understand the impact on the performance rankings of alternative system configurations.

This paper describes a case study using the COMBATXXI closed-loop simulation to estimate the performance sensitivity of land combat vehicle configurations within a doctrinal scenario. In total, there were 22 configurations with different combinations of firepower, protection and other sub-system components that were required to be analysed. A multiple comparison procedure involving statistical tests was used to analyse the baseline scenario against a number of performance metrics. In order to isolate the effects of the sub-systems, regression analysis was used.

To improve the robustness of the baseline results, sensitivity analysis using a fractional factorial experimental design was applied to uncertain environmental, tactical and system parameters in the combat simulation. The case study results identified a subset of parameters that contribute to changes in the metrics and, in turn, the performance rankings of the configurations. A combination of environmental and tactical parameters was found to alter the performance rankings of configurations when compared to the baseline results.

The differences in the configurations performances and the effects of the components were subjected to both statistical and practical significance tests. These significances are important to interpreting the insights for military experts. Performing sensitivity analysis and justifying the model assumptions allowed for an increased understanding between the model parameters and the performance rankings of the land combat vehicle configurations. This approach can be used to reduce uncertainty in the analysis and provide additional confidence for military decision makers.

Keywords: *Land combat, simulation, experimental design, sensitivity analysis*

Pragmatic Expert Elicitation for Defence Capability Analysis

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Abstract: Defence Capability Analysis examines the ability of a real or notional force to conduct military tasks. When faced with a paucity of quantitative data or lack of sufficient models, there is a need to rely on Expert Elicitation as a pragmatic form of preliminary assessment. Typically, Subject Matter Experts (SMEs) are brought together to work through a hierarchy of questions about the capability area under investigation.

In these activities, it is essential that individual responses are captured adequately, along with positive and negative feedback collected from the wider group, because analysts need to comprehend the substance of discussions and to identify where and why agreement or otherwise occurred. An overall sense of progress via aggregation of responses is needed by participants to frame the ongoing debate. Facilitators benefit from real-time support to guide discussion purposefully. Stakeholders wishing to explore the data and analysis products mean these must be persisted and remain accessible.

The analysis requirements have led the authors to implement a prototype web application called the Maritime Expert Elicitation Capability Analysis Tool (MEECAT). An overview of the system architecture is given, and the main strengths and weaknesses are discussed. MEECAT features include hierarchical structuring, anonymity of respondents, and a self-organising feedback loop in which participants comment on and promote/demote the responses of others. The tool assists in group facilitation through the visual way responses are aggregated, so that consensus or high variance are easily identified, and overall progress displayed. Participants, facilitators, analysts and interested observers benefit from the immediate remote browsability of all responses.

Some suggestions for enhancement of the tool and analytical technique are offered, based on experience, user comments and the enduring analytical aims driving the tool's inception.

The validity of this approach is ultimately gauged by its utility in systematically capturing warfighting problems and enumerating and articulating possible causes. MEECAT has been adopted successfully for a range of client centric activities from current force warfighting capability assessments to high level capability requirements elicitation and Navy strategic planning.

Keywords: *Capability analysis, experimentation, assessment frameworks, expert elicitation, structured analysis, web applications*

A Summary of the Analysis of Some Data from Two ABI Trials

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Abstract: Data fusion can be defined as the process of integrating data and information, typically from multiple sources and source types. The key to good data fusion is the ability to utilise all available information regardless of where it comes from in order to better understand the domain under surveillance. In addition, a growing area of interest in intelligence is in Activity Based Intelligence (ABI). It requires the combination of different pieces of data, from different sources and different in their semantic nature. That is, some data might be numerical and other data might be qualitative. In order to conduct ABI, consideration must also be given to human activity and relationships as these are not typically covered in low-level intelligence gathering.

The aim of this paper is to give an overview of some of the issues and challenges involved arising from the analysis of data from two ABI trials, Pimento and Jalapeño conducted by DST Group, including integrating different levels of fusion, which involves the human element of relationships. In Pimento, the goal was to develop and formulate some concepts that could be useful in understanding ABI. Taking the GPS as a proxy for tracks, techniques were developed to derive kinematics like speed and interactions like potential meetings, and cases where two or more entities might have travelled together were derived. More complex procedures involved the use of open source software tools to better understand the locations entities have crossed or visited. Interactions were also visualized through social network tools. In Jalapeño, many of these concepts remained with the aim there to combine data from different sources so that not only basic kinematic information was provided ("What") but also some contextual ("Why") data could be gleaned.

Keywords: *Activity-based intelligence, data fusion, social networks*

Obtaining Relational Data and Activity-Based Social Networks from Track Data: An Example from the WASABI Project

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Abstract: Activity Based Intelligence (ABI) is defined by the Office of the Undersecretary of Defense [US] as "a discipline of intelligence where the analysis and subsequent collection is focused on the activity and transactions associated with an entity, a population, or an area of interest." Functions which are typically coordinated include collection prioritisation, fusion and analysis. Similarly, relational data is concerned with the entities' relationships to other entities, through formal and informal institutions, social networks, and other means. Models from this data can be dynamic and might need constant validation to improve accuracy and usefulness. In other cases, relational data such as kinship, familial ties, leadership or friendship might be more long-lasting and stable. By clustering entities' activities with respect to time and space, relationships can be deduced for a given dataset. The purpose of this paper is to determine whether social networks could be derived from identifying entity interactions obtained from tracks. The work described here clearly relates entities and interactions to other entities by inferring a social network from tracks. Building (or adding to) the social network of a group of individuals can help an analyst understand more about each entity within the group, and conversely, more about the group as a whole. This can improve organisational knowledge about existing persons of interest and it can also enhance the tactical intelligence value of live observations by linking in to what is already known. In addition, this may be useful for an analyst in order to validate or complement an existing representation of a social network.

Keywords: *Activity-based intelligence, relational data, entity interactions, social networks*

Enhancing Defence Capability Analysis in New Zealand

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Abstract: Defence planning in New Zealand applies a capability based approach. Over the last two years, New Zealand's Ministry of Defence and Defence Force have been engaged in a change programme, called the Defence Capability Change Action Programme (DCCAP). The Programme aims to enhance the Defence capability management system in New Zealand, with a stated goal being to develop a system that is regarded as an international exemplar for a country of New Zealand's scale.

Operations analysts within NZ's Defence Technology Agency (DTA) and analysts within the Ministry of Defence have co-led a work stream within the DCCAP that will strengthen capability analysis. In particular this stream focuses on the methods by which capability needs are determined, and capability gaps are discovered and characterised.

Central to this effort, and to a range of wider Defence planning needs, is the establishment of baseline planning scenarios. These scenarios will support the translation of high-level policy into practical military situations that can be analysed. To be useful, the scenarios must also be complemented by the development and formalisation of appropriate analytic methodologies.

This presented paper will describe the framework approach that we have developed, and will describe how we plan to apply this in support of overall force structure development, analysis at the capability set level (segmented by military effects), and for assisted option development in individual capability investment initiatives. It will show how our approach is expected to help deliver coherent capability analysis outcomes, and to support investment initiatives by providing a strong foundation for the definition of their capability needs and performance requirements.

We have relied heavily on consideration of the capability planning systems that are employed by our international partners in order to ensure good practise is followed. A major avenue for such consideration has been through the now completed TTCP JSA TP-3 (Joint and Combined Analysis) panel. We have noted that, whilst the systems employed in the other nations are undoubtedly of high quality: their approaches are often based around a substantial analytic effort, which exists within a mature and well-resourced planning system. In theory the same approaches are applicable to New Zealand but in practise we have had to adapt to allow for the realities of local resourcing levels and planning system maturity. Adaptations have included the lack of the use of a detailed pre-defined effects hierarchy, rather allowing this to be defined by practitioners, and a focus on qualitative methods such as wargaming over quantitative methods. It is of note that some of the decisions to be made in New Zealand are less complicated than those in other nations, which further supports such adaptation.

It is of note that a similar approach has been used to a limited extent in New Zealand previously; this was for some particular capability acquisition projects and for Defence Review '09. In all such cases scenarios were developed and analysed in a one-off instance for their application and they were not re-used for other purposes. The innovation in the current work is in its use of standardised methods and data, including the development and application of a central baseline scenario set and through its consideration of scalability and sustainability.

Because our endeavours are very much a "work in progress" we will focus on both the eventual steady-state aim point of the system, as well as detailing the practical steps that we are taking towards its introduction into business as usual practice. We will particularly note that we are trialling aspects of this system on current capability decisions in New Zealand and that we will aim to continuously improve our system based upon feedback from such application.

Keywords: *Scenario analysis, capability based planning, acquisition, portfolio analysis*

Operations Analysis – the Sharp Tip of the S&T Spear

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Abstract: It is a fact that since early engagement in Iraq during 2005 and the following military effort in Afghanistan, all major decisions affecting the employment, structures and processes of the ADF conducting military operations have been scrutinised by some form of operations analysis (OA). The location of our senior HQ in the Middle East Region (MER) - HQJTF633, the duration of ADF member's deployments, our concept of operations and resultant execution, the CIED battle and Force Protection measures have all involved careful analysis outside of conventional military planning processes. Supply and distribution activities have been subjected to simulated optimisation studies, tactical manoeuvre has been structured and conducted after scientific injects into the Joint Military Appreciation Process (JMAP) and data collected through extensive questionnaires and surveys have allowed commanders at all levels to make better informed decisions based on a greater understanding of the very complex human and physical environment they are operating in and to then assess the range of effects they are impacting on that environment.

Until the last decade, when dealing with the frailties and inconsistencies of "humans in the decision loop" the long standing ***art of war*** has put us in good stead. Experience, intuition and military schooling have been the mainstay of commander's decisions and have served well. But as access to *real* knowledge becomes a greater possibility and the tool box of analytical opportunities increases, what our commanders *think* is no longer enough. Commanders need now to *know.* Good decisions need to be based on *evidence* – not *intuition.*

Enter the ***science of war***, not to replace the art, but to supplement it. Trusted data to trusted decisions… *the art of military science*.

During this brief presentation I hope to introduce you to the utility and versatility of Operations Analysis currently deployed with our ADF contingents around the world. To set up some mental images of what form this might take I will look briefly at all 8 functional areas of the military construct and give a snap-shot example of how we are bringing commanders to a closer understanding of their complex environments and in doing so, enhance their ability to make good decisions…

The on-going appetite for supporting S&T deployments and the establishment of Force Design Division and Service Warfare Centres has now led to a situation in which the demand for OA (both military and civilian) has far outstripped the supply. Recognising the problem, the Chief Defence Scientist wrote to CDF suggesting that DST Group assist the Service Chiefs raise, train and sustain the OA skills required for future roles in force design, capability requirements definition and warfare analysis.

The Graduate Program in Operations Analysis and Decision Analytics (OADA) has been developed to respond to this need. A collaboration between the Defence Science & Technology (DST) Group and the Australian Defence Force Academy (ADFA) at the University of New South Wales (UNSW), the Graduate Program in OADA provides a mixed civilian-military environment in which students are introduced to the theory and practical application of OA / DA for both operational and force design problems.

Targeted at military and civilian staff seeking to deploy on operations into an OA role or undertake significant analytical tasks as part of an ADF Headquarters or Warfare Centre posting, the Graduate Program in OADA constitutes a unique twelve month professional development program in applied operations analysis. The combination of both ADF and Defence civilian staff in a range of challenging team-based settings, in particular, provides an opportunity for mutually-beneficial learning and self-awareness spanning the civilian and military divide.

Keywords: *Operations Analysis, art of war, Graduate Program in Operations Analysis and Decision Analytics*

Methods of Distributed Processing for Combat Simulation Data Generation

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Abstract: Combat simulation requires an extensive amount of data to be generated for the execution of the simulations followed by an extensive amount of iterations of the simulation tool to produce quantities of data sufficient for analysis. Typically this generation process exceeds the capabilities of a single desktop computer to perform in a usable time period. Effective data generation requires a method of harnessing the power of multiple computers working towards the same goal.

To meet the data generation requirements of combat simulation execution a series of distributed processing architectures were developed. These have expanded from specific task solutions to generic task distributed processing architectures. Each implementation has to solve the issue of distributing processing tasks that were not initially developed with an existing distributed processing framework in mind (such as Map-Reduce). Each of the architectures has been built on experiences learned from previous implementations. These lessons have resulted in two architectures available for our distributed processing needs.

These architectures take a different approach to the distribution of jobs and the management of work execution and scheduling. The first is a Distributed Queue architecture that is based on a dynamic client pool of processing nodes that pull jobs from a well-known job description queue using transient data transfer. This approach allows cross-platform processing nodes to be added to the distribution network on a needs basis. The other is a Distributed Scheduler architecture uses a resource scheduling algorithm to distribute jobs to resources on a network. This scheduler can manage task dependencies and the transfer of persisted data between processing tasks. Both implementations have to manage for resource nodes not working correctly, processing errors on the remote tasks and monitoring the progress of any assigned tasks.

This paper will examine the history of the distributed processing architectures we have used. It will describe the two resulting architectures and the differences between them. It will then outline our selection criteria and the currently used distribution implementation and future improvements to the process.

Keywords: *Distributed processing, data generation, combat simulation*

Data-Driven Joint Force Design

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Abstract: Force Design has long been considered as experience-based, ad-hoc and campaign-driven activities. As a result of the First Principles Review, there has been significant organisational restructure along with a review of Defence business process, particularly the Capability Life Cycle (CLC). Force Design as a component of the CLC requires considerable development to provide the robust and repeatable processes that are needed to meet Government and Defence expectations. In order to meet these expectations, the newly instituted Force Design Cycle (FDC) and Defence Capability Assessment Program (DCAP) were established for delivering an integrated Joint Force by Design that is capable, potent and agile in achieving the strategic Defence objectives directed by the Government of Australia. There are various aspects critical for the successful execution of FDC and DCAP processes. We argue that having valid and sufficient data is one of the crucial aspects. Even though using large data to support Force Design remains challenging, it is critical to establish a systematic and enduring approach in data capturing and analytic process that contributes to the Force Design. By learning from the experiences of Force Design over the last two decades, especially drawing upon the recent experience with the HEADLIGHT17 (the centre-led Joint table-top seminar conducted to gain a deeper understanding of Gaps and Opportunities in designing Joint Force) this paper aims to report our experience, and highlight key challenges in collating and synthesising the data to provide the evidence base for Force Design decisions. The paper also introduces and discusses a data analysis approach that could improve the Force Design process, decision quality, transparency and ultimately Defence outcomes.

Keywords: *Force design, data architecture, data analysis,information system theory*

Modelling a Battle: Looking Beyond Numbers

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Abstract: The history of warfare shows that victory of the stronger side is not guaranteed even if the force balance is heavily in its favour. The expected outcome of analytical or computational models would be centred somewhere around victory for the stronger side being decisive, however presenting some small but realistic chance for the weaker side victory. This uncertainty reflects our ignorance regarding critically important information.

We suggest that analysing available information on a historical battle outcome may provide enough data to quantify these uncertainties.

We advocate that such analysis must involve three important steps: studying available historical evidence, building an analytical or semi-analytical model of the action, and running simulation games. We would like to emphasise that simulation games are a critically important part of this procedure that are used to weight competing hypotheses against each other and against reality.

We illustrate this thesis with analysis of a historical amphibious operation at Petropavlovsk in 1854. The Anglo-French assault forces outnumbered the defenders in the ratio 2:1 but still suffered a crushing defeat.

From the available historical data we were able to isolate a reason for Allied failure and define it to the point where it became possible to introduce it into a simulated battle. We concluded from an analysis of witness accounts that frequent cases of friendly fire between the Allies could be the main cause of the force defeat. We considered the action as two battles: one between the Allies and Russian troops, and the second between the British and French troops. We tested our hypothesis with an analytical attrition model as well as with a series of war games. The final outcomes of both methods were close to the historical outcome.

The simulation games we played helped us to see several directions of further inquiry: why these friendly fire episodes were so frequent and so devastating, and why the Allied commanders chose the particular plan of attack. We believe that properly designed simulation games are well-suited to investigate these problems, which will be topics for our future research.

Keywords: *War games, simulation, combat models*

Recommendations when using Tactical Simulation to set System Performance Requirements

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Abstract: A good simulation study is an effective tool for helping the client understand the solution space and make decisions. A poorly executed simulation study is ignored or, worse, the cause of bad decisions. Therefore guidelines exist providing general advice on how to build and conduct a simulation study. Their general recommendations have broad applications including the use of tactical simulation to help set system performance requirements. Recently, a tactical simulation was developed and used to help set the sonar and stealth requirements for Australia's Future Submarine. From that a number of recommendations were identified that are applicable to others intending to use tactical simulation to help set system performance requirements.

An overview of the completed case study is presented to contextualise and to illustrate the merits of these recommendations. The completed study used a tactical simulation that was created ahead of time to specifically help the acquisition project set the sonar and stealth requirements. The study was a success as the client is currently utilising this study's results to set and to justify those two system performance requirements.

The first recommendation relates to the first step of all studies, which is formulating the client's problem. Proactive problem formulation and preparation is essential when a tactical simulation approach is required. It takes considerable time to produce such a simulation, and can easily exceed the time available between when the client made the explicit request and when an answer was required. Concentrating the preparation on setting system performance requirements that are both major design drivers and major capability drivers maximises the potential impacts, and increases the certainty of the clients requesting the assistance.

The second phase of the general guidelines is related to simulation design. Simulations similar to other software development gain development efficiency by having a clear and agreed design before starting implementation to avoid unnecessary model development. Four recommendations for the simulation design phase are presented.

1. Set out measures of effectiveness that quantify both success and risk concurrently. Tactical decision has a strong bearing on mission success and risk. Adjusting the tactic can lead to higher success by accepting higher risk, or vice versa. Measuring success and risk concurrently avoids masking this trade-off between success and risk.
2. Ensure study assumptions are creditable by engaging with experts. In our case, having the sonar expert as part of the study team and being present to explain the technical assumptions to the client increases the client's confidence in the result's validity.
3. Scaled animation of the interactions between entities that are easy to modify help tactical behaviour elicitation from expert users, submariners in our case. It minimises miscommunication by providing a shared understanding of the situation, and helps the experts explain the information used to decide the next course of action. Quick modification of the animation which incorporates the new action allows the analyst and the experts to see the outcomes without interrupting the interview progress.
4. The elicited tactical decision logic can form the basis of deciding what and how aspects of the real world should be modelled by the simulation. The premise being that the mission outcomes strongly depend on the selected actions. A strong dependency between a real world factor and the action selection logic means that factor strongly influences the result, and must be modelled accurately.

The final, crucial step is making sure the client understands and trusts the results. Client trust was improved by demonstrating a sound understanding of the operation domain when describing the tactical scenarios, tactical assumptions and tactical behaviours modelled. Presenting the result in a relative manner overcame the limitations that the simulation result is true for a simplified simulated world, and not a real world prediction. The relative format still allowed the client to still see how effectiveness is influenced by external changes, and quantitatively demonstrated how improving system performance can offset any reduced success or increased risk.

Keywords: *Requirement analysis, tactical simulation, elicitation, simulation validity*

A Location-based Interface Approach to Developing a Systematic Event Analysis Tool

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Abstract: Forensic investigations of events involving significant damage or a loss of life require collecting and collating a vast amount of systematic data about the event to determine what happened. This can include maps of the area, plan drawings of any platforms involved, imagery, videos and witness accounts, repair histories along with a significant amount of other data that might be available. Advances in computing and multimedia technology provide new approaches for investigators to collate this data. They can also allow for other stakeholders to better interact with and contextualize the data to improve their understanding of what happened during the event.

This paper outlines techniques used to develop a location-based interface prototype for an interactive tool that allows users to intuitively explore and analyse data about an event. This prototype can easily add data in various forms, including the timeline of what occurred before, during and after the actual event, with the data positioned manually in the current prototype. The tool collates the data onto a map, plan drawing or (in future versions) a 3D model based upon the location where the data was captured. This allows users to move through the data spatially, keeping an intuitive sense of their relevant locations and eliminating the need to jump to different folders or data categories as they explore the data. With accurate recording of the locations where the data was captured, automated processes could collate the data, allowing a broader range of users to more quickly understand how the data fits together to indicate what happened during the event. Once the data analysis is finished, the tool can also visually demonstrate the findings of the investigation. The speed of data collation and investigation can make it useful for examining the cause of even minor events, which have less data collection than major incidents.

This paper provides an example of the prototype tool using data obtained from experiments on the ex-HMAS Derwent, which was used to investigate blast damage on a naval vessel. The paper shows how images, video, audio and written notes can be connected to the plan drawings of the ship based upon the location they were captured. It also demonstrates how overlays can be used to add additional information. Additional imagery demonstrates how this data can also be attached to 3D models of the platform where they are available. Such models could be used as part of Augmented or Virtual Reality interfaces. This would allow users to see data overlaid on top of a 3D model or scan of the platform or to create scenes where a user could potentially walk or fly through a virtual reconstruction of the event.

A similar type of tool to that used for event analysis could be used to collate information for a range of other uses. For example, this could be used to store the construction and maintenance history of individual platforms, whether in the land, sea or air domains. This tool could include readily accessible information of minor differences, such as electrical wiring or when and where components were last tested or painted. This information could be used to better inform and tailor maintenance and repair regimes, especially when issues arise while a ship is at sea, as the information could be deployed on-board as a readily accessible application. Appropriate authentication techniques must be included to ensure the security of the tool and the data, and that the user has access to the appropriate data. As such tools can run on low power devices connected to the data storage for the investigation, they could constantly update and provide the latest information, even during a maintenance cycle or during field operations.

Keywords: *Event analysis, data collection, multimedia interface, location-based interface*

Establishing Confidence in Combat Simulation Input Data

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Abstract: Combat simulation software routinely requires extensive input data files describing the performance of military systems. Typically these input files are built as lookup tables and can require hundreds of thousands of individual data points describing information such as weapon accuracy and lethality, sensor performance and mobility.

To combat the increasing complexity created by the manual generation of these data, input data generation processes are becoming increasingly automated, both in terms of technical performance models and algorithms to construct simulation databases. This has greatly reduced the time and manpower requirements of generating useful input data, such that databases that once took weeks to construct can be built in days or even hours.

However, such automation has introduced the danger of erroneous data or processes propagating through such an automated system. Depending on the nature of an error, it could potentially affect large portions of the output data. Worse still, automating processes tends to hide intermediate steps where an error may be caught early, with error in the final result being obfuscated.

To combat this we have developed a comprehensive verification and validation approach to our data generation practices. This approach uses a variety of methods to inspect various elements of the system, including source input data, intermediate data, physics-based algorithms and output data.

This paper will briefly present our automated data generation processes, which have also been described in a number of previous publications. It will then highlight, through examples, some of the dangers we have observed through the use of our automated system. Finally it will describe our verification and validation approach to ensure data quality.

Keywords: *Validation, verification, simulation, data*

Scenario Design for Verification and Validation, Hardware Testing and Operations Research

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Abstract: Modern military aircraft are complex with increasingly integrated sensing functionality. As mission system capability is increasingly implemented in software rather than hardware — particularly with the development of electronically steered antennas and increasing processing power for software implementations of former hardware components — the scope for specific data requirements and software loads that are tailored for missions is increasing. As the complexity of these loads increases, the operational effectiveness of each aircraft is increasingly dependent on each mission data load. Put simply: an aircraft with ten million lines of software, much of which is configurable by input data, has a significant part of its capability defined by that data.

How do we ensure that the aircraft mission systems perform as required in a complex operational environment? Further, how do we provide Operations Research (OR) to support experimental testing results? A task often given to OR personnel is to construct scenarios that provide context for all levels of experimental work, both hardware lab testing, and to support any OR experimentation that builds on these results. Any scenarios developed in this process need to provide both operational realism and sufficient levels of complexity to suit a testing program. This is problematic in that large scenarios that are generated by the selection of "important" features are by their very nature biased towards particular solutions. How do we avoid bias in the scenario generation?

A specific problem area is defined, namely testing the application of Intelligence Mission Data (IMD) to aircraft operations. How do you decide, with (1) a particular set of mission system hardware in a lab and a (2) reprogrammed mission data file set (MDFS) that provides the IMD in an operational form, that a fighter aircraft will be effective and survivable in a specific operational context. In testing IMD there is a need to consider all levels of the operational context as defined by a scenario:

- the strategic context gives purpose and the broader physical and electromagnetic environment via the specification of an area of operation,
- the operational context gives the goals or missions to be pursued, and
- the tactical flow can affect the specific mission performance as this describes the specific interplay of actors.

A scenario development process is defined. We use the term scenario to refer to the entire context description, including the strategic, operational and tactical levels. Strategic statements give the broader context of actors and reasoning as to the conflict, the operational level relates to the specific mission, and the tactical level refers to potential decision making within the mission. At any stage, there may be limitations on the scenario development: for example verification and validation (V&V) testing may prioritise particular threats, a time frame, the location of the operation, and so on.

Design of Experiments (DOE) approaches are employed to within experimental testing and supporting OR to ensure that the IMD process meet operational needs, dependent on the scenario context. We believe that a similar DOE approach should be employed to V&V the scenarios. This can provide a rigorously verifiable method for determining the extent of scenario coverage but, furthermore, techniques from the DOE literature might be applied to the task of generating scenarios in an effort to trade-off and estimate V&V effort against scenario requirement coverage. This could be combined in future with the experimental design process, but more attractively the development of an independent scenario design method that provides some level of orthogonality within the scenario construction could greatly expand the applicability of all levels of testing, and provide a more comprehensive coverage of the potential scenario space.

Keywords: *Scenario design, design of experiments*

A critical assessment of a partially-successful analytical campaign

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Abstract: In 2016, the author led a small team undertaking an investigation into capability acquisition and concept development for Army Headquarters. The ensuing analytical campaign spanned a dozen workshops and a week-long Limited Objective Experiment, with significant modelling work done over the course of twelve months. Whilst the final outcomes enabled the sponsor to meet a number of critical decision points, the overall objectives were only partially met and a large amount of work was ultimately fruitless. After a critical self-review of the analysis campaign, a set of distinct points of failure have been identified and, from these, valuable lessons have been extracted to take forth into future analytical campaigns.

Keywords: *Analytical campaigns, experimentation, lessons learned*

Evaluation of Joint Fires Management Process in Long Range Fires

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Abstract: Future battlespace is likely to be congested with all types of ordnance and platforms (friendly, neutral and enemy) to perform missions of simultaneous fires. Depending on the scale and complexity of the operation, both airspace deconfliction and ground clearance may require coordination of multiple air and land entities. Australian Defence Force's (ADF's) potential acquisition of a land-based long range fires (LRF) capability will present numerous battlespace challenges across an enlarged and congested battlespace. While capable of operating at long ranges (engaging targets up to 300km away) and high altitudes (far in excess of routinely established levels for coordination altitude), the targeting sequence for striking time sensitive targets using LRF is complicated by coordination and deconfliction requirements with friendly forces.

While acknowledging the deconfliction challenges, an opportunity existed to examine ADF's current joint warfighting paradigm and assess two operating concepts for airspace management to facilitate long range strike. Targeting efficiency is contingent on streamlined interactions between key entities to facilitate effective information exchanges. For each concept, three target locations within an illustrative scenario were considered for coordination and deconfliction of fires. The sequence of activities, decisions and associated communication events were recorded. Social network analysis was applied to investigate workflows and evaluate key entities and patterns of communication for battlespace management.

Compared to Condition 1 (airspace managed by the Air and Space Operations Centre), Condition 2 (airspace managed by the Joint Task Force) was found to improve the interaction by reducing numbers of steps and reliance on fewer key entities. For all three cases of target location, the quality of activity execution was improved in Condition 2 by minimising the overlap in responsibilities, thus alleviating the coordination requirements. Decision delegation in Condition 2 suggested improved responsiveness in airspace management, but also revealed the need to rebalance the skills of airspace management.

Despite initial results indicating improved workflows in Condition 2, this assessment is by no means conclusive but provides the groundwork for further validation and refinement of airspace control. Future analysis will allow evaluation of new and future operational concepts, and test various what-if scenarios to improve operational effectiveness and efficiency of airspace usage in a congested and contested airspace.

Keywords: *Joint fires, long range fires, airspace management, battlespace deconfliction, social network analysis*

Enhancing Defence Resilience to Critical Infrastructure Failures

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Abstract: There are many critical assets and enablers Defence relies on to meet its objectives, yet many are not owned by Defence. Most notable are key elements of national infrastructure and utilities such as electricity supply, fuel supply, communications networks, and road and rail systems etc., to name a few. These are most commonly owned and operated by national and international commercial entities, and they provide services to a large customer base in which Defence is only one of a number of potentially competing interests. As these systems often lie outside Defence's direct control, Defence is unable to ensure appropriate maintenance, or investment to build adequate resilience. It is therefore vital for Defence to understand the implications of critical infrastructure failure, in particular: the types of events that might lead to failure; the frequency of possible failures; the durations of failure; and the impact of failures on Defence objectives. Armed with such information, Defence will be in a stronger position to identify where it must enhance its own resilience in relation to the potential for external system disruption or breakdown.

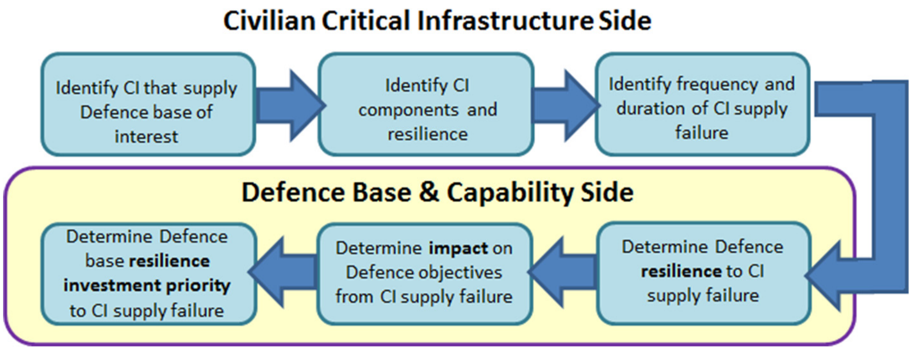

Figure 1. Translation of civilian owned critical infrastructure (CI) supply failures to Defence base resilience priorities.

This paper presents a method based on risk science to determine the risks of external supply failure to specific Defence bases and installations, and how Defence can determine its resilience status to such failures, in order to prioritise its investment in resilience enhancement options. To describe this process we use the case of a single hypothetical Defence base. The analytical method we describe requires an understanding of the criticality and resilience of Defence systems, the chance that civilian supply will fail to those systems, and the impacts to Defence if that occurs. The framework (Figure 1) is composed of several steps and sequentially considers two sides of the 'fence'. The first is the civilian side that generates and supplies the essential inputs. Determining the quality, redundancy and resilience of these systems can be useful to inform probability of supply failures (and durations) to Defence. Statistics on frequency, areal coverage and durations of failures must be kept by utility companies and this (big) data can be used by Defence to determine the chance and duration of failures at each Defence installation. Moving to the 'inside of the fence', Defence relies on inputs coming across the base boundary in order for them to contribute their capability to fulfil a variety of missions to achieve broader Defence objectives. This side of the analytical process considers: the individual Defence capability tolerance to outages and redundancy of these systems in order to inform Defence resilience to outages; identifying the criticality of Defence capability to achieve its missions, and therefore the impact from supply outages; and indications of investment priorities to increase Defence resilience to critical infrastructure failures. In this paper we focus on Defence, however the framework can also be applied to other sectors such as the health system or by individual corporations.

Keywords: *Risk, resilience, critical infrastructure, supply failure, investment prioritisation*

Development of a Ship Performance Modelling and Simulation Framework to Support Requirements Setting

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Abstract: With the Australian Defence Organisation's (ADO) adoption of the 'smart buyer' model for acquisitions, an opportunity exists to employ Modelling and Simulation (M&S) frameworks to assist the development of requirements during the Risk Reduction and Requirements Setting phase of acquisition. During this phase of knowledge building, M&S can facilitate capability design activities to assist the development of requirements. The design activities support an improved understanding and more rigorous definition of the requirements released to industry in order to constrain the technical solutions to those that accurately reflect the capability need. In an Off-the-Shelf acquisition this ensures only suitable designs from industry are received for consideration/selection of the preferred solution. To enable this process, capability design activities are conducted within an M&S environment to establish links between capability design parameters and whole of system performance. The potential benefit of M&S to support Royal Australian Navy (RAN) platform acquisitions was tested through the development of a ship performance M&S framework.

A Model Based Systems Engineering (MBSE) methodology for Concept and Requirements Exploration (C&RE) has previously been proposed by DST Group to facilitate the tracing of capability design parameters to mission performance through employment of parametric and surrogate modelling techniques. The current work builds upon the MBSE C&RE methodology by integrating naval architecture design modelling and performance prediction tools into a model-based simulation environment provided by the commercial ModelCenter® software package. Within ModelCenter®, individual models were created to perform design and performance prediction tasks. The ship performance M&S framework is the result of these models being appropriately integrated together enabling the tracking of requirements to ship performance as well as exploration of the design space. A benefit of this approach is that the M&S framework can be easily tailored to reflect the needs of each assessed capability by adapting and adding or removing models.

The M&S framework was tested by application for acquiring a new Hydrographic Survey (HS) capability. To reflect the needs of this capability the M&S framework comprised, at its foundation, the Ship Generation Model (SGM). This design based model employs 3D modelling software to rapidly generate a 3D hull form based on a number of principle and unique ship design parameters. Additionally, the M&S framework also comprised a number of performance prediction models including: resistance, weight, stability, propulsion and seakeeping. When integrated together, these models determine the required performance attributes of each generated hull form facilitating the linkage between ship design parameters and performance measures. Once established, the M&S framework was exploited using Design of Experiments methods to scan the design space and determine which vessel types and hull form characteristics exhibit optimal HS capability.

Performance measures used to evaluate the HS capability included the vessels seakeeping operability in transit and launch and recovery scenarios, range and endurance in various sea states. The results suggest that a hydrographic survey vessel exhibits optimal HS capability and outperforms other vessel types, including Offshore Patrol Vessels and frigates, by a considerable margin. This indicates that the other vessel types should not influence setting of the requirements. Additionally, the results indicate that vessels of increased length with low length to beam ratios exhibit optimal performance in the aforementioned measures. The results indicate the M&S framework was beneficial as a means of providing capability stakeholders with a possible design space that can be utilised to inform requirements development during the Risk Reduction and Requirements Setting phase of acquisition. Exploiting this design space, acquisition stakeholders could develop a specification containing appropriate requirements and constraints on design variables, ensuring the most suitable designs are received in response to a Request-for-Tender.

Keywords: *Modelling and simulation, requirements setting, hydrographic survey capability*

Integrating Spaceborne Sensing with Airborne Maritime Surveillance Patrols

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Abstract: Airborne surveillance patrols are frequently employed to maintain situational awareness of large maritime border regions. Manned airborne platforms are typically used due to their inherent flexibility to detect vessels and also conduct classification and identification by flying in for closer inspection. For large and remote border regions, airborne surveillance patrols can be expensive in terms of personnel and platform resourcing. The unpredictability of vessel densities can at times impact on the robustness of the surveillance coverage. When a patrol encounters too many vessels to inspect, the limited flying hours mean that parts of its original flight plan may be curtailed, potentially leaving gaps in surveillance coverage. Extra flights can be added but this adds significantly to the resourcing costs.

Satellites, in contrast, are able to cover large remote areas and distances at short timescales, with predictable schedules. Imaging satellite constellations with payloads such as electro-optical (EO) sensors and synthetic aperture radars (SAR) can provide complimentary capabilities to that of airborne patrols. Traditionally, the use of imaging satellites in maritime border surveillance has been decoupled from airborne surveillance patrols due to their long tasking-delivery timescales. With the increasing availability of high-performance commercial EO & SAR satellites and the availability of satellite direct access capabilities offering improved tasking-delivery latencies, there are opportunities to integrate and leverage spaceborne sensing with airborne platforms in maritime border security applications.

This paper identifies and explores the potential roles of a selected set of imaging satellites to support airborne surveillance patrols for large maritime border regions.

Four potential roles are proposed:

- Surveying an area to determine likely vessel density and vessel types to aid in airborne patrol mission planning
- Surveying sections of the maritime region to free up airborne patrols
- Surveying areas missed by airborne patrols
- Supporting geolocation awareness of specific vessels in between airborne patrols

We present simulation results examining current commercial direct-access available EO & SAR satellites and provide early insights into their feasibility to support the proposed roles.

Keywords: *Maritime surveillance, integrated surveillance, satellites, airborne patrols*

An Integrated Systems Modelling Case Study: What are the Operational Benefits of Covertly Refuelling Submarines at Sea?

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Abstract: Integrated performance modelling techniques are applied to generate insights relating to the variation of platform performance with specific concept of operations, design configurations, and mission parameters. Integrated performance modelling of modern conventional submarines is being conducted at Australia's Defence Science and Technology (DST) Group to support evidence-based decision-making on the procurement of Australia's Future Submarine.

DST has developed the Integrated Performance System Model (IPSM) to enable trade-off studies to be conducted between platform performance, platform configurations and concepts of operations. The IPSM integrates system models of power and energy; propulsion and drag; and atmosphere and habitability; and numerically computes the overall performance with respect to capability, performance requirements and constraints. Significant investment has also been made in the development of the IPSM's infrastructure, which includes unit/system level testing, continuous integration testing, data management in accordance with security requirements, post processing of simulation outputs and automatic report generation.

The focus of this study was to demonstrate the adaptability of the IPSM to examine novel technology concepts that exhibit low technology readiness levels. The advantage of using the IPSM at the conceptual phase is that it can be re-configured quickly to assess operational impacts resulting from different technologies, concepts of operations; and scenarios. Therefore the IPSM has the potential to provide valuable inputs to business cases that consider whether or not to develop a particular technology further. This makes the IPSM a powerful tool that could be used to support trade-off studies for future technology concepts considered as part of the FSP.

In this case study the IPSM was applied to assess the impacts of a novel technology concept comprising of refuelling a conventional diesel-electric submarine at sea. The intent of replenishment at sea (RAS) of diesel is to increase the level of capability achievable by existing submarines without significantly compromising the stealthy nature of their operations.

The data and outputs generated by simulations conducted by the IPSM provided valuable insights and inputs to measure the benefits for the concept of refuelling a conventional diesel-electric submarine at sea. As such it can be concluded that the IPSM was found to be a highly suitable tool for assessing the potential measures of success for novel technology concepts. With regard to the specific findings of the case study it was found that a maximum average transit speed exists such that the conventional submarine is likely to become operationally constrained by the initial quantity of fuel. In these situations the RAS of diesel can provide some relief, however, the quantity of additional diesel fuel required via RAS was very large, albeit dependent on the transit range. Further investigation is required across a range of mission types in order to fully determine the potential benefits of refuelling to submarine performance, which will be discussed in the presentation, in addition to other finding and lessons learnt from this case study.

Keywords: *Integrated performance modelling, refueling, future submarines, technology assessment*

Automating the Design of Battle Rhythms

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Abstract: A Battle Rhythm is the organisational process by which a Headquarters implements the decision cycle and thus generates shared situation awareness and war fighting decisions in a timely manner. In other words, a Battle Rhythm must sequence the execution of activities within a headquarters to regulate the flow and sharing of information including the generation of analysis in support of multiple decision cycles. Battle Rhythms must be synchronised across multiple Headquarters.

The ADF have a requirement to create new Battle Rhythms from time to time in response to new operational contexts and this is currently done by hand by staff with Battle Rhythm experience. Generating such a schedule of activities is both painstaking and error prone. Without an analytical framework, it is easy for the best officer to make a choice that will lead to slower response times than necessary or critical decision deadlines being missed. Such issues may not become apparent until the Battle Rhythm has been operational for some time.

Furthermore, the final Battle Rhythm does not communicate many of the requirements it seeks to meet. This makes it difficult to later add further requirements or tasks to the Rhythm and be sure that its current features will not fail. This is particularly true if such a Rhythm has to be modified by someone other than its original author.

This paper describes work in progress on a system whereby the user does not produce a particular Battle Rhythm but instead specifies the requirements they have of it. By making outputs such as decisions, documents and intermediate assessments along with deadlines and synchronisation points explicit, the system can not only automate the generation of Battle Rhythms but also provide assurances that the operational environment will meet its deadlines provided each intermediate activity described by the Battle Rhythm is completed on time.

The system will also be able to detect some faults and omissions in Battle Rhythm specifications such as overuse of resources, missing work products and general schedule infeasibility and can give meaningful diagnostic messages in these cases. The fact that requirements are fully documented allows the original specification to be easily augmented with extra requirements, should they arise during operations, and to produce a new Battle Rhythm that meets both the new and existing requirements.

This brief paper gives an overview of a Battle Rhythm specification language, a work in progress, and some of its potential. Realising the full potential of such a system will require experiments with generating real Battle Rhythms. Since examination of extant Battle Rhythms does not currently reveal all of the actual requirements behind them, the work will need to be progressed with experienced ADF officers. Only once the adequecy of the specification language is verified, along with the utility of the system, can we sensibly tackle questions of the best user interface.

Keywords: *Battle Rhythm, scheduling, constraint optimization, workflow, graph based analysis*

Challenges for Integration of Cyber into Portfolio-Level Defence Force Design

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Abstract: Cyber is now a ubiquitous enabler of modern military capability and provides both opportunities to disrupt an adversary and the threat of vulnerability in our own cyber-enabled force. The 2016 Defence White Paper and numerous other documents discuss the importance of strengthening the Defence cyber workforce and systems to deter and defend against the threat of cyber attack. However, cyber capability is difficult to characterise and to adequately address in portfolio-level defence force design.

The Australian Department of Defence Force Design Division was established in April 2016 to deliver a centralised, enduring process for translating Government strategic policy into a coherent force structure. There is a strong focus on providing a contestable evidence base to underpin Defence investment decisions, which is driving a deeper reliance on formal analysis methodologies to examine the whole-of-force capability rather than reliance on justification of individual projects in isolation. These methodologies include expert elicitation and heuristic decision science; modelling, simulation, experimentation and wargaming; options analysis (e.g. multi-criteria decision analysis); and balance-of-investment and portfolio analyses. These tools are ultimately used to explore the trade-offs between whole-of-force capabilities and investment.

There are challenges with integrating cyber into this force design process, where investment in new capability needs to be prioritised against conventional air, land and sea capabilities. Firstly, valuing cyber capability faces the same difficulty as other enabling functions in that it is difficult to map their contributions to the defence missions set out in strategic guidance because cyber cuts across all the missions. However, there are also problems that are unique to cyber. Characterising the effectiveness of the cyber capability itself is challenging and any such descriptions are perishable because the context is constantly changing. This makes it difficult to objectively assign weight or appropriately value the capability against conventional effects. The perishable nature of specific cyber tools, both defensive and offensive, means that detailed modelling of specific cyber interactions is unlikely to be a cost effective way of assessing capability.

Experimentation is a key tool in evaluating the ability of a proposed future force and defence experimentation relies heavily on expert judgement. In fact, defence experimentation can be viewed as a formal methodology for integrating individual intuitive judgements regarding relative defence capabilities into capability development decisions. When it comes to strategic level experimentation with cyber, it is rare that senior military participants have both a strategic perspective and also have experience and intuition that is relevant to contemporary cyber issues. Attempts to include cyber at the strategic level have either tended to a doom and gloom perspective in which all capability will be completely compromised, or to be optimistic that the impact of adversary actions in cyberspace is being exaggerated.

Finally, force design is necessarily a process of incremental changes to the existing force, creating significant bias towards the status quo and against wholesale changes to the operating concept for the force. This heuristic bias acts in favour of maintaining or expanding existing capabilities rather than investing in new capabilities such as cyber.

New analytical approaches are required and this paper will suggest avenues for development of tools to assess the investment in cyber capability alongside conventional military forces.

Keywords: *Force design, cyber, capability development, strategic planning*

Determining amphibious command and control staffing requirements using business process modelling and simulation

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Abstract: The Australian Defence Organisation has recently significantly increased its amphibious capability. To support this, the associated Command and Control (C2) Headquarters (HQ), led by Commander Australian Amphibious Task Group (COMAUSATG), has grown by up to 600% in ten years. However, COMAUSATG has not had strong evidence that the size and composition of this staff were correct, and consequently requested DST conduct a study.

A business process simulation model had previously been built to provide initial staff numbers prior to the introduction of the new capability. The current study updated the model to reflect current amphibious command and control processes now that there was experience in using the amphibious capability. Data was collected from an exercise as well as via workshops. It was found that good quality data could be obtained from well facilitated workshops, but the data obtained when staff were asked to self-record their activities during an exercise was of lesser quality. To validate the data collected in workshops, direct observations of tasks performed during an exercise or operation is required. Additional work is also required to ensure the tasks described are a complete set of tasks that should be performed.

There were also limitations on which Business Process Model (BPM) techniques can be used to explore C2 organisations. BPM is suitable for use with C2 when determining the staff composition and exploring the work load of individual roles. However, the technique of adjusting processes to explore the efficiency improvements is very difficult because the processes are not well defined to begin with and the impacts of any changes are difficult to assess. As tasks are complex, they are rarely performed the same way and thus it is difficult to obtain task durations with any statistical robustness. Consequently, BPM is not particularly well suited to optimising the processes for a C2 organisation.

One component of the study was to understand the effect of different types of missions upon the HQ construct. Use-cases covering the spectrum of mission types were built to represent the type and rates of HQ tasks. From these use-cases, suitable probability variables used within the model were determined by subject matter experts. The content and detail contained within the use-cases shapes the subject matter expert's estimates of the variables; consequently, a use-case framework that leads to more consistency across experts is desired.

Presenting the final results in a form suitable for the end-user is a critical component of a well-designed study. For this study an interactive colour-coded organisational structure diagram allowed COMAUSATG to explore the results and provide their interpretation. Allowing COMAUSATG to define and change the thresholds of 'low' and 'high' tasking meant that different operational tempos and needs could be explored and its effects seen across their organisation.

Keywords: *Workforce planning, business process modelling, defence, command and control, headquarters*

Using System Dynamics to study Army Reserve deployment sustainability

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Abstract: The reserve forces have been playing increasingly important roles in the Defence capability of developed countries, due to the skill shortages in regular forces and defence budget pressures. The Australian Defence Force (ADF) in particular, is increasing the employment of its Reservists to deliver defence capability, including the deployed capability on operations within Australia and overseas. The Australian Army Reserve (ARes) is an important component of Force Generation in Plan BEERSHEBA, which is a government endorsed force-structure modernisation program.

This work presents a case study on the "raise, train and sustain" aspects of a deployed ARes unit using System Dynamics (SD) simulation. More specifically, the SD model constructed examines the sustainability of the deployment of a volunteer-based Army Reserve unit in a low-intensity regional stabilisation operation. The soldiers' behavioural change over time, in terms of willingness to deploy (represented as the volunteer percentage), is modelled and its impact on the volunteer availability for a continuous deployment is simulated.

With the subject matter experts (SMEs) input about soldiers' willingness to deploy based on their deployment experience, the SD model provides insights on the following questions:

- How many volunteers at the rank of Private (PTE) can a given pool of soldiers supply to support a deployed ARes unit?
- What is the required size of the pool of PTE soldiers to support a battalion-sized ARes unit in deployment?

The SD supply model showed that a pool with 1970 PTE soldiers can provide a deployed unit with 240 volunteers in the long term, but there are only 158 PTE volunteers for the sixth rotation. A pool with 660 PTEs can supply a deployed force with 80 volunteers in the long term, but there are only 53 PTEs volunteering at the sixth rotation. A sensitivity analyses was also conducted by considering the worst and the best cases of the volunteer percentages. The SD demand model showed that to support a battalion-sized ARes unit, which demands 240 PTE Volunteers, a pool of 2230 PTEs is required.

In conclusion, this study demonstrates the applicability of SD simulation in sustainability analyses of ARes deployment. The model can be useful for Army Commanders in planning deployment of a volunteer-based ARes unit, and facilitating policy exploration to boost soldiers' willingness to deploy.

Keywords: *System dynamics, sustainability, Army Reserve deployment*

Quantitative Cyber Risk Model and Optimal Mitigation

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Abstract: Cyber security risks present themselves in many forms, for instance business interruption, theft of Intellectual Property, financial fraud and database breaches. Recent surveys of Australian business, in particular those from the Australian Stock Exchange and the Australian Prudential Regulation Authority, confirm these concerns. What is needed is a quantitative method to measure this cyber risk so as to suggest mitigations.

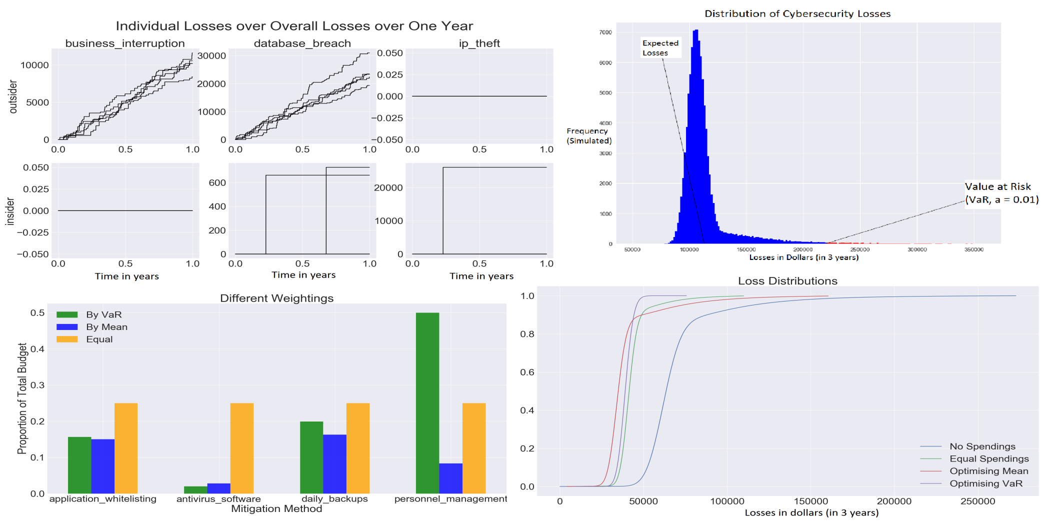
A parallel is the concept of Value at Risk (VaR), which gives an estimate of the losses that could occur in a financial portfolio, over a certain time horizon to a certain level of risk. The parallel is not exact however, as VaR applies to market observable processes, where cyber risk reveals itself only as damages. We formulate a model for losses from cyber risks as:

$$L(t) = \sum_{i=1}^{N(t)} X_i,$$

where $N(t)$ is the number of incidents and X_i are independent damages.

We extend this model firstly to consider several types of attacker aiming at several different risks for the organisation and secondly by modelling the impact of spending on defence, subject to a budget. The former is done simply by assuming independence at each juncture and the latter by assuming the probability of successful attack and the damage caused are influenced by a simple model of defence spending adapted from the Australian Signal Directorate's "Strategies to Mitigate Cyber Security Incidents".

A simple model is built with two types of attackers as *Outsider* (with frequent attacks of small damage) and *Insider* (with rare attacks of great damage) and three types of risks as *Business Interruption*, *Database Breach* and *Intellectual Property Theft*. Output from the model is given below. The panel in the top left shows damages from the two threats against the three risks and the top right panel shows a simulation of all damages after three years. The bottom two panels relate to optimal choice of mitigation strategies. The bottom left panel shows the choices according to optimising for the mean and VaR compared to simply choosing equally. The outcome distributions of damage are shown in the bottom right panel: no spending on mitigations gives the worst outcome; spending equally improves on this; optimising for the mean gives the best result on average but doesn't remove the tail risk; and optimising for the VaR removes the tail risk.



Keywords: *Cybersecurity risk, Value at risk (VaR), operational risk, extreme tail event, risk mitigation*

C2 and the Kuramoto Model: An Epistemological Retrospective

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Abstract: The Kuramoto Model is a simple model of synchronisation phenomena within networks of coupled oscillators. The model has been applied to military Command and Control (C2), as illustrated in Figure 1. The mapping between model and reality is summarised in Table 1.

In this paper we briefly summarise the Kuramoto Model, and report a simple agent-based combat simulation experiment justifying the applicability of the model to C2. In the experiment, a networked blue force consisting of 8 infantry fighting vehicles (supported by artillery) attempts to move through a region containing a red force of 40 units. There is a statistically significant monotonic nonlinear relationship between angle correlations in the Kuramoto Model and plan-agreement correlations in the combat simulation.

We conclude the paper with an epistemological reflection on the use of the Kuramoto Model, and the lessons that can be drawn from it for computer simulation of human processes, especially in the military domain.

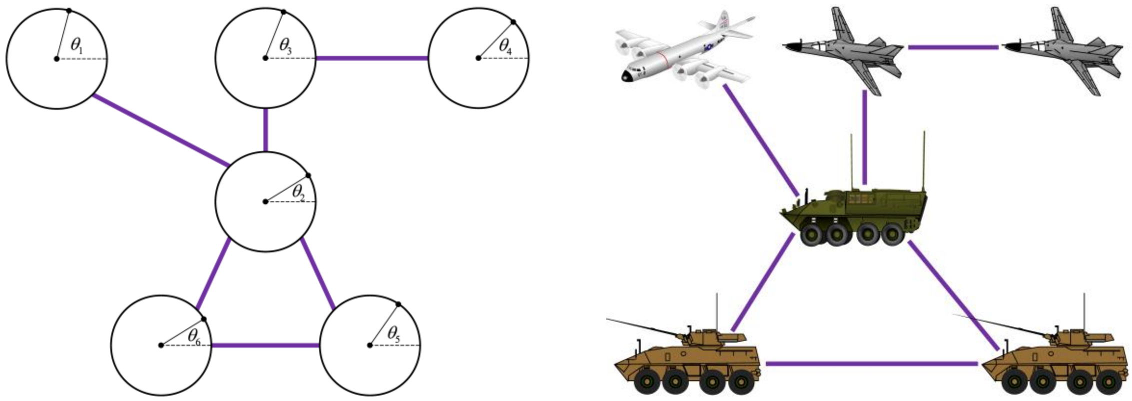

Figure 1. Model and reality: a network of oscillators (left) models a network of military nodes (right).

Table 1. Mapping the Kuramoto Model to the C2 domain.

Kuramoto Model		**C2 application**
Network of nodes with **angle θ** in each node	↔	Network of nodes with **plan** in each node
Difference between **angles** in different nodes	↔	**Level of conflict** between **plans** in different nodes
Feedback given by **differential equation** acts to reduce differences between angles	↔	Feedback given by **C2 processes** acts to reduce level of conflict between plans
Short network paths (low average distance) and multiple alternate network paths (high connectivity) support synchronisation	↔	Short network paths (low average distance) and multiple alternate network paths (high connectivity) support synchronisation
Problems in synchronising large cycles (artefact)	✗	–
–	✗	Many C2-relevant properties of synchronisation with no counterpart in the Kuramoto Model

Keywords: *Kuramoto Model, NetLogo, networks, synchronisation, command and control, epistemology*

On the Set-Union Budget Scenario Problem

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Abstract: At MODSIM 2015 (Taylor, 2015) formalised the *Budget Scenario Problem* as a simplified mathematical formulation of the problem presented by (Order, 2007, 2009). 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 score is calculated as a sum of best initiative scores within the collection for each scenario. In this paper we extend the mathematical model to take account of the dependency conditions expressed in words (see Table 2) in (Order, 2007, 2009) and to also accommodate the representation of synergies between initiatives. Since this extension is analogous to the Set-Union Knapsack Problem (Goldsmith, 1994) we call this formulation the Set-Union Budget Scenario Problem. In mathematical terms the Set-Union Budget Scenario Problem can be expressed as:

$$Maximise \sum_{i=1}^{m} s_i \max_{1\le j\le n}\left(v_{ij}(\alpha_j + \sum_{k=1}^{n} \beta_{jk} x_k) x_j \right), \quad (1)$$

$$\text{Subject to } \sum_{j=1}^{n} c_j x_j \le B, \quad (2)$$

where $x_j \in \{0,1\}$ is the decision to include initiative j or not, s_i is the probability of scenario i, v_{ij} is the value of score for scenario i and initiative j, α_j is the measure of independence for initiative j, β_{jk} is the value of interdependency between initiative j and k, c_j is the cost of initiative j and B is the cost bound.

The above formulation was tested on (Order, 2009) data but extended to different levels of dependency with results for dependency levels ranging from independent (Dependency Level = 0) to fully dependent (Dependency Level = 4) presented below in Figure 1.

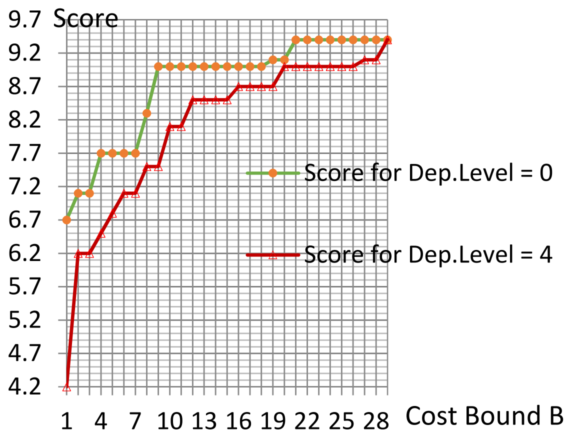

Figure 1. Score vs Cost Bound for Dependency Levels of 0 and 4

Results obtained from formulation (1) and (2) confirm the results produced by (Order, 2009) with some exceptions where (Order, 2009) appears to have not taken into account some dependencies (for example "B needs K"). The proposed formal approach has been applied to the interdependency context successfully and the obtained results are very encouraging and applicable to the force design domain.

Keywords: *Set-union knapsack problem, budget optimisation, decision making, interdependency*

Naval Gunfire Support Under Uncertainty

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Abstract: Warfare is inherently conducted under risk and uncertainty. Decisions need to be made quickly, often on the basis of incomplete and dynamically changing information. The ability to accurately recalibrate beliefs and modify tactics in response to new information is essential to effective warfighting.

A Bayesian framework is used to examine the optimal combat tactics and resource allocation in a naval gunfire support scenario, specifically, the optimal timing to withdraw from combat. Enemy targets reside in an area of operation and a friendly platform is available that can fire upon the targets. Elimination of the targets would improve the regional stability and supply chain effectiveness. However, there is an opportunity cost associated with allocating the platform to that particular region, creating a trade-off between the potential benefits of eliminating the adversary and the opportunity cost of the platform.

There is an additional complication in that the platform's ability to eliminate the targets is poorly characterized. This could arise from the novelty of the platform itself, a change in the operational environment, or changes in the adversary's tactics. Immediate feedback about whether the gunfire support hit or missed is available after each shot, so the platform's capabilities become better characterized throughout combat, leading to unpredictable and dynamic changes in the optimal tactics. The cases of a single target and an ensemble of homogeneous targets are modelled. It is found that ensemble combat motivates the platform to continue attacking longer than in the single target case as information gain becomes more valuable.

We compare the optimal Bayesian framework against other strategies such as unconditional attack, unconditional withdrawal, use of the posterior mode, and using the mean value of the prior distribution without updating the posterior distribution. The penalty of these approaches depends on the precise situations. We show that these strategies can fail catastrophically and identify the situations in which this is likely to occur.

This work provides a theoretical basis for incorporating uncertainty and information gain into contemporary combat models. It identifies ways in which classical approaches involving maximum likelihood estimates and basic sensitivity analysis can lead analysts astray. We anticipate this work will be important given the proliferation of new domains for combat (such as space and cyberspace) and difficulty in providing timely and low cost assessments of emerging strategies and weapon systems.

Keywords: *Naval gunfire support, Bayesian statistics, optimal stopping time, decision making*

Using column generation to solve an aircrew training timetabling problem

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Abstract: The Training Authority Aviation (TA-Avn) is an organisation within the Royal Australian Navy (RAN) responsible for managing aviation-specific training for all RAN personnel, who are to be employed in an aviation-related job category. In a temporal sense, the bulk of aircrew training consists of a sequence of major, structured courses and a number of mandatory short courses for which the prerequisite requirements are less strict. Both short and long courses are run repeatedly throughout a year with a fixed number of repetitions and are subject to high and extremely variable course pass rates. It is important to have an ability to quickly and easily regenerate a new timetable at short notice, potentially on a weekly basis depending on whether students have to repeat failed short courses.

In previous work we explored a number of approaches including a stochastic approach to optimisation. In this paper, we adopt a different methodology, using more conventional integer linear programming techniques, specifically, column generation. The problem of designing feasible schedules is formulated as a network flow problem that encompasses covering and prerequisite constraints. Then column generation is applied in order to improve the tractability of this large scale integer linear program. Here, the original problem is decomposed into a master and subproblem. The master problem is initialised with a set of dummy schedules to which we allocate the aircrew student population, whilst respecting class capacity limitations. The master problem then requests solutions from the subproblem that offer some promise of minimising the overall time spent in training. This process iterates between the master and subproblems until the solution of the master problem cannot be further improved and we have thus reached an optimal allocation of students to feasible schedules. Experimental results are compared with those of an ILP approach that assigns feasible schedules to labelled students.

Keywords: *Optimal timetabling, integer linear programming, network flow, column generation*

An optimal recruitment algorithm based on an efficient tree search policy

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Abstract: In the area of highly specialized skills training where the cost of training is high and available infrastructure is limited and limiting, recruitment and manpower training scheduling can be quite complex. For Royal Australian Navy (RAN) pilot training, there are some additional unique features such as feedback loops that are generated by the requirement for graduated pilots to return into the training continuum as instructors. Furthermore, the trainee numbers are relatively small, the failure rates are high and highly variable. In this paper, we consider a simplified RAN training scheduler solution as an optimal control problem having feedback loops and cost functions that penalize prolonged waiting periods between courses (buffers) with an overall objective of minimizing the total training time. The solution algorithm converges on an optimal recruitment strategy through which the training continuum maintains a functional squadron over a specific timeframe, while imposing the least possible cost to the organisation. Solutions also take into account course pass rates, squadron wastage, the number of trainees in each course or the number of trainees waiting in the intermediate buffers. The proposed algorithm uses states and actions as used in Markov Decision Processes (MDP) where current states and actions are used to predict new states to minimize cost. The algorithm differs from MDPs in so far as the MDP "optimal policy" for prediction future states and associated optimal actions is replaced by an optimal tree search process where traversing a level in the tree is interpreted as taking an action resulting in a transition from one state to another. The algorithm uses a recruitment-wastage near-equilibrium condition to prune the tree avoiding suboptimal solutions. To select the best recruitment strategy, the combined cost from root-to-leaf is considered as the final merit thus replacing the *stochastic MDP* policy approach with a *deterministic optimal tree search* strategy. The algorithm benefits from a solution archive that maintains a sorted list of the best *n* created solutions. The result of the experiments show that the algorithm can efficiently perform tree search in order to rapidly find feasible recruitment policies with optimal costs.

Keywords: *Decision Support System (DSS), dynamic systems, Markov decision process (MDP), optimal recruitment, optimization*

Weighted random sampling for military aircrew timetabling

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Abstract: The problem we consider is motivated by the timetabling of training schedules for Royal Australian Navy (RAN) aircrew, in particular helicopter pilots. The RAN aircrew training syllabus is a sequence of courses with a prerequisite structure that enforces a strict ordering on some segments of the training continuum. Courses have several sessions (repetitions) each year, and each session has a limited student capacity. Current ap-proaches to timetabling RAN aircrew training result in students spending significant periods (several months, say) waiting between courses. Since students are paid salaries throughout their training, such delays are costly. Furthermore, significant waiting periods can negatively affect student morale. An efficient allocation of stu-dents to schedules minimises this waiting time.

Our recent work shows that it is possible to apply Knuth's "Dancing Links" algorithm to rapidly generate all feasible schedules for RAN aircrew students. In this context, a feasible schedule is a sequence of course sessions that includes a session of each course required by the syllabus, satisfies the prerequisite constraints and avoids time clashes. Upon generating all such feasible schedules, one allocates each student to a schedule, ensuring that course session capacities are not exceeded. The objective is to minimise the total cost, in this case the total makespan of the selected schedules. The makespan of a schedule is the total time between the start of its first course session and the end of its last course session.

Realistic RAN aircrew syllabuses can generate tens of millions of feasible schedules. The number of students is, however, relatively small: on the order of fifty. Earlier work on simple test syllabuses uses a linear pro-gramming relaxation to arrive at an approximately optimal solution to the allocation problem. However, as the number of feasible schedules generated by DLX grows, standard "off-the-shelf" Integer Linear Programming (ILP) solvers may no longer be a computationally feasible choice.

This paper proposes the use of a Weighted Random Sampling (WRS) algorithm to obtain from the set of all feasible schedules a fixed-size sample that satisfies session capacity constraints. Schedules are weighted according to their makespan — shorter schedules have greater weights — and the probability that a schedule is selected for the sample is determined by its relative weight.

We compare the results of this sampling approach to the optimal solution obtained by a deterministic ILP solver for some simple test cases, and demonstrate that provided one can efficiently obtain the set of all feasible schedules, the use of a WRS algorithm is a possible alternative to an ILP formulation of the allocation problem.

Keywords: *Weighted random sampling, timetabling, military aircrew training, Dancing Links*

Application of mathematical programming to prioritising interdependent Defence investment programs

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Abstract: Defence capability planning often requires prioritising a list of candidate programs/projects/products to determine the portfolio of investments that provide the best value for money given resource constraints and uncertainty, organisational constraints, and program interdependency constraints. Many prioritising methodologies such as ranking models, scoring models and the analytic hierarchy process (AHP) may work well for programs that are predominantly independent of one another. When the programs are interdependent, those methods fail to explicitly capture dependencies between programs and the resource uncertainty.

This paper explores the use of a mathematical programming methodology for prioritising interdependent Defence programs. A service-based interrelationship identification method is used to measure the different levels of interdependencies between programs. Resource uncertainty is modelled through variations of possible budget limitations. Strategic objectives are linked by multiple scenarios with different weights. For different application situations, two mathematical models, the Quadratic Knapsack Model (QKM) and the Budget Scenario Model (BSM), are proposed to formulate the optimisation problem for prioritising interdependent programs. Algorithms and properties of the proposed optimisation models are further discussed through the application of the models to two simple Defence capability prioritisation problems. The preliminary results have shown the models' potential applications in support of Defence capability planning.

Keywords: *Mathematical programming, interdependency, prioritisation*

Longitudinal Models for Project Expenditure Plans

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Abstract: The ability of project managers to generate accurate budget predictions for capital investments is critical for successful project completion and the management of the Australian Department of Defence budget. Accordingly, this paper discusses non-linear regression models to analyse planned time-phasing of expenditures for projects in an Australian Defence capital investment program. Earlier research on time-phasing primarily focuses on the theoretical foundation for applying the cumulative distribution function, usually of functional forms such as Rayleigh and Weibull curves, to model the distribution of project expenditures. Previous approaches have also relied on elementary regression techniques to estimate the parameters of the curves. However, these analyses have generally ignored the longitudinal, repeated measures nature of the data for each project, potentially compromising results because the data within projects is correlated. Here, a non-linear mixed-effects model is used to estimate the parameters of the time-phasing distributions for a large number of major capital investment projects. Unlike ordinary linear or non-linear regression, this has the advantage of accounting for within project correlation and unequal variance. The model can be thought of as a hierarchical model involving both fixed-effects associated with the population of projects and random-effects accounting for unexplained inter- and intra-project variability. The fixed part of the model incorporates military domain effects and project epochs, and random effects account for heteroscedasticity and correlations between the repeated measures. Analysis reveals significant differences between project's time-phasing due to their domain and epoch. The model may be used by project and portfolio planners to estimate required spending plans against project schedule and total planned expenditure; it therefore provides a tool to measure project and financial risk.

Keywords: *Non-linear regression, capital investment, time-phasing*

In Defence of Soft OR

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Abstract: Whilst there have been numerous examples of where soft Operations Research (soft OR) has been used to good effect to support the management of complex, messy, strategic problems, developing the skills to employ these methods remains a challenge. One explanation is that soft OR has been viewed as 'fluffy', not real Operations Research, and therefore potentially not a legitimate form of modelling. This perception to some extent can be justified as there are a number of poor applications of the methods resulting in the methods' credibility being eroded.

However, where there is an appetite, appreciation and organisational support to learn these modelling approaches along with a wealth of opportunities to use the soft OR methods within the organisation, the likelihood of success regarding embedding the skills increase. Alongside having a supportive culture, one of the areas where soft OR is experiencing a renaissance is defence, as military leaders and commanders recognise the need to manage complexity, attend to strategic/systemic issues and pay attention to the socio-political considerations.

This paper reflects on a project whereby training in a particular soft OR method, namely Strategic Options Development and Analysis (SODA), was undertaken. In particular attention was focused on ensuring that effective learning strategies were employed recognising the challenges postulated in the literature (i.e. appreciating the socio-political world; having comfort in not providing the 'right' answer; working with decision makers rather than modelling in the backroom; becoming comfortable in managing both the whole (complexity) along with specific details). The training additionally took cognisance of effective pedagogy and thus incorporated a range of learning devices (diaries, exercises, video, and illustrations/vignettes). In order to understand not just the effect of the training on the recipients but also its efficacy, the research took a longitudinal approach commencing with an investigation of existing competence, training to extend the extant skills, reflective activities and review of progress regarding usage.

The paper thus comprises initial design, engagement with materials, and application before concluding with reflections on the success of the training, limitations of the research and future steps.

Keywords: *Soft Operations Research, managing complexity, learning strategies, longitudinal training method*

EXTENDED ABSTRACT ONLY

New Zealand Defence Force Technology Trends Analysis - A Shift in Philosophy

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Abstract: New Zealand Defence Force (NZDF) Technology Trend (TT) reporting focuses on identifying technologies perceived to hold potential for future NZDF strategies, capabilities or threat assessments. Recent reports have provided value, however, without exception previous investigators have selected qualitative constructivism methods to both survey and forecast the technology landscapes of interest. While appropriate for thematic exploration, qualitative constructivism techniques provide limited predictive qualities and are vulnerable to subjectivism bias without considerable multidimensional effort and resources using complementary qualitative methodologies such as Key Assumption Checks (KACs), the Cone of Plausibility (CoP) or Analysis of Competing Hypotheses (ACH).

Cognisant of these limitations a recent study by the NZDF Defence Technology Agency (DTA) was initiated to investigate how these previous partial predictive outcomes might be improved for the NZDF. In exploring this opportunity for improvement, this six week study considered four broad phases of inquiry. The first phase examined two previous TT reports by DTA, considering actual and anecdotal drivers, employment of the methodologies selected, and an assessment of opportunities to utilise more sophisticated techniques. This phase also included reflexions upon complementary qualitative methods such as LACs, CoP and ACH, methods of source grading through literature reviews or otherwise, and Brier scoring to infer predictive success. In the second phase, three international military TT papers methods were examined in depth, with reflexions upon the selected explicit or implicit predictive methods, and selected communication approaches. Moving to phase three, two independent workshops were undertaken to elucidate feedback and insights on the two previous DTA reports, the three international papers, and tailored TT horizon scanning using two complementary, but parallel expert future focused groups. The first group was drawn from technical subject matter experts in DTA, and the second group from foresight future policy analysts in the NZ Ministry of Defence (MoD) and HQ NZDF Directorate of Future Force Development (DFFD). These workshops considered the methods selected, respective thematic approaches, source grading, and explicit or implicit implications of the bibliographies as inputs in each study. Contemporary methods such as 7 Questions, Issues Trees, Horizon Scanning, and GBN 'High Impact, Low Uncertainty' scenario elaboration was included to identify NZDF perspectives on TT fields of interest. In the final phase, a succinct contemporary study of the technical expertise in the NZ domestic environment was undertaken to identify prospects for future collaboration or consultation on abstruse topics and fields of interest to current and future military TT investigations.

In respect to the general TT field outcome, the study substantiates the general consensus, that: the applications of emerging technologies now appear more important than scientific breakthroughs; that economic market competitiveness is assessed as remaining more significant (to the NZDF in particular) than traditional military technological development; and that technology trends exhibit mathematical complexity, in particular exhibiting chaotic behaviour near the extremes of traditional technology 'hype-curves'. In addition, the study concluded that the emergent NZDF organisational processes of deriving and implementing TT foresight studies is more valuable holistically than the momentary accuracy of any specific technology forecast in the short term.

In respect to options to improve DTA and NZDF TT predictive methods and likely predictive successes, the study concluded that options are available within existing resource constraints and a recommended refurbished framework is described. Recommendations for future work are also provided, notably including: the potential to explore and identify behavioural tendencies with respect to NZDF adoption, implementation or abstention of emergent military technology; and the observation that this analysis for the NZDF, as a security provider in a technologically proficient, but small nation, may also provide useful insights to other small like-minded nations grappling with TT interests, representing an opportunity to collaborate and consult on future work.

Keywords: *Technology trends, New Zealand (NZ), New Zealand Defence Force (NZDF).*

Promoting worker adaptation in complex sociotechnical systems with Integrated System Design: Case study of team design

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Abstract: This paper is concerned with the challenging problem of developing effective team designs for complex sociotechnical systems (Naikar, Pearce, Drumm, & Sanderson, 2003). A strong case has already been made that the fundamental design objective should be that of promoting worker adaptation, so that workers can respond effectively to both anticipated and novel conditions (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). However, existing approaches for work analysis and design are limited in their ability to meet this objective because they focus on specifying how work should be done under anticipated conditions (normative approaches) or how work is currently done in recurring situations (descriptive approaches). A suitable starting point is offered by cognitive work analysis (CWA), a formative approach to work analysis, which focuses on the constraints that must be respected by workers irrespective of the situation. The problem is that while this approach can support workers in adapting their behaviour, it does not fully support workers in adapting their structure or work organisation. In addition, existing approaches utilising CWA for design focus on individual system elements, such as the interfaces, teams, training, or automation, so that all elements of the system design may not support adaptation in a consistent or unified manner

This paper will demonstrate how the integrated system design (ISD) approach described by Naikar and Elix (2015a, b) can be applied to develop adaptive team designs for complex sociotechnical systems. This approach proposes that to support workers in adapting their structure as well as their behaviour to deal with both routine and novel events effectively, it is necessary to delineate the set of possibilities for work organisation in a system independently of the situation. Subsequently, designs must be developed for each of the system elements that can support or accommodate these possibilities. Thus, a case study is presented to demonstrate how the set of possibilities for work organisation were demarcated for a future Australian maritime surveillance aircraft, based on extensions of CWA described by Naikar and Elix. In addition, it is shown how a team design was generated for this system that can accommodate the range of possibilities for work organisation. Consequently, this team design can support workers in adapting their structure as well as their behaviour to meet the demands of a variety of situations, including those that are unanticipated. Furthermore, this team design can be integrated with other elements of the system design through a common set of work organisation possibilities, such that the system design supports adaptation in a coherent manner.

Keywords: *Cognitive Work Analysis (CWA), Integrated System Design (ISD), complex sociotechnical systems*

Management by Hierarchical Control versus Mindfulness

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Abstract: Hierarchical control, as developed within systems engineering, and mindfulness, as developed within management science, offer contrasting approaches to organizational management for sociotechnical systems. The hierarchical control model proposes that the social and organizational processes within a sociotechnical system conform to a multi-level, hierarchical control structure. The model posits that the various levels of management and operations are connected by communication and control links, with a descending path propagating management decisions down the hierarchy and an ascending path propagating information about work-related processes up the hierarchy. These communication links between levels constitute interdependencies that are viewed as critical to the functioning of an effective system

Although it would seem to capture the essential multilevel character of complex sociotechnical systems, the between-level transactions promoted by the hierarchical control model have a formal and rational character. Those promoting this model appear to be ignoring the essential cognitive processes that make contemporary knowledge systems work. Following Weick and Sutcliffe (2001), we characterize those cognitive processes as elements of mindfulness; the cognitive state of being alert to and inquiring continuously about subtle and changing situational complexities. Those who are mindful understand that operational work has many subtle and complex details, they remain sensitive to operational demands, they defer to expertise, and they reflect zealously on the potential for failure.

As implied by the topic statement for this session, the design and management of large-scale sociotechnical systems pose significant challenges. In part, we continue to struggle with this because we do not have a comprehensive functional model that takes account of the essential melding between the socio and the technical. Here we propose that a hierarchical structure, when complemented with insights relating to organizational mindfulness, offers an innovative model that can guide us towards resolving that challenge.

Keywords: *System design, organizational factors, organizational cognition*

A Conceptual Model for the Identification of Suitable Personnel to Operate in High-risk, Physically Demanding Environments

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Abstract: When determining the suitability of human resources for employment in high-risk, physically demanding environments, it is crucial to ensure the most appropriate person is selected for each role. While the concepts and practices are well established (i.e. what they need to do, how they need to do it, and the desired effects while they are doing it) there is little research into who should be doing it. This gap may have significant effects on the task outcomes, the individual performing the task, and ultimately how well resources are managed. To bridge this gap, there is a need for assessment tools that can make use of basic fitness and medical assessments to determine an individual's predisposition to conduct a specific role in harsh environments. Using statistical modelling techniques—specifically Bayesian Networks (BN)—this research develops a conceptual model for identifying the suitability of personnel to operate in high-risk, physically demanding environments.

The aim of this ongoing research is to make use of the BN modelling methodology to help generate knowledge and tools that support the selection of personnel performing high risk physical roles. BN modelling offers several advantages, such as the ability to integrate qualitative and quantitative data, ease of communication due to transparent model structure, as well as the ability to handle data uncertainty. BN is also an adaptive modelling technique, which means that the model structure and parameters can be updated as new data becomes available. The intended outcome of the BN is to develop an integrated understanding of the factors (i.e. individual, task and environment), while illuminating knowledge gaps and further areas that warrant investigation.

We use a case study approach to support the development and validation of the BN. The selected case study aims to develop an assessment tool to support the selection of individuals to operate in individual protective equipment (IPE) in a chemical, biological, radiological, nuclear or explosive (CBRNE) environment. Here the intended outcome is to develop a metric for selecting the most appropriate personnel to operate within a CBRNE environment. This case study is a topical showcase as it will support a gap in the ability to select CBRNE operators to support military services to respond and operate at times where there are increasing threats of terrorist attacks. Findings from the study can be transferred to other applications, such as the selection of personnel to work in IPE for first responders, emergency and medical services.

Keywords: *Selection criteria, Bayesian Network (BN), high risk environments*

Systemic Design for Future Land Warfare Force Design

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Abstract: We report here on the application of systemic design to the framing question: how can we design a Land Force that can meet the likely 2050 Australian strategic defence objectives in an irreducibly uncertain and complex future? The timeframe of 2050 was chosen as a representative date on the basis that current capabilities would be almost entirely replaced by this point, providing the freedom to radically redesign the force, rather than work within the non-linearly interacting constraints of legacy capabilities. This date is also beyond the scope of the current Defence White Paper, meaning the design exercise is not constrained by official direction.

The workshop employed an advanced Design methodology called systemic design. Systemic design builds on and integrates two interdisciplinary practices, systems thinking and design thinking, in order to appreciate and intervene in complex environments. Systemic design is best thought of as a toolset and a mindset framed by a general methodology, rather than a well-defined process. Innovation in complex environments does not conform to a repeatable, follow-the-bouncing-ball procedure. However, it is a discipline that is informed by deep theory and enacted through participatory practice. We accept that we cannot predict the future as it will not be an extrapolation of the past; so we abandon our usual question of 'optimising' the future design and consider a new driving question. Rather than a process, systemic design can be viewed as a field of possibility that connects reflection with action and a systemic perspective with designerly intent. Within this field of possibility, many techniques from systems and design thinking can be recombined to craft a tailored approach to each unique challenge the systemic designer participates in. We work to inform better decisions by asking a new question: what possible options might we consider and what are their weaknesses and limitations and vulnerabilities? These decisions will be grounded in the very realistic notion of being survivable; knowing the limitations, so knowing what to avoid, and being able to adapt rapidly to unknowable future states. We choose adaptability to the conditions that may occur over optimality with respect to conditions that will likely occur.

Most of the Operational Analysis techniques currently employed on Force Design problems originate from within a paradigm of scientific support to decision making. We refer to this paradigm as technical rationality, because it seeks a systematic, objective and rational approach to ends-means matching between strategic objectives and available resources. Within certain boundary conditions, technical rationality is a highly effective approach to problem solving. However, for extremely complex situations, where objectives are ambiguous and statistically significant data is not available, the assumptions of technical rationality begin to break down. It is here that systemic design offers an alternative and complementary approach to designing responses to a complex situation.

We report on the process and outcomes of this exercise, noting that the results may differ from those arrived at had the participants been military experts. Our outcomes built on rapid adaption to unforeseen and unforeseeable circumstance by understanding vulnerabilities early enough to avoid exposure to critical failure and recognising viable opportunities early enough to take advantage of them.

Keywords: *Systemic design, design thinking, force design, uncertainty*

Big Ideas on Small Budgets: Un-manning Aerial ISR and Fire Support

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Abstract: Manned-Unmanned Systems teaming is rapidly gaining popularity as an effective concept of operations in highly lethal environments. The ability of Unmanned systems to remove the human from danger is being utilised not only in military, but also other situations where removing the human from a potentially dangerous situation reduces casualties while still accomplishing the mission, for example mining or underwater operations. This has resulted in an explosion of technological advances in unmanned systems, including autonomy/control, capacity and endurance, making them potential candidates for tasks where any of the following is required:

- sustained effort
- collecting and relaying large volumes of data
- being robust to prosecution by being able to operate undetected (thus avoiding attrition), or being resistant to it (for example through having expendable components).

Despite this commonality in task requirements, there is a large variety of capabilities of unmanned systems in terms of their characteristics, which means there is a vast range of ways they could be incorporated into any system, each with vastly different support requirements.

The Aerial ISR and Fire Support domain meets the task requirements where unmanned systems can bring a benefit. It has long been characterised by the need to collect information from within a contested environment, needing to withstand prosecution (which the system achieves by manoeuvrability). Allied nations are already future-proofing their capabilities by investing in their system's ability to incorporate unmanned components.

However, within the relatively small context of the Australian Battlefield Aviation, the application of these concepts needs to be judicious. To further complicate matters, the use of unmanned systems in the military is plagued with trust issues due to the perception that a human decision-maker is able to better judge unexpected situations. The possibility of a cyber-attack further exacerbates this perception that human control is necessary for safety, especially with armed systems. The usual lag between the uptake of new technologies, and the associated doctrine and legislative matters governing their use also play a role.

We synthesised a number of concepts of operations which could meet the operational needs of missions occurring in the Aerial ISR and Fire Support domain. In order to span the space of potential uses of unmanned systems, firstly the roles for all platform class exemplars were identified. Then a morphological enumeration method was used to ensure that both unmanned and manned-unmanned combinations were represented within the set of possible options developed. A C2 concept for each combination of platforms was defined to describe how a number of typical missions would be conducted.

The concepts were rapidly assessed for technological feasibility and efficiency, to down-select a manageable number of concepts for further evaluation, ensuring that the selected concepts still span the space of potential unmanned system applications.

The down-selected concepts were evaluated for their operational effectiveness from two perspectives: (1) platform level and (2) concept level. The platform level evaluation focussed on the platform class examples and the impact of their performance characteristics now and into the future on the conduct of missions. This included aspects such as platform vulnerability, potential technology issues such as performance requirements or further development required as well as impacts on training, manning, logistics and doctrinal implications. The concept level evaluation identified the strengths and weaknesses of the proposed concepts in the conduct of Aerial ISR and Fire Support.

Our study provides an overview of how unmanned platforms might impact the conduct of Aerial ISR and Fire Support, and outlines some of the areas of tension between technology development and doctrine now and into the future.

Keywords: *Concept development, concept evaluation, unmanned aerial systems*

Assessing the impact of the bathtub curve failure rate on fleet performance using designed simulation experiments

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Abstract: This work seeks to determine the impact of the 'bathtub curve' failure rate on the performance of a fleet of military aircraft. Previous work in this area using a simulation modelling approach (e.g., Mattila and Virtanen, 2014; Marlow et al., 2015) has assumed a constant failure rate for unscheduled maintenance throughout a fleet life. We seek to ascertain whether a fleet is able to absorb the potential impacts of a representative bathtub curve through other actions such as implementing better fleet management policies, and at what point the effect of the bathtub overwhelms any mitigation procedures.

The bathtub curve is a concept used in reliability engineering to describe the varying failure rates of a system over time. It consists of three main periods:

- the 'infant mortality' or 'burn in' period, where the failure rate is high as initial faults are identified, before decreasing over time, resembling the left-hand side of a bathtub (viewed in cross-section);
- the 'random failures' period in the 'middle' of the bathtub, where failures occur at a constant rate; and
- the 'wear-out' period, where the failure rate increases as the system ages, resembling the right-hand side of a bathtub.

We incorporate the bathtub curve effect into our aircraft fleet simulation model used in previous work for a naval helicopter fleet (Marlow et al., 2015) but applicable to any fleet. The model represents the movement of aircraft between states for each day of a 30 year fleet life. Aircraft may be embarked on ships or ashore; they may be serviceable (able to fly) or in various types of scheduled or unscheduled maintenance. Aircraft change states once particular criteria are met – e.g., entering maintenance after achieving a certain number of flying hours. The primary measures of effectiveness (MoEs) for the model are to achieve the required number of embarked aircraft each day, and the required annual embarked and ashore flying hours. In order to evaluate the impact of the bathtub curve on fleet performance, we include additional MoEs that calculate the percentage of years that the fleet does not meet its annual embarked and ashore requirements. The model also includes a range of pre-determined policies to assist the fleet in meeting its MoEs. There are six policy categories: flying allocation, maintenance allocation, crew rotation between maintenance areas, tail rotation between multiple squadrons, policies to balance the total flying hours across the fleet, and squadron sharing.

The two new input variables to the model represent the 'height' of the bathtub (corresponding with an increase in the unscheduled maintenance failure rate of 2^{height}) and the 'duration' in years of each end of the symmetrical bathtub. To represent the bathtub curve effect, we use a 'thinning' technique (Lewis and Shedler, 1979) to create time-dependent rates over the fleet life. We generate gamma-distributed potential failure events at a rate corresponding to the maximum bathtub height, and accept or reject the generated events with a probability determined by the height of the bathtub at the time of the event. The probability decreases linearly from 1 to $1/2^{\text{height}}$ during the infant mortality period; takes the value $1/2^{\text{height}}$ in the random failures period; and increases linearly from $1/2^{\text{height}}$ to 1 during the wear-out period. In order to test various bathtub heights and durations, we use a designed simulation experiment approach (Sanchez and Wan, 2015) over 512 design points, with the height varying from 0 to 3 and duration varying from 0 to 10 years.

We perform statistical analysis of the results on the two new MoEs. For the percentage of years that the embarked annual flying requirements are not met, flying at a higher tempo (up to 7 hours per day) has the largest impact on the results, more so than the bathtub variables. For the percentage of years that the ashore annual flying requirements are not met, various combinations of existing policies, particularly sharing squadron resources, can be implemented to reduce the impact of the bathtub curve. However, if the bathtub effects last for longer than around 5 years at each end, and the height of the bathtub exceeds approximately 1.3 (i.e., slightly more the double the failure rate), negative impacts on the fleet performance eventuate.

Keywords: *Bathtub curve, aircraft fleet simulation model, unscheduled maintenance, failure rate*

Using predictive operational modelling to reform Army's aviation maintenance system

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Abstract: The Army Aviation (AAvn) capability has undergone signification changes in aircraft platforms, commercial arrangements and operational requirements resulting in the fleets not meeting their capability requirements and an excessive maintenance burden on the support system. Different agencies within Defence had proposed solutions to fix the current issues, but the agencies could not agree on the potential benefits from each potential reform activity. This was further exacerbated due to disagreement on the method used to calculate the maintenance burden of the AAvn fleet.

Relken developed a numerical maintenance liability model to conduct dynamic simulations of the maintenance-related performance characteristics of the ARH Tiger, MRH 90 Taipan, CH-47F Chinook, and S70-A9 Blackhawk to inform workforce planning and efficiency reform decisions. The focus of the model was to quantify the impact to operations due to changes to the support system or rate of effort. This provided a means to prioritise reform activities and estimate the cumulative benefit to the capability. The model also provided line of sight for engineering, maintenance, supply and operations as to the impact of changes to their systems.

Some models and analysis existed within the AAvn organisations, but was reliant upon simple ratios that could not model the complexity of the maintenance system, and therefore could not model the differences between the reform activities being proposed. Furthermore, the existing analysis techniques did not quantify the impact on operations and therefore could not be used to unify Defence to agree on the high impact improvement activities to proceed with. Relken considered developing the simulation in commercial software but found limitations in the ability to incorporate: non-continuous demand systems; on condition events; multiple life units; after maintenance triggers; variable usage rates, probabilistic interval triggers; concurrent activities; certification and trade constrains. It was therefore agreed with The Australian Army that a bespoke simulation model would be developed in MATLAB using Tableau to visually present the model outputs.

Relken's approach focused on obtaining agreement of the model inputs and outputs from the different agencies and stakeholders. Relken conducted detailed reviews of the maintenance policies for each platform, interviewed maintenance staff, and performed analysis of data from historic maintenance records. Importantly, the data from the computer maintenance management system was only used to elicit estimates from subject matter experts for most of the model inputs. The simulation model outputs were validated against historic performance of the platform and the inputs and outputs agreed to by the units flying the aircraft. Once validated, the model was then used to simulate possible operational and support system changes to estimate their impact.

The delivery and acceptance of an end-user validated model resulted in informed decisions about capability and a trusted model to enable AAvn fleet planning and maintenance workforce restructuring.

Keywords: Operational modelling, Army aviation capability, benefits quantification, maintenance, Defence capability wide decision support tool

Modelling RMB Internationalization and Impact on Capital Flow

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Abstract: China began its economic reforms in the end of the 1970s, which have successfully transformed the country into an important trading nation and manufacturing centre in the world over the past three decades. Despite China's recent economic slowdown, the IMF forecasts that China will continue to be the largest contributor to global GDP growth. In addition, the rate of return for holding RMB over the past ten years has been one of the highest, which explains the strong portfolio capital inflows since 2004. Probably the only remaining issue is about China's capital control, especially over the flows of portfolio investment. The progress of RMB internationalization helps facilitate the short term capital flows, and is believed to have a new interactive effects on the exchange rate expectation and capital flows nexus.

This paper intends to employ the asset portfolio balance model to explore the effect of RMB exchange rate expectation on RMB internationalization. In particular, we empirically explore the relationship between RMB exchange rate expectation, RMB internationalization and short-term capital flow by using SVAR model and the monthly data from February 2004 to November 2014. The results indicates that RMB exchange rate appreciation could increase the demand of foreign investors for RMB and RMB denominated bonds and vice versa, and also attract short-term capital inflow through reducing the capital flow cost. This paper implies that, associated with the rapid RMB internationalization, the central bank needs to pay more attention to the short term capital flow as its destabilizing effect may cause panic to the financial system.

JEL Classification: G28, F21

Keywords: *RMB exchange rate expectation, RMB internationalization, short-term capital flow, interactive mechanism*

Modelling MNCs' Market Entry Order Strategy: Evidence from China

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Abstract: There are a number of studies focusing on firms' export behavior and market entry decisions, but mostly applying the Net Present Value (NPV) Theory to the developed market economies and a few studies on the market entry order of multinational enterprises (MNEs) in the emerging economies (EM), especially on the largest trading country and the fastest growing emerging economy of China.

The purpose of this paper is to study the market entry order of the Chinese exporters and document the contribution of extensive margin during the internationalization process of Chinese MNEs by incorporating the unique institutional feature and matching the big data of China's Customs Database and Chinese Industrial Enterprise Database. In particular, we use the big matched data to screen exporting firms in a "new product-market combination" along with the extensive margin and at different product and ownership level from 2001 to 2006, and then examine whether a firm behaves as a pioneer or a follower when exporting a new combination and when a firm follows the pioneer to enter the market once they decide to become a follower in a new combination. To our knowledge this is among the first to study comprehensively the market entry order of Chinese MNEs in their internationalization process. This study implies three major contributions. First, it performs a comprehensive big data matching by industry, market, product line and ownership using China's Customs Database and Chinese Industrial Enterprise Database to study the market entry order of Chinese MNEs. This will allow us to better understand firms' export behaviors and market entry order and contribute to the existing literature. Then, this study examines not only Chinese MNEs' decision choice of being a pioneer or a follower, but also the timing of entry to the international market under different product categories and ownership. This advances our knowledge of how the Chinese MNEs internationalize and how to compare with MNEs from other countries. Finally, this study documents the dynamic contribution of extensive margin for the Chinese MNEs, and draws important policy implications on how and if China can sustain its rapid export growth.

The results show that firms' choice of being a pioneer or a follower in exporting each new product-market portfolio is jointly determined by the firm-level and host-country-level characteristics, and that firms with larger scale, higher productivity, lower production costs, less fierce competition and smaller credit constraints are more likely to be pioneers. We also find that the timing when to follow is influenced by the pioneers' performance and product category. The results further confirm the existence of crowding out effect and spillover effect between pioneers and followers.

JEL Classification: F02; F23; G21

Keywords: *Market entry order, extensive margin, new product-market portfolio (new portfolio), pioneers, followers*

Separation of R&D Processes in a Biopharmaceutical R&D

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Abstract: This paper describes the R&D productivity of a biopharmaceutical company, with emphasis on separation of the research and development processes. Many previous studies focus pharmaceutical R&D, but they focus low-molecular compound drug only. The pharmaceutical R&D can be divided into the research and the development processes. The research process is the process to seek a NCEs (New Chemical Entities) or NBEs (New Biological Entities) candidate protected by patents. On the other hand, the development process makes one of the NCEs or NBEs into a new drug. For this reason, we analyze not only the research process but also the development process.

The estimation results for low-molecular compound drug R&D are summarized as follows: (i) The research process shows decreasing returns to R&D investment scale, but the development process shows increasing returns; (ii) The empirical effect of patents on the number of new drug is not significant.

After the 2000s, most of the profit of the pharmaceutical companies is gained by biotech new drugs. We employ Amgen Inc. as an example of an independent biologic pharmaceutical company. We measured the research process output in terms of patents on underlying core technology, and the development process output in terms of patents concerning manufacturing or marketing final product. By regression analysis and case study method, we obtain three implications that contrast with previous results from chemical synthesis pharmaceutical companies: (i) Economies of scale may exist in both research and development processes; (ii) Persistency is more markedly seen in the development process than in the research process; (iii) Research and development processes tends to diverge.

Keywords: *Biopharmaceutical R&D, scale effect, separation of R&D, Amgen Inc.*

Understanding and modelling fluorescent dissolved organic matter probe readings for improved coagulation performance in water treatment plants

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Abstract: Removing dissolved organic matter (DOM) from the source water is critical for the drinking water treatment process; the low molecular weight hydrophilic fraction of DOM is generally recalcitrant to removal by coagulation, and the DOM bypassing the coagulation/filtration stages of treatment will likely react with the disinfecting agent in the end of the treatment process, leading to the formation of potentially carcinogenic disinfection by products (DBPs) such as trihalomethanes (THMs). Each specific fraction of DOM reacts with a particular disinfecting agent to form different DBPs, some with higher toxicity and carcinogenicity than others and varying on health guidelines values. Understanding the DBPs formation pathways, however, is a difficult task since humic substances present in the source water are likely to be highly degraded compounds that differ from each other, forming a mixture of diverse molecules which is extremely challenging to individually characterize. Hence there is a need for monitoring certain fractions of DOM, tracking down DOM character and its concentration in source waters.

DOM characterization techniques can be divided into three groups. The first group investigates the abundance and nature of structural units, providing detailed structural information. The second looks into the chemical behaviour of DOM, its molecular weight, molecular size, distribution, hydrophobicity-hydrophilicity, focusing on its polymeric nature and providing good molecular separation. The third measures the fluorescence signal of DOM in situ, without directly scrutinizing chemical identities of functional groups or molecules. However, the methods of the first two groups are not simple and time-intensive, hence not suitable for online monitoring of DOM characteristics; in contrast, the currently available fluorescence probes are a simple, sensitive, rapid, non-invasive way of providing an in-situ estimation of the fluorescent DOM (fDOM). Despite the potential beneficial applications of this relatively new technology, field fDOM measurements are subject to interferences caused by changes in temperature, turbidity, pH, salinity and inner filter effect (IFE). This often makes probe readings untrustworthy, and as a result they are rarely used by the water treatment plant operators. Thus accurate, reliable compensation models should be designed and applied.

In this study, we firstly conducted a number of field sampling and laboratory experiments to investigate the effects of temperature, turbidity and IFE on fDOM sensor measurements. We collected the required data and developed compensation models, in order to understand what the actual amount of fDOM is, compared to what the probe reads. The methodology adopted for each of these investigations was perfected from previous studies, albeit using unusual equipment deployed in particular water bodies (i.e. instrument-specific temperature compensation, site-specific and instrument-specific turbidity compensation, instrument-specific secondary IFE compensation). Threshold autoregressive models were explored as an attempt to best describe nonlinearities of light scattering and light absorption due to suspended particles on fDOM readings. In the second stage of this project, we will conduct further experiments to determine the character and molecular weight of the DOM contained in our samples, collected in a South-East Queensland reservoir; finally, data-driven models will be developed to link compensated fDOM readings with DOM character and other commonly measured quantities (e.g. SUVA and UV_{254}). The benefit of a better understanding and modelling of the actual fraction of DOM measured by the fDOM sensor is the possibility to build a more precise, real-time tool for the estimation of the ideal pH during coagulation, amount and type of coagulants to be dosed, in order to maximize DOM removal and avoid the formation of DBPs in the distribution systems.

Keywords: *Dissolved organic matter, drinking water treatment, fluorescence, remote sensing*

Volatility Spillovers and Causality of Carbon Emissions, Oil and Coal Spot and Futures for the EU and USA

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Abstract: Recent research shows that efforts to limit climate change should focus on reducing emissions of carbon dioxide over other greenhouse gases or air pollutants. Many countries are paying substantial attention to carbon emissions to improve air quality and public health. The largest source of carbon emissions from human activities in some countries in Europe and elsewhere is from burning fossil fuels for electricity, heat, and transportation. The prices of fuel and carbon emissions can influence each other. Owing to the importance of carbon emissions and their connection to fossil fuels, and the possibility of Granger (1980) causality in spot and futures prices, returns and volatility of carbon emissions, crude oil and coal have recently become very important research topics. For the USA, daily spot and futures prices are available for crude oil and coal, but there are no daily futures prices for carbon emissions. For the EU, there are no daily spot prices for coal or carbon emissions, but there are daily futures prices for crude oil, coal and carbon emissions. For this reason, daily prices will be used to analyse Granger causality and volatility spillovers in spot and futures prices of carbon emissions, crude oil, and coal. As the estimators are based on QMLE under the incorrect assumption of a normal distribution, we modify the likelihood ratio (LR) test to a quasi-likelihood ratio test (QLR) to test the multivariate conditional volatility Diagonal BEKK model, which estimates and tests volatility spillovers, and has valid regularity conditions and asymptotic properties, against the alternative Full BEKK model, which also estimates volatility spillovers, but has valid regularity conditions and asymptotic properties only under the null hypothesis of zero off-diagonal elements. Dynamic hedging strategies using optimal hedge ratios are suggested to analyse market fluctuations in the spot and futures returns and volatility of carbon emissions, crude oil and coal prices.

Keywords: *Carbon emissions, fossil fuels, low carbon targets and green energy, Spot and futures prices, Granger causality and volatility spillovers, Quasi likelihood ratio (QLR) test of Diagonal and Full BEKK*

The Correct Regularity Condition and Interpretation of Asymmetry in EGARCH

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Abstract: In the class of univariate conditional volatility models, the three most popular are the generalized autoregressive conditional heteroskedasticity (GARCH) model of Engle (1982) and Bollerslev (1986), the GJR (or threshold GARCH) model of Glosten, Jagannathan and Runkle (1992), and the exponential GARCH (or EGARCH) model of Nelson (1990, 1991). For purposes of deriving the mathematical regularity properties, including invertibility, to determine the likelihood function for estimation, and the statistical conditions to establish asymptotic properties, it is convenient to understand the stochastic properties underlying the three univariate models. The random coefficient autoregressive process was used to obtain GARCH by Tsay (1987), an extension of which was used by McAleer (2014) to obtain GJR. A random coefficient complex nonlinear moving average process was used by McAleer and Hafner (2014) to obtain EGARCH. These models can be used to capture asymmetry, which denotes the different effects on conditional volatility of positive and negative effects of equal magnitude, and possibly also leverage, which is the negative correlation between returns shocks and subsequent shocks to volatility (see Black 1976F). McAleer (2014) showed that asymmetry was possible for GJR, but not leverage. McAleer and Hafner (2014) showed that leverage was not possible for EGARCH. Surprisingly, the conditions for asymmetry in EGARCH seem to have been ignored in the literature, or have concentrated on the incorrect conditions, with no clear explanation, and hence with associated misleading interpretations. The purpose of the paper is to derive the regularity condition for asymmetry in EGARCH to provide the correct interpretation. It is shown that, in practice, EGARCH always displays asymmetry, though not leverage.

Keywords: *Conditional volatility models, random coefficient complex nonlinear moving average process, EGARCH, asymmetry, leverage, regularity condition*

The Fiction of Full BEKK

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Abstract: The purpose of the paper is to (i) show that univariate GARCH is not a special case of multivariate GARCH, specifically the Full BEKK model, except under parametric restrictions on the off-diagonal elements of the random coefficient autoregressive coefficient matrix, that are not consistent with Full BEKK, and (ii) provide the regularity conditions that arise from the underlying random coefficient autoregressive process, for which the (quasi-) maximum likelihood estimates have valid asymptotic properties under the appropriate parametric restrictions. The paper provides a discussion of the stochastic processes that lead to the alternative specifications, regularity conditions, and asymptotic properties of the univariate and multivariate GARCH models. It is shown that the Full BEKK model, which in empirical practice is estimated almost exclusively compared with Diagonal BEKK, has no underlying stochastic process that leads to its specification, regularity conditions, or asymptotic properties

Keywords: *Random coefficient stochastic process, Off-diagonal parametric restrictions, Diagonal BEKK, Full BEKK, regularity conditions, asymptotic properties, conditional volatility*

Estimation when both the covariance matrix and the precision matrix are sparse

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Abstract: Estimating covariance matrices is fundamental to many fields, including applications to Markowitz theory in finance for instance. Methods of imposing sparsity in the covariance matrix, or more commonly in the inverse of the covariance matrix (the precision matrix), have attracted a great deal of attention. One reason these methods are important is that when there are more zero entries in those matrices, the corresponding model is more simply interpretable. A very popular example of such an approach is the graphical Lasso. There are also other approaches that are based on regression interpretations of the entries of the precision matrix or the covariance matrix, or regression interpretations of the entries of their Cholesky factors. Such methods often do succeed in imposing sparsity in the precision matrix. However, in that case, the corresponding covariance matrix is usually not sparse (and *vice-versa*, if the covariance matrix is sparse then the precision matrix is typically not sparse). Currently available methods are usually not able to impose sparsity in both the covariance matrix and the precision matrix.

I describe novel approaches to imposing sparsity in both. Part of the challenge to developing such approaches is that only special algebraic structures can respect these simultaneous constraints on both the covariance matrix and its inverse. The focus is on a particular class of sparsity patterns that correspond to chordal graphs, for which those key algebraic structures can be elucidated. Banded matrices correspond to a special class of chordal graphs, for example. In the case of a banded matrix, it is worth noting that we allow the possibility of some zero entries inside the bandwidth. Being subordinate to a chordal graph is a key property, and although there has already been a great deal of work done on chordal graphs and understanding their local inverse structures in one direction, there has been much less done on understanding the special cases where these algebraic structures simultaneously apply in 'both directions.'

Motivation for the approaches that I describe comes partly from comments of Rothman, Levina & Zhu (*Biometrika*, 97, p539-550, 2010) that "As a rule of thumb in practice, if it is not clear from the problem whether it is preferable to regularize the covariance or the inverse, we would recommend fitting both and choosing the sparser estimate." With this inspiration, I demonstrate these sentiments can now be taken one step further: we now have practical ways to ask for sparsity in *both* the covariance matrix and in its inverse.

Keywords: *Dempster completion, graphical Lasso, regularization and node-wise regression, graphical models*

Hedging Barrier Options through a Log-Normal Local Stochastic Volatility Model

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Abstract: In the equity and foreign exchange (FX) markets, there has been a shift towards using non-affine pricing models as these have been shown to produce more realistic volatility distributions and more accurately capture market dynamics. One such non-affine model is the Inverse Gamma model, which we have incorporated into a Local-Stochastic Volatility (LSV) model termed the Log-normal-LSV (LN-LSV) that can, once calibrated, accurately reproduce market prices of exotic options Langrene and Zhu [2016]. The LN-LSV model is a non-parametric combination of local volatility and stochastic volatility models, in which both the spot price and stochastic volatility follow log-normal processes. The LN-LSV model is calibrated using both the market-traded implied volatility surface and market exotic option prices.

However, while the accurate pricing of exotic options is necessary for good pricing model performance, it is also necessary for models to perform in risk management applications, where hedges are entered into to minimise risk. Therefore, the accurate calculation of the derivatives of the option price with respect to the asset or volatility (the Greeks) is also necessary for good model performance.

This paper aims to characterise the hedging performance of the Log-normal Local-Stochastic Volatility model for a variety of hedging instruments using an historical dataset consisting of daily spots and volatility surfaces for the EUR/USD market over a five-year time period. We use delta-gamma hedging for different barrier options under the LN-LSV model and compare the hedging performance with that of the Black-Scholes (BS) model. Then we use the numerical results to demonstrate that the LN-LSV model is more effective than the BS model.

We use five types of reverse knock-out options as test cases over a time period of five years. On each trading day from 2007 to 2011, the five options are firstly priced using the LN-LSV model. After pricing, each option is hedged daily until the expiry date of the option using a delta-gamma neutral scheme under both the LN-LSV and BS models. To measure the hedging performance, each profit-loss outcome forms one point of the P&L distribution. During Jan 2007 to Dec 2011, the profit and loss of a total of 1100 traded options for each option type forms the P&L distribution. Compared to the Black-Scholes model, the P&L distribution of the numerical results from LN-LSV model is more symmetric and is less likely to have extreme profit-loss outliers. Thus it produces more superior hedging performance.

Keywords: *Barrier option, Delta-Gamma hedging, Black-Scholes model, Log-Normal Local Stochastic Volatility model, hedging performance*

Managing adverse weather conditions through financial instruments: rainfall and temperature

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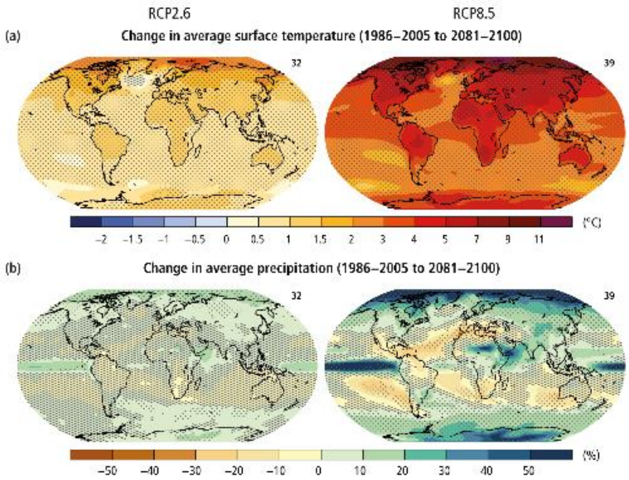
Abstract: National and international policy initiatives have focused on reducing carbon emissions as a means by which to limit future climate warming. Much less attention has been paid by policymakers to monitoring, modelling and managing the impacts of climate change on the dynamics of Earth surface systems, including glaciers, rivers, mountains and coasts. However, it is almost universally recognized that the risks connected to climatic changes are high and somehow unpredictable in their consequences. Moreover, the attempts of managing the climatic changes at a global level, i.e. the decisions taken in the 2015 Paris conference, have been recently counterbalanced by a not clear-cut US policy. Surprisingly, the financial world does not seem to care much about the problem. Yet, it is estimated that 80% of world industry is affected (totally or in part) by climate. In particular, agriculture, building industry and hospitality activities are heavily dependent on climate. Rain or low temperatures may cause cancellations or change of destination for tourists; heavy rain or high temperature damage crops and cause exit of farmers from the market. The present work contributes to the financial and climate literature by proposing a scientific framework for rainfall and temperature risk management using specific financial instruments: the weather derivatives. The aim is to mitigate the negative impacts of rain or temperature on the business performance of a company. As a first step, based on a well-established literature we propose a technique for modelling temperature time series; then, we price a financial instrument (one-month forward) for hedging against high levels of temperature.



A similar analysis is performed on rainfall and a one-month forward is also priced. We checked our results in the geographical area of Arezzo, Tuscany, for temperature daily data 1951-2016 and rainfall daily data 1992-2016. We show how a "negative" weather performance can be counterbalanced by the "positive" performance of the correspondent financial instrument.

Those financial instruments, typically exchanged Over the Counter, can be personalized and tailored according to the specific needs. This can be done through the pricing of the tick size (one Celsius degree or one rain mm) and the specific weather station close to the client. In our analysis, we have chosen 20€ as a tick size both for temperature and rainfall, but of course building contractors and farmers could give different values.

JANUARY 2017 – HDD with threshold 2.43 °C	
Price	139.58 €
Risk loading	34.74 €
Final price	174.32 €
Hedging	
Payoff	451.60 €
Gain (lossa)	277.28 €

FEBRUARY – HDD with threshold7.5 °C	
Price	565.61 €
Risk loading	98.86 €
Final price	664.47 €
Hedging	
Payoff	167 €
Gain (loss)	(497.47 €)

Keywords: *Climate change, weather derivatives, temperature, rainfall*

Do Socially Responsible Investments Strategies Significantly Reduce Diversification Benefits?

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Abstract: The performance of Socially Responsible Investments (SRI) funds is one of the hottest debate in SRI research. As the process of constructing SRI funds employs many non-financial criteria, the performance of SRI might be influenced because of lack of diversification. With socially responsible consideration, the construction of SRI is restricted by many non-financial criteria. Therefore, the diversification of SRI funds would be reduced in two ways. Firstly, investment may be constrained in certain highly correlated scope. Secondly, some good investment opportunities may be excluded by the non-financial criteria. Using a number of screening criteria to measure the screening intensity, most studies found that the number of screens negatively impacts SRI fund performance. This research is motivated to answer a beleaguering question - do social, ethical, environmental and corporate governance friendly consideration and non-financial criteria employed in screening social responsible investment reduce SRI diversification benefits?

There are three research questions answered by this paper. First, this paper studies whether the diversification of SRI funds is significantly different from the diversification of peer conventional funds. Peer conventional funds are selected with matching fund approach by considering fund domicile, year of inception and funds size. Diversification degree of fund in this paper is measured by six variables: the number of stocks, the percentage of top 10 holdings, and asset allocation in cash, bond, and equity. Both Mood's median test and Student's t-test are used in this paper to examine the significance of difference in diversification between SRI funds and peer conventional funds. Second, this paper investigates whether the influence of socially responsible screening criteria on SRI funds diversification is significantly negative. The results of t-test indicate whether the difference in diversification between SRI and conventional funds is significantly negatively. Third, this paper observes the diversification difference between environmental focus SRI funds and environment, social, and governance (ESG) focus SRI funds to determine whether the difference in diversification benefits of these different group of funds (with different screening strategies) is statistically significant. Both Mood's median test and t-test are applied in this part. As the group of environmental focus SRI funds and the group of ESG focus SRI funds are different in size, independent t-test for means is used in this comparison.

Based on maturity of SRI market and data availability, empirical research on social responsible investment is mainly concentrated in the US and some developed European countries. However, economic growth in Asia-Pacific region is rapid and prominent, and the SRI markets in Asia are full of potentiality of development. To fill the gap on SRI research and explore SRI developing in emerging market, this study expands SRI research to Asia-Pacific region. This study uses data gathered from Morningstar and Datastream for a period of 13 years from 2004 to 2016 on five Asia-Pacific countries (United States, South Korea, Japan, Australia and China). This paper contributes to the literature on SRI funds in three aspects. First, unlike most studies on SRI funds that focus on performance of SRI funds, this paper highlights the diversification benefits of SRI funds. Second, unlike most studies that focus on US and European markets, this paper expands research in Asia-Pacific region. The five countries selected are top five countries in the Asia-Pacific region that have highest number of socially responsible funds in Morningstar. A total of 721 SRI funds included in this study represents 90 percent of total SRI funds in Asia-Pacific region. Third, this paper provides a cross-country analyses on SRI diversification between the five countries selected. Findings of this paper show that diversification between SRI and conventional funds, as well as, environmental focus SRI funds and ESG focus SRI funds were significantly different, but the influence of SRI screening on fund diversification are not all negative. Such results support findings in some paper on SRI fund performance that SRI funds do not significantly underperform conventional funds.

Keywords: *Ethical, investments, fund management, diversification*

Semi-Coherent Multi-Population Mortality Modeling: The Impact on Longevity Risk Securitization

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Abstract: Multi-population mortality models play an important role in longevity risk transfers involving more than one population. Most of the existing multi-population mortality models are built on the hypothesis of full coherence, which assumes that there always exists a force that brings the mortality differential between any two populations back to a constant long-term equilibrium level. This hypothesis prevents diverging long-term forecasts, which do not seem to be biologically reasonable. On the other hand, mortality forecasts generated by an arbitrary combination of single-population models are generally non-coherent.

Inspired by the limitations of non- and full-coherence, we propose a new concept called semi-coherence, which is less restrictive than full-coherence, but still includes some sort of mean-reversion (with respect to the difference in mortality between two populations) to avoid an indefinite divergence. The concept of semi-coherence lies in a tolerance corridor, which is imposed on the mortality differential between two populations. Provided that the differential lies within the tolerance corridor, the expected mortality trajectories of the two populations can diverge. However, when the tolerance corridor is exceeded, then the stochastic process driving the mortality dynamics of the two populations should switch to another state, in which the expected paces of mortality reduction for the two populations are changed in such a way that the differential (in absolute value) is expected to shrink over time. In terms of modeling techniques, semi-coherence requires the underlying stochastic process to encompass multiple regimes. The switch between regimes should be driven by the mortality differentials between the two populations being modeled over a certain lookback period.

In particular, we use a three-regime vector threshold autoregressive (VETAR) process to model $\mathbf{Z}_t = (\Delta\kappa_t^{(1)}, \Delta\kappa_t^{(2)})'$, where Δ is the difference operator and the prime sign denotes transpose. We can understand $\Delta\kappa_t^{(i)}$ as the overall mortality improvement for population i from time $t-1$ to t. In different regimes, the dynamics of the improvement rates of the two populations being modeled are different. In general, a VETAR model for a three-regime vector time-series can be expressed as follows:

$$\mathbf{Z}_t = \begin{cases} \omega_0^{(1)} + \sum_{j=1}^{p_1} \mathbf{\Phi}_j^{(1)}\mathbf{Z}_{t-j} + \mathbf{a}_t^{(1)}, & y_{t-d} \le r_1 \\ \omega_0^{(2)} + \sum_{j=1}^{p_2} \mathbf{\Phi}_j^{(2)}\mathbf{Z}_{t-j} + \mathbf{a}_t^{(2)}, & r_1 < y_{t-d} \le r_2 \\ \omega_0^{(3)} + \sum_{j=1}^{p_k} \mathbf{\Phi}_j^{(3)}\mathbf{Z}_{t-j} + \mathbf{a}_t^{(3)}, & r_2 < y_{t-d} \end{cases}.$$

The innovation vector in regime i is given by $\mathbf{a}_t^{(i)}$, which satisfies the equation $\mathbf{a}_t^{(i)} = \mathbf{\Sigma}_i^{1/2}\mathbf{e}_t$, where $\mathbf{\Sigma}_t^{1/2}$ is a symmetric positive definite matrix and $\{\mathbf{e}_t\}$ is a sequence of serially uncorrelated normal random vectors with zero mean vector and identity covariance matrix. The threshold random variable y_{t-d}, where d is the delay parameter, is assumed to be stationary and depends on the history of the time-series in question up to and including time $t-d$. Because we intend to have the change in regime driven by the difference in mortality between the two populations, we define the threshold random variable as

$$y_t = \frac{1}{\ell}\sum_{i=0}^{\ell-1}(\kappa_{t-i}^{(1)} - \kappa_{t-i}^{(2)}),$$

which can be interpreted to mean the average difference in the general mortality levels between the two populations over a lookback period of ℓ years.

The proposed modeling approach is illustrated with mortality data from US and English and Welsh male populations, and is applied successfully to several pricing and hedging scenarios.

Keywords: *Longevity bonds, population basis risk, vector threshold autoregression*

Edge deletion tests in graphical models for time series

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Abstract: In this research, the primary aim is to examine graphical modelling in the context of multivariate time series. This work develops on previous work, which provided two approaches, the GMTS and SIN methods, which gave results for the conditional independencies between the variables in datasets. These methods will be compared with a more recent range of methods for estimating the structure of the graphical model, called ℓ_1-regularization, which focused on inducing sparsity in the model. Examining a Gaussian graphical model context, the aim becomes to estimate the covariance/precision matrix, and then produce the partial correlations between variables. This matrix then provides the significant or insignificant edges (lines) between vertices/nodes (variables) in the Conditional Independence Graph (CIG).These methods are compared using a Monte Carlo simulation study, where structural vector autoregressive models (SVAR) are a mathematical form of representing the dependencies between variables. These simulation studies suggest that the original GMTS and SIN methods produced very useful results in the classification analysis, compared to some of the four ℓ_1-regularization methods used in these studies. Convergence rate analysis and more details on each of these ℓ_1-regularization methods are provided in a comprehensive discussion.

An issue becomes apparent when comparing with the ℓ_1-regularization methods. When the aim of the research is to provide a sparse structure for the model, the SIN and GMTS merely provide different tests for conditional independencies between variables, and do not have a method of inducing sparsity in the structure of the graphical model, like the penalization methods in ℓ_1-regularization. However, perhaps penalization methods are not always necessary when it comes to finding the Conditional Independence Graph (CIG) of the dataset, as shown by the superior results from the GMTS and SIN methods.

Even in terms of the convergence rates, the simpler testing procedures (GMTS and SIN) were a more attractive prospect using these simulated datasets, due to the lack of optimization required in the process. A more formal comparison of the speeds of convergence is required for each of the ℓ_1-regularization methods, since basic observations of process speeds does not provide any proper results in the context of research in this area.

Keywords: *Multivariate time series, sparsity*

Stochastic global optimization using random forests

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Abstract: Global optimization problems occur in many fields including mathematics, statistics, computer science, engineering, and economics. The purpose of a global optimization algorithm is to efficiently find an objective function's global minimum. In this article we consider bound constrained global optimization, where the search is performed in a box, denoted Ω. The global optimization problem is deceptively simple and it is usually difficult to find the global minimum. One of the difficulties is that there is often no way to verify that a local minimum is indeed the global minimum. If the objective function is convex, the local minimum is also the global minimum. However, many optimization problems are not convex. Of particular interest in this article are objective functions that lack any special properties such as continuity, smoothness, or a Lipschitz constant.

The CARTopt algorithm is a stochastic algorithm for bound constrained global optimization. This algorithm alternates between partition and sampling phases. At each iteration, points sampled from Ω are classified low or high based on their objective function values. These classified points define training data that is used to partition Ω in boxes using classification and regression trees (CART). The objective function is then evaluated at a number of points drawn from the boxes classified low and some are drawn from Ω itself. Drawing points from the low boxes focuses the search in regions where the objective function is known to be low. Sampling Ω reduces the risk of missing the global minimum and is necessary to establish convergence. The new points are then added to the existing training data and the method repeats.

In this article we provide an alternative partitioning strategy for the CARTopt algorithm. Rather than using a CART partition at each iteration, we propose using a random forest partition. Pure CART partitions are known to over-fit training data and have low bias and high variance. A random forest partition has less variance than a CART partition, and hence provides a more stable approximation to where the objective function is expected to be low. We also provide a method for sampling low regions defined by random forest partitions. A preliminary simulation study showed that using random forests in the CARTopt algorithm was an effective strategy for solving a variety of global optimization test problems. The authors are currently refining the method and extending the set of test problems.

Keywords: *Bound constrained global optimization, CART, CARTopt, random search*

Optimising irrigated agricultural productivity under varying water availability: industry challenges in northern Victoria

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Abstract: In an environment of uncertain water allocations, irrigated agriculture in Northern Victoria is being challenged to meet the opportunities of a growing domestic and international market. Historically, increased agricultural demand has relied on access to readily available water and productive land. Under current environmental flow obligations and water caps, access to high- and low-reliability water varies by season and is constrained by sustainable diversion limits (SDLs). Assessing options to increase irrigated agricultural production under varying water allocations required the development of an economic framework to enable an evaluation of the balance between environmental flow obligations, consumptive water-use demands, crop performance and farm profitability.

The developed bio-economic model, known as the Water Policy Model (WPM), considers all irrigation districts in northern Victoria and evaluates the economic efficiency implications of specific water allocations and water allocation methods (such as water trading) to ensure that environmental goals are achieved at lowest economic cost. The range of farm activities modelled includes permanent horticulture, summer and winter crops, livestock production, hay production for on-farm use or sale, and maintaining and feeding pasture. The commodities considered are irrigated and dryland pastures, summer and winter grains, pome fruits, grapes, tomatoes, citrus, stone fruits, almonds, olives, dairy cattle, beef cattle and sheep. The total area modelled is 1,601,474 ha.

The model adopts a non-linear optimisation approach and is capable of assessing: the impact of various trading rules; the relative impacts of improvements in crop yields and water delivery technologies on profitability and water use; the economic impacts of substitution of surface water with groundwater; the impacts of commodity price shocks on water use and enterprise type; and the conditions resulting in the transition between irrigated dairy, mixed cropping and irrigated horticulture. The design of the optimisation model is to maximise total net benefits under various constraints including water availability, farm activity, available irrigated farming area, trading rules, SDLs (surface water and groundwater) and production volume. The model utilises satellite data and water/yield production functions based on farming system models.

Results suggest that farm gate profitability from irrigated agriculture in northern Victoria can be increased from $2.2b to $3.6b assuming the current range of land uses, or $3.8b if available groundwater within SDL settings is 50% utilised and to $4.4b with access to additional groundwater and adoption of 10% improvement in water efficiency via genetic improvement, system design and precision water management. Overall, these results imply that achieving maximum profitability for irrigated agriculture industries under future water availability scenarios involves political and economic implications related to land use and access to various sources of water.

The results have been used to inform government and stakeholders of the likely costs in achieving environmental outcomes. Due to the interactive and agile modelling approach developed in this study, enhanced engagement with stakeholders through active participation was achieved. This resulted in improved understanding of complex interactions and informed discussion about the potential trade-offs between meeting environmental flow obligations and maintaining irrigated agricultural profitability in northern Victoria.

Keywords: *Bio-economic model, Decision Support System (DSS), irrigated agriculture*

Floods, amenities and urbanization: tracing dynamics of housing markets and direct damages in flood prone areas

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Abstract: Climate change imposes severe consequences for urban development in hazard-prone coastal and delta areas. The issue is complicated by the fact that disaster risk is spatially correlated with rich environmental and urban amenities of those locations. They drive population clustering and growth of property values in hazard-prone areas, rapidly increasing exposure and vulnerability. Individual preferences for locations play a crucial role in the formation of spatial patterns in urban land markets. In other words, they determine how much capital at stake will specific locations attract, and into how much of direct flood damage would it translate. However, prices in flood prone areas are sensitive to the timing after a hazard event. At the times of natural disasters price trends in flood prone areas shift significantly and abruptly implying that there are systemic changes in property markets. On the one hand, it implies that transactions in the past may not be representative anymore when making current price assessments or projections for the future. On the other hand, it is essential to trace the link between individual risk perceptions and macro-level market outcomes as the former fuel these structural market shifts. This calls for new computation economic methods for assessing capital-at risk and its fluctuations as shocks occur and markets aggregate individual reactions to these natural hazards.

We address this methodological challenge by incorporating adaptive price expectations about land market dynamics into a spatial agent-based model (ABM). An ABM of a housing market in flood prone areas – RHEA – is presented. We build upon previous research on agent-based modeling of urban land markets, and make a step forward towards empirical modeling by using actual hedonic analysis and spatial data for a flood-prone area in North Carolina, USA. A rigorous assessment of property prices and of housing market dynamics in disaster-prone areas should ideally be done based on the most recent sales, which are likely to form a rather small dataset. While hedonic analysis is widely used to understand how various factors contribute to the housing price formation, the robustness of its assessment is undermined when the analysis needs to be performed on relatively small samples. The price expectation procedure in our spatial agent-based housing market model uses hedonic analysis advanced with kriging to capture the neighborhood quality, and accounts for the temporal shifts in the excess of demand or supply. In our ABM heterogeneous household agents (buyers and sellers) exchange heterogeneous spatial goods (houses) via simulated bilateral market interactions with decentralized price determination. Risk perception related to floods plays a central role in the agent's decision making. An agent adapts its housing utility and expectations about property prices on the bases of new information and social learning in areas with increasing climate-driven hazard probabilities. Besides modeling price expectations under flood risk explicitly, our model also traces an evolution of housing prices – and consequently direct flood damages – emerging from interactions of heterogeneous household agents with various individual representations of risk perceptions. We compare market outcomes under three common behavioral models: expected utility, prospect theory and risk negligence Our results demonstrate non-linearity between agents' individuals risk perceptions and aggregated price discount, which uncovers the nature of the gap between the two measurement approaches. In addition, we discuss how an empirical adaptive agent-based model can be applied to simulate the impacts of the flood insurance requirement on housing market under the scenario of the complete take-up. Our approach combines the empirical hedonic analysis with the computational economic framework to examine capitalization of insurance premiums in housing prices, and changes in the capital at stake in the case of a complete insurance take-up. Potential implications for policy as well as synergies with other types of modeling are discussed.

Keywords: *Coastal cities, human behavior, decisions under uncertainty, agent-based modeling, economic policy models*

What Has Changed - A Decomposition of Income Inequality in Australia Between 2001 and 2015

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Abstract: Income inequality in Australia has attracted much attention from the public as well as academic literature throughout the past decade (Wilkins, 2014; Johnson & Wilkins, 2006; Atkinson and Leigh, 2007). While the inequality itself in Australia has not changed dramatically in the past years, several factors such as the financial crisis, have contributed to the fluctuations in the income inequality with varying degrees. Despite the recognition that social inequality may have short and long-term implications for social cohesion and growth (Wilkinson and Pickett, 2009), relatively little is known about the sources of the changes, and to what extent the tax and transfer system affects the income distribution in Australia.

The paper examines the trend in the household equalized income inequality and decomposes the changes in the income inequality in Australia into four main components, namely the changes in the market income (wage and non-wage) and employment, changes in demography and household composition, policy reform in the tax and transfer system and others including behavioural response and indirect effects. We investigate the contribution of each factor to the overall inequality between 2001 and 2015.

The data in this paper draws from the Household, Income and Labour Dynamics in Australia (HILDA) Survey data, a longitudinal survey conducted annually since 2001. Each wave of HILDA contains a representative sample of the Australian population at the time, and we use the first 15 waves for our analysis. This time period offers many policies and market income shocks, including the rise and the fall of the substantial investment in the mining sectors, the financial crisis, and numerous welfare policy reforms that aim at strengthening the work incentives.

Using a decomposition framework similar to Bourguignon et al. (2008), we account for the effects of each of the factors by simulating the counterfactual inequalities levels with changes in the driving factors. Such approach extends the ubiquitous Oaxaca-Blinder decomposition by accounting entire distribution rather than focusing on the mean value. It also allows detailed parameterization of the policy parameters which allows refined examination of policy changes. To estimate the disposable income of the household under different scenario, we use a tax and transfer simulation model called STINMOD+, which is designed to evaluate the distributional and fiscal impact of tax and transfer policies. The model simulates the likely benefit amount and the tax liability of a household conditional on income and other socioeconomic characteristics. The simulation covers all major taxation and welfare schemes (including subsidies and rebates) in Australia and incorporates comprehensive income and asset testing (Li and La, 2017).

Our finding suggests that the inequality level in Australia only fluctuated moderately over the past decade. The market volatility is often the most important driver of income inequality in Australia during this period, although its impact differs for the lower and the higher end of income distribution. Both demographic transitions and policy reforms tend to push for a more equal income distribution, offsetting the growing inequality caused by the market shift. In another word, the income inequality in Australia would have been higher without the accumulated policy reforms over the past 15 years and the demographic change. On average, the observed factors – distribution of the market income, the tax and transfer policies and the demographic transition explain majority of the variations of income inequality in Australia.

By exploiting the income, policy and the demographic variations in HILDA, we shed some lights on the nature of the inequality in Australia. This would help us to understand the mediating role of the tax and transfer system, informing policymakers with the appropriate policy measures.

Keywords: *Inequality, STINMOD+, microsimulation, income decomposition*

Introducing the MERIT economic model: a dynamic general equilibrium-*seeking* model to support decision analysis when out-of-equilibrium dynamics are important

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Abstract: MERIT (Modelling the Economics of Resilient Infrastructure Tool) is a decision-support tool originally developed under the New Zealand government-funded science programme Economics of Resilient Infrastructure (C05X1205). Additional research and consulting programmes, including the government's National Science Challenge: Resilience to Nature's Challenges and the government sponsored evaluation of the (14 Nov 2016) Kaikoura earthquake have since provided opportunities for further refinement and application of this tool.

A key objective in developing MERIT was to provide policy makers with an economic model with capabilities to (1) better understand the economic consequences of natural hazards and other events that cause disruptions to infrastructure services, including how these consequences occur over time, and (2) better evaluate intervention options for mitigating risks and enhancing resilience. On review no prior-existing economic modelling approach was found to provide an adequate framework for development of this model. Computable General Equilibrium (CGE) models had many of the necessary elements (multi-sectorial, ability to consider flow-on or cascading impacts, incorporation of price changes), but are typically based around the identification of steady states of economic equilibrium. In the case of infrastructure disruption this is particularly important, as the time to reach equilibrium will often be longer than the actual length of the infrastructure outage, and during the period of disruption the economy is likely to be exhibiting non-equilibrium behaviour (e.g. industries may be operating at a loss).

The economic model constructed for MERIT incorporates many of the core features of a CGE model, but differs from a 'standard' CGE model in that it is a System Dynamics model formulated using differential equations that describe how the elements in the system change with time. Specifically, System Dynamics considers how stocks change over time based on rates of change. In this presentation I will outline the key modelling tools or 'tricks' used to transfer the CGE modelling approach into the System Dynamics framework. This includes the incorporation of multiple negative-feedback (self-regulating) structures, goal seeking algorithms that alter 'base' prices (i.e. those at the base of the Constant Elasticity of Substitution/Transformation functional-trees typically encountered in CGE models) in response to imbalances between supply and demand, and smoothing functions that allow agents' behaviour to adjust gradually over time to reflect learning and changes in perception avoiding dramatic and unrealistic fluctuations.

We note that some of the features in MERIT that enable it to describe 'disruption economics' or 'economic transitions' have also started to be addressed by analogous extensions within the CGE community. Inclusion of lag times for adjustment in labour dynamic models is one example. An interesting question for reflection is whether MERIT's System Dynamics–based economic model indeed presents a distinct approach, or is better viewed as a natural extension to existing or emerging approaches, utilising a particular set of numerical methods for approximating solutions in the context of complex systems.

Keywords: *Economic disruption, natural hazards, system dynamics, general equilibrium, economic transition*

The impact of newer motor vehicles on fuel expenditure

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Abstract: Petrol is one of the limited resources used extensively for transport. As petrol prices increase, and public concerns regarding climate change and CO2 emissions increase, there has been a trend toward purchasing newer, more fuel efficient cars which provide savings to households in lower fuel costs.

This paper looks at the take up of newer vehicles from 2013 to 2016, and estimates how much households have benefited from moving to newer vehicles, in terms of the costs saved in fuel (based on KM travelled). Over this period, fuel prices in Australia did not change much, so any change in fuel expenditure per KM can be attributed to more efficient vehicles.

The estimation is conducted using a microsimulation model of vehicle use, which has allocated vehicles from the Motor Vehicle census in 2013 and 2016 to households on a synthetic small area population. The paper shows an innovative use of synthetic small area populations, and the power of a synthetic population in terms of the ability to impute data from other sources, like the Motor Vehicle census, onto the population.

Because a spatial microsimulation model was used, distributional results could be derived, so results for small areas; for different family types; and for household income deciles.

The results show that in many regional and remote areas of Australia, the amount spend on fuel per KM driven has decreased from 2013 to 2016. This change has been driven by a move from larger, less fuel efficient and older vehicles to newer, more fuel efficient vehicles.

In Australian cities, the change in fuel costs per KM travelled has been minimal, except in areas just outside cites, where it has increased.

Looking at state results, Tasmania was the only State where households paid more on fuel per KM in 2016 compared to 2013. This could partly be driven by lower incomes in Tasmania, so less capacity for updating to more efficient vehicles.

Looking at different family types, the family type that saved the most in fuel expenditure from 2013 to 2016 was one parent families who saved $3.01 per week ($157 per year). Lone person households spent more per KM on fuel over this period by 41c per week, or $21 per year.

Looking at the results by income decile, households in the lowest income decile experience the greatest increase in fuel costs, while households in all other income deciles spent less on fuel per KM driven in 2016 compared to 2013. This is mainly because households in the lowest income decile do not update to more efficient vehicles as often as households in higher income deciles.

Overall, this paper show how spatial microsimulation and data imputation can be used to observe the impact of changes in behavior (in this case purchasing of more efficient motor vehicles) on different groups in the population, and the power of modelling that allows the imputation of data from one dataset to another. In this case, the motor vehicle census was used to impute motor vehicles onto households from the household expenditure survey. This then means that the benchmarked household level variables on the household expenditure survey are available to derive cross-tabulated results.

Keywords: *Fuel expenditure, microsimulation, fuel efficiency*

Simulating scalable Long Range Wide Area Networks for very low power monitoring applications

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Abstract: The recent emergence of Machine-to-Machine networks and the Internet of Things has generated interest in technologies that can underpin networks of low power devices that sporadically exchange data. Both the research and the standardization communities have been actively participating in seeking and defining tech-nologies of the underlying structure of future networks. These Low Power Wide Area Networks (LPWAN) will support large number of nodes with long-range wireless communications on the one hand, while guaranteeing a long life for very cheap sensing devices on the other. Among the many applications that can be supported on these network, there is a wide range of monitoring applications which include low power tracking and radiolocation. The radiolocation application enables a device to determine its position using signals from base stations. It is similar in spirit to GPS except that the signals of radiolocation are provided by terrestrial base stations instead of satellites. This contribution focuses on one such LPWAN technology, called Long Range Wide Area Networks (LoRaWAN) which incorporates the necessary features for radiolocation purposes. A LoRaWAN consists of a central controller which controls several gateways, that in turn listen to incoming data sent by low powered end-devices over sub-gigahertz unlicensed spectra. The geographical placement is such that a signal sent by one end-device is received by at least three gateways. Multilateration for the location of an end-device can be performed by using a combination of both the strength of the signals and the time difference of arrivals measured at the multiple gateways which are in the transmission range of this end-device.

In order to feature LoRaWAN in city scaled scenarios, it is very important to design a proper positioning scheme for gateways and end-devices to assess the related performances in several network conditions. Given the lack of simulation instruments targeting scalable LoRaWAN deployments, this contribution introduces an event based simulation environment that has been developed to characterize the performances of very large LoRaWAN scenarios. Through huge simulation campaigns, the capacity of such network has been thoroughly evaluated in order to predict the impact of low power radiolocation for future tracking applications. Simulation results have also validated the expected probability models for the LoRaWAN throughput and have provided a realistic description of more complex application scenarios.

Keywords: *Low power wide area networks, performance evaluation, scalable deployments, simulations*

Getting to work: smart work centers reduce morning peak traffic flow

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Abstract: Current transport planning in Australia appears to concentrate on increasing supply of transport infrastructure and services and we invert the problem and consider a transport demand management option: smart work centers or hubs located 'close to load'. Smart work centres are an alternative to CBD office space or home-based work or "third space" options like libraries and cafes. Well-equipped, connected and secure, they are small scale and designed to accommodate small businesses, collaborations and corporate employees working closer to where they live. In principle this is the workplace analogue of water saving devices in the home or distributed energy generation. However, the implementation of smart work centers (SWC) is sparse or close to existing major workplace locations. The research question of this paper is: if SWCs were specifically located near where commuting populations reside (rather than where they work) how would multiple SWCs influence traffic flow on a key arterial road in Sydney?

We selected Sydney CBD as a destination zone from the NSW Bureau of Transport Statistics' origin-destination peak AM data on trips and travel time. We selected only trips by non-mass transit passenger vehicles and used census data to further selected for occupation types that would use a SWC (exclusively Managers, Professionals, Clerical and administrative workers). From this we ranked the origin zones that had the greatest potential for a SWC based on peak AM person hours commuting.

For this proof of principle exercise, we selected two segments of Parramatta Road (Sydney's main western arterial road), which have AM peak flows of ~ 1600 vehicles/hour. From the Sydney Coordinated Adaptive Traffic System (SCATS) we obtained vehicle flow rate and speed data for 15minute intervals over the AM peak for the study segments. From this we derived an elasticity of travel time with flow rate with a parabolic regression function.

Based on detailed census and traffic flow data, and a conservative assumption about SWC utilization (50%), we find that 8 SWCs can reduce flow by more than 80 vehicles/hour. This equates to *all* commuters saving approximately 1minute travel time on the study road segments. This is a promising result that suggests further research is worthwhile: investigating the effect of a larger population of SWC on the same study segment; assessing the effect of a larger population of SWC on the metropolitan road network and; surveying the commuting population regarding likely uptake.

Keywords: *Origin, destination, transport modeling, work hub, congestion, commuting*

Importance of the order of the modules in TransMob [Huynh et al., 2015]

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Abstract: Nowadays, a wide range of microsimulations are performed thanks to agent based simulations. This frame-work allows to model the interactions between agents and environment in a flexible way. Such models should be initialised with a given set of agents representing the initial population, and their interactions rules should be set. Very often the initial population of agents is obtained using a synthetic population generator.

TransMob is an agent-based model that aims to simulate transport and land use interdependencies for urban planning. TransMob contains two types of modules responsible for: the dynamics of the social structure within the population (ageing, divorces,...); and the travel behaviour of the individuals (assigning diaries, ...). In the current version of TransMob, the processes happening in the agents everyday life are modelled and performed in a specific order: first ageing, then death, divorce, marriage and finally giving birth.

This work focus on the impact of the ordering in which the different modules responsible for the update of the social structure are applied. This presentation aims at analysing the impact on the results if the order of the procedures is changed. For instance, how will the results change if the divorces are performed after the marriages? Let us denote the processes age, die, divorce, marriage and birth by 0, 1, 2, 3, 4 respectively. All possible orders are then given by the set of all permutations of the integers from 0 to 4. Thus, 120 different orders could be analysed.

However, if birth is applied before age, then in the first iteration, we will add new babies to the babies already in the initial population, resulting in an artificial peak of 1 year old agents in the first simulated year , 2 years old in the second simulated year, etc. For this reason, we only consider orders performing age before birth. This reduces the number of feasible orders to 60.

The analysis is performed using clustering and decision trees. The first results show that the place of ageing with respect to the place of death influences strongly the results. For instance, when ageing the agents is done before death, the final population is younger.

We aim to continue in this direction to further identify the consequences of choosing any particular order. The goal of this work and future research is to make scholars aware of the impact of a choice and provide them with findings to help them chose the best order for their application.

Keywords: *Spatial microsimulation, agent-based modelling, classification*

A Global and Local Learning Model of Transport (GALLM-T)

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Abstract: The transport sector is accounts for 14% of global greenhouse gas emissions (Sims, et al., 2014) but is also an essential service underpinning economic growth and societal well-being. The transport sector will therefore need to maintain or enhance mobility while transitioning to lower emission modes, fuels and technologies. Globally the road sector is the largest source (72%) of transport emissions. Most road vehicle fuel efficiency improvements reduce the total cost of travel and therefore represent a negative abatement cost. However, other abatement opportunities such as vehicle electrification and other alternative fuels involve switching vehicle technologies, with emerging technologies initially having higher costs than the existing more emissions-intensive alternative. Uptake of these technologies helps reduce their costs through 'learning by doing', where cost reduces as uptake increases. Economies of scale in manufacturing of these vehicles will also reduce their cost. To explore the impacts of policy and economic drivers on the transport mix, CSIRO has developed a partial equilibrium model of the global transport sector, GALLM-T, which explicitly includes learning by doing.

The model uses experience curves to endogenously determine the future cost and uptake of fuel conversion technologies related to transport. GALLM-T features 13 regions, 17 fuel conversion technologies, 16 fuels, 5 passenger modes and 7 modes of freight transport. Technologies subject to learning include batteries in electric vehicles and fuel cells in fuel cell vehicles. Component learning is included where technology components have shared learning among technologies that have those components. For example, the carbon capture and storage (CCS) component in fuel production facilities is a component that is shared among all facilities that include CCS technologies.

The nonlinear experience curves have been approximated as piecewise-linear functions, and the model's `selection' of which linear piece it is on at each point in time forms the core integer part of GALLM-T. GALLM-T is solved in GAMS as a mixed integer linear program.

This paper introduces the model and provides results from its application in the second of CSIRO's National Outlook projections, a project which explores different futures for Australia, within the global context, through quantitative scenario analysis. In the Outlook, global transport, electricity, land use and economic models are linked to generate a consistent set of inputs for national models that explore Australian outcomes in more detail.

Future demand for transport has been sourced from linking GALLM-T with a global general equilibrium model (GTAP.ME-3). GALLM-T has also been linked with CSIRO's GALLM-E model, which is used to determine the future cost and uptake of electricity generation technologies. Both GALLM-E and GALLM-T have the capacity to project uptake of batteries and fuel cells. Where this occurs in both models, the combined impact pushes these technologies down the experience curves faster, accelerating the rate of cost reduction.

This paper compares results from scenarios with moderate and strong global climate action. Illustrative results show a more than 60% share of electric drive trains in the total stock of passenger vehicles and 70% in light commercial vehicles by 2050 under both carbon price scenarios (\$31/tCO_2e and \$65/tCO_2e by 2050). There is a limited uptake of fuel cell drive trains in cars and light commercial vehicles. Low coal prices also lead to the construction of coal to liquids plants (with and without CCS), mainly providing fuel for the freight sector which continues to have a high share of diesel engines. There is a greater share of production of biofuels, which displaces conventional and alternative fossil fuels under the higher carbon price scenario from the year 2040 onwards.

Keywords: *Learning curves, transport, electric vehicles*

Optimising Thermoelectric Generation for Recovering Waste Heat from Vehicle Engines

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Abstract: About 60% of the generated energy in internal combustion (IC) engines of vehicles is lost in the form of waste heat, being either exhaust heat, or absorbed by the engine cooling system. Thermoelectric generation (TEG) could be used to harvest the waste heat and convert it directly into electricity. One of the challenges to improve the heat-to-electricity conversion has been perceived to be maximising the amount of waste heat that can be captured by the TEG device from hot gas flowing through the engine exhaust system, since waste heat carried by the gas would be permanently lost upon leaving the exhaust.

At the start of the investigation, a benchtop TEG testing system, consisting of an exhaust pipe, a hot air gun, a heat exchanger, TEG modules, and cooling units is established. The electrical output power generated by TEG modules is recorded, and the temperatures are measured at the hot air inlet to the pipe, the pipe external surfaces, the heat exchanger, the cooling unit, and the outlet where the hot-air exits the pipe.

During the course of the experimental study, the focus is on the effectiveness of a vertical TEG structure to capture waste heat, transport it to the TEGs, and convert it into electricity, which can be indicated by temperature difference between the inlet and outlet of the exhaust pipe as well as electrical power output. Two different designs of heat exchanger fins proposed in the literature having significantly different ability in capturing heat were incorporated in the vertical TEG structure. At the completion of the experimental study, the dependence of this effectiveness on the design of the heat exchanger fins, TEGs and the interfaces between TEGs and others is established.

A Computational Fluid Dynamics (CFD) model of heat transfer and fluid dynamics has been developed to simulate the interactions between the hot air flow, the heat exchanger fins and the thermoelectric generation device in terms of the heat capture and transportation and electrical energy generation. Mechanisms of waste heat capture and transfer are analysed in relation to conductive heat transfer through the solid structure as well as heat transfer through gas-solid (gas/heat exchanger fins) and solid-solid (substrate/TEG module) interfaces. In this study, a linear heat transfer model was used to represent heat transport through the solid-liquid (TEG module/cooling water) interface.

The combination of the experimental and CFD modelling work leads to identification of key structural and operational parameters that influence density of the heat flux between the heat exchanger and the TEGs, and hence electricity generation. This work has found that the heat exchanger design, TEG materials specification, the contact quality between TEGs and others play critical roles in maximising electrical energy generation and minimising lead-time required to reach maximum thermoelectric generation. This confirms the importance of a comprehensive approach that covers both TEG material research and engineering design of the heat exchanger unit to develop high-performance TEG modules for vehicle engine applications in future R&D.

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Keywords: *Vehicle, waste heat recovery, thermoelectric generation, computational fluid dynamics (CFD)*

Green, Affordable Housing: Enhancing Residential Operational Utility Efficiency for Low-income Households. A Integrated Systems Thinking Approach.

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Abstract: Housing affordability subsidies to low and middle income households consistently represent an approximate annual expenditure in excess of $1.9 billion AUD to the Australian taxpayer. The National Rental Affordability Scheme (NRAS) is being phased out, presenting an opportunity to innovate for polices which are targeted to the amelioration of 'housing stress' for low-middle income households.

Escalating energy and water expenses are increasing net housing costs for average Australian households at a rate in excess of the consumer price index. By metrics of 'housing stress'- low and middle income households are most affected. Whilst escalating utility rates apply increasing pressure on households bottom line, conversely, investments made in operational efficiency improvements early in a buildings lifecycle improve the overall net present value proposition when looking at ongoing government housing affordability subsidies as a system.

Developers and landlords have been reluctant to invest in 'Green building' principles for low-middle income rental developments due to a lack of incentive. In an era of globally compressing bond yields, the emergence alternate 'low-carbon' funding sources (ie. Green Bonds) present an opportunity to channel a burgeoning 'Socially Responsible Investment' (SRI) portfolio from institutional investors towards the affordable housing problem, whilst promoting a national effort towards a 'green economy' and carbon-reduction commitments made under the UN Framework Convention(s) on Climate Change. This opportunity is particularly relevant when backed by government.

The success of the adoption of NRAS by the private (and later) institutional sector has demonstrated that there is a strong appetite for long term (10 year fixed income) government backed policies offering a reliable (and arguably generous) return on investment for those dwellings accepted into the NRAS pool.

Data has been analysed for an average Brisbane apartment building, suitable to low-middle income households. At current utility escalation rates (not inclusive of connection fees), utility consumption costs borne by the tenant comprise approximately 8-15% (1 to 3-bedroom units respectively) of total housing costs over a 10 year period (2016-2026). An initial investment into green building principles (such as operationally efficient lighting, appliances) from the beginning of the period can reduce these costs by 1.7-3.8% respectively. The study found that these 'green' 'low carbon' improvements could be offset through the effective use of low interest debt- particularly via the issuance of a government backed 'Green Bond'.

This paper shall expand upon this analysis, testing a variety of scenarios with systems dynamics. The complex interconnection between the variety of stakeholders involved in the delivery and management of social/affordable housing developments in Australia will be explored. These main stakeholders include Government (Federal, Local and State), Developers, Investors (private and institutional) and Tenants.

Keywords: *Green economy, National Rental Affordability Scheme, low income housing, housing stress*

Spatially optimised tree plantings to minimise urban heat

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Abstract: There is a notable increase of "Greener City" strategies which indicates a re-discovery of the many benefits urban greenspace provides. The planning of urban green space, particularly urban forests, on a relatively large scale in a very complex multi layered urban environment is however a challenging task. Multiple benefits must be simultaneously evaluated and traded-off. Here, we present a feasibility concept which combines spatial analysis and tree architecture with concepts from operations research to spatially target planting locations. We demonstrate the concept in a highly simplified approach to reduce urban heat. Because of its prototype character and its simplified assumptions, particularly around local heat balances, we do not advocate an application of the method in current planning processes but stress the need to integrate a more sophisticated heat balance model. Though urban trees provide many other benefits such as visual amenity, recreational and health benefits and constraints such as root impacts on infrastructure exist these are presently excluded from the initial model and may be incorporated in subsequent model extensions.

Keywords: *Urban heat island effect, urban forest, allometry, spatial optimization*

Assessing Infrastructure System of Systems Integrity

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Abstract: Infrastructure refers to the fundamental facilities and systems serving a country, city, or area, including the services and facilities necessary for its economy to function. Infrastructure systems typically consist of interrelated constituent systems forming what is known as *system of systems* (SoS). Infrastructure systems present numerous challenges throughout their lifecycles. This paper addresses one of these challenges that is presented during operation, when managers need to report 'how well' the system is performing and finding ways to address the consequences of unexpected events that often degrade the intended performance. This state of system 'wellbeing' will be referred as *system integrity* (SI).

When applied to infrastructure systems this paper proposes a model suggesting that *system integrity* is a combination of operational performance, safety and resilience which become the set of criteria to assess SI. Each of these three factors is assessed by considering their specific 'key performance indicators' (KPI): Operational KPIs (KO), Safety KPIs (KS) and Resilience KPIs (KR). KOs could include KPIs for quality of service, reliability, availability, maintainability and cost; KSs could include KPIs for number and severity of accidents; and KRs could include KPIs for level of disruption and time for recovery to acceptable levels.

In accordance with the proposed model *system integrity* can be defined as the *"state of a system where it is performing its intended functions safely without being degraded or impaired by changes or disruptions in its internal or external environments"*. When the system achieves the state of perfect condition its *system integrity* is 100% or 1.0. Infrastructure systems may operate at lesser levels of *system integrity* (SI) and it is important to assess and monitor SI to make sure the system is operating within acceptable levels and to envisage ways to improve SI in the event of unexpected situations.

The proposed model based on the on-going operational performance, safety and resilience of the each constituent system in the SoS is then developed into a method that applies the Analytic Hierarchy Process (AHP) (Saaty 1994) to create a quantitative assessment derived from qualitative and quantitative information. The method assumes that there is a set of KPIs for each of the agreed assessment criterion for operational performance, safety and resilience which were defined, agreed and can be individually assessed. The method uses qualitative experience-based information to weight the KPIs for each of the three criteria relatively to each other using AHP to obtain the overall assessment for operational performance, safety and resilience for each individual constituent system. These three criteria are also compared and weighted using the same approach to determine their level of contribution to SI which is then calculated using the actual value measured or estimated for each KPI. The method is then expanded to calculate the SI for SoS by applying the concept of 'supermatrix' proposed by AHP to address systems with feedback loops where individual components and assessment criteria influence each other. The SoS SI method is then applied into a hypothetical urban transport system for illustration purposes.

Keywords: *Infrastructure, system of systems, system integrity, urban transport*

Breaking away from trend-based analysis for regional modelling and planning

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Abstract: Traditional approaches to regional modelling and planning rely on trend-based analyses whereby demographic projections are used to initialise and bootstrap future demand for housing, transport and jobs. Besides, most of these approaches cannot adequately take into account the intricate interactions between land use, transport and regional economic drivers. The model developed for the Illawarra region (south of Sydney, Australia), called Vision Illawarra, draws upon and expands the Metronamica© platform developed by RIKS (Netherlands) into a 4-component dynamic model. A regional economic model (CGE) drives the number of jobs available and informs a demographic model (Synthetic Population) on employment levels and migration needs. The land use model (cellular automaton) spatially allocates the residential, commercial and industrial areas based on demand set by the economic and population models and existing/future zoning plans. A 4-step transport model is informed by the land use model and provides a dynamic feedback on land accessibility. Vision Illawarra has been calibrated for the period 2006 - 2011 and the simulation of scenarios uses the time window between 2011 and 2031. In this paper, we present the development and calibration of the model, as well as the exploration of three plausible scenarios with the model.

Keywords: *Regional planning, integrated modelling, Vision Illawarra*

Modular System Approach for Modelling Socio-Technical Transitions towards Alternative Energy Infrastructures in Urban Areas

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Abstract: Reducing greenhouse gas emissions (GHGE) in urban energy systems requires the implementation of alter-native infrastructure configurations across different geographical, technical and social scales. Furthermore, alternative configurations may improve systems resilience and democratization of service provision. How-ever, unlike current centralised systems, which are well understood from the technical and social perspectives, there is a lack of knowledge on the socio-technical interplay across multiple intermediate scales of alternative infrastructures, defined as all the possible configurations in between off-grid and centralised infrastructure. There are various concepts in the literature describing decentralised, distributed and integrated systems using different primary energy resources and generating various energy carriers -for electricity, heating, and cool-ing. However, the information on alternative models is limited to the technical requirements leaving a gap in knowledge on the societal requirements. Alternative infrastructure models potentially reduce GHGE but they may require unique forms of social organisation structures to support their adoption and increase the pace towards decarbonisation. To obtain in-depth understanding of the socio-technical interplay of alternative in-frastructures across scales, this paper draws on complexity theory, the concept of modularity and transitions modelling literature. This aid in the definition of the proposed conceptual framework and the Service Provision Modules (SPM). This conceptual framework serves as the basis for spatially specific modelling and simula-tion. The SPM may use different types of networks and can represent any type of conventional or alternative infrastructure configuration. The conceptual framework then uses the modules to construct the socio-technical layouts for the baseline and possible future configurations in a given area. The paper briefly outlines various concepts in the literature which technically define alternative energy systems, then presents a description of the conceptual framework and the definition of an SPM. Finally, the SPMs are used to represent the Australian electricity system.

Keywords: *Socio-technical systems, synergies, transitions, modelling, urban*

How to choose the right planning horizon? Using multi-objective optimization to support urban planning

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Abstract: To be useful to urban planners, urban models need to deliver plausible futures. However, the complexity of urban processes and related uncertainties make it difficult not only for urban planners, but also for urban models, to deliver plausible futures. Such uncertainties may for example involve population growth and the preferences of different stakeholders, which may change over time. In addition, urban planning outcomes are multi-dimensional and usually there are many trade-offs involved. To account for uncertainties in a multi-dimensional context we propose a modelling approach based on multi-objective optimization. We applied this approach in an artificial experiment and to a city in Switzerland accounting for two objectives. These were to preserve high-quality agricultural soils and to guarantee compact city development. As the most productive soils are often located close to existing urban areas, these two objectives are strongly conflicting and can cause a large trade-off. Our methodological approach involved two steps. First, in an artificial experiment, we demonstrated that uncertainties related to population growth or choosing a wrong planning horizon can prevent planners from reaching optimal solutions. We then tested the results from the artificial experiment for a real-world problem, which was the city of Uster in Switzerland. As the real-world problem was very complex, we used a metaheuristic for solving the multi-objective optimization problem of allocating new urban areas in all possible ways that would protect the most fertile soils and guarantee the compactness of the urban patterns. The used metaheuristic was the genetic algorithm NSGA-II. In order to account for the spatial nature of the optimization problem, we used a modified version of the original algorithm. After this, we ran the modified NSGA-II many times in order to create several Pareto Fronts for different planning horizons or if including uncertainties in population growth. We show that despite uncertainties and even when choosing a short planning horizon we may still be able to reach optimal urban patterns in a distant future, which is surprising as we are dealing with a highly non-linear combinatorial problem. In conclusion, the methodology we developed could help urban and spatial planners to identify the right planning horizon for a large variety of urban and spatial planning problems. In addition, the results from the multi-objective optimization can be used to improve interactive decision-making processes. By not only presenting a limited number of scenarios, but a whole range of different Pareto-optimal trade-off solutions to the decision-makers, they may be able to choose an efficient solution that fits their preferences very well.

Keywords: *Multi-objective optimization, urban planning, peri-urban agriculture, preserving soil quality*

Infrastructure Disruption using Spatial-MERIT within Greater Auckland, New Zealand

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Abstract: Urban planning is multi-dimensional: policy-makers, planners and infrastructure providers must balance multiple and often conflicting objectives and values as held by diverse stakeholders. It also must focus on the long term, given that decisions will have long-lasting, and often irreversible, consequences for communities – extremely challenging given the highly uncertain nature of future socio-economic, environmental and technological change. Against this backdrop it is increasingly recognised that tools to support robust decision-making should provide capabilities to test multiple plausible futures and transition pathways, including scenarios involving extreme impact, but low probability, disruption events such as natural hazards (storm surge, earthquake, tsunami, volcanic eruption) or anthropogenic disruption events (terrorism, cyber-attack).

This paper describes Spatial-MERIT as developed within the New Zealand government-funded 'The Economics of Resilient Infrastructure' research programme. Spatial-MERIT is decision-support tool developed in the Geonamica model integration toolkit capable of simulating the ex-ante impacts of infrastructure disruption within the greater Auckland urban area across space and through time. It is intended to support urban policy development and decision-making by enhancing understanding of the wider systemic (including 'higher order', cascading and critical interdependencies) impacts of disruptions, and importantly, the societal value of investing in resilience-building mitigations and adaptations. We pay particular attention to the complex nature of robust decision-making in post-event response/recovery which is characterised by self-reinforcing feedback loops, time lags, and high levels of uncertainty.

Spatial-MERIT applies a 'system of systems' approach to simulating the implications of infrastructure disruption. Theory-based generative modelling is at the heart of Spatial-MERIT, with demographic, economic, land use, transport and organisational behavioural change sub-systems dynamically coupled to understand the implications of prioritisation and bundling of resilience-building initiatives through time. Or, put alternatively, to gain a fuller understanding of the impacts of different 'dynamic transition pathways'. Key spin-offs discussed include out-of-equilibrium dynamics, incorporation of organisational behavioural change, and the fully integrated nature of the economic, land use and transport sub-systems, simulated through continuous internal feedback loops.

Our modelling is showcased using a hypothetical volcanic event in the Auckland isthmus. We discuss the implications of the event on the socio-economic activities in the affected area and the impact this has on the transport and mobility of the wider region. We assess the implications on the economy of the region, directly after the event up until its recovery and consider the behaviour of businesses during the recovery period. To understand how the impact of an event might change into the future, we assess not only the implications of an event according to the current lay-out of the Auckland region, but also calculate how the spatial configuration of land uses, activities and infrastructure networks is likely to change in future as different activity levels and a different activity distribution will have implications on the impact of the event. Intervention scenarios then allow us to consider how planning and infrastructure development can contribute to a more resilient urban environment.

Keywords: *Economic assessment, Decision Support System, infrastructure resilience, integrated modelling, land use modelling*

Algorithms for estimating global solar radiation on an inclined plane

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Abstract: To evaluate the expected thermal performance of a building, for instance using Accurate, or the electrical output of a PV system, one needs estimates of the global solar radiation on various inclined surfaces. Typically, the data available comes in three possible configurations:

1. Measured Global horizontal irradiation (GHI), Diffuse on the horizontal (D_H) and Direct normal irradiation (DNI), the last meaning on a plane perpendicular to the sun's rays.
2. Measured GHI only.
3. GHI estimated from satellite images, rather than measured - this is the common situation in Australia, as there are less than ten measuring stations operated by the Bureau of Meteorology. Note that this is data for a 5 km by 5 km grid, rather than a single location.

Each of the three cases above have to be treated separately, although 2. and 3. are treated in a similar fashion, with just one simple added assumption for 3. The methods are as follows:

1. One uses spherical trigonometry to convert the DNI to Direct on the required plane. Trigonometry cannot be used for the D_H as that would need the assumption of the diffuse being isotropic over the sky dome, which is not the case. So, one uses a semi-empirical method devised by Perez and co-workers. Then one simply adds the two components together to obtain the global on the plane.
2. This situation is more complicated, as we first have to estimate the D_H and the Direct on the horizontal from the GHI. This has been the subject of much research since the area was first proposed by Lui and Jordan in the early 1960s. The most parsimonious model for this purpose is the Boland-Ridley-Lauret (BRL) model. One uses the BRL model to estimate the diffuse fraction (the fraction of the global that emanates from bouncing off the particles in the atmosphere to the location) and from that the Diffuse and Direct on the horizontal. Then one follows the procedure in 1. to obtain the global on the plane.
3. This follows the same procedure as in 2. except that one must assume that the estimated GHI for the grid is homogeneous through the grid and thus holds for the location in mind.

I will describe the use of the algorithms for two specific cases in diverse climate zones.

Keywords: Global radiation, Direct normal radiation, Diffuse radiation, BRL Diffuse model

INVITED PAPER

EXTENDED ABSTRACT ONLY

Where, when and how electricity is produced and consumed – from individual households to region-wide estimations

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Abstract: At times of peak demand, during simultaneous strong customer demand, the electricity network is under stress and can collapse. This happens when temperatures reach extremes, industry is operating and energy-intensive appliances are in use. While air-conditioners and hot water systems have been identified as the main contributors to residential peak load, other types of loads can also strongly contribute to peak load and this contribution can vary depending on the location on the network. With the increase in local electricity production from rooftop solar panels, some or all of these loads could be covered using a good energy management system and/or battery system, for individual or groups of premises (e.g. for a street, or a larger area under a same branch of the network). Understanding location specific load contributions in terms of magnitude and time is then necessary to effectively target load management and reduction with adapted solutions. This will prevent network stress, and in turn avoid costly network augmentation while ensuring safe and reliable electricity delivery.

Thanks to greater availability of smart-meter data, access to individual circuit loads is now possible. We have used such data to extend MODAM, an agent-based simulation platform that assesses the impact of trajectories of electricity consumption and production from decentralised generators, on the different assets of the electricity grid. This extension allows MODAM to perform simulations not only at the medium voltage network, it now includes load information from individual circuits at residential premises that can be used for simulations on the low voltage network. This extension of the software allows:

1. Quantifying the contribution of the different load types at different times of the day and the year, and at specific locations on the network using actual data,
2. Identifying which of these load types can be reduced or shifted for the given network locations, and quantifying their effect,
3. Investigating solutions that would help reduce/shift these loads while still answering the needs of the people and of the grid. These can be
    a. Technological options – e.g. installing additional solar panels, household or community batteries, using home energy management systems, etc…
    b. Social or behavioural options– e.g. engaging with the customer to better understand their needs, as well as for them to understand how their usage impacts the network,
4. Running of simulations with such options over large areas of the network to assess how they help reduce the load overall and during peak times.

Simulations and analyses have been undertaken for a case study in Townsville where each house has solar panels. A technological solution (installation of batteries) was investigated, showing how peak load could be reduced by up to 35% at the transformer under two equivalent installation types –where individual houses had their own battery or they pooled in a common battery. Comparison of the benefit of community batteries versus individual ones in terms of battery usage, network coverage and individual costs were also undertaken as a way for the user to decide what options would suit them best, while still helping the grid.

Keywords: *Electricity distribution network, low voltage, decentralised generation*

Can rooftop solar panels cover increased electricity loads during heatwaves?

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Abstract: With climate change, it is expected that frequency and intensity of extreme weather events will increase. An example of extreme weather event is heat waves, which are defined as three or more consecutive days of unusually high temperatures. These long periods of hot weather have serious effects on health and have caused many mortalities in the past. To better cope with such weather conditions, many people have installed air-conditioners. However, when many such cooling appliances are all switched on at the same time and industry is operating, the electricity demand peaks, often leading to great stress on the network. Understanding the impact of heatwaves on the health of the electricity network is therefore important, especially as these types of events are expected to increase.

We have analysed the impact of heatwave on electricity consumption in Queensland, and investigated rooftop solar panels as an option to reduce peak demand during such weather events. Two analyses were undertaken for the February 2017 heatwave for two levels of details: a global analysis at the state level and a detailed analysis on a low voltage network. The first study compares the electricity demand for the whole state of New South Wales during the heatwave event and quantifies the contribution of solar panels output in reducing electricity demand. It showed that the peak consumption was reduced by about 4% (where PV generated 597 MW over half an hour) thanks to the rooftop solar panels contribution. The second study focusses on the consumption of nine individual premises located in a same street in Townsville. The contribution of the solar panels in reducing the households' demand from the grid varied quite significantly amongst the different users, from 0.6% to 25%, with a median of 3.5%.

While the first study gives an estimate of how much solar panels can help reduce the demand on the state overall, the second one which is location specific takes into account the network constraints in terms of consumption and production of electricity. This location-specific study highlights the importance of understanding where, when and how electricity is consumed and produced. It provides a better estimate when considering solar panels to alleviate the impact of extreme weather events which can be used when planning the network.

Keywords: *Heatwave, electricity grid, rooftop solar panels*

EXTENDED ABSTRACT ONLY

Minimising energy cost for a refrigeration system with thermal storage

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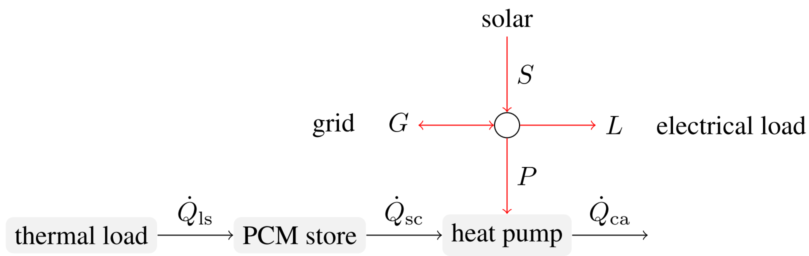
Abstract: Operators of large refrigeration systems often have electricity tariffs with components that include a daily connection charge, a time-varying charge for energy use, and charges for peak power demand. Energy costs and demand costs can be reduced by installing photovoltaic generation on site, but solar energy might not be generated at the times when the the price of electricity imported from the grid is high. Thermal storage can provide flexibility in when the refrigeration compressors need to be run impacting when energy is imported from the grid and ultimately the cost of electricity from the grid.

We consider a refrigeration system where heat is to be removed from a thermal load. The schematic diagram below shows the thermal and electrical power flows within the system.



Electrical power P is applied to the compressor of a heat pump, which draws heat from the thermal load via a thermal storage unit that uses a phase change material (PCM) to store or release heat. The heat $\dot{Q}_{\mathrm{sc}}$ drawn into the heat pump depends on the coefficient of performance of the heat pump, which in turn depends on the temperature of the PCM store and the ambient temperature of the environment into which the heat is transferred. The rate $\dot{Q}_{\mathrm{ls}}$ at which heat flows out of the load depends on the temperature of the load and the temperature of the store. Any difference between the heat flow into the store and the heat flow out of the store is taken up by either freezing or melting the PCM. The capacity of a store is typically sized to meet demand during high price periods each day.

In the electrical parts of the system, we control the power P to the heat pump compressor. The supply S from the photovoltaic system and the other electrical loads L are known (or predicted) functions of time. The power flow G to or from the grid depends on the solar power S, the load L and the controlled pump power, P.

We know the time-varying cost of electricity imported from the grid and the time-varying price paid for electricity exported to the grid. Our aim is to control the compressor power P to minimise the net cost of electricity from the grid over the next few days.

We use Pontryagin's principle to determine necessary conditions for an optimal control. Thermal stores typically have efficiencies exceeding 95%. If we assume that the store is perfectly efficient then the optimal control has just two regular control modes: melt the PCM when the price for imported electricity is high, and freeze the PCM when the price is high. We can use these modes to construct operating strategies that take into account power limits for electrical and thermal power flows, and when the store becomes completely melted or completely frozen.

Acknowledgement. This project was partly funded by the Australian Renewable Energy Agency (ARENA).

Keywords: *Renewable energy, refrigeration, thermal energy storage, optimal control*

Nonparametric short-term probabilistic forecasting of solar radiation

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Abstract: In recent years there has been a substantial interest in developing new methods for forecasting renewable energy, and particularly in developing methods for probabilistic forecasting. Probabilistic forecasting allows one to both assess a wide range of uncertainties and facilitate decision-making.

We previously developed a computationally efficient and data-driven method for short-term probabilistic forecasting of solar radiation, using a nonparametric bootstrapping method and a map of sun positions.

We develop a new point forecasting method that combines perfect knowledge of the day-ahead daily solar radiation with our previous hourly point forecasting method. Obviously perfect knowledge of the day-ahead daily solar radiation is not feasible. Ideally we would prefer to use a day-ahead daily forecast from a numerical weather prediction (NWP) model because a daily NWP forecast is known to be very accurate. However, a NWP is unavailable at this time. Instead we use perfect knowledge of the day-ahead daily value as a proxy. The idea here is to demonstrate the potential performance improvements of combining a daily NWP with an hourly solar radiation forecasted, generated from our statistical model. Statistical methods perform better at hourly time scales and NWP methods perform better at daily time scales.

We test the performance of our new point forecasting method against our old point forecasting method at three locations: Adelaide, Darwin and Mildura. These locations are chosen to represent three distinct climates. The NRMSE results ranged from 19.14–22.75% for our old method and ranged from 19.16–12.34% for our new method. The MBE results ranged from 0.72–1.32% for our old method and ranged from 0.39–0.57% for our new method. The MAE results ranged from 10.83–15.86% for our old method and ranged from 8.43–13.22% for our new method.

Results show that perfect knowledge of the day-ahead daily solar radiation improves the point forecast model. These results suggests there might be performance gains from combining a daily NWP with our hourly statistical model.

We also develop a new probabilistic forecasting method by extending our previous bootstrap method to a case of an exponentially decaying heteroscedastic model for tracking dynamics in solar radiance. Our previous method catered for the global systematic variation in variance of solar radiation, whereas our new method also caters for the local variation in variance.

We test the performance of our new probabilistic forecasting method against our old probabilistic forecasting method at the same three locations using the commonly used *coverage width-based criterion* (CWC). The CWC metric quantifies the trade-off between coverage and prediction interval width. The CWC results for all combinations of point forecasting and probabilistic forecasting methods are shown below.

Point forecast	Original		Known day ahead	
Probabilistic forecast	Old	New	Old	New
Adelaide	0.74	0.71	0.64	0.57
Darwin	0.80	0.91	0.69	0.78
Mildura	0.67	0.61	0.56	0.49

The CWC results from our new probabilistic forecasting method are mixed. Our new method performs better than our previous method at Adelaide and Mildura; regions with a higher proportion of clear sky days. Whereas our previous method performs better than our new method at Darwin; a region with a lower proportion of clear sky days. These results suggest that the ideal probabilistic forecasting method might be climate specific.

Keywords: *Solar radiation, nonparametric, probabilistic forecasting, bootstrap*

Probabilistic Modelling of Energy Networks

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Abstract: For over a century, the state of an electricity network has been analysed by deterministic methods, principally involving the solution of Kirchhoff's laws, along with specified known currents and/or potential differences on the network. These have been augmented by network mapping methods (such as Tellegen's theorem), various optimisation methods (such as minimum or maximum power), and more recently by dynamical simulation and genetic programming methods. However, such methods make the fundamental assumption that the network properties are not subject to uncertainty, either due to fluctuations in specified quantities, or due to a lack of information on the properties of the network. To handle such uncertainties – and indeed to develop a true risk management framework - it is necessary to adopt a probabilistic framework for the modelling of energy networks.

To address these problems, we have developed probabilistic methods for energy network analysis, based on the maximum entropy (MaxEnt) method of Jaynes. In this method, an entropy function – defined over the uncertainties in the network – is maximised subject to constraints on the network, to infer the state of the network. The constraints can include "observable" constraints on various observable parameters (such as currents and voltages), "physical" constraints such as conservation laws, and resistance or impedance properties, and "graphical" constraints arising from uncertainty in the network structure itself. The analysis yields a probability density function which expresses the (probabilistic) state of the network, from which any parameter values of interest (such as mean flow rates and variances) can be extracted. Over the past few years, we have developed the major analytical and numerical tools for this method, including (i) the handling of nonlinear frictional resistances; (ii) physically motivated prior probabilities; (iii) automated integration schemes for the integration of partition functions; (iv) soft constraints imposed in the prior; and (v) a reduced-parameter method for the consistent analysis of pipe flow networks. We have in parallel also developed a separate framework for Bayesian analysis of flow networks. The probabilistic methods have been applied to the analysis of urban electricity networks, including a 400-node electricity network in Campbell, ACT, Australia, with solar forcing by photovoltaic cells, as shown in Figure 1.

The probabilistic framework is now available for network-scale applications, such as probabilistic network design, new suburb integration, metering validation and loss detection.

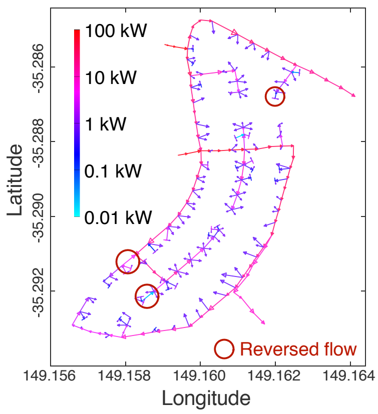

Figure 1. Mean power flow rates predicted by the MaxEnt method for an electricity grid in Campbell, ACT, Australia, under solar forcing, showing reversed flows.

Keywords: *Maximum entropy analysis, Bayesian inference, distributed electrical networks, solar energy, non-linear constraints, probabilistic prediction*

A Method for Deriving Empirical Fragility Curves for use as a tool to forecast the Consequences of Electricity Distribution Network Faults due to Windstorms

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Abstract: In order to quantify the potential impacts of wind storms we must first understand the relationship between wind intensity and damage. In terms of the built environment, functions describing the relationships between these two variables are known as fragility curves (when considering damage impacts) and vulnerability curves (in the case of economic cost), and these are the fundamental tools for risk assessment. They are particularly useful to insurance companies and insurance analysts as they provide a rational means of calculating potential losses to an insurance portfolio.

We present a novel modelling approach that couples high-resolution reanalysis wind data with large-scale electricity asset and fault databases to produce empirical, probabilistic estimates of faults for a given magnitude wind storm. Our technique uses regression analysis and curve fitting techniques to derive non-linear relationships between wind gust speed and the number of faults in a region. We also consider the potential consequence of each wind storm event, by quantifying the likely number of consumers to be affected by faults in the high voltage distribution network. We conduct our analysis at different resolutions ranging from the whole of the District Network Operator region (of circa 10000 km^2) down to sub-areas (of circa 1000 km^2). This allows us to determine the impact of scale and data accuracy on the resulting fragility curves and consequence analysis.

We will discuss how our fragility curves can be incorporated into a Monte-Carlo simulation that can be used as a predictive tool to estimate the number of faults occurring in a given area or region from a wind storm, using the forecasted wind gust speed in the area of interest. The faults are then translated into customers without power in a given region using empirical relationships supplied by the energy network operator. The gust data is obtained from the Met Office UKV Model results, which is run every 3 hours across the UK using forcing data (wind gust observations) assimilated into the model at the start of each simulation. The UKV model output includes hourly forecasts for up to 36 hours ahead. Therefore, given a set of historical storms and forecast data (from 2010 to 2016) it is possible to compare the forecasts made up to 36 hours ahead against the observations and to then compare the predictions of faults made using forecast data against those made using the observations (to determine the skill of the predictive model when used with forecast data).

Lastly, we discuss the sources and different levels of uncertainty associated with both the weather forecasts and the fault information that was used to generate the fault probabilities. This enables us to (i) assess the feasibility for this method to be used in pre-storm assessments of impacts resulting from wind storms, and (ii) assess how these may be improved by infrastructure owners recording more detailed information in their failure databases.

Keywords: *Consequence forecasting, damage modelling, wind, Monte-Carlo simulation*

Role of a ‘combination rule’ in hybrid short-term prediction of hydrological events

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Abstract: Data-driven hydrological predictions based on supervised classification have recently gained momentum. This technique supports the classification of waterbodies and flood events that occur at different watersheds, predictions of a class of a hydrological event, e.g., ‘high-’ or ‘low-flow’, as opposed to forecasting magnitudes of streamflow characteristics generated by ANNs, regression models or other modelling tools. Flood management teams declare a state of emergency and/or take mitigation measures based on a set of business rules reflecting water level exceedance of an established threshold. Therefore, predicting a class of a hydrological event, e.g. ‘flood’ or ‘no-flood’, carries even more important information for operational flood managers than projected magnitudes of streamflow characteristics. When predictions of a class of an event are obtained based on data available in real-time, they can be easily deployed in flood management. Scientific literature has demonstrated the usefulness of various classification algorithms (inducers) in applied hydrology. The performance of these inducers, however, deviated notably on different data sets. To alleviate these deviations and generate forecasts with reduced generalization error, an ensemble of classifier can be constructed.

One of the important steps in developing an ensemble of classifiers is identifying the approach to aggregate individual predictions into a final judgement. The current study investigates the effect of various weighting schemes on the accuracy of the generated forecasts of hydrological events. The predictors were developed using C4.5, CART, REPTree, NBTree, Ridor, JRip, and Random Forest inducers trained on data collected by stream and rain gauges located on a small highly urbanized watershed during two hydrologically distinct years. The data sets were first transformed into time series of various granularity from 15 minutes to 60 minutes. Time series of the same granularity and corresponding to the same year were converted to an augmented phase space providing datasets for training and testing developed predictors. Ensembles were constructed using five combination rules: majority vote, maximum probability, minimum probability, average probability, and product of probabilities. The ensemble’s generalization error was estimated using two measures: recall and *F*-score.

Combining the results of predictors constructed via training of individual inducers allows to develop a more robust model generating reliable predictions. However, the estimates of the ensemble’s generalization error vary up to 28% depending on the combination rule used to aggregate individual predictions into the final judgement. The issue of selecting a combination rule which is the most suitable for an application domain has both theoretical importance and practical significance. Computational experiments revealed that the classifier constructed with the minimum probability combination rule outperformed the others. It consistently delivered the most accurate results for all investigated data sets and all lead time intervals. The performance of classifiers utilizing the maximum probability rule on all data sets was the weakest, contrasting to its interpretation as a rule which identifies a classifier with the highest estimated confidence. Although the results of data-driven analysis are site-specific, they suggest further investigation of this rule, including theoretical considerations and application of the rule to data sets from other watersheds. Another combination rule which should not be easily discarded for the given problem domain, is the majority vote.

Keywords: *Supervised classification, hydrological event, ensemble of classifiers, combination rule, short-term prediction*

Developing a modelling component of a DSS for management of biological invasion cases

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Abstract: Invasion of non-native species is considered as one of the most pressing global challenges, causing substantial environmental, economic and social harm. Invasive species are organisms (plant, animal, fungus, or bacterium) occurring in non-native locations outside of their natural habitat, being able to successfully compete with indigenous populations, establish themselves in foreign environments and spread to the extent of causing damage to the environment, human economy and human health.

The scope and importance of the threats created by invasive species increasingly call for adequate management actions at different decision-making levels. At the same time, decisions about the management of invasive cases are inherently difficult because of the multifactorial and multi-attribute scope of the problem and are hardly possible without a support of software tools. To facilitate management efforts, decision-makers and environmental practitioners require a software tool integrating relevant knowledge and acting as a supporting expert. A modelling component is a core unit of the Decision Support System (DSS) for management of biological invasion cases, and it includes the following models:

- Models of pre-invaded dynamics of native species and the ecosystem as a whole;
- Models of invasive dynamics of the alien species, including mechanisms underlying their invasive success;
- Models of invasive-resident species interactions (e.g., competition for light, space, nutrient resources; possible symbiotic mutualisms, etc.) and their modification by biotic and environmental drivers;
- Models of persistence capabilities to sustain the invasion and probable transformations in invaded ecosystems;
- Models of effect of invasion on critical functions of the ecosystem; that is ecosystem services;
- Models predicting ecosystem components, their short- and long-term dynamics, ecosystem persistence capacity and restoration capabilities in response to each potential managerial effort or scenario;
- Models aimed at selection of the best possible scenario for managing the invasion.

In these modelling modules, one has to examine a particular phase of the invasion process (i.e., entry, establishment, spread and impact). Tree development stages are another import aspect in modelling of woody invasion. The latter will proceed from a seed planting and germination leading to the establishment of seedlings, their further transition to saplings and eventually to the mature adult trees. It is commonly accepted that alien species produce substantial negative effects on the composition, structure and functioning of the invaded ecosystems. Therefore, an ecosystem scope needs to be taken into consideration in the analysis and modelling of the invasive cases, including the persistence capacity and probable transformations in invaded ecosystems as they react to the stress caused by non-native intervention. From the ecosystem perspectives, persistence to invasion occurs in the form of competition from the native communities and may concern light and soil nutrient resources or display itself through allelopathic interference and disruption of mycorrhizal associations. In its turn, the resistance to invasion in forest ecosystems can be modified by environmental factors, such as soil moisture and nutrient levels or soil pH. Though a software tool in support of decision-making regarding biological invasion presented in this paper originates in the case of Norway maple (*Acer platanoides*) invasion to North America, there are good reasons to believe that the suggested solutions are suitable for a broader range of the cases of biological invasion.

Keywords: *Biological invasion, Decision Support System (DSS), alien species, software tool*

Predicting the impacts of urbanisation on biodiversity

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Abstract: Currently just over half of the world's population lives in an urban place, but this is expected to increase to two thirds by the year 2050. One outcome of rapid urbanisation is a decline in biodiversity as urban landscapes are significantly altered and become less natural. The Greater Adelaide Region of South Australia seems typical of many rapidly urbanising cities, with official predictions that over the next 30 years an extra 560 000 people will need to be accommodated in 258 000 new dwellings, requiring an additional 14 000 Ha of new land.

This research uses the Greater Adelaide Region of South Australia as a case study to model the relationship between urban development and biodiversity, and asks: what is the actual impact of urbanisation on biodiversity? And, most importantly, can they both thrive together?

The current local planning approach used in many of Australian cities is to 'densify' existing urbanised areas by adding more dwellings and people. Whist this has many positive benefits it also means that the amount of land available for growing vegetation (back yards, front yards and open green space) is reducing substantially with a probable loss of biodiversity, although this has been difficult to easily measure. What if any forms of urban development can be employed to reduce the anticipated impact of biodiversity loss due to increasing urbanisation, especially with the wide spread densification of our urban areas? Could it be as simple as leaving larger areas of open green space as is often required of land developers?

A complex geospatial – temporal quantitative model has been developed explaining the relationship between the various forms of urban development in the Greater Adelaide Region and the distribution of biodiversity (using bird presence, which is an excellent indicator for biodiversity). Citizen scientists (in this case expert bird identifiers) helped to collect the massive amount of bird data needed for to model an entire year so that all four seasons were included.

Bird species distribution models across the study area were derived using the MaxEnt package with only bird presence data available. Preliminary results show that as areas become more urbanised, the number of birds can be reduced by 40%, bird species can reduce by up to 30%, and the number of invasive (pest) bird species can increase by up to 30%, whilst many smaller bird species (key indicators) all but disappear. This suggests that as areas become more urbanised biodiversity can be substantially compromised, and conservation areas like national parks may come under increasing pressure, which may not be sustainable in the medium to longer term. The modeling shows that biodiversity changes linked to urbanisation are much more complex than just local human population densities or dwelling densities. Environmental variables such as the availability of water and local food sources (and the time of availability) and especially local vegetation quantity and vegetation structure are also important. Local parks may have to be increasingly viewed and managed as important biodiversity habitats in addition to their traditional recreational and aesthetic roles.

Various geospatial – temporal simulations have been used to predict the impacts of future urban development scenarios on biodiversity (e.g. ranging from low to extremely high densities of housing) up to 30 years ahead, and the potential impact of changing environmental variables (e.g. temperature, rainfall and vegetation variations), based on various climate change scenarios.

Using this approach, a set of tools is being developed that will be useful for planners, developers and governments for long term planning. This approach can be easily modified enabling it to be applied to many urban and urbanising landscapes both nationally and globally.

Keywords: *Urbanisation, biodiversity modelling, geospatial modelling and simulation*

Modeling Biological Survey to Effectively Obtain Habitat Map

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Abstract: Understanding the spatial properties of ecosystems is one of the central challenges in ecology. Such knowledge is necessary for ecosystem management and conservation biology due to an increasing need for spatially explicit approaches in these fields. Introducing effective marine or terrestrial reserve network is one of such examples. Habitat or occurrence map is often used for spatially explicit ecosystem managements and conservation planning to discuss the critical or high priority regions to be protected. Hence, the quality of habitat map is crucial to decision-making processes on management and conservation actions, and conservation recommendation made. For example, the decision making of strategic marine and terrestrial reserve placements are usually based on available habitat data. Although habitat data often comes from the result of biological surveys, there is no systematic framework for the survey that enables us to predict how accurate habitat map would be obtained given a survey design. In reality, *ad hoc* or conventional manners are often used to setup survey designs, but the habitat map obtained through this way may contain uncertain errors, and the estimation of the error is usually omitted.

Designs for any biological surveys may inherently involve multiple spatial scales to be determined beforehand by managers with time and budgetary constraints. Such spatial scales are the spatial extension of the ecosystem under concern W, mapping unit (resolution of habitat map) M, and spatial scale of survey unit S. Although all these scales are determined arbitrarily by the managers or researchers conduct a biological survey, any changes in these spatial scales may affect the habitat map, therefore its accuracy, obtained through the survey. Therefore, to develop a systematic framework for biological survey, we need to understand the mutual dependence of these spatial scales on the quality of habitat map. In addition, as target region of ecosystem managements or ecosystem conservations varies greatly from local scale to nation wide, we need to understand survey design across a wide range of observation windows W.

With a relatively sessile species such as plant or coral species in mind, a spatially explicit model to assess the accuracy of habitat map is developed. Within the model, individual distribution patterns are described by point processes, a spatially explicit stochastic model. Point processes are widely applied to ecological studies such as spatial patterns of plant and coral community, and bird nests due to its flexibility and relatively straightforward biological interpretations of underlying mechanisms. It is also amenable to mathematical analysis. The developed model is capable of examining various survey designs and scenarios, such as using a different set of above-mentioned spatial scales and individual detection rate, as well as assuming different distribution patterns of concerned species, including random and clustering patterns of individual distributions.

Regardless of individual distribution pattern assumed, the choice of resolution of habitat map largely affects accuracy of habitat map, such as the average rate to correctly map existing individuals. For both individual distribution patterns, the trade-off between the accuracy and the resolution of the habitat map is found, associated with asymptotic behaviors at sufficiently small and large scales of mapping, the region less sensitive to the change of map resolutions. This asymptotic behavior suggests that there is a certain scale of the mapping unit above or below which the performance of an biological survey does not change. Thus, in practice, we need to choose a mapping scale between these asymptotic limits. For the survey with random individual distributions, it is possible to give an analytical formulation showing all the parameter dependences across scales of observation windows on the accuracy of the habitat map.

The developed theory provides an expected accuracy of habitat map before ecosystem assessment is conducted, and thus it may facilitate management decision making on ecosystem assessment and inform the design of data gathering. The developed theory also complements spatially explicit ecosystem management, and makes its prediction more reliable.

Keywords: *Biological survey, habitat map, point processes, multiple scales*

A web-based Decision Support Tool to support efficient management of multi-stressed aquatic ecosystems

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Abstract: Aquatic ecosystems are exposed to multiple pressures due to increased water demands for sustaining an ever growing population and changes in climatic conditions. The European Community funded GLOBAQUA project aims to identify the prevalence of, and interaction between, stressors under water scarcity in order to improve water management practices and policies. Integrated river basin management must meet environmental targets while preserving the economic activities of its communities. Stakeholder decisions need to consider conflicting trade-offs between legislative environmental targets and economic activities, while maintaining a basis of transparency and accountability. We present a web-based Decision Support Tool (DST) that can be used by key stakeholders to evaluate management options to achieve pressure reduction targets of European water bodies. In order to support river basin management and planning using scientific knowledge available at European scale, the web interface provides a user friendly point of access for stakeholders to perform analyses of efficient pressure reduction strategies reflecting their perception of costs, political difficulty and social acceptability of the available solutions. The DST enables comparisons between management solutions and allows quantifying environmental and economic trade-offs inherent to the decision making process. The model addresses water abstractions and nutrient pollution. The impact of management on nutrient loads is assessed with pre-calibrated pan-European models. The DST comes with a user friendly, non-technical interface; stakeholders can express preferences and perceived difficulties in addressing each pressure by assigning relative weights. An optimization engine identifies trade-offs in terms of Pareto front solutions (e.g. Figure 1) between improvements in the status of water bodies and the effort required to achieve that status. The application of the tool in a Mediterranean basin is provided as an example. The DST can be accessed through internet and enables transparent and informed decision making. In the future, the DST can be expanded to include chemicals and plastics when data for these pollutants are available to a sufficient extent for informing robust model parameterization at European scale.

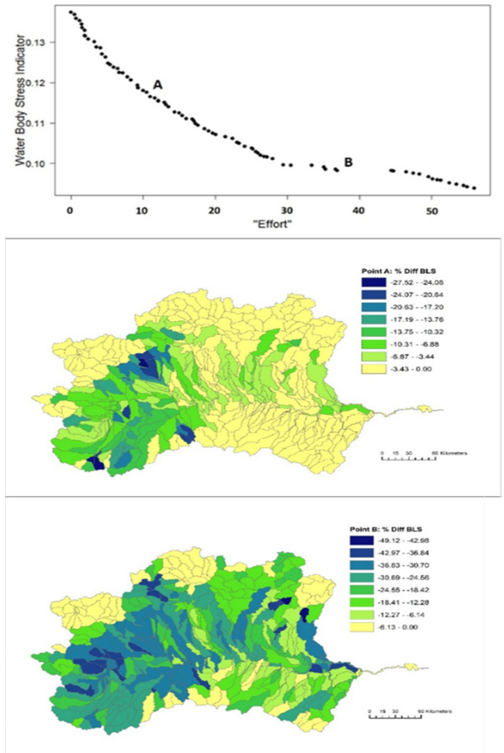

Figure 1. Pareto front of Water Exploitation Index optimization and WEI improvements under selected scenarios A and B

Keywords: *Decision support tool, integrated basin management, Pareto-front, water quality, Globaqua project*

Estimating soil organic carbon stocks using machine learning methods in the semi-arid rangelands of New South Wales

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Abstract: Soil organic carbon (SOC) is pivotal for biological, chemical and physical processes and provides vital information on changes in soil fertility and land degradation. Rangelands, accounting for about 81% of Australian land area, represent considerable carbon storage potential. Efficient modelling techniques to evaluate the potential for rangeland SOC stocks are vitally important in the assessment for the global carbon cycle and quantum abatement. This study aimed to evaluate boosted regression trees (BRT) and random forest (RF) in predicting SOC stocks from ground measured and remotely-sensed variables using two feature selection techniques to identify the dominant variables that affect SOC stocks in the rangelands. Using field-based measurement of SOC stock collected from 564 sites across the study area and 28 of GIS-based environmental variables including climate, topography, radiometry, vegetation and land fractional cover data, we employed stepwise regression (SR, linear approach) and genetic algorithm (GA, nonlinear approach) to select the most informative variables. These selected predictors were then used to train the BRT and RF models. In all, four models were evaluated; BRT using stepwise selection of predictors (SR_BRT); RF using stepwise (SR_RF); BRT using GA selection of predictors (GA_BRT) and RF using GA (GA_RF). In addition, BRT using all predictors (All_BRT) and the RF using all predictors (All_RF) were used as benchmarks to test the performance of the four models. Of the field-based data, 75% was used to train the model ("calibration dataset") and the remaining 25% was used to validate the prediction of SOC stocks ("validation dataset"). The results indicate that the RF exhibited a better performance in predicting SOC stocks than the BRT regardless of input variables. The two models explained ~45% of the total SOC stocks. In addition, we verified that feature selection for both machine learning techniques is necessary for estimating SOC stocks, even though BRT was relatively insensitive to the input features selected by SR. The GA_RF was the most promising model with reliable predictors to predict SOC stocks, with the lowest root mean square error (RMSE) and the highest R^2 values (7.44 Mg C ha^{-1} and 0.48, respectively), suggesting that the proposed methodology may provide a cost effective method to predict SOC stocks in the rangelands. The important variables for explaining the observed SOC stocks were rainfall, elevation, prescott index (PI), and land fractional cover (bare ground fraction).

Keywords: *Soil organic carbon stocks, random forest, boosted regression tree, genetic algorithm, stepwise regression*

Ecohydrological modelling of vegetation composition in semi-arid ecosystems with shallow saline groundwater systems

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Abstract: Soil salinity management is becoming increasingly urgent in view of a growing world population, demand in food production and increasing drought risk. Semi-arid soils are prone to salinization due to interactions with saline groundwater which can affect vegetation distribution. Plant communities in those regions create heterogeneous, self-reinforcing spatial structures consisting of densely vegetated and less vegetated or bare patches. Vegetation influences groundwater recharge and salt dynamics and vice versa, hence it is necessary to meet the challenge of understanding salinity-vegetation interactions and determining stable system states. Different patterns have been associated with changes of system states, which have been found to be warning signs of desertification. Understanding and predicting these system changes can aid in adjusting land management measures to prevent catastrophic shifts. Groundwater-salt dynamics and the resulting vegetation response are not completely understood yet, the role of salinity has to be assessed, especially in interaction with vegetation dynamics and in a changing climate. We present a modelling tool that has been developed for analyzing the influence of a choice of environmental factors on vegetation pattern formation in semiarid ecosystems. The base is an extension of an existing model that bases pattern formation on increased infiltration under vegetated patches. Suitable parameterizations for the new extensions have been chosen.

- Salinity effects on vegetation occur as osmotic effects leading to reduced water availability (virtual saturation) and toxicity effects leading to reduced plant growth, fertility, seed germination and increased mortality. These effects are linked to an ecosystem carrying capacity determined by salinity and plant sensitivity to salinity
- In order to account for groundwater influence by capillary rise and thus salt transport into the root zone, vertical drainage and rise has been implemented with an analytical solution
- Positive and negative plant interactions in terms of facilitation and competition as a function of distance
- Stress-gradient-hypothesis: Change in relative dominance of competition and facilitation corresponding with increasing stress, also salinity stress
- Species with complementary traits (sensitivity to drought and salinity, spatial ranges of facilitation)
- Microtopography influences ecohydrological process. Hence surface elevation heterogeneity has been included and an algorithm to account for ponding and surface water redistribution using *DInfinity* flow routing has been proposed

Further, an outline for extensive simulation cases has been developed. It aims at assessing the influence of hillslope, seasonal and non-seasonal Poisson-distributed precipitation, groundwater depth and salinity levels and soil type. To interpret the results regarding their influence on vegetation patterns, patch geometry analysis such as shape indices as well as species composition (diversity) indices have been chosen. First simplified tests were conducted that test different DEM, rainfall, groundwater table depth and salt concentrations in one- and multi-species scenarios. Results show the model's ability to simulate vegetation pattern formation. They further suggest salinity to enhance or accelerate pattern formation in one-species scenarios. Patterns in mono- and multi-species scenarios differ. Multi-species scenario tests suggest the ranges of facilitation and competition to be influential on species dominance. It is crucial to understand these interactions and assess salinity impacts separately before further irreversible soil fertility loss has occurred. This study could hence contribute to sustainable land use practices, saline site restoration and invasive species management.

Keywords: *Ecohydrology, salinity, groundwater, vegetation competition, vegetation patterns*

A vegetation-focused soil-plant-atmospheric-continuum model to study hydrodynamic soil-plant water relations

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Abstract: A simple plant resistance module was introduced to a commonly used vadose zone soil and solute transport simulation model (LEACHM). The coupled new model (refer to as v-SPAC model) can simulate soil and plant water state simultaneously. Different from previous soil models that constrain plant transpiration solely with soil water stress, the new model demonstrates the additional regulation of transpiration of plant water state itself. Also, different from plant-focus model that simulates plant xylem water state in detail but under simple or constant soil water conditions, the new model can predict the subdaily plant water potential under transient soil water states.

The model was tested on a water controlled experiment of *Eucalyptus crenulata* saplings. The simulation results demonstrate the robustness of the model in reproducing plant and soil water state and water flux under none water stressed to modest water stressed conditions. The model, however, could not simulate well the severe drought period and its subsequent recovery period after irrigation due to the simplification of the plant representation. Nevertheless, the model could be used to diagnose the relevance of the soil and plant resistances during the recovery periods. The diagnosis simulations reveal that the soil-water interfacial resistance may play a significant role in the wet-dry-wet water cycling of the saplings. The model also identified the resilience of the plant xylem resistance system, showing that the plant resistance system returns to pre-drought treatment level during the recovery period.

Keywords: *SPAC model, stem water potential, vulnerability curve, Acacia pycnantha, Eucalyptus crenulata*

Ecohydrology simulation of an eucalyptus forest

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Abstract: Gas exchange fluxes of eucalyptus dominated ecosystems in Australia have been estimated with different ecohydrological and/or land-surface models. However, there is always need for improvement in simulations by trying different modelling approaches and investigating sensitivity of input parameters to the model estimation.

In this study, a multilayer canopy-root-soil model (MLCan) has been used to study the ecohydrology of a eucalyptus forest located in south-eastern Australia. This model has not been previously tested in this type of ecosystem. MLCan couples vertically resolved aboveground and belowground processes in order to improve the simulations of vegetation, water and atmosphere interactions. Model inputs include canopy and root structure, meteorological data, initial soil moisture and temperature and model parameters. Canopy and root structure data and most of the model parameters have been extracted from the literature in the study area. This point-scale model includes a hydraulic redistribution mechanism. This mechanism has been recognised to be important to capture observed root water uptake and soil moisture distribution, and to improve latent heat flux and soil moisture estimations.

The detailed ecohydrology model MLCan was applied to simulate the ecosystem exchange fluxes of water and energy in the Tumbarumba eucalyptus forest, in NSW. Tumbarumba is one of the oldest monitoring sites in OzFlux network that has a longer record of flux measurements and has been simulated using various models in the past. The meteorological data, eddy covariance fluxes of CO_2 (F_c), latent heat (*LE*) and sensible heat (*H*) and the soil moisture (*SWS*) data measured in Tumbarumba for the year 2005 have been used for model calibration and validation. A set of simulations was performed to examine the effects of different number of canopy layers on the canopy exchange fluxes and these results indicated 12 layers as the optimum number of canopy layers. This result showed that the results from the 12-layer canopy model differed less than 5% relative to 50-layer canopy model.

Sensitivity analysis enhances our understanding on how different model parameterisations affect the model behaviour. As a result, sensitive and insensitive parameters were identified. Using the GLUE method, a sensitivity analysis of nine model parameters was performed. These parameters were selected because their values could not be identified from previous literature. The Nash-Sutcliff (*NS*) objective function and dotty plots were used to analyse the model behaviour and sensitivity of the results for each of the nine parameters, and to evaluate the model performance against the observations. As a result of this analysis, we found that among the nine selected parameters, m and b (slope and intercept of Ball-Berry stomatal conductance model) are identifiable when estimating the soil moisture, latent and sensible heat fluxes; while R_o (soil respiration at 10°C) is the only identifiable parameter for the estimation of CO_2 flux.

Model parameters were calibrated for single (i.e. one dataset by itself) and multiple objectives (i.e. combinations of the four datasets including the latent heat, sensible heat, and CO_2 fluxes and soil moisture). In the multi-objective model calibration, the *NS* values for latent heat, sensible heat, CO_2 fluxes and soil moisture were 0.45, 0.70, 0.52 and 0.77, respectively. Similarly, in the single-objective calibration, the *NS* values were 0.49, 0.76, 0.53 and 0.85, respectively. *NS* values close to 1 show the best agreement between the estimation and observation. We also found that the initial conditions of soil moisture deeper in the profile strongly influenced the calibration of parameters and improved the results.

The sensitivity analysis for the parameters produced several sets of values that yielded reasonable estimations. The calibrated parameters were used for model validation for the period 2002-2008. Validation of the model resulted in a good fit to the observed data, which demonstrates that the model is reasonably capturing the ecohydrologic fluxes at this site.

Keywords: *Ecohydrology, Eucalyptus forest, parameter sensitivity*

Eco-hydro-geomorphic feedbacks and degradation thresholds in semiarid Australia

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Abstract: Dryland areas are sensitive to human and climatic disturbances and prone to critical degradation thresholds, which make rehabilitation efforts considerably difficult. In the Mulga lands of Australia, ecosystem health and productivity are strongly affected by ecogeomorphic feedbacks. Disturbances to vegetation cover can trigger erosion and substantial water losses by increasing landscape hydrological connectivity. In this study, we combine remote sensing observations with an eco-geomorphologic model approach to investigate changes in ecosystem connectivity and the existence of threshold behaviour along a precipitation gradient in selected sites of the Mulga Lands Bioregion (250 to 490mm annual average rainfall).

We first investigate the impact of degradation processes induced by vegetation disturbances (mostly due to grazing pressure) on ecosystem function and connectivity along the precipitation gradient using a combination of remote sensing observations and topographic data. In order to investigate changes in ecosystem function, we estimate rainfall use efficiency (RUE) using carefully selected precipitation data records and MODIS vegetation indices over several plots along the rainfall gradient. For these sites we also estimate vegetation cover from high resolution remote sensing images. We use the vegetation cover binary maps and topographic data to compute mean inter-patch flowlength as an indicator of structural hydrologic connectivity. Here we usse the term "connectivity" as the extent to which water and sediment can move and be redistributed within the landscape. When the hydrologic connectivity of these semiarid systems is altered, erosion leading to degradation can be triggered. Trends of connectivity and RUE for several sites along the precipitation gradient are analysed. Results show that disturbances substantially increase hydrologic connectivity following a threshold behaviour that affects landscape functionality. Hillslopes with high vegetation cover display low hydrologic connectivity and high RUE. However, below a threshold value of vegetation cover hillslopes become highly "dysfunctional" and are characterized by high connectivity and low RUE.

This dataset is used to model the coevolution of landforms and vegetation in order to analytically investigate the processes and possible triggering mechanisms responsible for the observed threshold dynamics. We use the model to analyse changes in structural and functional hydrologic and sediment connectivity for selected plots along this precipitation gradient. We compute mean values of functional connectivity for these sites, based on an index that captures variable contributing area and changes in spatially distributed run-on values. We analyse the spatial variability and evolution of this functional connectivity index in time and its relation to the observed structural connectivity to further understand the observed threshold behaviour for ecosystem function. Both observations and modelling results suggest that sites with higher rainfall are more resilient to changes in surface connectivity, even if these changes are quite profound. The analysis demonstrates that degradation trends and the observed threshold behaviour are intimately linked to coevolving eco-geomorphic processes, and highlight the usefulness of indicators derived from landscape hydrological connectivity analysis for monitoring landscape health. Implications for ecosystem resilience and land management strategies are discussed.

Keywords: *Eco-hydro-geomorphology model, semiarid ecohydrology, vegetation patterns, hydrologic connectivity*

Bayesian multi-objective calibration and uncertainty analysis in ecohydrological modeling

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Abstract: Bayesian model inference is an approach whereby the existing knowledge about model parameters and any observation data can be combined. The outputs of Bayesian inference are a set of probability distributions of model parameters which allow modelers to analyze model uncertainties. Therefore, Bayesian inference has become a popular tool for hydrological studies for characterization and assessment of model uncertainties. Ecohydrological models integrate hydrological and ecological processes and are typically more complex and high dimensional than hydrological models, involving multiple observed ecosystem variables. The application of Bayesian calibration approaches in ecohydrological modeling are particularly appealing, given the potential for increased uncertainty about the model parameters and observations. Traditionally in ecohydrologic model calibration, a multi-objective optimization approach that optimizes different catchment variables simultaneously is used. However, such approaches do not provide probabilistic outputs for the model parameters. Most recently, multi-objective Bayesian calibration has been used as an alternative to the traditional Pareto-based multi-objective optimization. The approach requires specified prior distributions for error parameters, which may be interpreted as weights for each observed variable. Challenges remain in appropriately calibrating both of the objectives according to modelers' preference and the catchment observations in an ecohydrological modeling study. Our research focuses on applying a formal Bayesian multi-objective framework for a conceptual ecohydrological model. The difficulty is to define appropriate prior distributions for error parameters which reflect the different emphasis on each of the objective. In our work, we used information from a Pareto-based multi-objective optimization approach to derive informative prior distributions. Simulations focused on one objective (streamflow/LAI) and multiple objectives (streamflow and LAI) with different emphases defined via prior distributions for error parameters. Input and output uncertainties are then included in the model simulations with different error descriptions.

The methodology implemented here provides insight into the usefulness of multi-objective Bayesian calibration framework for ecohydrological systems to analyze model uncertainties (Figure 1). Results demonstrate the model parameters and predicted outputs are well conditioned by the informative prior distributions for error parameters. Model error parameters can be reduced by incorporating input/output uncertainty component. A simple error description works well for both streamflow and LAI predictions as LAI data are not sufficiently informative to update complex error model parameters.

Keywords: *Ecohydrology, multi-objective optimization, Bayesian inference, prior distribution, Pareto front*

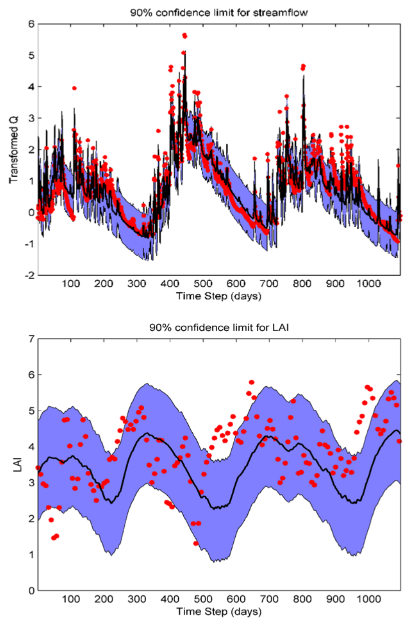

Figure 1. 90% confidence limit of the residuals between observations and predictions using Bayesian multi-objective framework.

Comparison of root water uptake models and their influence on modelled soil CO_2 dynamics

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Abstract: Soil respiration is one of the major fluxes of CO_2 from the land to the atmosphere. Therefore, changes in these fluxes might have a large effect on atmospheric CO_2 concentrations. The modelling of these fluxes and their relationship with biotic and abiotic factors, although challenging, is important to better predict the magnitude of soil respiration. Because soil water content is one the main drivers of air-phase soil CO_2 dynamics, the formulation of root water uptake used in models of soil water flow indirectly influences the modelling of soil respiration.

The aim of this study is to compare different models of root water uptake to determine their effect on modeled transpiration rates, and soil CO_2 production and efflux. The analysis focuses on the effects due to the modelling of root water compensation (i.e., the ability of roots to take water from soil layers where water is more available) and hydraulic redistribution (i.e., the ability of the root system to transfer water from soil layer at different water potentials).

The model used is one-dimensional and combines the Richards equation for soil water flow to equations describing heat transfer and air-phase CO_2 production and flow. A model for root water uptake, accounting for root water compensation by re-scaling water uptake rates across the vertical profile, was compare to a model estimating water uptake as a function of the difference between soil and root xylem water potential. This second model was manipulated to account for just root water compensation in one case, and both compensation and hydraulic redistribution in another case. These models were compared in a scenario where the water table was assumed to be shallow to allow the root system to have access to near surface water during and right after rainfall events as well as water at deeper soil layers near the capillary fringe.

Results suggest that the formulation of the root water uptake term in the Richards equation has an important role in the modeling of daily patterns and magnitudes of transpiration rates. In the case of CO_2 dynamics, the different soil moisture levels caused by different root water uptake functions modulated heterotrophic and autotrophic production thereby leading to different rates of soil respiration. The differences between models reached up to 20% in the estimated water transpired over a period of 50 days and up to about 14% in carbon emitted from the soil. The study shows that choosing root water uptake models not only affects modelled transpiration rates but also affect the modelling of other processes associated with soil water content, such as soil respiration.

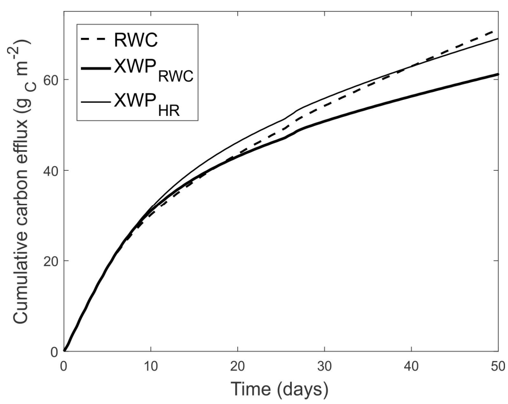

Figure 1. Cumulative carbon efflux (i.e., soil respiration) over the simulation period for three models (root water compensation (RWC), xylem water potential accounting for only root water compensation (XWP_{RWC}), and xylem water potential accounting also accounting for hydraulic redistribution (XWP_{HR})).

Keywords: *Root water compensation, hydraulic redistribution, soil respiration, autotrophic respiration, heterotrophic respiration*

EXTENDED ABSTRACT ONLY

Capturing variation in evapotranspiration within catchments

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Abstract: Spatial variations in evapotranspiration across catchments affect stream flow. To make predictions of impacts of land use change, we need to simulate the ecohydrological variation in the vegetation or land use cover evapotranspiration, as detailed measurements across large spatial scales are scarce. This relies on two major assumptions: that an ecohydrological model can accurately predict the local evapotranspiration; and some accurate measurement of the spatial distribution of evapotranspiration is available (preferably at both local and catchment scale). To test these assumptions, we compare the ecohydrological simulation of evapotranspiration across three different scales, from the point/stand scale to the satellite grid and from the grid scale to the catchment. At each of these scales, ecohydrological modelling is needed to translate radiation and water input into growth and evapotranspiration, as this is not an easily measurable flux. Each of these modelling components introduces uncertainty around the prediction.

The Cotter catchment in Australia is an important water supply catchment for Canberra. However, it has been affected by several serious bushfires, with the last large scale fire taking place in 2003. The loss of tree cover not only affects water quality, but also can affect water quantity.

Here we use the 1-dimensional model WAVES (Water Atmosphere Vegetation Energy and Soil) and the catchment model SWAT (Soil Water Assessment Tool) to predict local and catchment scale actual evapotranspiration. Observed data included limited sapflow and soil moisture at two depths at 7 locations (~2011 – May 2012), as well as soil hydraulic characterisation. WAVES was calibrated using either sapflow and soil moisture data, satellite MODIS16 ET and soil moisture data or MODIS15 LAI and soil moisture data. SWAT was parameterised and calibrated on streamflow and on streamflow and MODIS16 ET. By comparing our modelled estimates of actual ET against observations, from sapflow measurements at the finest scale to MODIS16 ET measurements at the largest scale, we cross validate the modelled estimates and highlight uncertainty at each scale.

Results shows that SWAT calibrated on streamflow cannot represent the spatial distribution of ET across the catchment, constraining the calibration also on MODIS16 ET improves the spatial representation. However, because the variance of the streamflow data is much greater than the variance in the MODIS16 ET data, the calibration on ET hardly affects the streamflow prediction. Locally, calibration on MODIS15 LAI data does not lead to good ET predictions, possibly due to the inaccuracies in the MODIS15 LAI data in the area. Calibration on MODIS16 ET or sapflow data in combination with soil moisture data leads to reasonable performance, even though the model shows high equifinality and therefore high uncertainty in the fitted vegetation and soil parameters. The fitted parameter distributions however fall mostly within the reported literature values, but show no consistent trend across vegetation species or locations. This suggests that WAVES is well suited to model "generic" vegetation, but cannot capture species specific characteristics.

The final prediction of catchment scale ET using SWAT, can then be dis-aggregated to the smaller scales. This shows that the local WAVES model calibrated on MODIS16 ET and the global SWAT model give similar predictions across the catchment, suggesting the MODIS16 ET data is a reasonable surrogate for total local actual ET. This means the resulting model is more realistic and allows understanding of the spatial variation of ET at monitored and unmonitored locations. However, further work is needed to understand how the spatial prediction of actual ET can be improved in the model.

Keywords: *Ecohydrology, evapotranspiration, model calibration, uncertainty*

Empirical modelling of river water temperature in water scarce European basins

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Abstract: GLOBAQUA is a European Union (EU)-funded project aiming to identify the prevalence of, and interaction between, stressors under water scarcity in order to improve water management practices and policies. River water temperature (RWT) plays a pivotal role in aquatic freshwater ecosystems, impacting the distribution of aquatic species and water quality. In this study, we aimed at assessing RWT in three data-poor, water scarce basin of the European Mediterranean region to enable projections of RWT as one of the multiple stressors that aquatic habitats face currently and likely more in the future. Given that water thermal inertia regulates RWT response to Ta, stream discharge (Q) should be considered in predicting RWT in water scarce basins. To be pragmatic, we opted for applying a published empirical regression of RWT as a function of Ta and Q for application in three European basins, namely the Adige (Italy, 28 stations), the Ebro (Spain, 39 stations), and the Sava (Western Balkans, 10 stations). Time series comprised data observed from 1967 to 2014; observed RWT ranged from -5 to 34 °C, Ta ranged from -50 to 39 °C and stream discharge ranged from 0 to 5000 m^3/s. For each basin, the regression coefficients were estimated with Bayesian inference using a calibration dataset that comprised about 75% of basin stations. Initial collinearity analysis showed that correlation between regression coefficients reduced identifiability of all empirical parameters, thence the asymptotic minimum RWT was set at zero while the asymptotic maximum was set according to the distribution of the highest 4% of recorded RWT. MCMC runs converged to acceptable solutions in all basins. The root mean square error (RMSE) in the calibration and in the validation datasets varied from 2 to 3.15 °C, which was deemed acceptable for application at basin scale. However, while statistic results were acceptable, the projected impact of stream discharge on RWT resulted to be either negligible (in the Sava basin) or unrealistic, e.g. in the Adige basin. Furthermore, the empirical equation seemed conceptually flaw at low temperatures, where low discharge would increase rather than decrease RWT. Repeating the analysis after dropping the stream discharge variable allowed reaching the same estimation errors, i.e. neglecting the hypothesized discharge impact did not degrade the empirical RWT estimation. In view of data limitations, the logistic regression of RWT as a function of Ta was considered sufficient to assess RWT changes in foreseeable future in the three studied basins. We further conclude that despite statistical convergence and acceptable goodness of fit, the hypothesized empirical relationship of RWT and Q should be revised. Alternatively, in data richer environments, stream discharge could be used in regionalization schemes to extend regression parameters in between observation stations.

Keywords: *River water temperature, empirical regression, water quality, Globaqua project*

Hydrological flow metrics for ecological impact assessment of river basins in Northern Australia

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Abstract: Understanding the nature of flow regimes is important for the management of engineering, environmental and ecological assets in a river-floodplain system. This study presents results from an analysis on nine hydrological flow metrics that are considered important for ecological impact assessment. The study includes river basins across three regions of northern Australia (the Fitzroy River in Western Australia, the Finniss, Adelaide, Mary and Wildman rivers in the Northern Territory and the Mitchell River in Queensland). The goal of this research is to provide a rapid characterisation of flow variability occurring throughout the regions and a baseline understanding of river flows to inform ongoing river modelling and ecological impact assessment studies. The analyses include an assessment of the availability and quality of observed streamflow data for the northern Australian rivers and quantification of nine flow metrics representing variability in high, low and long-term flows. Observed daily streamflow data for northern Australian regions were downloaded from WA's Department of Water (27 stations for the Fitzroy), NT's Government Water Data Portal (30 stations for Darwin Catchments), and QLD's Water-Monitoring Information Portal (30 stations for the Mitchell). Flow data were also obtained for Cooper Creek (arid), Belyando River (dry tropical) and Tully River (wet tropical) for comparison. Data quality for each stream gauge was checked using R-Script and categorised as good, fair, poor, unverified, non-conforming or missing. Flow Duration Curves (FDCs) and nine ecologically significant flow metrics, hereafter referred to Hydrological Response Variables (HRVs) were investigated. HRVs were compared within and between the catchments to flow characterises of individual catchment were evaluated. FDCs were calculated in two ways, firstly for the whole data series together and secondly for each year to produce a visual understanding of inter annual variability. To further characterise the river flow nine HRVs were extracted representing flow variability in low and high flow conditions. These include the (i) first percentile (P01), (ii) number of zero flow days per year (ZFD), (iii) number of low flow days per year (LFD), (iv) number of low flow spell (LFS) and (v) length of the longest low flow spell (LLFS) representing low flow condition, (vi) 99th percentile flow (P99) and (vii) number of high flow days (HFD) representing high flow condition, and (viii) annual flow volume (AF) and (ix) inter-quartile range in daily flow (IQR) representing flow volume and variability.

Results show both high and low flow regimes are highly variable within and between river basins across the northern region which appears to be part of the current natural flow regime. High variability means that streamflow persists some years and not others and implies that slight changes in water extraction may affect this balance. The Fitzroy has a higher degree of streamflow of variability than the Mitchell. Comparison with other catchments shows, that the Tully River (wet tropical) has the most reliable flow while Cooper Creek (arid) and Belyando River (dry tropical) are less reliable. The HRVs, being a yearly plot, affords a graphical representation of the number of years of data, while showing the inter-annual variability. The Fitzroy River (at Fitzroy Crossing) has the maximum number of no flow days, while the Mitchell has few no flow days. There is scope for more detailed comparisons to be made both within and between the catchments and to gap fill some of the data used due to the missing and unverified data that it contains. Data could also be correlated with the available rainfall data and historic records. Regular updates with new data as it becomes available will increase the data quantity and quality. This information will be useful to ecological assessment on future agricultural and/or infrastructure developments projects in north regions Australia.

Keywords: *Streamflow, ecology, hydrological response variable, Fitzroy, Mitchell, Darwin*

Influence of climate change and hydroclimate variability on the impact of coal resource development on runoff

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Abstract: There have been a number of proposals to further develop coal seam gas and coal resources in eastern Australia. These developments may have an impact on water resources and the environment. The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), in partnership with the Department of Environment and Energy, the Bureau of Meteorology and Geoscience Australia, have undertaken a series of "Bioregional Assessments" to assess the potential impacts of coal seam gas and coal mining development on water resources and water dependent assets such as wetlands and groundwater bores.

This paper investigates the sensitivity of the bioregional assessment results to climate change and hydroclimate variability, using the Gloucester subregion as an example. Specifically, the paper quantifies (i) the relative impact of coal mining development versus impact from potential climate change, (ii) the modelled impact of additional coal mining development (relative to "baseline" development) for different plausible climate futures, and (iii) the influence of hydroclimate variability (sequencing of future hydroclimate time series, particularly when the mine footprint is largest) on the modelled impact of additional coal mining development.

The results for the Gloucester subregion indicate that the impact of climate change on runoff can be considerably greater than the impact of coal mine development. However, the difference in the modelled impact of additional coal resource development relative to the baseline for a given climate future is relatively small, but not insignificant. The sequencing of hydroclimate series (hydroclimate variability), particularly the rainfall when the mine footprint is largest, significantly influences the modelled maximum additional coal resource development impact, and much more so than the future mean annual rainfall. If the rainfall is high in the period when the mine footprint is largest, the modelled maximum impact on volumetric and high flow hydrological variables will be higher, and the modelled maximum impact on low flow hydrological variables will be lower.

The results suggest that detailed analysis of coal resource development impact where proposed development is large should take into account climate change and hydroclimate variability. The relative and combined impact (which can enhance or compensate) from climate change and coal resource development should be modelled, as well as the range of possible rainfall sequencing (stochasticity and uncertainty) when the mine footprint is large.

Keywords: *Cumulative impact, coal resource development, climate change, hydroclimate variability, hydrological modelling, Bioregional Assessments*

Lessons learned in the Bioregional Assessments Programme from modelling the changes in groundwater due to large coal mines and CSG

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Abstract: The Australian Government's Bioregional Assessment Programme provides transparent scientific information to better understand the potential impacts of coal seam gas and coal mining developments on water resources and water-dependent assets. This presentation is an overview of the groundwater modelling that was conducted in six subregions: Gloucester, Hunter, Namoi, Galilee, Clarence-Morton and Maranoa-Balonne-Condamine.

Although each model was developed using different code, they addressed the same research question in a similar way. Each model provides a probabilistic prediction of the changes in drawdown and surface water – groundwater interactions for two alternate futures, a baseline and additional coal resource development. All of these models have been designed to be numerically robust to enable a comprehensive sensitivity analysis to be conducted resulting in a comprehensive uncertainty analysis of the model predictions.

The sensitivity analysis revealed that the model parameters that the predictions are sensitive to are not always the same model parameters that the observations are sensitive to. This has major implications for our confidence in model predictions – a well calibrated model may not be constraining the predictive uncertainty. This has resulted in drawdown predictions where the 95th percentile can be several orders of magnitude greater than the 5th percentile.

Overall, the drawdown at the water table was greatest for open cut coal mines but they had the smallest extent, conversely coal seam gas developments had the least drawdown at the water table but over a greater area. The potential for cumulative impacts on drawdown of the water table exist where developments are close together.

This suite of models is developed independent of the proponents and regulators of coal resource developments and so can provide unbiased information to all stakeholders. To demonstrate transparency of the modelling, all inputs, outputs and executables will be available from http://www.bioregionalassessments.gov.au.

Keywords: *Groundwater modelling, Bioregional Assessments*

Interaction dynamics are not inherent to threat combinations

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Abstract: Species and ecosystems usually face more than one threat. Although the impact (E) of multiple threats can accumulate linearly (i.e., E(A&B) = E(A)+E(B)), their interactions can also be nonlinear: either subadditive (E(A&B) < (E(A)+E(B)) or superadditive (E(A&B) > E(A)+E(B)). Threat interactions are most commonly investigated using laboratory or field experiments, which often draw conflicting conclusions about the interaction type of particular threat combinations. Since threat interaction types are generally considered inherent to the combination of threats, this inconsistency is often explained as the result of different experimental set-ups. Here, we show that the threat interaction type changes with different threat intensities, suggesting an alternate explanation for the differing results.

We use theoretical population modelling to investigate how multiple threats accumulate to cause population level effects. Threats impact populations by reducing one or more important population processes. For example, habitat destruction can reduce a population's maximum carrying capacity in that habitat. Our simulations used 10^6 randomly chosen population parameter sets to represent populations of a range of species. Analytical analysis and simulations are used to identify the conditions under which the impact of threats on populations display super- or subadditive behavior.

Our results reveal that threats do not always display consistent additive behavior, even in simple systems. Instead, they exhibit a combination of sub- and superadditivity, depending on the intensity of each threat and the process impacted by the threat. Most combinations we considered initially exhibited superadditivity, both when the threats acted on the same process, and when they acted on different processes. The interaction type also consistently switched from super- to subadditivity with increasing threat intensity. Therefore should not expect interaction types to be inherent to threat combinations. The threat intensity that triggers the switch from super- to subadditivity can differ depending on the process impacted, the population parameters and the presence of harvesting. Interestingly, the only time that the interaction type was consistent for all intensities was when considering equal intensities of threats on both pathways.

This fact might be able to explain the opposing results that experimental studies on interactions of threats display, and suggests that attention should be re-focused on the intensity of threats, and the community dynamics of the ecosystems they affect.

Keywords: *Theoretical analysis, threat interactions, superadditivity, subadditivity, multiple threats*

Bioregional Assessments: Assessing impacts to water resources and ecosystems from coal resource development

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Abstract: The Australian Government Department of the Environment and Energy has commissioned an ambitious, multi-disciplinary programme of bioregional assessments to improve understanding of the potential impacts of coal seam gas and large coal mining activities on water resources and ecosystems across six bioregions in eastern and central Australia.

A bioregional assessment (BA) is a regional cumulative analysis of the water-related impacts and risks that may arise in response to current and future pathways of coal seam gas and coal mining development. The analysis considers the geology, hydrogeology, hydrology and ecology. It seeks to help governments, industry and the community make better-informed regulatory, water management and planning decisions. A BA flags where future efforts of regulators and proponents should be directed, and where further attention is not necessary.

The impact and risk analysis is the key output of BAs, and must meet the objectives of the BA methodology, while addressing the complexity of the bioregions and assets, and respecting good practice in risk assessment. A series of design choices are required to ensure that BA meet these requirements, and are credible, timely and thus can constructively inform public debate and decision making. These design choices include factors such as a dedicated hazard analysis, a focus on the predictive uncertainty, the decomposition of the predictions into conditionally independent components, an ecosystem classification, the use of expert opinion where empirical data is limited or not available, and the automation of the analysis.

Impact on and risks to water resources and ecosystems are reported and communicated by characterising the potential hydrological change, the potential ecosystem changes that may result from those hydrological changes, and implications for ecological, economic and sociocultural water-dependent assets that occur within and across those ecosystems.

This paper outlines the motivation and objectives for the bioregional assessment programme. The primary focus is on describing the overall scientific logic that runs through the assessment, connects coal resource development to water resources and ecosystems, and culminates in the impact and risk analysis for a bioregion or subregion. Importantly, it also provides the over-arching context for several presentations and papers that occur in this session and that explore aspects of the assessment in more detail.

Further details of the programme as well as the reports published thus far can be found at http://www.bioregionalassessments.gov.au.

Keywords: *Bioregional Assessment, risk, impact, ecosystem, coal resource development*

Using water-mediated causal pathways to assess cumulative impacts of coal resource development

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Abstract: A critical part of assessing cumulative impacts at a regional scale is understanding the water-mediated causal pathways from coal resource development activities to potential impacts on water resources and ecosystems. This paper describes the 'conceptual model of causal pathways' approach that underpins the Bioregional Assessment Programme in Australia. Bioregional assessments are independent scientific assessments of potential cumulative impacts of coal resource development on water resources and water dependent assets such as rivers, wetlands and groundwater systems. In bioregional assessments, causal pathways describe the mechanisms whereby water-dependent ecosystems may be affected by hazards associated with coal resource development activities. The conceptual model of causal pathways integrates the hydrological changes identified by the systematic hazard analysis and the ecohydrological conceptualisation to describe the logical chain of events that link coal resource development activities and potential impacts on water resources and ecosystems.

The systematic hazard analysis is used to identify activities that occur as part of coal resource development that may result in a change in the quality or quantity of surface water or groundwater, such as aquifer depressurisation due to groundwater extraction. Hazards are prioritised according to the likelihood, severity and detectability of potential impacts. Individual hazards are not represented in hydrological models, instead causal pathway groups, the main hydrological pathways by which the effects of a hazard can propagate from its origin, are represented in hydrological models through their conceptualisations and parameterisations. Outputs from hydrological models do not identify individual causal pathways, but rather integrate all possible causal pathways into the predicted hydrological responses at particular points in space and time. Not all hydrological effects can be modelled due to scale or complexity and are instead addressed qualitatively using the current conceptual understanding and knowledge base.

To assess potential impacts to the natural and human-modified ecosystems, landscapes are classified based on the ecohydrological conceptualisation, a simplified representation of integrated hydrological and ecological systems. Ecohydrological classification describes the important mechanisms and processes; whilst retaining sufficient detail and resolution to adequately represent key system components and their interactions at a landscape scale. Ecohydrological classes integrate available knowledge about the geology, geomorphology, hydrogeology, land use and ecology of landscapes. Ecohydrological conceptualisations can be simple narrative, or more formal qualitative mathematical models that translate hydrological changes, such as groundwater drawdown, into indicators of potential ecosystem change, such as vegetation canopy condition.

Keywords: *Cumulative impact, coal resource development, causal pathway, ecohydrological classification*

Predicting cumulative impacts of coal resource development induced hydrological changes on ecological indicators

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Abstract: A statistical methodology is presented that enables empirical investigation into the cumulative impacts of coal resource development across multiple water-dependent ecological systems over different spatial extents. The method was designed to support the analysis of cumulative impacts on ecology within a bioregional assessment programme. The challenge of predicting ecological response to cumulative impacts was made tractable by focussing attention on measurable properties of water-dependent ecosystems while progressing the staged development of a probabilistic prediction model. The objective was to predict how an ecological variable may respond across an ecosystem given changes in hydrology while coherently managing uncertainty within the context of cumulative impacts.

A given region may contain several different types of water-dependent ecosystems, for example, forested wetlands or perennial gravel cobble stream. For a given ecosystem, a group expert elicitation session was conducted to identify key ecological variables, important surface water and groundwater variables and the relationships among these defined variables. From this elicited ecosystem structure, a prioritised list of ecological indicators was derived. Quantitative hydrological response variables (HRVs) were developed in consultation with surface water and groundwater hydrologists. These HRVs defined the hydrological inputs into a probabilistic model.

The probabilistic framework was constructed to accommodate the following factors: 1) potential empirical data, 2) domain expertise and expert synthesis of knowledge and experience, 3) flexible response surface of an ecological indicator given relevant HRVs and 4) uncertainty in the predicted ecological response. The model was defined by a generalised linear model with likelihood function determined by the target ecological indicator. A flexible response surface allowed for convex or concave relationships as well as antagonistic or synergistic effects of HRVs on the target ecological indicator. The ecological indicator was also allowed to depend on past values; such temporal dependence may be induced for ecological indicators with long lifespans, for instance, or perhaps ecosystem engineering or long term influences on successional stages. The probabilistic model was constructed to provide predictions for three timeframes represented by specific assessment years: the recent historical past (2012), short term future (2042) and long term future (2102). Experts contributed subjective probability distributions that captured the predicted response of the ecological indicator to proposed hydrological scenarios. The expert elicited responses were then used to induce a prior for the unknown coefficients of the generalised linear model.

The probabilistic models were developed to provide predictions under two coal resource development pathways. The process was rolled out for 18 ecological indicators and 8 hydrological response variables from 14 landscape classes distributed over 4 different regions. Contributing experts varied based on the geographical location and the ecological indicators targeted. The probabilistic models have been developed to enable coherent updating by the inclusion of new expert input or empirical data or both. Moreover, the developed models are testable and can be probabilistically assessed with empirical data. The constructed models can also be used to advise the design of efficient monitoring programs that may be developed to reduce the uncertainty of relationships between an ecological variable and identified hydrological variables of importance.

Keywords: *Bayesian analysis, expert elicitation, Monte Carlo, risk analysis*

Basic spatial partitioning of large multi-sourced vector datasets to massively increase query yield for users

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Abstract: The problem we faced was a need to produce data from a very large multi-sourced spatial database for assessing the potential impact of coal resource development on Australia's water resources. The water resources included irrigation water sources, wetlands, rivers, groundwater aquifers and groundwater dependent ecosystems. The data had to meet scientific analysis and public policy needs where users could request any subset of many thousands of queries. The queries needed to be based on precisely the same source data. The requested data also needed to be presented back to the user at different levels of aggregation ranging from precise copies of the original input data through to highly simplified summary datasets. We were not in a high performance computing environment and initial testing indicated that conventional GIS geoprocessing methods would severely limit the number and timeliness of queries able to be produced. In response, we implemented a data structure that transferred much of the spatial information into relational database attributes yet retained the source data geometry (Figure 1). We pre-processed the data with a basic spatial partitioning method while cogniscent of the constraints conferred by the varying qualities of the input data, key information resolutions and the purpose of the queries. The pre-processing method placed all spatial geometries into a vector format partitioned by standardised 1x1 km box polygons (tiles) with unique tile IDs.

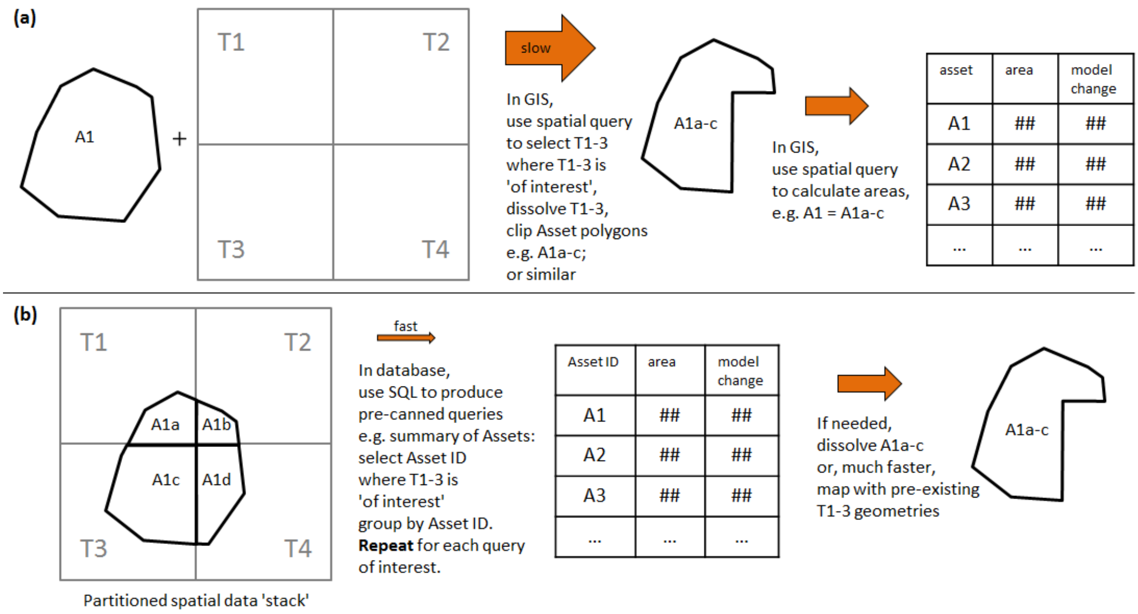

Figure 1. Two main options for processing the heterogeneous spatial data stack into thousands of pre-canned updateable queries (a) conventional geoprocessing approach and (b) vector partitioning approach used.

The resulting Postgres relational database safely ingested the spatial information and is capable of very rapid production of thousands of pre-canned queries (currently over 15,000) and, based on user-specified requirements, returns aggregated data including reassembled or partitioned geometries or original source data geometries. The requested data are returned either via a web feature service implemented for consumption by the scientist's ArcGIS computing environment or via a publically-available analysis presentation portal implemented as a web feature service delivering into a web browser with a customized user-directed query interface. The system is capable of very rapid amendments to queries (in seconds) and the addition of new data sets and queries (1-2 hours). Once updated, the data are available immediately via the public web portal.

Keywords: *Geospatial vector data, partitioning, SQL, pre-canned queries, applied*

Proposed guidance for developing ecohydrological models

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Abstract: Water resource development, including infrastructure and extraction, has long been recognized to change water-dependent species, populations, their habitats and supporting processes. Management of the flow in rivers through environmental flows is one way to limit adverse environmental change. Environmental flows describe the quantity, timing and quality of water to support ecosystems and the human livelihoods that are reliant on these.

Since the formalisation of environmental flow science in the late 1940's, a range of environmental flow frameworks have been developed ranging from the simple to the complex, from hydrological to socio-ecological systems-based approaches. The development of ecohydrological models has been a critical part of such frameworks, with many applications presented in the literature. Such a broad range of applications has created a rich variety of ecohydrological models that are available for researchers and practitioners to choose from. However, there are many aspects to this decision process that are required to ensure the approach taken is fit for the intended purpose. Whilst there is a rich literature of ecohydrological frameworks and modelling approaches, to date there have been few attempts to guide practitioners in how to go about selecting the most appropriate ecohydrological model to suite their purpose. This paper is intended to guide practitioners in their decisions for ecohydrological modelling.

We contend that the selection and development of ecohydrological models is based on the following key questions:

- What is the model purpose?
- Over what scales does the model need to be applied?
- What is the 'right' balance of model uncertainty and credibility?
- What are the choice of indicators, given purpose and scale?
- What are common ecohydrological modeling approaches that are available?

In this paper, we discuss each of these considerations, with examples drawn from the Murray-Darling Basin. We discuss how different modeling families are often applied in a context of assessing environmental flows given their underlying structure, data requirements and the level of uncertainty, noting the various sources of uncertainty and how this relates to fit for purpose modelling in a management context.

Keywords: *Ecohydrology, guidance, ecology, environmental flows*

Risky language: communicating the probabilities of impacts of coal resource development on ecosystems and water resources

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Abstract: Communicating complex scientific information about risk and uncertainty is challenging, particularly in politically contentious spaces where stakeholders are sensitive about nuances of language. This paper describes the lessons learned with respect to language used in reporting results from the Bioregional Assessment Programme.

Bioregional assessments are independent scientific assessments of potential cumulative impacts of coal resource development on ecosystems and water resources. The models used in these assessments produced a large number of hydrological and ecological predictions rather than a single number. This results in a range or distribution of predictions, which are typically reported as probabilities – 95%, 50% or 5% chance of exceeding thresholds. This approach allows an assessment of the likelihood of exceeding a given magnitude of change, and underpins the assessment of risk.

This probabilistic modelling has not been used to date by regulators of coal resource development, nor by proponents, therefore the method of reporting results needed to be developed, so that they were understandable and useful to both audiences. Across all 13 bioregional assessments, a common language for expressing probabilities was used as per the approach of the Intergovernmental Panel on Climate Change: the term '*very likely*' was used to describe where there is a greater than 95% chance that the model results exceed thresholds, and '*very unlikely*' was used where there is a less than 5% chance. Agreement on these terms (and many others) was facilitated across disciplines and geographic areas, and published in an online glossary.

However, not all results were quantitative: in some cases there was insufficient evidence to report anything but qualitative results based on logic. As qualitative data often requires expression using natural language instead of numbers, authors used terms such as 'negligible', 'minimal' or 'large'. The varying stakeholders were sensitive to nuances in these terms, and sometimes had conflicting requirements. Ultimately the Programme needed to balance the users' needs for formal definitions of terms that describe risk and uncertainty, with the authors' need for a range of words that communicate complex scientific information in an unbiased way without overstating the confidence in results.

Keywords: *Cumulative impact, coal resource development, language, risk, uncertainty, communication*

Probabilistic simulation of regional scale groundwater flow for prediction uncertainty analysis of coal seam gas and coal mining impacts in the Namoi region

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Abstract: Quantification of prediction uncertainty of potential water related impacts caused by coal seam gas and large coal mining developments are critical to inform regulatory decision making. This study was conducted for the probabilistic quantification of potential drawdown and changes in surface water – groundwater flux caused by coal seam gas (CSG) and coal mining developments in the Namoi catchment. As part of Australian Government's Bioregional Assessments programme, a regional scale groundwater model simulated the probability of maximum changes in groundwater pressure and water table elevation related to future coal mining and coal seam gas developments in the Namoi river catchment. The model, which included the Gunnedah-Oxley Basin, parts of the Surat Basin in NSW and the Namoi alluvium, was solved using MODFLOW-USG. The use of unstructured grids enabled selective refining of the model, for e.g. near the coal mines and CSG fields (figure). The modelling focused on changes in hydrogeological stress and the hydraulic properties, rather than on history matching or predicting future state variables such as groundwater levels. The probabilistic aspect of the analysis implied that modelling does not provide a single best estimate of the change, but rather it provides a probability distribution.

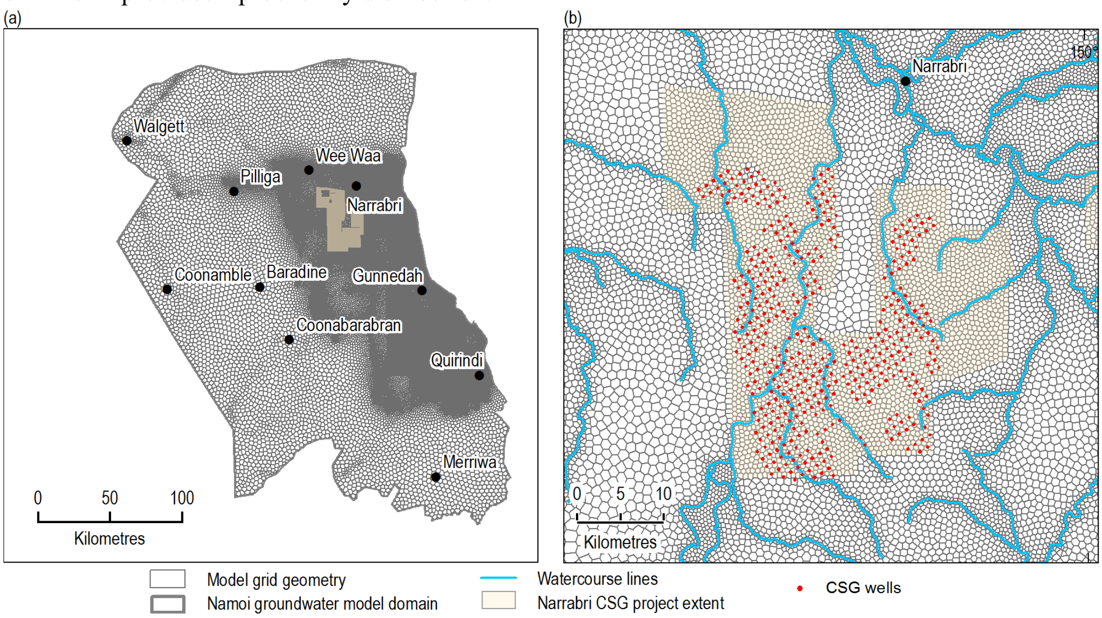

Figure 1. Plan view of the model grid and refinement of the Voronoi grid within the Narrabri Gas Project area

Existing data from a number of past studies for the Namoi catchment was compiled to develop a conceptual model of the groundwater system. The hydrostratigraphic data was compiled from environmental impact statements and other studies conducted for the Gunnedah and Surat basins. Field measurements informed the prior distributions of hydraulic properties. The results of the study indicated that the probabilistic simulation approach is useful for robust quantification of prediction uncertainty in drawdown and flux. While large scale uncertainty in characterization of deep sedimentary basins exists, these were not hindering the meaningful quantification of groundwater drawdown and surface water change probabilities that can aid in regulatory decision making.

Keywords: *Coal Seam Gas, coal mining, groundwater modelling, uncertainty*

An ecological trajectories architecture for use in the Murray-Darling Basin

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Abstract: Tracking the progress of water management actions against Basin Plan objectives in the Murray-Darling Basin requires an ability to forecast the condition of the Basin's environmental assets into plausible hydrological futures. Understanding and modelling how asset condition changes through time is referend to as trajectory modelling. Asset trajectories originating from a particular starting condition are bound by a range of possible future conditions. This range increases through time in association with different sequences of environmental conditions (created through the flow regime), and is bound by the rate of response of the environmental asset. This rate of response is associated with factors largely intrinsic to the different environmental assets, for example, the rate at which generation of biomass is associated with vegetation recovery. Tracking ecological outcomes through time requires understanding and quantifying environmental water needs, responses to event sequencing and antecedent condition within a broader systems framework. Many factors are likely to influence the extent to which environmental watering can achieve Basin Plan objectives. These include natural variability in the flow regime, strategic (long-term) water management decisions, short-term prioritisation of environmental water and other threats and influences outside of water management (such as multi-species interactions). Throughout the record of historical flows, natural variability has been a major cause of change in environmental condition. Short-term incremental decision-making (or prioritization based upon annual objectives and opportunities) and the uncertainty of future conditions influence the ability to achieve longer-term objectives.

The Murray-Darling Basin Authority (MDBA) currently uses a range of ecological modelling tools and methods to inform water management priorities and decision-making within the Basin. In this paper, we outline the development of a method that builds upon existing frameworks and methods used by MDBA and integrates them into a trajectories modelling architecture. The trajectories architecture uses an automated workflow to incorporate the variability of historic flow regimes combined with scenario analyses that are linked to eco-hydrological models. The goal is to develop methods to inform possible outcomes of water management over periods amenable to both long- and short-term decision making processes and align with timelines for Basin Plan objectives and beyond. We demonstrate the architecture using a case-study of woody floodplain vegetation.

Keywords: *Trajectories, environmental outcomes, ecology, ecological response, Basin Plan, response modelling*

Integrating biological degradation potential into ecological risk assessment

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Abstract: Expanding agricultural activities and industrial operations have resulted in the accumulation of toxic chemicals in our environment, and have become a potential threat to human health as well as to the flora and fauna in our ecosystems. The assessment of contamination risk to our environment mainly relies on mathematical models that estimate the contaminant concentrations and the leaching rates into aquifers. The contaminant level is commonly determined by comparing the concentrations predicted by models against a threshold concentration, and the ecosystem is considered at risk if the predicted contaminant concentration is above a threshold value. Although environmental models can describe contaminant transport and adsorption processes relatively well, most of these models do not take into account the capability of microorganisms to degrade toxic contaminants into less toxic or non-toxic molecules. Many experimental and in-situ studies have shown that soil microbial activity can result in a relatively fast rate of contaminant degradation, therefore implying that the time required to "clean-up" a contaminated site may be substantially shorter in the presence of receptive microorganisms. Hence, ecological risk assessments not accounting for microbial load and specific catabolic processes can overstate the risks and lead to the making of policies and management strategies only partly suitable to specific contaminated ecosystems.

In this study, we integrated the biodegradation potential ψ_B of a contaminant into ecological risk assessment index through the specific biomass affinity ϕ. We focused on atrazine (ATZ), one of the most extensively used herbicides in Australia, as the model contaminant using data from la Cecilia and Maggi (2017), and the Hazard Quotient as the modeled ecological risk index (Suter II, 2007). Model parameters were estimated from laboratory experiments, while simulations were extended to a 60-year time scale to analyze the Hazard Quotient of ATZ contamination in groundwater with the inclusion of ATZ biodegradation potential under scenarios of different ATZ application rates. These analyses demonstrated that ATZ contamination level can be overestimated if the biodegradation potential were not taken into account. The use of contaminant biodegradation potential in ecological risk assessments can improve information for optimum decision making in environment and resources management.

Keywords: *Atrazine, agrochemicals, contamination, ecological risk index, specific biomass affinity*

Sampling Bias and Implicit Knowledge in Ecological Niche Modelling

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Abstract: Ecological niche modelling is an important method for predicting the range of a species, which can be used to support conservation efforts and assist in biological understanding. Ecological niche modelling relies on observations by field biologists, but these may suffer from sampling bias, due to difficulties such as those illustrated in Figure 1.

In this paper we use synthetic species distribution data to evaluate a number of modelling mechanisms for dealing with sampling bias in data from the field (Phillips *et al*. 2009; Syfert *et al*. 2013; Kramer-Schadt, *et al*. 2013), and we simulate a modeller attempting to reconstruct the distribution from that data. Synthetic data lets us assess the modeller's work against "ground truth." The modeller typically uses a machine learning algorithm like Maxent or Random Forests, together with 'presence' datapoints from field biologists and randomly generated 'background' datapoints. We consider bias in general terms, rather than simulating a specific bias mechanism. Figure 2 shows the ecological niche modelling process we have simulated.

Our results show that, in cases of sampling bias, the Maxent algorithm generally performs as well as or better than Random Forests. Where the field biologists have concentrated their sampling efforts in a specific 'focus area,' there is generally a benefit in a 'boost' of additional 'background' datapoints within that area. Using implicit biological knowledge to exclude 'impossible' regions from the study area has mixed effects. Spatial filtering, as suggested by Kramer-Schadt, *et al*. (2013), may sometimes have significant negative effects.

Our results also show that, where sampling bias occurs, AUC scores are a poor guide to true algorithm performance (although, without knowledge of the true distribution, it is generally the best available guide).

Figure 1. Sampling difficulties: ***vegetation*** (horizontal scrub, *Anodopetalum biglandulosum*, in Tasmania – photo by Phillip Hirst, 2010), ***terrain*** (highlands of Papau New Guinea – photo by eGuide Travel, 2010), and ***distance from roads*** (Sahara desert, Kebili, Tunisia – photo by "wonker," 2010). Images from www.flickr.com/photos/{phil_hirst/4310391447,eguidetravel/5986605253,wonker/4300464711}.

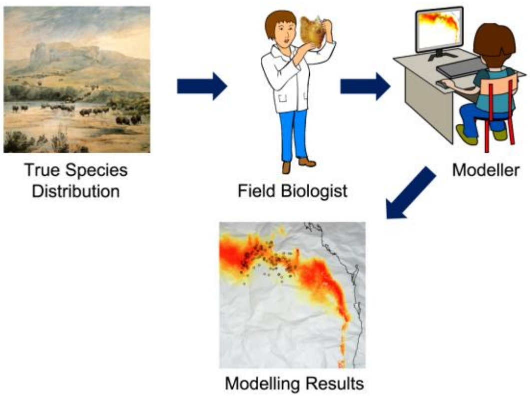

Figure 2. The process of ecological niche modelling, which we study in this paper.

Keywords: *Ecological niche modelling, Species distribution modelling, Sampling bias, Maxent*

Rapid spatial risk modelling for invasion management under uncertainty

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Abstract: Across the globe, invasive alien plant species are a major threat to biodiversity and agricultural industries. Invasive plant spread is an ongoing process that plays out at different spatiotemporal scales. When an invasive 'weed' emerges in a new country, region or landscape, there is often a distinct lag phase during which population increase and invasive spread is slow. Rapid response by biosecurity managers to new incursions may bring the greatest opportunities with regard to facilitating eradication or effective containment as well as minimizing long-term control costs and negative impacts. An important consideration for allocating finite management resources is the spatial distribution of invasion risk. However, hard data is rarely available to assess risk, and decisions are consequently made under considerable uncertainty.

We developed a flexible, spatially-explicit methodology for rapidly modelling invasion risk using Bayesian networks and Geographic Information Systems (GIS). In this well-established modelling framework, the key processes of invasion and the major risk variables affecting these processes are represented as a Bayesian network. GIS analysis is used to link each risk variable contained in the model to one or several spatial data proxies and to map model predictions. Here, we present a simplified implementation that can be used rapidly and under limited knowledge, using the case study of Mexican bean tree (*Cecropia* spp.) in North Queensland. We modelled two aspects of invasion risk: (a) the potential, time-independent environmental suitability of a site for plant establishment and persistence, and (b) the actual susceptibility of suitable sites to propagule introduction from source infestations recorded during annual 'detection periods'. We derived risk variables and spatial data proxies via desktop research and used simple mathematical functions to model the interplay between risk variables, invasion processes (establishment, persistence and propagule pressure), and invasion risk (suitability and susceptibility). We also evaluated the ability of our model to accurately predict the observed spatial progression of the *Cecropia* spp. invasion in North Queensland by validating mapped annual susceptibility against subsequently observed infestations.

The majority of North Queensland's Wet Tropics was predicted to be potentially highly or moderately suitable for *Cecropia* spp. invasion. Actual susceptibility to invasion in a given fruiting season is more restricted due to dispersal constraints from source infestations. In each evaluated detection period, modelled susceptibility was a good predictor of actual *Cecropia* spp. detections in subsequent years. Annual susceptibility maps may be used for allocating surveillance and containment resources around existing infestations. Low-frequency long-distance dispersal or human-mediated translocations were not captured in the model. Further automation of risk factor / spatial proxy selection and data pre-processing may make our methodology for rapidly modelling invasion risk accessible to biosecurity agencies that typically have significant field knowledge and GIS capacities but may have limited expertise in applying complex modelling methods.

Keywords: *Emerging weeds, incursion response, Cecropia spp., Bayesian network, suitability, susceptibility*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Routing water flow on square grids

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Abstract: While triangular meshes and curvilinear flow meshes are often used for numerical modelling of flows, there are still situations where regular square grids are preferred. One example is calculating contributing area and flow paths on gridded digital elevation models (DEMs). A recurring concern with routing flow over square grids is whether flow should be allowed across the corners of the cells, with eight possible flow directions, or whether it should only be across the four edges. From a mathematical point of view, the flow through a point should be zero, but most contributing area methods allow diagonal flows, often without a clear justification of how the amount of flow across edges and corners is determined. Most of the methods appear to work reasonably well, but the lack of good theoretical underpinnings has led to a proliferation of methods with minor variations in the details of flow routing.

Flow routing and contributing area calculations make a lot more sense when they are associated with flow lines across cell edges, not with cell areas or points at the centres of cells. Each cell edge usually has a clearly defined upstream and downstream area and a clearly defined flow width. With this approach there is no troublesome flow across corners but in some areas there are cells in valleys that appear to be sinks with inflow across all four edges. The underlying cause is that the actual flow lines are strongly curved and flow enters and leaves the cell along the same edge, which the simple view of one-directional flow across each edge cannot represent. Representing curved flow lines through cells is not a realistic option due to the massive increase in complexity and the number of special cases that must be handled.

There are several possible solutions to this dilemma. One is to simply allow diagonal flow paths in those special cases; the consequence is that all flow paths out of that cell are concentrated onto a line. That is not necessarily a bad thing, since convergence of flow paths along valleys eventually requires concentration of multiple paths onto a single line. A second solution is to reverse the flow direction on the least uphill edge to provide an outflow without resorting to diagonal flow. The cost of this approach is allowing flow in what appears to be an uphill direction from a lower cell to a higher cell, with some distortion in flow paths. The benefit is that distinct flow lines are maintained. A third approach is to add internal detail to the cell to approximate the effects of the curved flow lines. Subdividing the cell into four (2×2) or nine (3×3) sub-cells allows flow to be routed through the smaller cells avoiding diagonals. Adjacent cells would have to be similarly divided to both receive and deliver flow along a single edge, but the subdivision would not propagate further than one cell because the remaining edges of the adjacent cells already have unidirectional flow.

A typical case showing actual curved flow lines and simpler representations using diagonal and diverted flow lines is illustrated in Figure 1. A plausible strategy is to allow diagonal flow paths where there is likely to be actual convergence of flow into a channel smaller than the cell size, and flow reversal where the flow is not already concentrated and maintaining separate flow lines is worth the minor distortion in flow pathways.

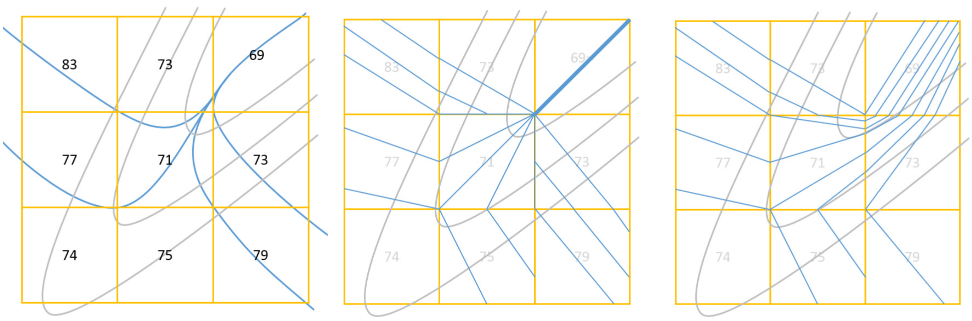

Figure 1. (a) contours in grey and flow lines in blue; (b) simplified flow lines using diagonal flow and (c) using diverted flow.

Keywords: *Flow routing, digital elevation models, contributing area, diagonal flow*

Using REST API, map tile processor, and JavaScript libraries to develop an integrated and interactive geospatial modelling platform

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Abstract: The "SmartSea – Gulf of Bothnia as Resource for Sustainable Growth" project of the Strategic Research Programme of the Academy of Finland will develop an open-source toolbox for Maritime Spatial Planning (MSP). A prototype of the toolbox has been developed as a software system platform utilizing several existing open-source software libraries, a relational database, three programming languages, and the client-server distributed application structure. The system supports flexible modelling of the maritime spatial planning problem and mathematical modelling of the spatial planning problem using a range of techniques. The results of the project will be used to help MSP practitioners in Finland.

MSP is a relatively new concept and thus few fixed rules, and institutions exist for it. Analysis and allocation of spatial and temporal distribution of human activities in the light of existing knowledge of ecological values is at the heart of MSP. Modelling is needed for structuring the planning problem and for solving specific valuation, comparison, and evaluation problems.

The platform comprises five integrated components

- dataset preparation tools and a dataset database,
- database for spatial plans and its APIs,
- a web map tile server (WMTS) and the tile processor,
- web browser app for editing plans and associated models, and
- desktop GIS plugin for integration with other spatial tools.

Integration in the platform is achieved via commonly used software libraries (DBIx::Class object – relational mapper, GDAL geospatial data abstraction library) and protocols (WMTS, REST).

Spatial planning using the platform proceeds from defining types of uses for space and various criteria and/or attributes for them. A type of use is defined by a scheme of activities, while a use in a plan is defined by a suite of spatial attributes such as the suitability of any given location for the use, or the benefit/harm generated by allowing the activities take place at those locations. A simple cumulative ecological impact model based on expert knowledge is implemented on the platform. In addition, arbitrary spatial attributes can be computed from input data with a range of mathematical models.

Three types of mathematical models for computing spatial attributes have been implemented into the system. The simplest one simply excludes or includes spatial cells from the result based on rules, which are simple comparison predicates. The more advanced ones compute a weighted sum of input values. The weight can be a simple value or augmented with a pattern windowing a range of input values. The third type of mathematical model is a Bayesian network (BN). A BN represents the conditional dependencies between random variables and it can be used for example to infer the value of an unobserved variable. The system uses a BN engine to compute the value of each cell in the spatial attribute layer from input data.

The main new result of the work is a technique linking the models associated with spatial plans to a tile processor thus implementing a dynamic WMTS that can be used for spatial modelling purposes. The tile processor was relatively easy to implement since the tile server software was also developed by the author. Only small changes to the server software were required to make it route the tile response through the plugin. The server software was written in Perl taking advantage of the DBIx::Class and Plack frameworks.

A client app was written in JavaScript taking advantage of OpenLayers are JQuery libraries and the MVC application development pattern. The QGIS plugin was written in Python but its functionality is limited due to differences in how it implements WMTS compared to OpenLayers.

Keywords: *Maritime Spatial Planning (MSP), web mapping, spatial modelling*

Modelling wind erosion for Australia for prioritisation of national Landcare investments

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Abstract: Soil underpins Australia's agricultural production, biodiversity and provides ecosystem services that benefit the entire community. Wind erosion threatens the soil asset through its removal of soil and nutrients and its redistribution across the landscape. Wind erosion also threatens air and water quality. Therefore, the management of ground cover by farmers and graziers is critical to the provision of ecosystem services and ecosystem and agricultural productivity. The National Landcare program Phase 2 is to continue investment in natural resource management. Funds will be targeted to those areas where the need is greatest to protect and enhance Australia's natural resources.

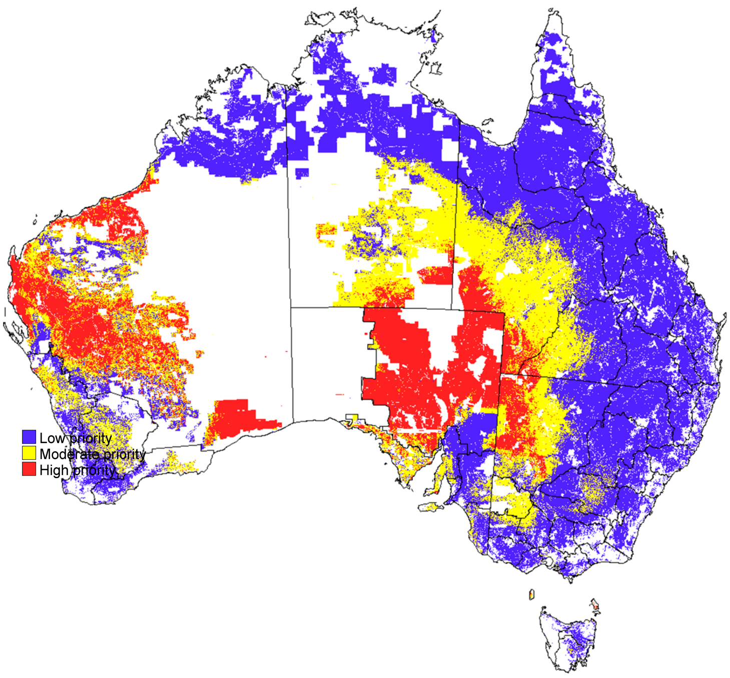

Figure 1. Priority areas for investment to reduce soil loss through control wind erosion on agricultural land. Boundaries for states and territories and natural resource management regions shown, White = non-agricultural land

The purpose of this study is to produce advice for the National Landcare Program to identify where funding of improvements in ground cover management on agricultural lands will give the best returns on investment (Figure 1). The process was to use the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS–S) to combine three principal layers to form a priority map for investment. The three layers were: 1) A new modelled map of wind erosion severity for the period 2000-2010, 2) An index map of the total soil fertility loss derived from The Soil and Landscape Grid of Australia, and 3) Two maps of "room for improvement in land management practices" for cropping and grazing lands sourced from the 2012 Agricultural Resource Management Survey data.

This project improves on the 2012 Caring for Our Country prioritisation process by using a more physically based model and enabling finer scale mapping that show more landscape features. When combined with the land management improvement data this also helps weight investment to regions with lower levels of desirable management practices.

***Keywords**: Modelling, wind erosion, multi-criteria analysis*

Experimenting with Modelling via a Virtual Laboratory: Evaluating pseudo-absence strategies to refine a species distribution model

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Abstract: Virtual laboratories (VLs) are fast becoming realities in many fields of enquiry. For instance, the Biodiversity and Climate Change Virtual Laboratory (BCCVL) provides users with a high-performance computational platform to enable more efficient investigation of biological systems. This kind of VL is more than a mere portal to dispersed data sources and a diverse range of modelling options; it also reduces computational overheads and tedium required to implement models. In this way, a VL allows users to explore each model to more fully apply scientific method in model development. Here we explore how the BCCVL can be used to support an iterative process of investigating and refining models, through experimentation.

The BCCVL supports many kinds of modelling for biodiversity, measured by species presence, traits or aggregate measures such as species richness. Here we narrow our focus to consider species distribution modelling (SDM), and in particular, the source of absence data. Absences in SDM provide a useful case study for exploring models in VLs, as there are many potential settings, known to substantially impact SDM results. When absence of the species has not been explicitly recorded, several strategies are available to impute 'pseudo-absences'. New users may inadvertently specify pseudo-absences in a way that leads to issues such as 'naughty noughts' or pseudo-replication. It is possible to identify those issues during SDM, and this process can be accelerated through a VL. Additionally after initial exploration in a VL, it is easy to export data for analysis into a statistical package, such as R, and continue to refine SDMs.

Here we show how the SDM for the Golden bowerbird is sensitive to the strategy for generating pseudo-absences, as defined by settings that can be altered within the BCCVL. A sequence of well-defined experiments gradually helps refine the options defining this strategy. We begin with the study region, which implicitly delimits search effort, and potentially defined by: the continent, a bioregion or a convex hull delimited by the farthest occurrences. At the same time BCCVL makes it easy to compare SDM algorithms. We consider regression (GLM), tree (CTA) and machine learning (MaxEnt) algorithms. Next we undertake separate experiments to further refine selection of pseudo-absences. The sampling strategy may be: completely random; constrained by a disc centred at occurrences; or defined by a Surface Range Envelope, comprising locations that fall outside the usual range of predictors evaluated at occurrences. In comparison to the number of occurrences, the intensity of pseudo-absences may be set to be equal or any other ratio. We export model results for out-of-VL analysis, and apply recursive partitioning trees in R to investigate naughty noughts.

The Golden bowerbird is similar to many specialist species in Australia: generating pseudo-absences across the continent gave a large contrast between occurrence and absence, as evidenced by the distribution of predicted probability of presences. Constraining pseudo-absences to a bioregion, we were able to choose an SDM algorithm that permitted examination of gradients from absence to presence, whilst retaining high accuracy. Further experimentation assessed sensitivity to the sampling strategy of pseudo-absences, with a good option being a 10:1 sampling ratio at least 10km from occurrences. Exporting these pseudo-absences to R, tree modelling identified uninhabited climates (with high mean temperature of the warmest quarter). When omitted, the estimates of climate effects on this species' presence were greatly sharpened. This demonstrates how a VL may be used to refine modelling, evaluating sensitivity to settings via performance measures relevant at each stage. In this case the choice of pseudo-absence strategy to support SDM for the Golden bowerbird might have been discarded using a 'one-off' modelling approach that focussed on a single indicator.

Keywords: *Iterative modelling, computer experiments, naughty noughts, probability of presence*

Investigating the Potential Role of Visualisation in Natural Resource Decision-making

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Abstract: Computer-aided visualisation can be applied to natural environments to understand the impact of proposed developments or management strategies, but little evaluation of the effectiveness of these tools has been undertaken. In seeking to manage natural environments, it is desirable to model and understand these complex interactions in order to compare the outcomes of applying different management strategies.

The purpose of this study was to investigate whether there are significant differences in knowledge outcomes 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 water levels on the flora and fauna, as well as plants and animals living in and around the Lake. 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.

In order to test for the effect of interactive versus non-interactive forms of visualization, we conducted an experiment with forty participants (randomly assigned to two test groups) who have various interests at Te Waihora. We provided them with either an interactive or a non-interactive form of visualisation. Results were recorded from a structured interview after the test. The findings revealed that interactive visualisation was key to advantageous learning about changes in environmental behaviour. We argue that the techniques presented have the potential to stimulate meaningful discussions in natural resource situations that involve contested resources or a multiplicity of interests, but at the same time, there is an urgent need for evaluation of such tools in participatory decision-making processes.

Keywords: *Personal understanding, interactive visualisation, static visualisation, evaluation, visual simulation*

Quantifying the effect of population mobility on exposure to priority air pollutants – a case study for the UK focusing on ozone, nitrogen dioxides and fine particulate matter

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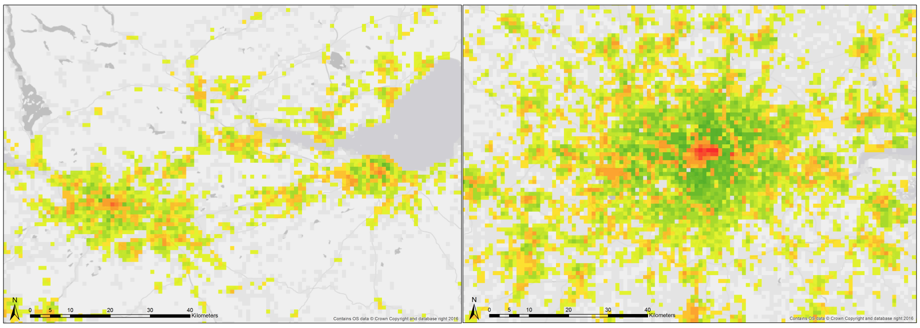
Abstract: The quantification of population level exposure to ambient air pollution is typically based on static population distributions inferred from the postcode of residence, and annual average concentrations of priority air pollutants at that location. Contemporary atmospheric chemistry transport 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. 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' population maps include usual residents and others present in an output area during regular working hours and complements regular population maps, without double-counting.



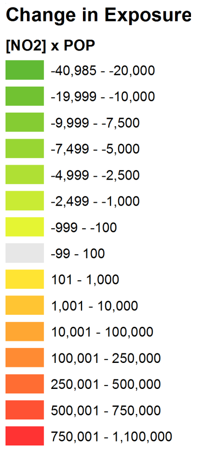


Illustration of the difference in population exposure to ambient nitrogen dioxide exposure in the Scottish Central Belt (left) and the Greater London area (right). The units depict *number of population × concentration in µg* in a 1 km x 1 km grid cell for the year 2015, showing the difference between calculating population exposure using residential population only. Negative values indicate reductions in exposure.

In this presentation, we demonstrate, for the first time, how accounting for personal mobility (e.g. commuting to place of work or study, or spending time away from the main residential address) affects the exposure of the UK population to selected priority air pollutants (fine particulate matter, $PM_{2.5}$; ground level ozone, O_3; nitrogen dioxides, NO_2). The presentation will focus on the spatial data processing and evaluation of an integrated approach utilising land-use data, output from state-of-the-art ACTMs and the latest data on population distribution for the UK. The results presented quantify potential under- or overestimation of population level exposures and pave the way for the routine application of this integrated modelling approach. Enabling better estimates of public health effects of current air pollution, as well as improving the capability to model future scenarios and the effectiveness of air pollution control measures implemented by local and national scale policy makers is the objective of this work.

Keywords: *Air pollution, public health, personal exposure, atmospheric chemistry transport modelling*

Spatially-explicit modelling of ecological processes in complex agricultural landscapes: connecting 'artificial' landscapes with 'reality'

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Abstract: Artificial landscapes are often used in landscape ecological models to investigate questions around movement of individuals, the spread of invasive plants and diseases or the stability of meta-populations. Using these artificial landscapes has some strong benefits such as simplification of landscape complexity, a means to replicate landscape scenarios or the potential to study systematic gradients. Communicating the results to non-theoreticians, however, is often difficult because there is often no quantitative comparison made to link them with reality. Other models that directly use digitized real landscapes as input do not have this barrier, but they are often lacking generalizability or the potential to forecast the effect of changes in the environment.

In this study, we propose a method to generate artificial landscapes with key parameters derived *a priori* from real landscapes through analyses based on Geographical Information Systems (GIS) data: surface cover, spatial aggregation and patch size. Existing methods of generating artificial landscape often do only *a posteriori* comparisons to prove that their landscapes are 'realistic'. We show that, by estimating the parameters beforehand, we can generate artificial landscapes incorporating multiple land use types that can be directly compared to existing landscapes in a quantitative manner. This allows for more targeted landscape generation and vastly reduces the parameter space that needs to be covered. At the same time, this method does not reduce the potential of the models in terms of being reproducible and transferable.

We show an application of this method with two contrasting, complex agricultural landscapes from eastern Sub-Saharan Africa and South-east Australia. We artificially generated landscapes using key parameters from an analysis of digitized real landscapes and found that the algorithm allows flexibility in single target parameters while retaining 'realism'. Realism is assessed in different way. For the Australian data, we compare ranges in land use cover and aggregation between real and generated landscapes. For the African data, we found a log-linear relationship between these two variables in the empirical data that we then used to generate the realistic artificial landscapes. By creating a measurable link between real and artificial landscapes this method will help reduce communication barriers between theoretical scientists and the general public, increasing the impact of our science.

Keywords: *Artificial landscapes, landscape generation algorithm, ecological modelling, Geographical Information System*

Modelling historical air pollution and dementia/cognitive decline

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Abstract: Exposure to air pollution has been linked to a wide variety of health problems but, due to the lack of systematic and wide-ranging air pollution monitoring before the 1980s, investigations into the role of atmospheric pollution in the development of chronic health conditions such as dementia have not been possible. Dementia is a major (and growing) public health concern with approximately a third of risk variance unexplained. It is now clear that origins of this condition lie much earlier in life, potentially decades before symptoms appear, therefore attention to determinants of risk in earlier life need to be widened to include longer-term air pollution exposure.

This study investigates the feasibility of integrating modelled historic air pollution with later life health outcomes in Scotland by;

1. Modelling mid-20th century air pollution conditions.

2. Linking this historic modelled data to two existing birth cohorts (1936 and 1947) to investigate association between pollution exposure and dementia/cognitive decline.

A spatial modelling approach is necessary to estimate historic air pollution concentrations in Scotland due to the scarcity of pollution monitoring pre-1980 (particularly network-based monitoring). This is achieved by creating an historical emissions inventory for sources of pollutants such as nitrogen dioxides (NO_x), sulphur dioxide (SO_2) and fine particulate matter ($PM_{2.5}$ and PM_{10}), with subsequent concentrations calculated using the EMEP4UK atmospheric chemistry transport model framework. Initial results show concentrations of SO_2 and NO_x up to 240 and 150 $\mu g\ m^{-3}$ respectively, for a 5 km resolution grid.

This modelled data is currently being analysed against to two existing cohorts: the Scottish Mental Survey 1947 (SMS1947, N=70,805, born in 1936) and the Lothian Birth Cohort 1936 (LBC1936, a subset of SMS1947, N=1,091). The SMS1947 cohort is linked to the 1939 National Register and to subsequent health records to identify dementia diagnoses, while the LBC1936 cohort, focused on a smaller area surrounding Edinburgh, is a more detailed dataset including serial clinical and cognitive assessments.

All data are used in logistic regression models to investigate the exposure to air pollution and dementia status while disease mapping models investigate geographical variation of dementia risk. The study demonstrates how using historical modelled data can compensate for the lack of historical monitoring data and how modelled air pollution data can be combined with long-term health data to investigate the origins of dementia risk within a life course epidemiology paradigm.

Keywords: *Atmospheric pollution, dementia, historical pollution, life course epidemiology*

An alternative method for deriving a USLE nomograph K factor equation

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Abstract: Soil erodibility (K factor) is an important component of the Universal Soil Loss Equation (USLE) / Revised USLE (RUSLE) and is used in many erosion models. A soil erodibility nomograph developed by Wischmeier et al. (1971) allows for a simple and repeatable method for calculating a K factor based on five key soil attributes. These attributes include the percentage of silt + very fine sand, sand and organic matter to calculate a first approximation of K. A value for soil structure and a value for permeability can then be used to complete the nomograph where a first approximation is insufficient.

Following the development of the nomograph, an equation was created to bypass the otherwise tedious and time consuming manual process. This classical soil K factor equation can emulate the nomograph with some accuracy, but has shown to lack the required precision in certain circumstances. In this research a new method for deriving an equation directly from the soil erodibility nomograph is demonstrated and tested against the classical K factor equation.

The main aims of this work are to:

1. Test a method for deriving a K factor equation that facilitates graphical modification to the nomograph prior to generating an equation.
2. Compare the results against those achieved using the classical K factor equation.
3. Create resources (including open-source scripts and a custom toolbox for ESRI ArcGIS) to allow ease of access to these methods for researchers and landscape managers alike.

The method assumes that by segmenting the nomograph into zones according to the percentage of silt + fine sand, the relationship between key soil properties and erodibility can then be considered as a series of linear equations and can hence be solved within a linear systems framework.

This method allows for iterative creation of new equations to fit any graphical changes made to the nomograph, and results show it can produce equations that emulate the nomograph solution with higher accuracy than the classical K factor equation.

When tested on 100 randomly generated theoretical soil samples, this method achieves an average difference of just 25% from the nomograph solution. The classical equation achieves an average difference of 38% from the nomograph solution when tested on the same set of theoretical soil samples.

Furthermore, where the classical equation is limited to soil samples with < 70% silt + fine sand, this new method can solve the full range of values taken by the nomograph and does not require additional equations for edge cases.

This work shows that alternatives methods can solve the soil erodibility nomograph with higher accuracy than the classical equation, and the method is not restricted to the soil erodibility nomograph, it can also be applied to other biophysical nomographs.

A custom toolbox is developed for ESRI ArcGIS software to allow use of the equations developed here without the need to replicate the methods. A range of open-source scripts written in the Python programming language are also available.

Keywords: *Universal Soil Loss Equation (USLE), soil erodibility nomograph, K factor equation*

Rainfall extreme changes and the impacts on hillslope erosion across the Alpine Region in NSW

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Abstract: In recent decades, changes in climate extremes have received considerable attention because extreme climate events are often more important to natural and human systems than their mean values. Rainfall extremes have been studied on global, regional and national scales. These studies found some significant changes in percentiles and frequency of extreme events, and the magnitude and the sign of the changes vary with seasons and regions. Consequently, hillslope erosion rates may be expected to change in response to changes in the erosive power of rainfall or rainfall extremes.

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 south-east Australia for the baseline (1990-2009), near future (2020-2039) and far future (2060-2079) periods. The aim of this study was to model and predict the changes of rainfall extremes and the impacts hillslope erosion risk across the Alpine region in NSW based on the NARCliM projections. Outcomes from this study are to assist the long-term climate change adaptation and regional planning for the Alpine Region.

In this study, the NARCliM projected rainfall data at three time slices (1990-2009, 2020-2039, 2060-2079) were used to calculate ten rainfall extreme indices. These indices in the baseline period (1990-2009) were compared to these calculated from the Bureau of Meteorology rainfall data. We further examined the relationship between rainfall extreme indices and hillslope erosion rates across the Alpine Region. The relationship of the selected indices, such as the maximum 5-day accumulated precipitation index (Rx5Day), was used to predict hillslope erosion based on the revised universal soil loss equation (RUSLE) along with the slope-steepness factor and the soil erodibility factor. Time series (monthly and annual) rainfall extremes and erosion risk maps for Alpine Region for all 60 years have been produced at a spatial resolution of 100 m. Statistical tests were used to quantify the spatial and temporal changes of rainfall extremes and the impacts on hillslope erosion in the region. Inventory of the time series maps for the 60-year periods can be used to identify the high erosion risk seasons and areas across the region. Automated scripts in a geographic information system have been developed to calculate the time-series rainfall erosivity and hillslope erosion so that the processes of large quantity NARCliM data could be realistic, repeatable and portable.

The results show that: 1) Rx5day index has the strongest correlation with rainfall erosivity for all the three periods ($R^2 > 0.83$); 2) there is strong seasonal variation in rainfall extremes and erosivity, particularly in summer; and 3) the predicted hillslope erosion in near future increases about 2.63% and about 16.57% in far future on average. These imply the importance of groundcover maintenance and soil management in this region, particularly for the areas with consistently high erosion risk as shown in the time series maps.

Keywords: *Rainfall extremes, hillslope erosion, climate change, Alpine Region, NARCliM*

Atmospheric correction for a Landsat and Sentinel-2 product over water surfaces

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Abstract: In the last decade, satellite derived standard land products have increasingly been produced for medium resolution satellites such as Landsat and (more recently) Sentinel-2. These mostly involve estimating surface reflectance and surface temperature. The products generally remove or standardise atmospheric effects with some normalizing for surface bidirectional reflectance distribution function (BRDF) and terrain illumination effects to provide consistent time series and mosaics. The products have been used in various land surface applications, for instance, land cover, fractional cover, water identification, flooding mapping, crop monitoring and other time series analysis. However, the products are generally not immediately sufficient for applications over persistent water areas, such as estimating water quality, benthic cover, sediment transport, erosion and shallow water bathymetry. These need additional corrections with different physics that are not included in standard land products. In this paper, a method is proposed that treats persistent water areas separately within the standard product and includes corrections not generally applied to the land. The processing has been designed to be fully consistent between water and land in atmospheric correction and to provide comparable definition of reflectance factors so that they can be combined in the same time series and form mosaics. The first step in this process is the use of an effective and up-to-date classification to separate the persistent water and land. The water areas are then atmospherically corrected in the same way as the land without applying BRDF or shading effects. For the water areas, adjacency effects are more significant near the water-land interfaces due to the large contrast between land and water. Water surface effects have also different physics from land surfaces. Therefore, the extra corrections currently include correction for adjacency effects, regional sun glint and sky radiation effects. The water mask and these corrections have been added to the current existing atmospheric, BRDF and terrain corrected surface reflectance product (standard product) from Geoscience Australia (GA). However, at the scale of the Landsat and higher resolution satellite images, residual local surface and bidirectional effects still occur and are discussed in this paper. Results from the new processing strategy have been compared with GA standard products in test images of Canberra and the North Queensland coast near Ingham and used as a basis to discuss the likely residuals of surface and atmospheric effects and options for the inclusion of methods to overcome them in a standard product. The results show that:

- Both inland and sea water signatures behave as expected from other data and models.
- Adjacency correction seems most useful where a water-Land interface is close to the water body.
- Sky glint removal is sometimes too much in the Canberra site when water is shielded by local terrain.
- Sun and sky glint correction greatly improves the coast and deep sea water signatures.

Keywords: *Adjacency correction, sky and sun glint correction*

Disaggregation of Regional Soil Organic Carbon Content Map to Farm Scale Information using Bayesian Area-to-Point Regression Kriging

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Abstract: The proliferation of Digital soil mapping (DSM) and modelling techniques during the past decades to address soil data and information needs has resulted in an ample amount of digital soil information. However, when it comes to specific requirements, more often the spatial scale of available products does not match the user requirements. This spatial scale incompatibility creates a need for spatial scaling; up-scaling or down-scaling available information to outfit the user demands.

In recent years, disaggregation of soil resource information is becoming more important as many soil management activities are needed in local or fine scales, such as for nutrient applications and site specific soil management. Area to point kriging (ATPK) and its variants such as area to point regression kriging (ATPRK) are the most common techniques applied to disaggregate soil resource information. Disaggregation is a change of support problem. The use of Bayesian inference of the ATPRK system allows quantifying the uncertainty associated with inferring point support variogram from the block support variogram in addition to estimating the product uncertainty. To the best of our knowledge, Bayesian ATPRK has not been used for downscaling soil information. In this study, for the first time we propose Bayesian ATPRK for downscaling soil attributes. The study focuses on downscaling soil organic carbon. Soil organic carbon is a key soil property due to its conferring benefits to the soil physical and chemical properties and its potential to store atmospheric carbon. Therefore, availability of fine scale soil carbon data is important in the context of soil management. We disaggregated the topsoil organic carbon map (100m) of Nowley, New South Wales, Australia.

The theoretical background behind the Bayesian ATPRK as follows. Let us assume the observing soil organic carbon content *(Z)* is a continuous variable with a second- order Gaussian stationary random process. We denote the process as Z_p for locations $p \in$ D region of interest. For block support (B) data where $B \subset D$, we assume that the observations arise as block averages. $Z_B = |B|^{-1} \int_B Z_p \quad dp$. The underlying random process is characterized by mean function $x\beta$ and covariance function $C(\theta)$. Where $x\beta$ is a trend surface with β vector of coefficients of x fine scale covariates and θ denotes the parameters of the covariance function. Since $x\beta, \theta$ are jointly Gaussian, the parameters of the model can be inferenced using a Bayesian approach using maximum likelihood fitting. Also, Z_B and Z_p are jointly Gaussian, and the predictions at point locations is straightforward as $\hat{Z}_p = x\beta + C_{pB}{}' C_{BB}(Z_B - X\beta)$. Where C_{pB} is the point to block covariance, C_{BB} denotes block to block covariance, and $X\beta$ resembles the trend surface at coarse scale.

The estimation of point support variogram along with the parameters and associated uncertainties of the process model was done using Monte Carlo integration using Metropolis Hasting algorithm. The disaggregated fine scale map (10m) using Bayesian ATPRK has a 85% strong concordance correlation with the coarse scale map. It clearly captures fine scale variations and obviously resembles the patterns of coarse scale map. Therefore, Bayesian ATPRK can be used as a reliable technique to estimate the spatial distribution associated uncertainties of fine scale soil organic carbon from a regional scale map.

Keywords: *Spatial support, area-to-point, Bayesian, uncertainties*

EXTENDED ABSTRACT ONLY

Identify Vegetation Clearing Events using Landsat Time Series Data

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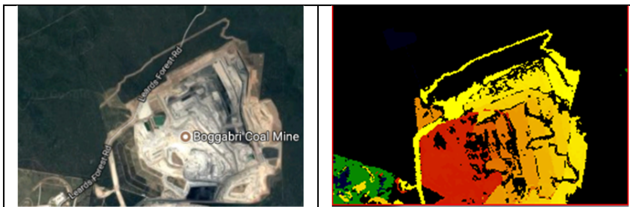
Abstract: This paper describes a statistical modelling scheme for detecting vegetation cover change events using Landsat time series data supplied by Digital Earth Australia (DEA). Vegetation cover change activities, such as urban development and mine building, often have great environmental impacts. Identifying timing and locations of such events is essential for environmental monitoring and land account audits.

Digital Earth Australia (DEA) is a series of data structures and tools which organise and enable the analysis of large Earth observation satellite data. DEA uses spatial and temporal metadata to link calibrated and standardised geoscience data sets from various sources to provide governments, individuals, and businesses access to over 30 years of Earth observation satellite imagery and related datasets over the Australian region.

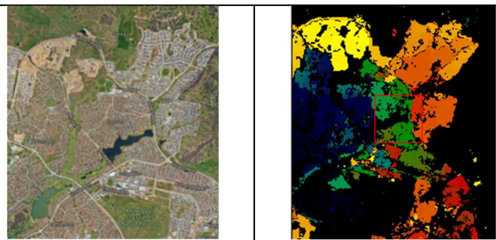
This method of change detection in vegetation cover relies on two steps: noise removal and statistical time series modelling. Most remote sensing data is affected by noise, such as abnormal sensor reading, clouds, cloud shadows and intermittent surface water cover. To obtain accurate change detection results, such noise in the time series must be detected and excluded from subsequent data modelling processes. A noise detection algorithm is developed to classify each pixel in a time series into clear, cloud and cloud shadow categories. The algorithm identifies noise by comparing reflectance data to statistics of local time series neighbours, thus does not rely on predefined thresholds. The advantage of using such unsupervised approach is that the implicit thresholds are self-adaptive to various underlying landcover types. The result of this step is per-pixel per-observation noise detection, and observations that are flagged as cloud or cloud shadow are excluded from time series analysis in the second step.

The second step applies a statistical time series model to detect long term ground cover change. For our purpose, two time series of Landsat surface reflectance indices are created, of albedo (mean of 6 spectral bands) and the Enhanced Vegetation Index (EVI). A moving average time window is applied to both time series, with the window size depending on observation density, with the lengths of the windows ranging from 1 to 2 years. This creates a pair of adjacent moving windows that scans through each time series, and the differences of the average and the standard deviation of the pair of the moving windows are recorded. These statistics are then fed into a statistical change detection model, which outputs the locations and the timing of vegetation cover change events.

The proposed method was tested on several areas where known vegetation clearing events have occurred. Experimental results show that the method successfully identifies locations and timings of these events. Figures below show experimental results in 2 sites: mine development at Maules Creek, NSW and urban development at Gungahlin, ACT. The cool colours represent events occurring at an earlier date while the warm colours represent events occurring more recently.



Mine development at Maules Creek, NSW



Urban development at Gungahlin, ACT

Keywords: *Time series analysis, ground cover change detection*

Upscaling UAV-borne high resolution vegetation index to satellite resolutions over a vineyard

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Abstract: Vegetation indices retrieved by optical satellite sensors provide important information related to the vigour, biomass and growth of plants. Homogeneous biophysical state within a satellite footprint is often assumed to make the spectral vegetation indices a reliable predictor of the vegetation condition. However, the image pixel resolution for the most widely used optical satellites, such as Landsat (30 m by 30 m) and Moderate Resolution Imaging Spectroradiometer (MODIS, 250 m by 250 m ~ 500 m by 500 m), includes vegetation canopies with varying degree of heterogeneity within single pixels. This pixel-level heterogeneity makes it difficult to predict individual plant-level vegetation biomass and vigour from satellite imagery. In particular, the structured nature of vineyard fields comprising predominantly of bare soil and grapevines pose challenges when estimating the vine-level biomass and vigour from the coarse-resolution satellite images, that present signals averaged over vine canopies and non-canopies (e.g., soil). In this study, we examine how the normalized difference vegetation index (NDVI) varies with aggregating pixel scales from sub-5-cm to 30-m and 250-m resolutions using very-high-resolution images collected by a multispectral imaging sensor on-board an unmanned aerial vehicle (UAV). The aggregated 30-m and 250-m scale NDVI values were compared with Landsat 8 (30 m) and MODIS (250 m) products collected from a commercial vineyard in Victoria, Australia within a narrow time window (25 hours). Results showed that when upscaling the high-resolution NDVI values (by aggregating input multispectral bands for NDVI) to coarser resolutions in highly structured vineyard fields, NDVI decreased initially up to the field heterogeneity scale (spacing between vine rows in this study site) and then levelled off beyond the scale. Furthermore, the difference between NDVIs at Landsat 8 pixels was mainly caused by the areal fractions of canopy and soil pixels and the NDVI values of the soil rows.

Keywords: *Normalized Difference Vegetation Index (NDVI), Unmanned Aerial Vehicle (UAV), pixel aggregation, upscaling imagery*

The application of satellite earth observation data in nationwide models of recharge and groundwater level in New Zealand

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Abstract: The application of large-scale models and satellite earth observation data in catchment-scale studies has increased in recent years, due to the improved availability and dissemination of these 'Big data'. Large-scale models and satellite data can fill in the gaps between observed data points in national, regional and sub-regional studies and can also provide the boundary conditions for smaller scale models. However, these models and data are also uncertain: large-scale models are often simplified and can thus embed large uncertainty; and satellite earth observation data are measured from tens to hundreds of kilometres from the earths surface and can therefore contain (e.g., atmospheric) noise. Therefore, ideally, large-scale models and satellite data are used in conjunction with other available data sources, such as ground observations, national databases, or other available models. This study presents an approach to use global satellite data of evapotranspiration in nationwide models of New Zealand that estimate rainfall recharge to groundwater, and subsequently a national water table.

The satellite data used are the global monthly MOD16 actual evapotranspiration (AET). Analyses of those data for application in New Zealand led to the insight that MOD16 AET data are of sufficient quality for use in New Zealand water budget studies. Uncertainty analyses using a multivariate distribution of correlated random ET input components also led to the insight that most ET methods, including the MOD16 algorithm, can lead to substantial uncertainty of the potential ET estimate of 10 to 40 percent.

The design of the national recharge model (NGRM) is largely based on the global WaterGAP recharge model. The NGRM shows that, with MOD16 AET data, national datasets, and minor model adjustments, nation-wide models compare well to most local ground observations and regional recharge models. The uncertainty analysis of this model, which includes variance and covariance of input components, shows that most of the uncertainty is caused by the monthly character of the model and by the uncertainty of rainfall data input.

The national water table (NWT) model is based on the global-scale 'Equilibrium Water Table' model, but uses improved data of elevation and geology. The NWT also uses the NGRM recharge. The NWT model identifies main alluvial aquifers and can be used to improve the delineation of existing aquifer boundaries. The NWT model also provide data in areas where ground-observed groundwater levels are sparse.

Although the large-scale models in this study are simplified and satellite data are known to contain noise, the results of our ET, recharge and water table studies compare mostly well to local-scale and catchment-scale studies in New Zealand. Furthermore, our analyses of uncertainty of ET and recharge estimates could help to better quantify the data worth of large-scale, simplified, models and satellite earth observation data in catchment-scale studies. Future improvements of these recharge and water table estimates will include the use of higher resolution satellite data (e.g., Sentinel-2) to calculate ET.

Keywords: *Nationwide, models, satellite, uncertainty, evapotranspiration, recharge, water table*

Assessing impacts of topographic factor and its resolutions on hillslope erosion modelling

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Abstract: The topographic factor (slope length and steepness) accounts for the effect of topography on erosion and it's an essential factor in many hillslope erosion models such as the revised universal soil loss equation (RUSLE). When using RUSLE, the component factors relating to rainfall erosivity (R), slope length and steepness (LS), soil erodibility (K), ground cover (C) and soil conservation practices (P) are multiplied to calculate the average annual soil loss per unit area (e.g. t.ha^{-1}yr^{-1}).

Digital elevation models (DEMs) are widely used to estimate the topographic factor. But DEMs with different resolutions and accuracies can often produce varied topographic features, which can in turn affect predictions of soil erosion. This study investigates the effects of DEMs on deriving topographic factor, and on predicting hillslope erosion using RUSLE. We chose Warrumbungle National Park (WNP) as study site to assess the topographic resolution impacts on soil loss for reasons that; 1) there were several bushfires in WNP followed by extreme rainfall and soil erosion, and 2) various DEM source data are available in this area.

DEMs at different resolutions were used to compare and determine the most appropriate scale to estimate post-fire erosion in the burnt park. The LS factor was calculated from hydrologically corrected 1 second (about 30 m) DEM derived from Shuttle Radar Topography Mission (SRTM), 25 m DEM from topographic maps, and Light Detection and Ranging (LiDAR) derived DEMs at resolutions of 1 m, 5 m and 10 m. The model results of LS values and sediment yields were compared with field observations at twelve soil plots across WNP. DEMs with different resolutions and sources generated different hillslope lengths and gradients, and produced substantially different erosion predictions by RUSLE. The relative difference of LS values can reach up to 60% among these DEMs, with underestimation by the 1 m LiDAR DEM (-40%) and overestimate by the 30 m SRTM DEM (60%). The 10 m DEM reached a relative error less than 10% and the 5 m DEM with less than 13% error. Our study implies that DEMs at about 10 m resolution can delineate adequate details of topographic features for hillslope erosion modelling in a medium or small watershed. However, applications of the high-resolution prediction and risk analysis to soil loss rates in regional and local scale are yet restricted due to high cost of topography detection and mismatch issues from inconsistent resolution to each factor.

Keywords: *DEM, LS factor, soil loss, RUSLE, resolution and scale, bushfire, GIS*

Visualising Flood Scenarios to Support Communication and Decision Making

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Abstract: Decision making for the design of flood prevention infrastructure can be challenging due to the complex nature of the systems involved. Complexity can arise from the effects of terrain geometry and any pre-existing hydraulic structures, which makes it difficult to effectively communicate flood risk. This issue is further complicated by the fact that floods are often compound events caused by multiple correlated drivers. For example, estuarine floods can be caused by a combination of storm surge and heavy rainfall, which both originate from the same meteorological system. To understand the risk of these compound floods, one needs to understand the contribution of different flood drivers and how risk changes as different drivers change. One way to achieve this understanding is to use counterfactual analysis which illustrates "what-if" scenarios.

Counterfactual analysis refers to the comparison of historical events and their counterfactual scenarios (i.e. scenarios created based on historical events with adjustments to contributing factors), to investigate the impact of different contributing factors. Counterfactual analysis has the potential to explore a wide range of flood scenarios, which allows for improved perception of flood risk for a given location. While the results of counterfactual analysis provide important analytical information to decision makers, they can be difficult to interpret. As a result, the traditional flood risk visualisation techniques via flood maps from either a 1D or 2D hydrodynamic model are not effective when trying to convey the messages from counterfactual analysis to stakeholders, who are often not experts in flood risk analysis. In addition, these traditional techniques do not provide an in-depth understanding of localised impacts. Consequently, this project involves the development of a visualisation tool to demonstrate, in a 3D environment using virtual reality technology, the risk associated with different flood scenarios from counterfactual analysis of flood risk.

Using areas located in both Perth and Adelaide as examples, we demonstrate that this visualisation tool has the potential to provide precise and accurate renderings of floods resulting from different counterfactual scenarios (e.g. varying combinations of flood drivers) and at different risk levels. It also provides an enhanced visual experience to decision makers and end users alike, which offers a powerful means of communicating flood risk and design concepts to stakeholders. In addition, the portable nature of the equipment and technology (i.e. a smartphone application) makes the tool easily marketable and distributable, which will facilitate information transfer and lead to a more effective feedback and decision making process.

Despite the potential for improved communication, we currently rely on conventional methods for conveying flood risk, which can be difficult for those with limited hydrological knowledge to understand. This project shows that there is potential for significant improvement regarding how we communicate risk using new techniques in an engaging, immersive manner. This technology will not only improve the effectiveness of communication of model results in the area of water engineering for decision making; once developed, it also has the potential to improve communication in fields such as insurance, real estate, and disaster planning.

Keywords: *Communication, decision making, flood risk, simulation, visualisation, virtual reality*

Evaluation of Flood Impact Variables and Development of Flood Damage Function

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Abstract: Estimating flood damage by identifying flood damage characteristics and evaluating flood impact variables or factors is very important for flood prevention and flood damage reduction studies. Flood damage can be divided into public assets and private assets. In Particular, flood damage about residential buildings and contents among private property is directly related to the people. However, in Korea, there is no systematic method of questionnaire survey for collecting flood damage information. Therefore, flood damage about residential buildings and contents tend to be underestimated. In this study, we evaluated and analyzed the importance of the factors by using correlation analysis, decision tree model, relationship between flood damage rate and factors, and random forest technique. In addition, the flood damage function for residential buildings and contents based on the evaluation of flood impact variables was developed and applied to the study area. As a result, the flood impact variables about residential buildings were water depth and the height of the entrance. The variables about contents were water depth and contaminations. The flood damage functions for the residential buildings and contents were developed by the regression analysis using water depth. The estimated flood damages by the developed damage functions were compared with those by the MD-FDA. The results showed that the estimated flood damages by MD-FDA for residential building were larger than those by the damage functions. On the other hand, the estimated flood damages by the flood damage functions for the contents were larger than those by MD-FDA. This study evaluated the flood impact variables for residential buildings and contents. The evaluation results can be used to establish the flood mitigation measures considering the variables. Also, the flood damage functions for residential buildings and contents developed in this study can be used for estimating flood damage.

ACKNOWLEDGMENTS

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Keywords: *Flood damage, flood impact variable, residential buildings and contents, damage function*

Effective representation of river bathymetry in hydraulic flood forecasting models

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Abstract: Riverine flooding is one of the most frequent and destructive natural disasters worldwide. An accurate and reliable flood forecast can provide vital information for water and land management and emergency response. Hydraulic models are used to compute water level and velocity in the river network, and when the storage capacity of the river is exceeded, in the floodplain.

Accurate modelling of river flow dynamics is essential to simulate floodplain inundation. Bathymetric data are thus critical to the application of hydraulic models. However, it is impossible to measure river bathymetry along the total river length, especially in large basins. While river width can be generally retrieved from space, river depth and channel shape cannot be systematically observed remotely. Where channel geometry is unknown, channel shape, depth, and friction can be estimated through calibration, but different parameter sets can often map model predictions to the observed data generating an equifinality problem. Moreover, channel shape, depth, and friction affect wave propagation in rather different ways. Without the structural correction provided by channel shape and depth, the calibrated effective values can lead to spurious non-physical effects. Conversely, an approximated knowledge of river bathymetry can provide a more robust model setup. There is therefore a need to investigate the level of geometrical complexity required for the representation of river bathymetry in hydraulic flood forecasting models. Furthermore, the definition of a data parsimonious methodology for the representation of river bathymetry can support the implementation of hydraulic models in other catchments worldwide.

These research topics were investigated using the upper Clarence catchment (NSW) as a case study. A number of simplified geometrical models of river bathymetry were derived from 65 cross sections sampled along a 20 km long river reach. These simplified geometrical models had to be data-parsimonious. This means that each geometrical model was built from the combination of a limited number of measured cross sections selected from the complete field database, a global database and remote sensing data.

The effectiveness of the proposed simplified geometrical models for floods was tested using a numerical experiment. The inertial formulation of the raster-based, two-dimensional LISFLOOD-FP hydraulic model was used to simulate a flood event in the upper Clarence catchment. A high resolution model realization based on all available bathymetric field data was considered as truth. Subsequently, each simplified geometrical model of river shape was embedded into LISFLOOD-FP and the results compared against "true" water level hydrographs and maps of flood extent and levels. Based on this analysis, a data-parsimonious methodology for the definition of an effective river bathymetry representation in medium to high resolution raster-based flood forecasting hydraulic models was derived. Specifically, a rectangular, width-varying shape was identified as the most effective simplified geometrical model, with width values derived from remote-sensing data; depth values assessed using a combination of global database and limited field data. Alternatively, an exponential cross section shape could be used; shape, depth and width were estimated using a combination of a global database and limited field data.

Keywords: *Flood forecast, hydraulic model, river bathymetry*

River reconstruction using orthogonal distance maps

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Abstract: Bathymetric reconstruction of riverine systems is essential for ensuring correct flow modelling in dynamic simulations. Typically, bathymetry is measured from soundings taken over the river resulting in sets of transect or point depths. A number of algorithms exist for reconstructing bathymetry from such transects which are based on sweeping techniques in curvilinear space. We introduce a straightforward algorithm based on distance maps which can create reconstructions at a fraction of the computational cost and mathematical complexity of curvilinear reconstruction. Distance maps are discretised grids containing the nearest distance to a specified interface in each cell of the grid. These are fast and simple to calculate using algorithms such as fast marching methods, and available in many geographic information system (GIS) tools.

The reconstruction algorithm was tested on a 13 km long reach of the Balonne River in Queensland, Australia for which a highly accurate field data was available. The reconstruction steps are shown in Fig. 1. The reconstruction used a rasterised mask of the river derived from remotely sensed data sources as an input (red area in Fig. 1a). Two distance maps are generated within the river: the distance downstream (the u co-ordinate, Fig. 1b) and the distance from the nearest river bank (the v co-ordinate, Fig. 1c). The v co-ordinate is calculated using the gradient of the u co-ordinate. Bathymetric depths sampled in the river were converted using these distance maps to (u, v) space and fitted to a suitable surface. For example, a least squares surface fit to a 9th order polynomial exponentially weighted in the v direction is shown in Fig. 1d, with the sampled points transformed to (u, v) space shown in white. This polynomial was used to interpolate and fill depth values within the river, resulting in a rasterised bathmetric depth map, shown in Fig. 1e.

A major advantage of the method over existing methods is that it can handle topological feature such as islands and branches, as illustrated in the example. Existing curvilinear sweeping algorithms are unable to process such features as they are only designed for a single flow path. Furthermore, the algorithm works well for limited data points and can be used with any suitable surface interpolation function. The method may allow bathmetric maps to be generated from remotely sensed data for high resolution hydrodynamic flood models.

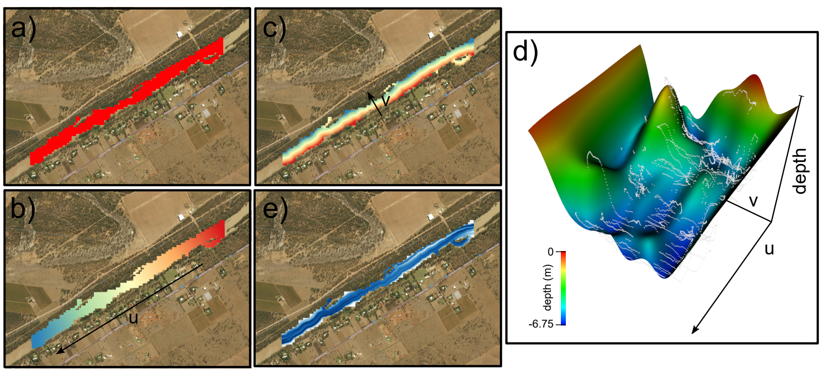

Figure 1. Stages in river reconstruction algorithm a) River mask derived from Landsat satellite data source showing river sections in red. b) Lengthwise river distance function (u co-ordinate) shaded by distance down-river. c) Crosswise distance function (v co-ordinate) shaded by distance across the river. d) Surface reconstruction in (u, v) space. Points sampled in the river and transformed to (u, v) space are shown as white points. e) Final bathymetric reconstruction shaded by river depth, where darker blue represents lower depth.

Keywords: *Remote sensing, Bathymetric reconstruction, surface fitting*

Assimilation of remotely sensed soil moisture for flood forecasting: a synthetic study

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Abstract: River floods are among the most destructive natural hazards, accounting for a large proportion of disaster-related fatalities, and economic and ecological losses. A timely and reliable forecast has great significance for the delivery of warnings and emergency response. Nevertheless, current operational forecasting systems suffer from various sources of uncertainties, specifically in the rainfall forecast, initial wetness condition, model structure, and model parameters.

Soil moisture is a control variable in catchment hydrologic processes. It plays a key role in runoff generation which affects the flood forecasts. Recent advances in remote sensing techniques provide a new capability for large scale surface soil moisture monitoring. Consequently, assimilation of soil moisture for flood forecasting has attracted increased attention from the scientific and operational communities. However, there has not been a consensus on the benefit of assimilation of soil moisture for streamflow forecasting. Furthermore, the question on how to optimally integrate the remotely sensed products to improve the forecasts remains a significant challenge.

This study investigates the potential benefit on flood forecasting of using a "smoother" approach for incorporating surface soil moisture information backwards in time. A two-soil-layer hydrologic model called GRKAL was used in this study. The model was applied in a lumped catchment system and calibrated through a joint calibration scheme using gauged streamflow and remotely sensed soil moisture data. Based on the calibrated model, a synthetic study was conducted to assimilate surface soil moisture information to update the forecasting model using an ensemble Kalman smoother (EnKS). The performance of the EnKS was compared with a traditional ensemble Kalman filter (EnKF). The results indicate that the smoothing method addressed errors in antecedent state variables more thoroughly compared with the direct filtering approach. The improvement in the antecedent state variable analysis was then propagated to the streamflow forecasts through the routing process so as to improve flood forecasting. The benefit of using the EnKS compared with the EnKF had its highest significance right after the assimilation and decreased with the increase of forecasting lead time. The strength of the smoothing approach exhibited in the synthetic study indicates a potential to improve flood forecasting in real world applications.

Keywords: *Soil moisture, data assimilation, flood forecasting, ensemble Kalman smoother*

Impact of quality control and interpolation of gauged rainfall on streamflow simulation

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Abstract: Rainfall is a key input to hydrological modelling and forecasting systems. The quality and accuracy of rainfall data have a significant impact on the performance of the modelling system. Rain gauges are widely used to obtain temporally continuous point rainfall records, which are then interpolated into spatial rainfall data to force hydrological models. However, the rainfall measurements and interpolation procedure are subject to various uncertainties, which can be reduced by applying quality control and selecting appropriate spatial interpolation approaches. Nevertheless, the impact of the quality control and various interpolation approaches on streamflow simulation is under-researched.

This study applied a quality control procedure to the hourly rainfall measurements obtained from 35 gauges in the Warwick catchment, an upstream catchment of the Condamine River Basin in eastern Australia. The grid-based daily precipitation from the Australian Water Availability Project (AWAP) was used as a reference. The correlation coefficient between the daily accumulation of the gauged rainfall and the AWAP data was used to eliminate gauges with significant quality issues. The unrealistic large and small values were censored based on a comparison between gauged rainfall and AWAP. Four interpolation methods, including the inverse distance weighting (IDW), nearest neighbors (NN), linear spline (LN), and ordinary Kriging (OK), were implemented and compared. The four methods were firstly assessed through a cross-validation process using the quality controlled rainfall data. Then the impacts of the quality control and interpolation on streamflow simulation were evaluated through a semi-distributed hydrological model.

The result showed that the Nash–Sutcliffe model efficiency coefficient (NSE) and mean error (Bias) of the streamflow simulations were significantly improved after quality control. In the cross-validation, the OK exhibited the highest accuracy in cross-validation by producing a relatively low root mean squared error (RMSE) and Bias. The IDW resulted in a relatively low RMSE but the highest Bias, while the LN resulted in the lowest Bias but had a relatively high RMSE. In hydrological simulation, the IDW led to the most consistent streamflow predictions compared with observations according to the validation at five streamflow-gauged locations. The OK tended to be the second best according to the performance at the five gauges in the calibration period and the performance at four internal gauges during the validation period. However, it produced the worst prediction at the outlet of the catchment in the validation period, indicating a low robustness. The NN and LN were not recommended according to the overall performance.

Keywords: *Rainfall, quality control, interpolation, streamflow prediction*

Uncovering risk thresholds in coastal communities for use in adaptation pathways planning

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Abstract: Projecting the future impact of changing coastal hazards in low-lying coastal communities is increasingly uncertain across multi-decadal timeframes. This makes it challenging for planners to assess questions such as *'what change in the community could lead to unacceptable impacts?'*, and *'when might such change occur?'*. Additionally, factors such as ambiguity, differing stakeholder risk perceptions, regional climate variability and climate change response, and sparse data records can challenge long-term planning activities.

In this research, we use open source spatial data and programming languages to provide a GIS-based platform for simulating and analysing coastal flood risks, with a view of uncovering thresholds in coastal communities that cause unacceptable impacts to people, property and lifestyle objectives. We draw upon the strengths of robust decision making (RDM) to identify thresholds beyond which the impacts to people, property and lifestyle objectives would be unacceptable, before integrating this within a dynamic adaptive policy pathways (DAPP) framework to illustrate how flexible adaptation pathways can begin to evolve at the community scale.

The approach is illustrated in the peri-urban coastal suburb of Kingston Beach, Tasmania, which has a population of 2,000 people. One-quarter of the 965 dwellings in the suburb are situated less than 3 m above mean sea-level with some of these houses also located in the floodplain of the adjacent Browns River. We define impacts to people as being the annual average number of people exposed to coastal inundation, impacts to property as the annual average damages to residential houses, and impacts to lifestyle as the average beach width at mean high spring water tide. After specifying uncertain parameters such as sea-level rise, changes to rainfall intensity and damage curves, we generate 1,000 scenarios – reflecting different realisations of the future – and assess impacts to the people, property and lifestyle objectives. The scenarios are assessed in ArcGIS using Python programming language, calling upon geoprocessing tools and raster datasets. Rules of thumb are used to generate *proxy* peak floodwater elevation rasters for each scenario assessed.

Through a process of scenario discovery, we find that a modest 4.8% increase to the critical 9-hour rainfall intensity combined with a dwelling replacement cost greater $1,536/m^2 leads to unacceptable impacts to low-lying houses in the study area, whilst a 6.3% increase to rainfall intensity with an average household size exceeding 2.4 people per dwelling leads to an unacceptable number of people exposed to inundation. Additionally, a sea-level rise of 30 cm could reduce the average beach width to less than 5 m, which may exceed social lifestyle thresholds for many residents in the suburb who assign value to this landscape.

Using sea-level rise and changing rainfall intensity projections, we then assess the timing at which the identified thresholds could be reached. If global emissions were to continue rising throughout the century following the RCP8.5 projection, we find that thresholds begin to be exceeded in the case study area from the year 2040. At such a time, adaptation measures would need to be implemented to maintain coastal flood risk within the community at accepted levels.

Notwithstanding the challenges that remain, our case study demonstrates how an improved understanding of thresholds, together with better simulation modelling and detection of environmental change, can improve coastal flood risk management and increase the legitimacy of adaptation planning in the community, from which adaptation pathways can develop.

Keywords: *Adaptation, coastal flooding, risk, tipping point*

Validation of surface water maps in selected Australian floodplains derived from Landsat imagery using hydrodynamic modelling

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Abstract: Mapping spatial inundation dynamics during floods is important for environmental management and disaster monitoring. Remote sensing technologies provide an affordable means for the routine monitoring of flood size and dynamics with reasonable spatial and temporal coverage. Landsat imagery (30-m horizontal resolution) can provide the appropriate spatial detail for many water mapping applications, although its temporal frequency is every 16 days. The public release of Geoscience Australia's Australian Geoscience Datacube (AGDC) offers opportunities for the consistent, repeatable production of surface water maps. The AGDC is based on the entire Landsat archive for Australia, following orthorectification and correction to surface reflectance with associated cloud masks. However, validation of these Landsat derived surface water maps is essential to provide confidence in them.

Hydrodynamic (HD) modelling tools are widely used for floodplain inundation modelling. While these tools require large amounts of data for model configuration and calibration, and can take a long time to process, they are highly effective in producing detailed characteristics of floodplain inundation with high accuracy at sub-daily time-steps throughout a flood event. For arid floodplains, antecedent soil moisture conditions and groundwater infiltration may need to be incorporated in such modelling.

This study compares two methods used for mapping surface water with Landsat in an Australian catchment and compares them to output derived from a well calibrated/validated, high resolution two-dimensional (2D) HD model. Using the 2D HD model to validate surface water extent derived from remote sensing has a number of advantages compared to the more common methods, which use higher resolution optical imagery or the same Landsat data to manually create a water/non-water dataset. The HD model provides an independent source of information, is available at a high spatial resolution, can be extracted to occur at a similar time as the image acquisition used to derive the water map, and can have full spatial coverage of the floodplain of interest. It is hoped that independent validation methods can help to provide confidence to the end user in the adoption of Landsat derived water maps.

Keywords: *Flood mapping, remote sensing, floodplain inundation, hydrodynamic modelling*

The Global Streamflow Indices and Metadata Archive (GSIM) – A compilation of 12 international streamflow databases

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Abstract: This paper presents the Global Streamflow Indices and Metadata archive (GSIM), a worldwide collection of metadata and indices derived from more than 35,002 daily streamflow timeseries. The paper focuses on the compilation of the daily streamflow timeseries based on 12 free-to-access streamflow databases (seven national databases and five international collections). It also describes the development of three metadata products (freely available at https://iacweb.ethz.ch/staff/lukasgu/GSIM/GSIM_metadata.zip):

(1) a GSIM catalogue collating basic metadata associated with each timeseries,

(2) catchment boundaries for the contributing area of each gauge, and

(3) catchment metadata extracted from 12 gridded global data products representing essential properties such as land cover type, soil type, climate and topographic characteristics.

Having collated an unprecedented number of stations and associated metadata, GSIM can be used to advance large-scale hydrological research and improve understanding of hydrological extreme events at the global scale.

Keywords: *Hydrological data, global dataset, streamflow indices, algorithm, large-scale hydrology*

Does a fifteen-hour shift make much difference? – Influence of time lag between rainfall and discharge data on model calibration

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Abstract: Hydrological modelling requires accurate datasets that include input forcing data (precipitation and PET) and response data (mainly discharge data). For models based on daily data, ideally, both the input and response data are resampled in identical time intervals. However, there could be time lags between the rainfall and discharge data due to multiple time intervals used in real situations. The daily discharge data provided by the Australian Bureau of Meteorology Water Data Online (Q_WDO) has a fifteen-hour delay to the daily rainfall and PET data, while the discharge data from the Australian Bureau of Meteorology Hydrological Reference Stations (Q_HRS) can match the daily input forcing data. Both the Q_WDO and Q_HRS were applied in two conceptual rainfall-runoff models (GR4J and PDM) to investigate the influences of time lag between input and response data. The effects of different catchment characteristics on this issue were examined. The results suggested that the time lag between input and response data could significantly decrease the performance of hydrological models that are based on daily datasets, and the degradation of performance is more likely to happen in catchments with smaller areas, lower elevations, wetter climate conditions and higher interannual variability. The time lag issue can be significant and more attentions should be paid to resampling daily datasets.

Keywords: *Hydrological modelling, time lag, daily data, catchment characteristics*

Computing the relative land subsidence at Venice, Italy, over the last fifty years

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Abstract: Land subsidence causes various damages to the infrastructures and cultural heritage in many cities worldwide. Urban flooding is one of the main consequences of land subsidence in coastal cities, where it is exacerbated by sea-level rise accompanying global climate change, but also in inland metropolitan areas such as Mexico City, where subsidence zones are increasingly flooded following intense rainstorms.

The subsidence of Venice, one of the most beautiful and famous cities in the world, is well known not for the magnitude of subsidence but because subsidence has seriously compromised the heritage and the safety of the city in relation to its small elevation above the sea. The storm that flooded the historical center of Venice on November 4, 1966 dramatically revealed its fragility with respect to land subsidence and sea-level rise, or the Relative Land Subsidence (RLS), i.e. land movement with respect to sea-level changes. That event signaled the beginning of a systematic monitoring of the loss in elevation of the ground surface of Venice with respect to the mean level of the Northern Adriatic (NA) Sea. Tide gauge measurements, available from the beginning of the last century, have been supplied historically by levelling and more recently by Synthetic Aperture Radar (SAR)-based Interferometry.

On the occasion of the 50th anniversary of the 1966 flood event, we quantify the RLS experienced by the city over these last five decades with a detail never achieved before. The computation of the loss of elevation has been obtained by processing and superposing the results of levelling surveys carried out in 1961, 1969, 1973, and 1993, together with the results of Interferometric processing of SAR images acquired from satellites: 1993 to 2002 by ERS-1/2, 2003 and 2010 by ENVISAT, 2008 to 2013 by TerraSAR-X, and 2012 to 2016 by COSMO-SkyMED. The records from the tide gauge in Trieste, which is a city on the coast of the NA Sea close to the Alps and known to be stable, are used to evaluate the sea-level rise over the targeted time interval.

The mean land velocity (v) for each analyzed period has been obtained by interpolating the original measurements using the Kriging method on a same regular 50-m grid covering the entire city. Then, cumulative land subsidence *(LS_{tot}))* from 1966 to 2016 has been simulated in a GIS environment by summing the partial land subsidence over the various periods covered by the levelling and SAR surveys.

The results point out that in the Venice historical center between 1966 and 2016:

- Land subsidence rate has been more variable in space but less variable over time than the changes of the NA mean sea level;
- average subsidence has amounted to 0.8 mm/yr and the average NA msl rise to 1.9 mm/yr;
- minimum and maximum cumulative subsidence has totalled 8 mm and 93 mm, respectively; and
- maximum loss of elevation with respect to the NA msl (i.e. RLS) has been 190 mm.

RLS has produced a tangible effect on the Venice historical center revealed by the continuous increase in frequency of the flooding events, locally called "acqua alta". In the next years, any further loss of elevation with respect to the mean sea level, even a few mm, will threaten the city's survival with severe social and environmental impacts. Considering the present average land subsidence of Venice and sea level rise of the NA (i.e. both about 1.2 mm/yr), an additional loss of elevation of about 190 mm will likely occur by 2100. Actually, according to conservative and pessimistic IPCC scenarios, the sea-level accompanying global climate change is expected to rise from 32 to 56 cm. Therefore, the outcomes from this study should be properly taken in account for the planning of effective interventions for the mitigation of climate changes to maintain the historical center of this unique city.

Keywords: *Coastal subsidence, sea level rise, Venice historical center*

Ground ruptures and intensive groundwater use in urban zones: a parametric FE-IE modeling investigation

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Abstract: Ground ruptures (earth fissures and reactivation of pre-existing surface faults) caused by extraction of groundwater from the subsurface have been observed in several semi-arid sedimentary basins worldwide. Rupture developments have been observed both within the areas where the exploitation of the aquifer resources occurs and along the boundaries of these zones. A clear example is Jocotepec, a city located in the Trans-Mexican Volcanic Belt, Mexico, which is critically threatened by ground ruptures developed as a consequence of aquifer resource exploitation to supply water for agricultural and, secondarily, potable water demand. Three 2-km-long ruptures cross the urban area, with strong displacement gradients affecting roads, canals, and walls of dozens of masonry houses intersected by the fissures. The ruptures have similar orientation and kinematics as the faults in the Jocotepec area, and the multilayered aquifer system beneath the urban area is characterized by the presence of soft piedmont-fluvial deposits and stiff alluvial-lacustrine deposits, with possibly abrupt changes between the two sequences. Density, shape, length, aperture, depth, and dislocation of the ruptures vary greatly between the rupture zones and are directly related to the stratigraphic variations.

A hypothetical modeling analysis was used to investigate the relative susceptibility of various geologic configurations to rupture generation. A geomechanical Finite Element (FE) - Interface Element (IE) modeling approach is used to simulate rupture generation and propagation for three typical processes: *i*) reactivation of an existing fault caused by horizontal displacements; *ii*) tensile fracturing above a bedrock ridge; and *iii*) differential compaction due to heterogeneous thickness of aquifer/aquitard (sand/clay) layers. A sensitivity analysis was used to address various factors of the rupture processes, including the thickness of the compacting layers, their depth below the land surface, the ratio between compressibility and thickness of sand/clay layers in heterogeneous formations, and the height of the bedrock ridge with respect to the thickness of the compacting alluvial sequence.

The modeling results suggest that rupture inception typically occurs at two specific depths: the top of the pumped aquifer, and at the ground surface, in correspondence with the geologic discontinuities. Indeed, a high stress state is induced within the aquifer by contraction, which can create favorable conditions for rupture generation. Conversely, although the magnitude of the stress effects of water extraction are smaller in the shallowest deposit, the potential for triggering rupture is still high because of the limited natural stress regime, so failure is even more likely. The evolution of rupture was analyzed and can be summarized in two cases. In the first case the rupture does not propagate and remains confined either at the aquifer top or at land surface. In the second case, the rupture expands from the aquifer top toward the surface and/or from the land surface downward. The aquifer depth is the most important factor controlling the occurrence of these behaviors. Specifically, the probability of a significant rupture propagation (and enlargement) is higher when the two inception zones are closer. Several simulations were carried out to address the possible ranges of parameter variations associated with the processes listed above, and the numerical results were elaborated by a statistical regression analysis. The model can be used to provide a preliminary evaluation of the possible mechanisms generating ground ruptures in subsiding basins.

Keywords: *Ground fissure mechanics, land subsidence, numerical modeling, finite elements, interface elements*

A novel elevation phase elimination method for PSInSAR in urban area with high buildings

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Abstract: The terrain phase elimination is a key step in the Permanent Scatterer Interferometric SAR technique (PSInSAR) for monitoring land deformation. The Shuttle Radar Topography Mission digital elevation model (SRTM DEM) is widely used. In high-rise urban areas, there are main effects that high buildings have on land subsidence where SRTM DEM is applied: after temporal and spatial filtering, a portion of the terrain phase errors propagates in the residual phase, which directly affects the precision of the land subsidence estimation. In this study, we propose a new method to minimize the errors. We have created a digital surface model (DSM) by overlying SRTM DEM with the layer of the building height obtained by SAR tomography. To validate the proposed approach, the land subsidence was calculated using the SRTM DEM and DSM correction methods. Based on the benchmarks used in the comparison, we show that the elevation phase elimination using DSM leads to more precise measurements of land subsidence rates.

Keywords: *PSInSAR, TomoSAR, DEM, DSM*

Exploring extratropical transition with hybrid idealised models

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Abstract: Tropical cyclones present a tangible risk to Australia's tropical coastal communities, however extratropical transition (ETT) of these storms can result in significant impacts in mid-latitude regions as well. Tropical systems are driven by latent heat release in the inner core of the cyclone. A fully tropical system is highly axisymmetric; with a warm-cored vortex that is readily represented by a simple radial profile (wind speed is a function of distance from the centre in all directions). Extratropical cyclones on the other hand are driven by strong thermal gradients and as a result have a highly asymmetric wind field that cannot be as easily parameterised for use in stochastic models. In order to accurately model the risk of these transitioning storms on communities such as Perth, the wind field of these storms needs to be parameterised for inclusion in stochastic models. These models allow large numbers of storms to be quickly simulated for use in risk modelling applications. Some authors have attempted to develop parameterisations that captures the unique shape of the surface wind field, with some recent success (Loridan et al. 2015), however an implementation for the Australian region has not yet been developed.

Geoscience Australia currently undertakes tropical cyclone risk assessments using a parameterised, 2D stochastic model called the Tropical Cyclone Risk Model (TCRM). TCRM uses parameterised wind fields to allow quick generation of thousands of tropical cyclones in order to develop a probabilistic understanding of tropical cyclone risk for Australia. At present, this model is not capable of simulating tropical cyclones undergoing ETT as a parameterisation of the wind field of these storms around Australia is not available. This work aims to explore ETT around Australia using a 3D, dynamical numerical weather prediction model with the ultimate goal of developing a parameterised wind field, suitable for inclusion in TCRM. This would allow risk assessments for these storms to be undertaken, and improve our understanding of the potential impact of such an event on large urban areas, such as Geraldton or Perth.

A modified version of the Weather Research and Forecast (WRF) model (Hybrid WRF) was used to simulate a number of hybrid idealised tropical cyclones, and steer them to undergo ETT. Hybrid WRF was developed to facilitate control over the track and location of landfall of a tropical cyclone, by introducing a steering flow to the boundary conditions of the model run. This method was used to steer a number of idealised tropical cyclones from off the northwest coast of Western Australia, south towards Perth, with the intent to force them to undergo ETT. Surface wind fields and other environmental characteristics (minimum pressure, latitude, thermal wind components, geopotential thickness and others) were analysed to determine the phase of ETT. This case study is the first example of Hybrid WRF being used to examine ETT, and while the steering flow did move the tropical cyclones into the extratropics as intended, only one storm was observed to undergo ETT. Further development of the code for Hybrid WRF is underway, with enhancements to permit time-varying lateral boundary conditions highlighted as a means to improve the realism of these experiments.

Based on these simulated events, we intend to develop time-evolving, storm-centred wind fields, as well as statistics on cyclone phase space parameters that can be used to determine the stage of transition to be used in a future stochastic-parametric model of tropical cyclones.

Keywords: *Hazard, parametric model, risk, tropical cyclone*

A Hybrid Approach to Determine Runoff Directions Based on DEMs

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Abstract: Simulation of runoff directions over digital terrain surface is a key component in distributed hydrological modelling. Single direction flow algorithm (Deterministic 8, D8) and various multi-flow direction algorithms (MFD) have been proposed and implemented in extraction of digital hydrological information from digital elevation models (DEMs). D8 has been used frequently in commercial and free software for its easiness of implementation. However it tends to generate artificial and parallel drainage lines. MFD algorithms distribute water flows in a divergent way and generate drainage information more naturally. However they introduce uncertainties in determination of upslope areas where surface runoff paths are prone to be convergent and present difficulties to trace deterministic upstream areas for most downslope areas.

In this paper, we propose a hybrid approach to determine runoff flow directions over DEM surface, in which D8 and MFD algorithms are used at different types of surfaces. First the given depressionless DEM is classified using a template-based shape detection method. Four types of terrain are distinguished according to convexity of local terrain: valley, ridge, slope and saddle areas. A slope threshold value is then determined based on heuristic rules to further classify slope areas. D8 algorithm is applied over steep slopes, valley and ridge areas due to its applicability in convergent terrain. Runoff directions in saddle and gentle slope areas are treated using a MFD algorithm. The threshold value can be determined based on a trial and error process.

The initial results of the new algorithm were compared with those by previous algorithms using real DEMs. The dispersive effect is apparently suppressed compared to MFD. The occurrence of straight parallel drainage lines is decreased remarkably compared to the results of D8 algorithm.

Keywords: *DEM, flow direction, hybrid flow direction algorithm, terrain classification*

Relationship between urban construction and land subsidence in Beijing region

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Abstract: Beijing is the capital of China with a population of about 21,729 million people, inhabiting an area of about 1,641 million square kilometers. Beijing has suffered land subsidence since 1935 and gradually formed five large land subsidence areas. With rapidly development of urban area, the constructions of multi-storey and high-rise buildings could accelerate land subsidence, and the uneven land subsidence could also affect building stability. Persistent Scatterer for Interferometric SAR technique (PS- InSAR) was used to obtain time-series surface displacement information of Beijing urban area based on more than 50 scenes of TerraSAR-X images during the periods of 2010-2016. In different hydrogeological background, large quantity of districts has been selected according to the age of building construction, the building load and building density. Standard deviation function has been used to detect uneven settlement blocks. We analyzed the relationship between land subsidence and urban construction from regional scale to local scale-using PS-InSAR and Geographic Information System (GIS) techniques. Results show that ground movements in Beijing is ranging from about -141mm/yr (sinking) to 19 mm/yr (uplift), and two subsidence funnel area mainly distributed in the east of Chaoyang district and gradually connected into a trip. The comparative analysis results indicate that the subsidence of the funnel area is still controlled by the compressible layer thickness at a depth 60-80m and the changes of groundwater level at regional scale, and not completely relevant with the age of the building construction. In different hydrogeological background we found that some serious settlement areas appear in villages with high building density, the built age of these buildings relatively long and its subsidence rate gradually decreased from the center to the surrounding with settlement rate more than 100mm/y. At local scale, 28 uneven settlement area has been discovered in subsidence funnel area. There are only two districts that the uneven subsidence shows relevant to building load, accounting for 7% of the overall uneven settlement area. The generation of uneven settlement blocks is still subject to the control of the water and the compressible layer thickness, and nothing to do with building age, building density and building load.

Keywords: *Land subsidence, urban construction, building load, building age*

Research on hierarchical method for extraction ground fissures through high resolution image

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Abstract: Earth fissures have been observed in hundreds of areas worldwide but their automatic detection is still a challenge. The use of remote sensing technology can effectively extract the information of ground fissures. Its application is of great utility especially in places hardly accessible to the in-situ reconnaissance, such as in coal-mining regions, where the monitoring of ground fissures is absolutely necessary to guarantee the safety of the mining operations. One of the most limits to the use of the automatic extraction of ground fissures by remote sensing is the low precision of the results. Aiming at this problem, this paper proposes a hierarchical extraction method to improve the accuracy of ground fissure automatic extraction on the basis of the GeoEye-1 optical images. Firstly, the image is segmented to set adjacent pixels as one object. According to the spectral and geometric characteristics of segmentation object, surface cover obviously different with the ground fissures are removed by mask tool. Then, the linear objects are extracted through the method of canny edge detection and the left surface cover is removed. Finally, the fractal characteristics of linear objects are calculated to distinguish the ground fissures from other linear surface factors. A coal-mining region of northeastern Ordos was chosen as a case test area to detect the validity of the proposed method. The results show that the method is better than the traditional method to extract ground fissures. The overall accuracy of the proposed method is 85.7%, while that of traditional supervised classification only 57.1%.

Keywords: *GeoEye image, ground fissures, hierarchical extraction method, feature extraction*

Assimilating stream flow, evapotranspiration and soil moisture data in AWRA-L model with particle filter

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Abstract: The Australian Water Resource Assessment-Landscape model (AWRA-L) is calibrated against a selection of data from ~500 gauged catchments around Australia to identify a single optimised set of model parameter with an emphasis on improving streamflow prediction. However, this regional approach to AWRA-L calibration can lead to high uncertainty in estimation, especially in ungauged catchments. An approach to help improve prediction in ungauged area is the assimilation of remotely sensed data into hydrological models. Streamflow discharges (Q), satellite soil moisture (SM) and satellite evapotranspiration (ET) observations have been individually assimilated into hydrological models to improve predicted outputs. This paper aims to evaluate performance of both individual and joint assimilation of these three hydrological observations into the AWRA-L model using particle filter technique.

The investigation used collected from six catchments across Australia with areas varying from 70 - 130 km^2. *In-situ* streamflow data from the Hydrological Reference Stations (HRS) are divided by their respective catchment area to generate observations with units that are consistent with AWRA-L modelled streamflow. The European Space Agency Climate Change Initiative (ESA-CCI) soil moisture products were normalised to ensure that observed and simulated soil moisture are comparable. We disaggregated the 8-day CSIRO MODIS ReScaled potential ET (CMRS-ET) product to daily ET estimates using daily potential evapotranspiration (PET) and a linear interpolation method. Forcing data, initial conditions and spatial parameters of six catchments are collected from the datasets used for calibration and validation of the AWRA-L model for 2010.

To address the limitation of high computational time required by the particle filter method in the grid-based AWRA-L model, we adopt a lump catchment approach where forcing inputs, initial conditions, and spatial parameters in each catchment were aggregated into one lumped value. Afterward the aggregated forcing is perturbed cell-wise using a normal distribution with 1000 samples to create a sample-based. These sample-based eventually are informed to the AWRA-L for the data assimilation process.

Four assimilation scenarios were investigated, namely: (1) sole assimilation of Q, (2) sole assimilation of satellite SM, (3) sole assimilation of satellite ET, and (4) joint assimilation of Q, SM and ET. In addition, an open-loop simulation, i.e. without assimilation, was run as a reference. Statistical metrics such as correlation coefficient (R^2), Nash-Sutcliffe model efficiency (NSE), root mean squared error (RMSE), and bias are used to assess the predicted outputs of the data assimilation model and open loop simulation.

Initial results indicated that only assimilating Q was successful in improving ET predictions in all study catchments. The assimilation of ET, however, did not improve streamflow predictions. Although assimilation of soil moisture produces a slight improvement in ET prediction, it degrades the predicted streamflow in this study. Difference with the single assimilations, the joint assimilation of all three observations can improve all predictions compared with the open loop simulation in some catchments. In addition, we found that the model performs poorly in a catchment with very small streamflow. These findings suggest further research efforts in order to fully understand the data assimilation problem. Nevertheless, the results in this paper have demonstrated the potential uses of data assimilation to reduce prediction uncertainty of the AWRA-L model across Australia.

Keywords: *AWRA-L model, particle filter, streamflow, soil moisture, evapotranspiration*

Performance of Different Ensemble Kalman Filter Structures to Assimilate GRACE Terrestrial Water Storage Estimates into a High Resolution Hydrological Model

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Abstract: The world's available freshwater supply is rapidly decreasing. Consequently, awareness of water availability, including Terrestrial Water Storage (TWS) and its compartments, is crucial to effective management. The Gravity Recovery and Climate Experiment (GRACE) mission provides TWS anomalies, unlike other water-related missions that just observe moisture in the top few centimetres of soil. However, the coarse temporal and spatial resolution, in addition to the vertical aggregation, complicate the use of GRACE TWS. Alternatively, hydrological models can provide an evaluation of the TWS by simulating the system using observed forcing data. However, because of inevitable structural and random uncertainties, errors are propagated into model predictions at each time step and this can severely affect the accuracy of the estimates. Data Assimilation (DA) techniques, specifically the Ensemble Kalman Filters (EnKF), are very useful tools to reduce errors at each time step by assimilating the observed states or fluxes into the model. By assimilating the GRACE TWS into a hydrological model, the shortcomings of the TWS retrievals can be mitigated. To achieve the most accurate results possible, an optimised structure of the EnKF is needed. However, due to the temporally and spatially coarse resolution and vertical aggregation of GRACE TWS, the optimal structure can be expected to differ from the regular EnKF structure.

Although previous studies have proposed alternative customised EnKF structures for the TWS assimilation, these have not yet been compared comprehensively. The differences among these structures are mostly limited to two major components of the EnKF, the observation operator, and calculation and implementation of increments. In this study, alternative structures (combinations of different alternatives of these two main components) were compared to find the optimal configuration. These alternatives were formed by 4 observation operators and 10 increment calculation and implementation strategies.

A generic EnKF framework was developed to facilitate the implementation of alternative DA structures. Then these were tested to assimilate synthetic GRACE observations into a hydrological model (Australian Water Resources Assessment - Landscape version 0.5, AWRA-L) of the upper Murrumbidgee catchment at a resolution of 0.01 degree (ca. 1 km).

The design of the synthetic problem was similar to the twin experiment of Forman and Reichle in 2013. In which, first, the forcing data was corrupted by adding some noise fields reflecting the errors in the estimation process. Since these errors are temporally and spatially auto- and cross- correlated, the noise fields were generated likewise. The simulation model with deliberately corrupted forcing data and model parameters was then applied to generate the 'true' state and flux variables. By vertically integration of variables relating to the TWS components, 'true' high resolution TWS values were generated. Finally, the TWS observations were produced by upscaling the high-resolution TWS and adding noises (reflecting observation errors) to it.

The observations were then assimilated into the AWRA-L model (with a different set of parameters) using alternative EnKF structures. Their performance was evaluated by calculating Bias and Root Mean Square Error (RMSE) between time series of the "truth" and the estimated state variables.

The results help determine the optimal structure of the EnKF for GRACE TWS observations, in addition to a better understanding of the effects of using different alternatives of the EnKF components.

Keywords: *Data assimilation, Ensemble Kalman Filter, GRACE, TWS*

Research roadmap for the creation of the digital multi-utility: Extracting value from concurrently collected high resolution water and energy data

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Abstract: Imagine a future where Google or another technology company is the retailer of water, wastewater, electricity and gas services, for your home or business. At first thought this concept seems confounding but in reality this future is not too far away, as integrated digital metering, advanced communications and big data analytics paves the way for the creation of global multi-utility retailer companies servicing millions if not billions of customers. For the customer, there are a number of benefits of the digital multi-utility retailer. Firstly, the customer only has to deal with liaison and payments to only one service provider offering a comprehensive web portal and phone application allowing accessibility to highly detailed data on their water, wastewater, electricity and gas consumption. Customers will be provided detailed reports on when (i.e. time of day, day, month, seasons, etc.), where (i.e. demand segmentation) and how (behavior trends, efficiency trends, etc.) they use particular utility resources, along with clearly articulated strategies on how they can reduce or shift demand in order to lower their monthly bill. Informatics on simultaneously collected multi-utility data allows the unpacking of water-energy nexus opportunities, such as how to shift or reduce water consumption to lower energy usage (e.g. hot water). Customer utility bills could be reduced significantly if an innovative retailer is provided with sufficient market positioning to influence reductions in the generation/supply and distribution cost components of utility resources through actively reducing water or electricity peak hour network or total daily demand by implementing intelligently delivered just-in-time demand management and price incentives. Some specific utility opportunities and benefits include using customer demand data analytics to optimize utility grids, reduced peak demand and thus prices through timely customized feedback of data and/or appliance control, source substitution equipment (e.g. solar PV), technical services (i.e. plumbers, electricians, etc.), to name a few.

However, several impediments will prevent or slow the introduction of the digital multi-utility retailer. Privacy is understandably a major community concern of people in the digital age. Potentially, hacked digital meters could inform robbers of premises that are not occupied. These and other scenarios scare the general public. Digital metering captures extensive demand information on customers, and multi-utility companies responsible for the collection and management of that information have important ethical and cyber security obligations to instill public confidence that they will be trustworthy custodians of their data. While digital metering technology and associated information systems are becoming affordable and reliable to implement, a number of technical challenges still detract from their widespread implementation, including, lost and missing data, communications network reliability, data storage and processing, battery life for meters remote from a power supply, lack of database and informatics expertise, vandal proofing, to name a few.

While these and other impediments and challenges are significant, none are insurmountable and can be overcome with appropriate government championing and regulation, targeted research and development (R&D), pilot implementation trials, robust software engineering, and passionate business entrepreneurship. This research creates a comprehensive research roadmap of R&D activities that must be addressed to realise the full applications and benefits of the digital multi-utility service provider. The R&D strategic roadmap covered in the paper discusses the following key areas: (1) regulatory and market transformation; (2) standardization and interoperability; (3) digital multi-utility transformation strategic planning; (4) fit-for-purpose communication systems; (5) data storage, management and mining; (6) big data analytics, machine learning and computational tools; (7) designing minimum energy devices; (8) digital multi-utility system production, installation and operational costs; (9) re-engineering multi-utility operational processes; (10) digital multi-utility metering and communications technologies; (11) societal readiness preparation; (12) cyber-security and privacy; (13) demonstration and commercial cases of digital multi-utility applications; (14) water-energy nexus pattern analysis and relationships; and (15) legal aspects.

Keywords: *Multi-utility, smart metering, water-energy nexus, pattern recognition, informatics*

Enhancement of water storage estimates using GRACE data assimilation with particle filter framework

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Abstract: An accurate knowledge of soil moisture and groundwater storage is crucial to understand hydrological process and extreme climate events. The model outputs of the terrestrial water storage are biased by inaccurate forcing data, inefficacious model physics, and improper model parameter calibration. To mitigate the model uncertainty, the observation (e.g., from remote sensing as well as ground in-situ data) are often integrated into the model to improve the simulation result via data assimilation (DA).

This study intends to enhance the estimation of soil moisture and groundwater storage by assimilating the Gravity Recovery And Climate Experiment (GRACE) observation into the Community Atmosphere Biosphere Land Exchange (CABLE) land surface model using the particle filter (PF) framework. The PF is developed for GRACE DA in order to accommodate different types of posterior error distribution and thus allow the realistic system representation where the distribution of model and observation errors are usually unknown. The early development of PF commonly suffered from the particle degeneracy and impoverishment problems, mainly caused by the insufficient number of particles. This study uses the sequential importance resampling (SIR) approach to reduce the problems. The simulation conducted to evaluate the filter performance and determine the effective number of particles shows that the SIR approach can deliver the accurate water storage estimates with the usage of only 100 particles. Moreover, the uncertainty of GRACE observation is obtained directly from the full error variance-covariance matrix provided as a part of the GRACE data product. This method demonstrates the use of a realistic representative of GRACE uncertainty, which is spatially correlated in nature, leads to an improvement of storage computation.

The developed GRACE DA scheme is demonstrated over the Goulburn catchment located in the Upper Hunter region, NSW, where the ground observations (surface soil moisture, root-zone soil moisture, and groundwater level) from the Scaling and Assimilation of Soil Moisture and Streamflow (SASMAS) network and the Department of Primary Industries, Office of Water, New South Wales are available for evaluation of our DA results. This study is the first time the GRACE-PF is exploited in a small catchment size ($\leq$ 6,540 km^2), proving an important insight about the potential of GRACE over a smaller region beyond its limit of spatial resolution at ~250 km.

Preliminary results show that our developed technique successfully disaggregates the catchment-scale GRACE information into finer vertical and spatial scale (~25 km), leading to a significant improvement particularly in groundwater and, marginally in deep soil moisture components. On average, GRACE DA improves the groundwater storage computation in terms of correlation coefficient (ρ) by approximately ~47 % (from 0.38 to 0.56). The ρ value changes from 0.535 to 0.543 by only 1.4 % for the deeper soil moisture (beneath 60 cm) computation. The improvement is found mainly from deeper layers with slower temporal variations, which is consistent with the interannual time scale of the GRACE signals being most characteristic over that catchment. However, GRACE DA slightly degrades the computation of the near surface soil moisture by approximately 2.2 % (in ρ). The coarse temporal and spatial resolution of GRACE is attributed to the less impact of the GRACE DA on surface soil moisture estimation.

In conclusion, it is apparent that GRACE DA provides a crucial benefit to deep storage computation. Further development will incorporate satellite soil moisture observations from Soil Moisture Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) missions with GRACE in the assimilation scheme to simultaneously improve different storage components, including surface soil moisture. Comprehensive evaluation of PF's results in comparison to EnKF results will also be conducted to understand the filter's performance with regard to accuracy of water storage estimates.

Keywords: *GRACE, data assimilation, particle filter, CABLE, Goulburn catchment, SASMAS, groundwater, soil moisture*

Global operational data services for storm surge and fluvial flood forecasting

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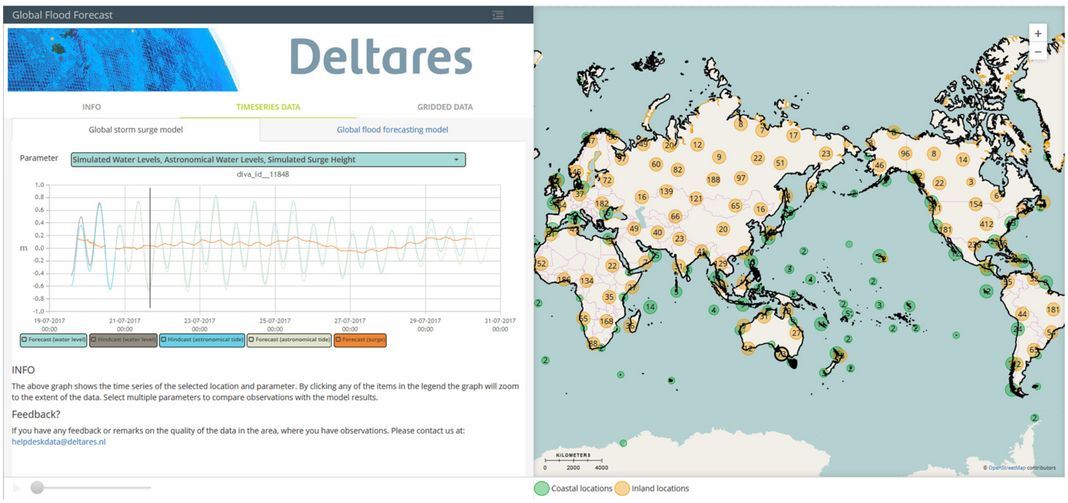
Abstract: Riverine floods and coastal inundation by storm surges are the most frequent of natural disasters, affecting millions of people across the globe every year. The forecasting of floods and storm surge at the global scale is crucial to preparing for severe events and providing early awareness where local models and warning services are lacking. Developments in modelling capabilities, data availability, and computational resources in recent years have made it possible to produce global scale flood forecasts. Operational systems currently have the capability to produce discharge and water level forecasts in the medium-range and disseminate forecasts and early warning products in real time across the globe, in support of national forecasting capabilities.

Deltares currently runs two global forecasting systems: Global Flood Forecasting Information System (GLOFFIS) and Global Storm Surge Information System (GLOSSIS). These systems are run from an open experimental information and communications technology facility, IdLab, and are being used to test new ideas around interoperability, hydrological/hydrodynamical predictability, big data, and visualization. GLOFFIS and GLOSSIS produce global flood and storm surge forecasts up to four times per day, with a 10 day forecast horizon (Deltares, 2017). These forecasts can be used for early warning in areas that currently lack adequate local forecasting capabilities. In areas where such capabilities are already available, these systems can provide boundary conditions to regional or local models to further improve these.

The underlying hydrodynamic and hydrological models are constantly improved and updated, to further increase their accuracy. With improvements in weather forecasting, future advances may include more seamless hydrological forecasting at the global scale alongside a move towards multi-model forecasts and grand ensemble techniques, responding to the need of developing multi-hazard early warning systems for disaster risk reduction.

The global forecasts from GLOFFIS and GLOSSIS are made available through various online channels, like web applications and FTP. A subset of results has been made available free of charge in June 2017 via www.GlobalFloodForecast.com. It is foreseen that the full or higher resolution results will be provided through a service with subscription fee by the end of 2017.



Keywords: *Global operational forecasting system, storm surge and tide, fluvial flooding*

Downscaling SMAP and SMOS soil moisture retrievals over the Goulburn River Catchment, Australia

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Abstract: Soil moisture is an important variable in a number of environmental processes – specifically the hydrological cycle, in the water-limited environments. Therefore, soil moisture data is important as an input variable in hydrologic, climatic modelling and agricultural applications. Many of these applications require high-resolution soil moisture data. However, most of the available soil moisture measurements are rarely available at high resolution, therefore unable to capture the spatial heterogeneity of soil moisture with required accuracy levels. Thus, upscaling or downscaling of soil moisture observations to higher spatial resolution is an essential requirement for these multidisciplinary applications. A long-term high-resolution soil moisture dataset is useful for planning and decision making in agriculture, climatology and hydrology. Developing a historic soil moisture dataset at high spatial resolution over a long period requires the use of different satellite soil moisture products. However, the use of different satellite products results in incompatibilities among each other due to discrepancies in overpass times, the wavelengths used, retrieval algorithms, orbital parameters and sensor errors. Therefore, validation and comparison of soil moisture retrievals from different satellite sensors and their downscaled products is important in evaluating the consistency of a long-term time series dataset of high-resolution soil moisture.

This study focusses on a downscaling algorithm based on the thermal inertia theory at two sub-catchments of the Goulburn River in south-eastern Australia, Krui and Merriwa River catchments. The goal is to downscale the radiometric soil moisture retrievals of Soil Moisture Active Passive (SMAP) and Soil Moisture and Ocean Salinity (SMOS) missions along with validation using established in-situ observation networks.

A linear regression model was developed between the daily surface temperature difference and daily mean soil moisture values from the in-situ observations of the Scaling and Assimilation of Soil Moisture and Streamflow (SASMAS) project. This relationship is modulated by the vegetation cover and soil attributes. The MODerate-resolution Imaging Spectroradiometer (MODIS) derived land surface temperature difference values were fitted into the lookup algorithms to estimate surface soil moisture at fine spatial resolution at 1 km. The coarse-resolution SMAP (36 km) and SMOS (25 km) radiometric soil moisture products were downscaled to 1 km.

The coarse-resolution SMAP and SMOS soil moisture datasets were compared with each other, and then against the SASMAS in-situ measurements. SMAP 36 km datasets show a reasonable agreement with the in-situ data with RMSEs of 0.07 and 0.05 cm^3/cm^3 over two SMAP pixels. However, SMOS 25 km soil moisture products show a general underestimation as compared to SMAP and SASMAS datasets. Therefore, the SMOS data were calibrated with SMAP data. Subsequently, the SMAP, SMOS and adjusted SMOS datasets over the Krui and Merriwa River catchments for the year 2015 were downscaled and compared.

The results show that the accuracy of the downscaled soil moisture datasets are highly influenced by the accuracy of the coarse-resolution satellite soil moisture products. The downscaled data were compared with in-situ data of five SASMAS monitoring stations. The downscaled SMAP, SMOS and adjusted SMOS datasets respectively showed average RMSEs of 0.10 (standard deviation, σ= 0.05), 0.19 (σ= 0.07) and 0.13 (σ= 0.02) cm^3/cm^3 with the SASMAS in-situ measurements. The three downscaled datasets of SMAP, SMOS and adjusted SMOS show consistent soil moisture pattern over the study catchments. The downscaled adjusted SMOS data displayed a better agreement with downscaled SMAP soil moisture data compared to the non-adjusted SMOS data.

Key words: *Downscaling, SMAP, SMOS, soil moisture, thermal inertia*

Anthropogenic and natural influences on atmospheric circulation during heatwaves in Melbourne and Perth

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Abstract: There have been several studies investigating the roles of human-induced climate change and natural variability in Australian heat events. In contrast, the relative influences of climate change and variability on atmospheric circulation during these heat events is less well understood.

Heatwaves in Melbourne and Perth are both commonly associated with circulation patterns that cause air flow from the inland. Using pressure difference indices relevant to those locations we study relationships with observed heat events using station data and ERA-Interim reanalysis to establish the nature of the observed circulation-temperature relationship.

We then use several sets of Weather@Home-ANZ regional model simulations to analyse the relative influences of anthropogenic climate change and the El Niño-Southern Oscillation (ENSO) on the occurrence and magnitude of heat extremes in Melbourne and Perth. We compute the same pressure difference indices in the model and compare between our groups of model simulations (with and without anthropogenic forcings, and under El Niño, La Niña, and ENSO-neutral conditions). The Weather@Home-ANZ model ensembles are generated using volunteers' spare computer time and this results in thousands of realisations representing each of our scenarios of interest. These very large numbers of model simulations allow us to make robust statements on the roles of human-induced climate change and ENSO-related variability in both the heatwaves and the circulation associated with the heatwave events.

Our initial findings suggest that the Weather@Home-ANZ model performs remarkably well in simulating both the summer temperatures in Perth and Melbourne, and the circulation associated with heatwave conditions at these locations, when compared with station data and ERA-Interim. We find there is a climate change signal increasing the likelihood of extreme heat events and the selected pressure indices show an appropriate correlation with higher temperatures. Perth appears to have a more significant change due to anthropogenic forcings than Melbourne in both the temperatures and the pressure indices, while the different ENSO phases are yet to be investigated.

Keywords: *Climate change, Weather@Home, attribution, heatwaves, Perth, Melbourne*

Characterizing change-points in climate series with a severe approach

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Abstract: An increasing number of papers have been published which analyse regime shifts within climate, in part or whole, seeking an embedded signal composed of abrupt changes, usually within the temperature record. Simultaneously a separate, related series of papers has addressed the reality of the so-called hiatus circa 1996/7, explaining it variously as an artifact of correctable data deficiencies, boreal cooling, or a statistical mis-identification. Previously, abrupt changes in 1976 and 1986 have been shown to be significant regimes shifts in the whole Earth system. We recently published a paper (Jones & Ricketts, 2017) henceforth JH2017, demonstrating the existence of abrupt level changes in global and zonal temperature records, observed and modelled, arguing that a substantial portion of the progression of temperature records can be validly attributed to regime state changes which vary in their regionality and occur on decadal time-scales.

Very few papers employ a severe testing approach, such as proposed by Deborah G. Mayo and Spanos (2006) to provide more nuanced information about such changes, leaving open questions about interpretation of findings. We have developed a method which extends the Maronna-Yohai (MY) Bivariate Test for inhomegeneities in measurement series, to detection of multiple step changes (the MSBV) in temperature series and reported it at MODSIM2015, and used it as a basis in JR2017. To support and further this work we have also developed a suite of tests which allow us to more severely examine inferences about the nature of the processes at the time of change, and so far to support our view that most abrupt change in global records is the result of rapid regional state changes.

Inference of the existence of abrupt shifts embedded within a complex times series requires detection methods sensitive to level changes and tolerant of simultaneous changes of trend, variance, autocorrelation, and red-drift, given that many of these parameters may shift together. In our work, the timing of events is key. Detection of abrupt level change precludes any form of low-pass filtering, hence we prefer to err on the side of false positives, using a simple detection method and re-assessing possible shift-points using methods grounded against a variety of null hypotheses. The so-called multiple testing problem is primarily a problem of multiply testing the same null against varied alternatives (an “accept if any” approach); whereas our approach tests separate aspects of the data to strengthen inference (an “accept if all” approach). In using the MY test (assuming stationarity) we trade precision in timing against uncertainty in level change, and elect to re-assess the significance against a disjoint segmented model using ANCOVA (in this application equivalent to a Chow test). We utilise three econometric tests to test for data which may show unit root-like behaviour (loosely, for a time-series, progression independent of time). These are the KPSS test for either trend stationarity or level stationarity against an alternative of unit root; the ADF (augmented Dickey-Fuller test) testing a null hypothesis of unit root against an alternative of stationarity after compensation for auto-correlation and trend; and the Zivot-Andrews (ZA) test which tests for a unit root with drift against stationarity plus a single change. We include a test under development (the disputed residuals t-test or DRT), that tests the residuals of a disjoint segmented model against the residuals of the non-disjoint model with the same trends, since it has been claimed that these cases cannot be sufficiently resolved. We use the studentized Breusch-Pagan test to assess the impact of the derived multiple change-point models on heteroskedacidicty since homoskedacidicity of residuals is expected.

These tests are applied to MSBV analyses of synthetic data then, global and zonal observed and modelled annual mean temperature records. Major results reported are that (1) determination of the timing of a trend change is much more precise than of a change of trend for numerical reasons, (2) global and zonal records appear to have the statistics of composites of a limited number of local to regional quasi-oscillatory processes, potentially interacting with forced warming, and (3) where unit root or red-noise behaviour influence on change-points is reported, it is likely to be an artefact of composition of the signal since spatial segmentation of zones markedly reduces the relevant indicators, (4) land based analyses show much less redness and unit root behaviour than ocean records in the same zones, supporting a view of rapid regime change over land following sustained ocean changes.

Keywords: *Change point, unit root, ADF, Zivot-Andrews, KPSS, Maronna-Yohai*

Precipitation and streamflow changes with temperature

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Abstract: Flooding is one of the costliest natural disasters Australia faces. The risk of flooding is controlled through adequate consideration in infrastructure design. However, with climate change, this risk of flooding is changing with implications for existing infrastructure and the design of future infrastructure. The changing nature of precipitation in a future warmer climate needs to be quantified if infrastructure is to be designed to the appropriate level of risk. It is generally accepted that the intensity of precipitation extremes will increase with higher temperatures. It is also expected that as a result of increases in precipitation extremes flooding will also increase. However, flooding does not just depend on the precipitation intensity - the resultant flood from an extreme precipitation event also depends on the pattern of the precipitation, as well as catchment specific conditions such as the antecedent soil moisture.

As predicting flooding for a future climate is of the upmost importance to control flood risk, we need ways to project changes in flooding for a future climate. Precipitation-temperature relationships have significant historical interest and have played a large part in evolving our understanding of how precipitation patterns may change in a warmer climate. Despite the simplicity of these relationships, they remain an active research area due to the complexity associated with simulating precipitation in climate simulations.

Here, using Australian sub-daily rainfall, we link changes in the temperature to the intensity of precipitation as well as its temporal and spatial patterns. It is shown that precipitation patterns generally intensify with warmer temperatures. High percentile precipitation intensities increase with increasing temperature, and in addition, the precipitation occurs in a shorter time and is more localized. The result is a more focused and destructive storm at higher temperatures that is likely to result in greater flooding, particularly in an urban environment where there is little precipitation lost to infiltration.

Assuming no changes in infiltration, increases in precipitation due to higher temperatures should also translate to increased streamflow in rural regions. To test this hypothesis a daily global discharge database of unregulated catchments was matched to a global database of gauged daily temperature. Despite increases in the intensity of extreme percentile daily precipitation with temperature, discharge records did not universally show increases. Only at the most extreme percentiles and in the smallest catchments are increases in streamflow related to precipitation increases. For the majority of cases, streamflow increases were less than those in precipitation, and for lower percentiles decreases in streamflow were observed. This result conclusively demonstrates that, as a result of warmer temperatures, precipitation lost to the soil and through interception and evaporation increases with higher temperatures and may be able to explain the divergent trends in historical streamflow records. If these relationships with temperature were to hold in a future warmer climate greater flooding could be expected in urban catchments, however, the results may not translate to rural areas except in the most extreme cases.

Keywords: *Precipitation, streamflow, temperature, climate change, global*

Designing elicitation of expert knowledge into conditional probability tables in Bayesian networks: choosing scenario

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Abstract: For many researchers there is increasing pressure to collect and analyze bigger datasets, from sources such as analytics, online surveys or spatial datasets. Bayesian networks (BNs) provide a feasible and intuitive means of developing explanatory models with diverse stakeholders, having limited quantitative expertise. However, when a large number of variables and levels are involved as potential inputs to a BN, the more resources are required to evaluate alternative models. Our motivation is to design a large species distribution modeling (SDM) experiment, in the Biodiversity and Climate Change Virtual Laboratory. We show how BNs, elicited from experts, can be used to inform design of these kinds of large computing experiments.

In this context we examine how settings of some SDM algorithms potentially affect the quality of the prediction. For example, one setting could be the choice of covariates used as input to the SDM, with three levels: a minimal, an extensive set or something in between. A conditional probability table (CPT) quantifies the child node (e.g. quality of prediction) as it depends conditionally on each of the parents (here settings). Guidelines on eliciting CPTs generally advise modellers to simplify the elicitation task by keeping to a minimum the number of parent nodes and parent/child states. The literature on BNs indicates that elicitation of more complex CPTs may be too demanding for experts, because of the time required.

In the context of large CPTs, an often encountered problem is the sheer amount of information asked of the expert (number of scenarios). Here we propose that an elicitation strategy can be designed according to statistical criteria: to ensure adequate coverage of the CPTs, in an efficient manner, to make best use of the scarce resources like the valuable time of the experts. This is essentially a problem of experimental design.

Some software tools such as CPT calculator support specification of large CPTs, but implicitly adopt a particular kind of experiment design. Here we conduct experiments to evaluate designs for eliciting expert knowledge to help quantify CPTs that define BNs. We consider three types of design of elicitation: Taguchi as a kind of screening design, CPT calculator's design, and a composite. In the case study, we asked modellers to consider how different settings affect the quality of an algorithm used to construct a SDM. Limiting the number of scenarios avoids tiring the experts, which can lead to inaccuracies. Eliciting and encoding CPTs was examined using a model-based "outside-in" Elicitator approach to quantitative elicitation, which allows experts to specify their opinions with uncertainty.

Our results determined that the most important settings with the largest positive impacts on the quality of prediction were: the choice of real absence data, quadratic complexity of the function and the choice of the expert's minimal subset of variables. In addition, there were differences arising due to the choice of design and the elicitation scenarios. Overall, we found that the Taguchi OA design was more efficient because the effect sizes estimated for CPT calculator had more uncertainties than for the Taguchi design.

Keywords: *Bayesian networks, conditional probability tables, elicitation of expert knowledge, design of elicitation, species distribution model*

Spatial characterisation of South Asia climate extremes from Big Data

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Abstract: South Asia (SA) is threatened by pronounced vulnerability to the impacts of climate variability on water resource management, agriculture productivity and energy access. Research on spatial characteristics of daily climate extremes which significantly affect the natural system and human society across SA is necessary to fill the gap of most studies conducted at catchment or national scale based on monthly or yearly data in the region.

This study exemplifies the application of existing big data in integrating cross-region information on climate extremes needed on the key challenges to water, food and energy security in SA. Freely downloadable regional/global gridded datasets, such as the Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) of the Water Resources, the Princeton Global Meteorological Forcing Dataset (PRINCETON) and the Water and Global Change (WATCH) dataset, provide valuable means of regional analysis to fill the gaps where gauging station is unavailable. They differ in terms of spatial resolution, temporal resolution, spatial and temporal coverage, types of basic data used (such as rain-gauge-based, or satellite-based), methods used for interpolation of data from the sample points to the grid points, and models used to assimilate climate variables and conditions/states. These datasets were compared against available gauge observations. Advanced technologies in geo-informatics were applied to processing large amount of time-series climate data though the fusion of geographical information systems (GIS), geodatabase, spatial statistics and computing programing. Evaluation results indicate that both APHRODITE and PRINCETON are suitable for the SA region. Based on these two datasets, a suit of more than 20 indices characterising climate variables and extreme conditions, including amount, frequency, and intensity of precipitation and temperature, were derived and mapped over the region covering Pakistan, India, Bangladesh and Nepal. In addition to examining spatiotemporal trends in indices for extremes of daily precipitation and temperature, the annual and long-term mean indices based on gridded daily values were also estimated for 1975 to 2004.

The results present a clearer picture of the patterns of trends in climate extremes across the region than has been seen locally, or with raw station data. They have improved the trans-boundary understanding of climate variability and its impact on the nexus between water, food and energy. The study provides useful insights and indication for resource planners, system managers, and policy makers concerning climate variability and change for supporting informed basin planning.

Keywords: *Big data, climate variables, indices of extreme climate conditions, gridded daily climate data*

China Land Cover Mapping and Above Ground Biomass Estimation

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Abstract: Land cover, as a geographic feature, is the synthesis of observable natural and artificial objects on the surface of the earth. It reflects the fundamental character of interactions between nature and society with both spatial and temporal attributes. In order to meet needs of China's ecological assessment and terrestrial ecosystem carbon budget estimation, we developed the China National Land Cover Database (ChinaCover) for 1990, 2000, 2005, 2010 and 2015 with 30m spatial resolution. ChinaCover has the following unique characteristics: 1. a remote sensing big-data with a large quantity of multi-source remote sensing images, field measurements and crowdsourcing based ground data, 2. a new classification system with 6 primary classes and 40 secondary classes, which conformed both to international classification criteria and the land cover features of China, 3. an object-oriented and deep learning combined classification method, as well as a change detection algorithm for ensuring data comparability over the five time periods, 4. a quality control specification system for data processing, segmentation, classification and validation.

In addition, above ground biomass (AGB) also plays an important role in carbon cycling. We built the AGB estimation model for forest, grassland and cropland respectively at national scale. For forest AGB, we firstly divided China into eight forest regions based on climate zones and forest types. In each region we calculated AGB in the typical study site through stepwise regression analysis based on canopy height and density obtained from the airborne LiDAR data and field measurements. Secondly, for each typical study site, based on the LiDAR-based AGB estimation, a scaling model was used for retrieving the AGB at 30m scale by Landsat data. Finally, the Landsat-based AGB estimation model was translated to MODIS 250m scale through regression model using multiple independent datasets, including regional canopy height retrieved from GLAS and MODIS BRDF data, time-series MODIS-NDVI, fractional vegetation cover (FVC), leaf area index and topographic factors. China grassland and cropland AGB were estimated based on a series of empirical models, which were established through regressing field measured AGB on multi-temporal MODIS-NDVI (early and peak living stage of the grassland and cropland) and FVC data.

Keywords: *Land cover, above ground biomass, classification, ChinaCover, LiDAR*

Interpreting transition and emission probabilities from a Hidden Markov Model of remotely sensed snow cover in a Himalayan Basin

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Abstract: Remote sensing is often used to monitor snow cover in areas without sufficient in-situ observations. However, a common problem with remotely sensed snow cover products is the mis-classification of snow cover due to obscuration of the land surface by cloud, along with the similar spectral characteristics of snow and cloud. In a two part preliminary investigation we assessed the ability of a Hidden Markov Model (HMM) to reduce classification errors in optical snow cover mapping along with the transition and emission probabilities output from the model, to our knowledge for the first time documented. This research focuses on the latter and was conducted within the Sustainable Development Investment Portfolio (SDIP) at CSIRO.

A Hidden Markov model can utilise a series of input observations and calculate the probability that they represent the ground state. These probabilities are then used to model the most likely series of states, this effectively provides a dynamic filter that can mitigate the problems faced when remotely sensing snow in mountainous areas. As part of a larger project, we applied this approach to snow cover mapping over a single sub-basin in the Himalayas in Eastern Nepal based on imagery from the (MODIS) instruments on the Terra and Aqua satellites. This study analysed spatially mapped transition and emission probabilities extracted from a two state Hidden Markov Model.

The ability of a Hidden Markov model to employ a dynamic filter that can utilise entire sequences of observations will likely offer improved accuracy when compared to other time-series filtering methods. This is because it is able to utilise a much larger number of observations without compounding losses in accuracy or causing reductions in temporal resolution. Our probability analysis shows the potential for a HMM approach to provide a robust and flexible method for processing 'noisy' data such as remotely sensed snow cover measurements. The improvement of spatio-temporal snow cover measurements has broader implications for hydrological modelling, particularly in countries dependent on snow melt for subsistence agriculture and hydroelectric facilities such as Nepal. Improvements also benefit the long-term analysis of snow cover trends which are an important proxy for assessing the impacts of climate change in sensitive mountain areas. Further studies should apply this method to multiple study sites and quantitatively compare it to other cloud-cover reduction techniques for snow cover imagery.

Keywords: *Hidden Markov Model (HMM), machine learning, remote sensing, snow, cryosphere*

Farm-scale minimum temperature mapping for strategic and tactical frost management

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Abstract: Frost causes millions of dollars of damage to broad acre cereal crops and is an important climate risk that presents a management challenge to grain growers in Australia. Management options to mitigate impact of frost include pre-season cropping decisions such as timing of sowing, choice of crop type and cultivar, and post-frost event management such as cutting for hay, or grazing frost-damaged crops. This study, conducted in close collaboration with growers and farm consultants, contributes to both pre-season and post-frost management through improved spatio-temporal understanding of frost risk.

This study aims to identify combinations of meteorological and terrain variables suitable for generating high spatial resolution (approx. 30 m) maps of minimum temperature (T_{min}). This mapping used Multivariate Adaptive Regression Splines (MARS) models to combine terrain indices with temperature data. Modelling and mapping were undertaken for two sites in the SE Australian cereal-cropping zone, Mintaro, South Australia and Hopetoun, Victoria. To facilitate the development of the mapping methodology, iButton® temperature loggers were deployed at each site during June-September 2016. A clustering-based sampling scheme, for 96 loggers at each site, sought to capture terrain-driven temperature variability at landscape scale (4 x 4 km at the Mintaro site; 5 x 3 km at the Hopetoun site). The logger dataset from the Mintaro site included data from 71 loggers over 25 cold nights (<2°C) and from the Hopetoun site 87 loggers over 20 cold nights, with temperatures recorded at 30 minute intervals.

MARS models were developed to predict the logger T_{min} values. We compared models using three separate sources of temperature data, a local weather station at each site, an official weather station and remotely sensed Moderate Resolution Imaging Spectroradiometer (MODIS) night-time land surface temperatures. We also developed models using temperature loggers themselves as predictors for the entire site, both individually, and with all 3-logger combinations for each site.

Comparing models which used local, distant, and remotely sensed temperature predictors showed that locally measured temperatures generate the best models. Then, using the individual loggers as predictors showed that wind speed and humidity were important predictors in many cases. Additionally, by modelling every three-logger combination for each site, we demonstrated that some logger locations were not used in any models, and further, some models using a single logger performed well.

There are several practical findings from this work. Firstly, local temperature measurements show the best potential for generating high-resolution maps of T_{min} at farm scale. Our results also suggest that remotely sensed temperature is not acquired reliably enough to make it suitable for this purpose. Models based on temperature data from one to three logger locations fitted well, but showed that location of loggers may be important. The improvement to models by including wind-speed and humidity measurements shows that these may be important parameters to measure. With further validation and refinement of the methods, we believe this method has the potential to be applied across the broad acre cropping areas of Australia.

Keywords: *Minimum temperature, terrain, Multivariate Adaptive Regression Splines (MARS), Moderate Resolution Imaging Spectroradiometer (MODIS)*

Comparing Landsat-MODIS blending with a statistical model for improved spatio-temporal quantification of large-scale floodplain inundation dynamics

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Abstract: A consistent spatio-temporal mapping of surface water (SW) dynamics (i.e. the distribution of SW through time) at the landscape scale holds great potential for assimilation into hydrodynamic, hydrological and climate models and improving the management of terrestrial freshwater ecosystems that continue to suffer alarming declines globally. Recent studies provided this type of quantification by developing first of their kind long-term records of SW maps on continental and global scales, using freely available time series data from the Landsat and MODIS satellites. Due to the spatial and temporal resolution constraint inherent to the majority of satellite sensors, however, existing time series are either of high spatial and low temporal resolution or vice versa. Our study addresses this limitation by comparing two approaches for generating a long-term record of Landsat resolution (30m) SW maps with a regular time step of 8 days for three semi-arid floodplain sites in Australia's Murray-Darling Basin. Firstly, we applied a previously developed statistical modeling framework that, based on an existing SW time series (1986-2011), relates remotely-sensed inundation extent to river flow to then predict inundation extent for additional time steps. For this approach, we fit generalized additive models (GAM) between SW extent on floodplain areas within 10x10 km grid cells and in-situ river flow, after applying a lag time to account for the flow travel time between the gauge and the modeling unit. Secondly, using data denial experiments, we applied and validated the STARFM and ESTARFM algorithms under both a blend-then-index and index-then-blend scheme for predicting 30m resolution Open Water Likelihood (OWL) via blending of Landsat and MODIS imagery. Best blending accuracies were achieved in the floodplain site that exhibited the slowest changes in inundation extent through time and lowest accuracies generally coincided with rapidly changing flood levels. On average, ESTARFM (r^2 = 0.8; RMSE = 0.16) slightly outperformed STARFM (r^2 = 0.71; RMSE = 0.20) in predicting OWL using the index-then-blend scheme, while both algorithms performed similarly when using the blend-then-index scheme. Based on these findings, we applied the ESTARFM index-then-blend scheme to generate 30m SW series with a regular 8-day time step for a 2-year flooding cycle in each site. Compared to using only cloud free Landsat observations, the ESTARFM SW series provided new and temporally dense information about changes in inundation extent within fine scale floodplain features (see ESTARFM in Figure 1) but also suffered from substantial accuracy issues that we attributed to the limited ability of both algorithms for modeling the rapid land surface changes during floods. In comparison, the statistical modeling approach provided a consistent mapping of inundation dynamics across the three test sites and a considerably more detailed spatio-temporal quantification of flood dynamics than existing alternatives (compare Statistical Model with Landsat and MODIS in Figure 1). The data-model fusion approach is applicable to other large and complex floodplain systems across the world and can provide spatio-temporally consistent SW records for improved management of SW resources.

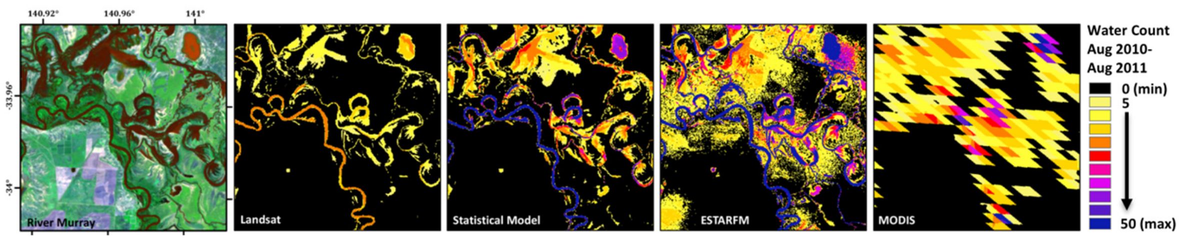

Figure 1. Water count maps for 10x10 km Murray floodplain area showing the number of times, each pixel was flagged as water within the August 2010 to August 2011 La Nina flood period in the Landsat only, statistically-modeled, ESTARFM and MODIS only surface water time series.

Keywords: *Surface water dynamics, flood inundation mapping, Landsat MODIS blending, ESTARFM*

Mapping flood inundation frequency based on a water observation dataset and time-series flow data

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Abstract: Flood inundation frequency is an essential factor to the well-being of flora and fauna communities along the rivers and around the lakes, because their living conditions are closely related to flooding water. *In situ* gauge data are the backbone of the current understanding of surface water dynamics, but they provide little information about the spatial dynamics of surface water extent in floodplains and wetlands, while remote sensing technology provides an effective approach to acquire information and inundation extent.

This study, therefore, tries to map the inundation frequency in the Murray-Darling Basin, Australia, using a combination of time-series flow data and a historical surface water observation dataset (Water Observation from Space, WOfS) derived from time-series Landsat images. In order to reduce the hydrological heterogeneity of this large river basin, spatial zoning has been conducted to separate this basin into 90 eco-hydrological zones. Each zone has a representative gauge that has collected a long flow record. Within each of these zones, flood inundation extent has a close relationship with the observed up-stream gauge flow volume. We assume that bigger flow always induces larger inundation in each zone. Under this zone-gauge framework, time-series flow data of each gauge were employed for a flood frequency analysis (FFA), which employs annual flood series method to select a flow peak for each water year. The Gringorten's model was then adopted for calculating the annual exceedance probabilities (AEPs) and return periods (average recurrence intervals, ARIs) of different flow peaks.

Inundation extents were selected from the WOfS dataset according to the date of those flow peaks, and were then linked to their corresponding peaks. Through spatial overlaying and analysis, two resultant maps were produced, a flood inundation frequency (FIF) map and a flood inundation probability (FIP) map. FIF map was derived by simply overlaying inundation extents corresponding to each flow peak. FIP map showing either the AEP or ARI of inundation was generated by assigning the AEPs or ARIs of flow peaks to their corresponding inundated extents, and then overlaying and combing them to fill the whole study area. Both maps either reveal the historic inundation or indicate the probability of future inundation, providing scientific basis for water resource management and wetland ecological studies.

Keywords: *Surface water, Murray-Darling Basin, eco-hydrological zone, observed flow, flood frequency analysis*

Spatiotemporal trends in surface water extent dynamics in a major dryland region with three decades of satellite observations

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Abstract: Spatiotemporal distribution and quantification of inland waters resources is critical for research on hydrological and biogeochemical cycles. Satellite remote sensing can monitor and quantify this distribution at large spatial scales and over decades. This is especially important in dryland systems, which cover one third of the globe and have high hydroclimatic variability. Focusing on one of the largest dryland systems, Australia's Murray-Darling Basin (MDB), the most important basin in Australia for crop production, wetlands, and biodiversity, here we quantified the spatial and temporal patterns in surface water extent dynamics. We used a new, statistically validated surface water extent dynamics data set derived from seasonally continuous Landsat time-series from 1986 to 2011, which yielded an overall accuracy of 99.9% (± 0.02% standard error) with 87% (± 3%) and 96% (±2%) producer's and user's accuracy of water, respectively. Overall, our results document dramatic swings in surface water extent dynamics during the Millennium Drought (1999-2009) and the wet, 2010-11 La Nina years. Besides the general pattern of lower surface water extent during the Millennium Drought, some of the years with the lowest surface water extent included 2002, 2006 and 2007. Large extent of surface water was seen not only during the 2010-11 La Nina years, but also in 1990 and 1998. Surface water frequency over the four Austral seasons (starting on March 1, June 1, Sept 1, and December 1, for autumn, winter, spring and summer, respectively) across the entire time series displayed different spatial patterns. Austral spring had the highest water frequency in the main Darling and Murray River channels as well as in the main irrigated agricultural areas. Overall, the northern part of the MDB had greater variability in surface water extent dynamics compared to the southern part of the MDB, which had larger floods in spring. Our results can act as the basis for understanding the impact of hydroclimatic variability on surface water extent of the MDB. The approach presented here is relevant to areas with competing water demands and can be further developed for other basins around the globe. Quantifying the uncertainty of the accuracy assessment and providing an unbiased accuracy estimate are imperative steps when remotely sensed data sets are used for quantifying trends in spatiotemporal surface water extent and follow on applications.

Keywords: *Surface water dynamics, space-time modeling, Landsat, time-series, seasonally continuous*

Crop Water Productivity Estimation and Analysis with Remote Sensing

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Abstract: Water resources crisis is a critical issue that had seriously hampered the development of social economy in Hai Basin, which is located in the north of China. As a major water consumption user, the development of agriculture will face the challenge of "less water consumption and more food production". Since 1980s, agriculture experienced the rapid development period of water conservation irrigation in the Basin. The implementation of water conservation measures greatly reduced the irrigation water retrieval amount, and improved the irrigation efficiency. The crisis, however, has not been erased and the ground water table is continually decreasing. Winter wheat is one of three important crops in basin. Due to the rainfall deficit, it is almost irrigated during the growth period. It is noticeable that most of ground water was extracted for wheat irrigation. This paper is no longer limited to the use of field scale research results, but also take the advantage of remote sensing on dynamically monitoring crop evapotranspiration, crop pattern and crop yield in temporal-spatial scales. ETWatch model was used to produce the monthly ET data for the study period for the basin, while the improved CASA model was used to get the biomass data for winter wheat. Then, the crop water productivity (CWP) for winter wheat was estimated using monthly ET data and biomass data.

The winter wheat CWP from the view of spatial pattern and temporal change were analyzed. The major results and conclusion include: (i) the mean CWP of winter wheat was 1.049kg/m^3. The spatial analysis showed the significant correlation between crop water consumption and crop yield (R^2=0.87), resulting in the relative stable CWP (0.95~1.08 kg/m^3); （ii） the temporal analysis were worked out for 8 agro-meteorological stations over the past 20 years, and conclusion was drew that the increase trend for winter wheat CWP in this basin relied on the significant increase of yield due to the application of fertilizer and new crop species; (iii) the above analysis indicated that the water saving conservations didn't play an important role on the reduction of water consumption, even though many research showed the great achievements on water draft. It is proposed that the development of water conservation irrigation agriculture need be evaluated from the new perspective of water consumption, and the water consumption management with stakeholder's participation would be an efficient way for the sustainable development of water resources.

Keywords: *Hai Basin, water conservation agriculture, crop water productivity, water saving potential*

The role of deep flaming in violent pyroconvection

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Abstract: Violent fire-driven convection can manifest as towering cumulus or cumulonimbus clouds, the latter of which are known as firestorms (pyroCb). These extreme fires can have devastating impacts on environment and society, and appear to be a worsening problem. The major concerns surrounding these large pyroconvective events are that their associated fire spread is highly unpredictable and that they're generally not suppressible. Indeed, current methods of fire spread prediction, including the use of empirical and semi-empirical modelling approaches, fall short when attempting to predict fire behaviour associated with these events. In particular, they commonly under-predict the rate of spread in such situations, when broader-scale fire-atmosphere interactions are dominant. To date, research into large pyroconvective events has either focused on the processes involved in normal atmospheric convection, or on surface fire weather and associated fuel conditions. While some investigations have combined the two approaches, a definitive study into both the effects of the surface conditions and the fire-atmosphere interactions is still needed to better understand their respective role in the development of extreme fires.

This paper incorporates recent insights into dynamic fire propagation into a coupled fire-atmosphere fire modelling framework to test the combined effects of fire behaviour and atmospheric structure on the occurrence of violent pyroconvective events. In particular, we consider the role of factors such as the spatial expanse and intensity of the fire, and the stability of the atmosphere (both in terms of temperature lapse and moisture profile). The effects of these variables on extreme pyroconvective development are investigated in a systematic way, varying these parameters using the coupled fire-atmosphere WRF-Fire (Weather Research and Forecasting Model (WRF)). In the initial work presented in this paper we focus on the case where the fire is represented by a static heat source of variable dimension and intensity.

Analyses were conducted to investigate how (a) the size of the fire (i.e. area of deep flaming) and (b) the intensity of the sensible heat source affects the plume development. Results from preliminary analyses of dry, static fires indicated that the areal expanse of the fire strongly influences the development of the column of deep convection associated with violent pyroconvective events. This supports the hypothesis that plumes above zones of deep flaming are less influenced by entrainment than plumes emanating from typical linear fire fronts. While air is entrained at the plume boundary, the inner core of the plume is less able to entrain air. As a consequence, the areal nature of the heat source driving convection has an influence on the dynamics of the plume - in particular, the heights it can attain. The magnitude of the heat flux produced by the fire is also important for areas of deep flaming up to a minimum of 2 km diameter, but as the size of the heat source increases beyond a 2 km diameter, this appears to be less influential on the way the plume develops.

Our findings provide motivation for further investigation into the effect of the fire's attributes on the immediate atmosphere. They also have the potential to significantly improve forecasting of blow up fire events. Indeed, by combining our findings with recent insights into dynamic fire propagation and improved operational information relating to the atmospheric profile (e.g. through enhanced capability to conduct atmospheric soundings) it is feasible to provide fire agency personnel with far more targeted methods and tools that can be used to better distinguish fires that are likely to develop into violent pyroconvective events.

Keywords: *Wildfire simulation, fire-atmosphere interaction, deep flaming, pyroconvection*

Decadal and multi-decadal variability in forest fire danger and its contributors

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Abstract: The behaviour of bushfires involves complex interactions between vegetation, soils and weather. Climatic change and variability will affect all three of these factors and so can be expected to have a subsequent effect on bushfire behaviour over time. Many studies have considered long-term trends in bush fire behaviour, using various fire danger indices as the reference quantity. For example, the McArthur Forest Fire Danger Index (FFDI) is a common measure used to assess the changes that could be expected in bushfire occurrence and behaviour in Australia under different climate change scenarios. The FFDI provides a measure of expected fire behaviour in eucalypt forests by combining information on antecedent rainfall and soil moisture, air temperature, relative humidity and wind speed.

While many studies have considered historical and projected changes in FFDI in terms of long-term linear trend analyses, there are few if any that consider variability over the shorter decadal or multi-decadal time scales. Understanding how FFDI and its drivers vary over these time scales can provide a clearer picture of the climatic processes that exact the greatest control over fire danger levels, which then helps in planning for the management of bushfires over pertinent time frames. In this study we consider monthly FFDI time series (restricted to the fire season Oct-Mar) and use Smoothing Ensemble Empirical Mode Decomposition (SEEMD) to decompose the monthly FFDI time series into intrinsic mode functions. SEEMD is a variant of the ensemble Empirical Mode Decomposition (EMD) method, which is based on smoothing spline interpolation, rather than the usual cubic interpolation. Recent studies have shown SEEMD to be more accurate and robust when applied to synthetic and environmental time series, than the standard ensemble EMD. The extracted modes of temporal variability are used to investigate FFDI variability over multiple time-scales; with our main focus on decadal and multi-decadal variability.

We also apply SEEMD to the constituents of FFDI to examine the relative importance of these driving factors over time and across different time-scales. In particular, we consider drought factor (a measure of fuel availability), temperature, relative humidity and wind speed. The modes of temporal variability, as determined independently by SEEMD for each of these constituent factors, are compared with the analogous modes extracted by SEEMD from the FFDI data. Moreover, the analyses are conducted on two sets of data – one from Sydney and one from Canberra, both over the period 1972-2015.

The results indicated that at the decadal time scale, relative humidity was the strongest factor driving variability in FFDI. Variation in temperature had the second strongest influence on FFDI variability, though this influence was more prominent at Canberra, perhaps due to lack of a maritime influence at that location. Interestingly, decadal variability in wind speed at Canberra bore little resemblance to that of FFDI. At the multi-decadal scale, variation in relative humidity was again the strongest influence of FFDI variability at Canberra, but not so at Sydney where variability in drought factor was the most highly correlated with FFDI. Wind speed was found to be the second-most highly correlated with FFDI at Canberra, while at Sydney it was relative humidity.

SEEMD found that the long-term residual trends at both locations, and for all factors, were nonlinear. In particular, the resultant trends in FFDI at Sydney and Canberra both indicated that FFDI had decreased in the early part of the period followed by a more pronounced increased in the latter part – for Sydney the trend reversal occurred in the mid-1980s, while for Canberra it occurred later in the early 1990s. At Sydney, the long-term trend in FFDI was most correlated with long-term changes in temperature, followed closely by changes in drought factor and relative humidity. At Canberra, long-term changes in FFDI were most highly correlated with changes in drought factor, followed by temperature. The results of these analyses indicate that changes in FFDI can be geographically specific – with changes away from the coast driven more by changes in atmospheric moisture.

Keywords: *Empirical mode decomposition, forest fire danger index, time series analysis*

A user-focused evaluation of fire spread simulators

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Abstract: Fire and land management agencies in Australia and other fire-prone regions increasingly rely on empirical fire spread models to provide decision support and risk modelling for incident management and planned fuel reduction. It is widely acknowledged, however, that this modelling is subject to a number of shortcomings, including limitations in the underlying equations relating the rate of fire spread to fuel state. Moreover, there are significant uncertainties in ignition, fuel and weather inputs required to drive the models. Fire behaviour analysts (FBANs), the main users of fire models, need information to help decide which model(s) to use and how much confidence to place in their output.

The Bureau of Meteorology collaborated with state fire services, universities, and NCAR to develop an evaluation framework to help FBANs make informed choices about fire spread models and to help direct model improvements. A generic software framework developed during the project enables different fire spread models to be installed and run in a consistent way. The framework allows the various models, built independently with different architectures and native operating systems, to be presented with input data formatted uniformly, and in such a way that the outputs could be evaluated automatically and consistently. We gathered reliable observations of burned areas for several bushfires around Australia to evaluate model predictions of fire area, spread rate and direction, which are amongst the variables of greatest interest to FBANs. To evaluate model performance, we employed several metrics, including: threat score (as an overall summary metric), bearing error, forward spread error and burnt area error. We ran the models using the best operational weather and ignition inputs available to FBANs at the times of the fires, to reflect the quality of inputs that would be realistically available, and used vegetation load and availability data current at the time of the bushfires, obtained from the responsible fire agencies. We also ran the models varying inputs with realistic levels of uncertainty applied, to assess their sensitivity to variations in input parameters. An early finding was the large sensitivity of some models to small deviations in ignition location, which led the NSW Rural Fire Service to change the way they ran those models operationally.

A number of recommendations resulted from the project, including:

- that fire spread simulators be run in an ensemble fashion, to attempt to account for uncertainties in inputs, and simulator sensitivity to input parameters;
- that simulator software releases be thoroughly tested and benchmarked using the developed framework, or a similar testing mechanism;
- that resources be allocated to the routine measurement of fire behaviour (at least, recording fire boundaries during the course of the fire), and that a library of fire case studies be established, to permit further simulator development.

Communicating the accuracy and the sensitivity of the models to users in a concise yet understandable way was challenging given the multi-dimensional nature of the evaluation. We developed approaches to display relative model accuracy and sensitivity together using an enhanced Hinton (matrix) diagram that portrays accuracy using colour on the one hand and sensitivity using boxes of different size on the other. In addition, categorical performance diagrams were used to inter-compare the performance of different models in absolute terms. Continuous consultation with the end-users was a critical component of this effort, producing an evaluation which will maximize value for decision makers. The project has helped agencies make strategic decisions on model development in the short term, but also established a robust evaluation framework for fire simulator improvement in the longer term.

Keywords: *Fire, simulator, evaluation*

Simulating the effectiveness of prescribed burning at altering wildfire behaviour in Tasmania

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Abstract: Prescribed burning is a widely accepted wildfire hazard reduction technique, however, knowledge of its effectiveness remains limited. Prescribed burning is designed to reduce fuel loads in flammable areas across a landscape, which in turn reduces the probability of wildfires encountering high fuel load areas. This should result in a reduction of both the extent and intensity of wildfire across a landscape. The effectiveness of prescribed burning at reducing the extent of wildfire has been quantified using the metric *leverage*: defined as the reduction in area burnt by wildfires resulting from one unit increase in area treated with prescribed burning. However, prescribed burns involve numerous potential negative social and ecological side effects. Therefore, understanding the trade-offs between the effectiveness of prescribed burning, particularly among different vegetation types, and its drawbacks is crucial.

To better understand these trade-offs, we employ simulations of the Phoenix Rapidfire model, a fire behaviour model that is widely used throughout southeast Australia. It is based on the McArthur Mk5 forest and CSIRO grassland fire behaviour models and calculates fire spread as a function of fuels, weather and topography. We simulated 62 series of 11,059 fires across the ecologically diverse island of Tasmania. Even though the Phoenix model was built for forests and grasslands, it has been adapted to Tasmania using empirically derived fuel accumulation curves for each vegetation type. For each series of simulations, we simulated a different fuel treatment plan, each of which falls under one of three broad treatment scenarios: a) no fuel treatment, b) an unrealistic maximal treatment, with the most prescribed burning possible within ecological and social constraints, and c) 12 more realistic implementable prescribed burning plans. In all simulations, we distributed ignitions uniformly and standardised fire weather inputs to represent typical dangerous fire weather conditions (i.e. the 99-99.5th percentile McArthur Forest Fire Danger Index (FFDI)) for each of 45 meteorological regions in Tasmania. It should be noted that, due to Tasmania's diverse climate, this fire weather simplification did not substantially constrain the range of FFDI values used in the analysis (8.7-38).

We analysed the maximum simulated fire intensity under the null and maximal treatments qualitatively, using maps, and quantitatively, using generalised linear modelling (GLMs). The maps revealed distinct geographic patterns relating to vegetation, region, and terrain. The GLMs showed that maximum fire intensity was primarily influenced by fuels (23% deviance explained) and secondarily influenced by slope and aspect (20% deviance explained), but only minimally influenced by regional climate (2% deviance explained). The GLMs also indicated that while maximal prescribed burning can reduce fire probability in almost every vegetation type, regardless of whether or not the vegetation was subject to treatment, it can only reduce fire intensity in the three vegetation types which were extensively treated. Meanwhile, the 12 implementable prescribed burning plans were considerably less effective than the maximal scenario at reducing fire extent and intensity in all vegetation types. These implementable plans exhibited leverage in four vegetation types: dry eucalypt forest (leverage: 0.28), native grassland (0.3), native scrub (0.2), and non-eucalypt forest (0.24), suggesting these plans were roughly half as effective as the maximal scenario. Additionally, our estimates of overall reductions in maximum intensity resulting from one hectare of prescribed burning (i.e. leverage intensity) were negligible for all vegetation types. These results suggest that intensive levels of prescribed burning are required to significantly alter fire activity, and that hypothetical plans that more closely reflect those implementable by fire managers will have little impact at an island-wide scale.

This study highlights that prescribed burning can be effective for wildfire mitigation, but suggests that an unrealistically large area would need to be treated with prescribed burning to meaningfully alter fire behaviour across the island of Tasmania. We argue that this indicates a need for intensive, but localised, fuel treatments. Therefore, we conclude that optimisation of prescribed burning requires careful landscape design based on improved fire behaviour modelling, empirical measurement of fuels, and analysis of actual wildfires.

Keywords: *Prescribed burning, Phoenix Rapidfire model, fire behaviour model simulations, leverage*

Exploring the future of fuel loads in Tasmania. Shifts in vegetation in response to changing fire weather, productivity, and fire frequency.

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Abstract: Vegetation mediates the interaction between fire and climate, since one of the key determinants of fire activity is the available fuel load. The fuel load is influenced by the structure and composition of the vegetation community, fuel age, rates of decomposition, and vegetation growth rates. Attempts to project future fire danger must therefore account for changes in vegetation growth and fuel dynamics under future climatic conditions.

Estimating fuel load under future conditions is complicated by the interactions that exist between the fire regime, vegetation, climate and human intervention. Feedbacks between these factors can lead to changes in the vegetation, which in turn influence the fire regime. Changes to the frequency of fire due to management decisions (eg. Prescribed burning or fire suppression) and climate change have the potential to affect the flammability of the vegetation, with long term effects on the vegetation structure and composition. Frequent fire in some vegetation types can lead to transformational change when a threshold is crossed, beyond which the vegetation type is radically altered, and this is not always a gradual process. These represent major challenges to projecting fuel loads under future climatic conditions.

However, it is possible to project several important factors determining fire activity into the future. In Tasmania, values for future climate conditions, including fire weather, Soil Dryness Index and productivity are available from a dynamically downscaled climate model (the Climate Futures for Tasmania projections). For other ecological factors, general trends can be estimated (e.g. growth rate, time to maturity), allowing potential pathways of change to be identified, starting with the current flammability and sensitivity to fire of broad vegetation types.

Prescribed burning regimes are likely to change in the future, in response to shifts in community attitudes (eg. With increased concerns about the health effects of smoke), resourcing, and/or a narrowing window available for burning. For this reason, it is important to explore future potential fire activity under different scenarios of fire frequency. We identify the main drivers of change to potential fire activity under future climate change in Tasmania, and explore potential pathways of change to broad vegetation types affecting flammability across the landscape. We use a "pathway modelling" approach to consider multiple transitional pathways that may occur under different fire frequencies. The model is not a predictive model of vegetation flammability or spread under future conditions. Rather, it is a tool to illustrate the potential impacts of climate change (described here using the Climate Futures for Tasmania projections), in combination with the influence of management decisions about frequency of prescribed burning. Within the model, ecological theory is translated into visualizations and summaries of potential landscape-scale change, enabling the impact of fire frequency on vegetation type and potential future fire activity to be considered.

The pathway approach could be used as a tool in community adaptation, to frame potential futures, and identify the consequences of decisions seeking to manage fire risk in the future. Change over time, under different management regimes (frequency of prescribed burning), can be spatially represented to show the shifts in vegetation type, and hence flammability, across Tasmania.

***Keywords*:** *Adaptation, climate change, Climate Futures for Tasmania projections, prescribed burning, TasVeg, vegetation*

Dynamic modelling of radiant heat from wildfires

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Abstract: Risk evaluation in wildfire prone areas requires the determination of the radiant heat incident on structures and other elements. The radiant heat flux profile can be used to determine the likelihood of failure of various ele-ments through ignition of thermal degradation. The radiant heat flux incident at a particular point is, however, challenging to calculate as it requires evaluation of all possible lines of sight from an emitting (hot) surface to the point with possible obstruction and attenuation through smoke and vegetation. This is compounded by the behaviour of wildfires, which dynamically change over short time scales creating complex spatially and temporally varying emitting surfaces.

In this study we implemented a digital differential analyser (DDA) ray casting algorithm for calculation of radiant heat flux view factors on graphics processing units (GPUs). GPUs are a new generation of processing architecture that allow for massively parallel calculations on commonly available computer hardware. We show that implementation of a ray casting DDA algorithm on GPUs allows radiant heat fluxes to be calculated orders of magnitude faster than CPU-based implementations. The method can also handle factors such as obstructions and variable transmission coefficients.

The GPU-based DDA method is rapid enough to allow heat fluxes to be evaluated for dynamic fire spread scenarios. The method can be linked to any predefined scene or fire simulator. In this study it was coupled to Spark, a wildfire simulation toolkit (http://research.csiro.au/spark/), which was used to model the behaviour of small fires and create three-dimensional flame regions. An example of the maximum heat flux on two spherical receivers ('A' and 'B') from a simulation using the McArthur rate-of-spread model is shown in Fig. 1a. To demonstrate the ability of the method to handle shielding one receiver ('A') was partially shielded by an 'L' shaped obstruction. The profile in Fig. 1b shows the heat flux over time at the two receivers and demonstrates the reduction due to shielding. The method can be used to calculate accurate heat fluxes from dynamic fire scenarios to inform risk metrics and to trial and evaluate mitigation strategies for homes and infrastructure.

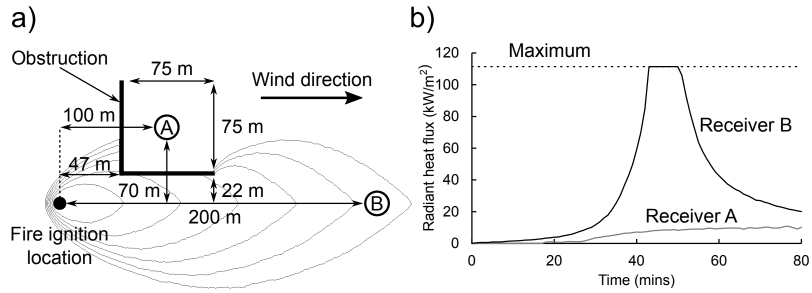

Figure 1. a) Schematic set up of dynamic test case with two receivers, one partially shielded ('A') and one in the path of the flame ('B'). Ten minute isochrones of the fire simulation are shown as contours. b) Plot of radiant heat flux at the two receivers against time. The maximum possible heat flux with a view factor $F = 1$ and the parameters used in the test case is plotted as horizontal dashed line.

Keywords: *Wildfires, heat flux, modelling*

Simulation of spot fire coalescence with dynamic feedback

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Abstract: Under certain situations, high densities of viable firebrands can ignite closely-spaced spot fires downwind of a fire front. The manner in which these spot fires coalesce determines the overall heat release rate. Here, we simulate the merging and interaction of multiple spot fires to assess the time taken to merge and determine fire intensity curves to assess maximum power output during the coalescence process. The growth of the spot fires is governed by a rate-of-spread model coupled with a pyrogenic model simulating the inflow of air to high intensity regions within the fires. The inflow is governed by a Poisson equation for a pyrogenic potential with a forcing term, α, proportional to the local fire intensity. The gradient of this pyrogenic potential gives the velocity field for the inflow of air.

The effect of increasing the spot fire density and magnitude of the forcing term on the non-dimensionalised intensity I' is shown in Fig. 1. For a fixed number of spot fires, increasing the forcing term, α, results in a higher peak intensity profile (Fig. 1a). The profile has been corrected by subtracting the linear intensity trend for a single spotfire (Fig. 1b). The peak of the intensity profile scales with the number of spot fires, N, per area (Fig. 1c). Crucially, above a certain spot density, all simulations taking into account inflow of air generated by the fire result in higher peak intensities over simulations without inflow. Models of coalescence without this attribute are therefore likely to underestimate the maximum fire intensity. These results may provide a better understanding of the dynamics of mass spot fire coalescence events and lead to improved predictive models.

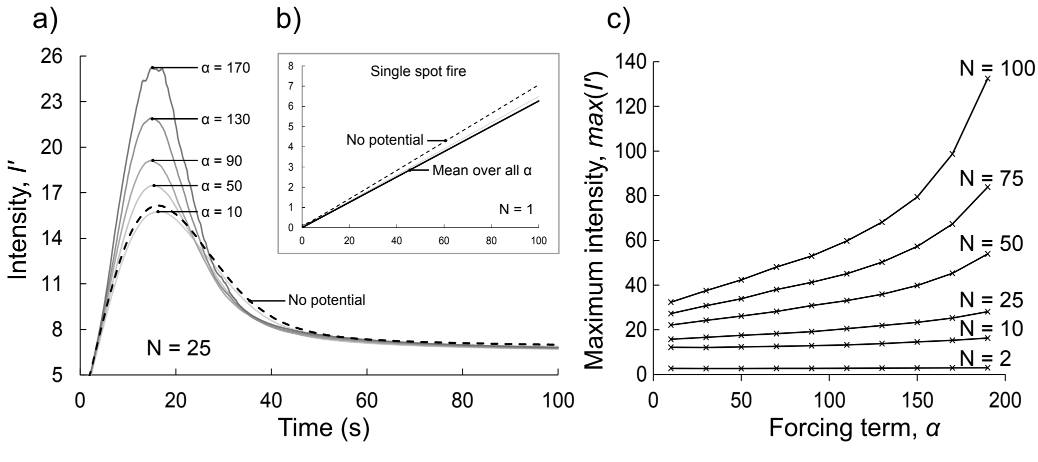

Figure 1. a) Non-dimensionalised intensity against time for 25 spot fires of 2 cm radius placed randomly within a 2 m $\times$ 2 m area coalescing for different forcing values, α. Each curve is the average of 100 simulations with randomised spot spatial placements. Dashed curve shows intensity profile without pyrogenic potential model. b) Single spot fire showing monotonic increase in fire line intensity as the fire grows under constant conditions both with (solid line) and without (dashed line) pyrogenic potential model. c) The maximum intensity as a function of number of spots N (for a fixed area of 2 m $\times$ 2 m) and forcing term α.

Keywords: *Wildfires, energy release, modelling*

Polynomial Chaos for sensitivity analysis in wildfire modelling

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Abstract: Computational models for wildfire propagation rely on a number of input variables such as fuel state, weather conditions and landscape features. These are typically forecast, estimated or measured and each has an associated degree of variability or uncertainty. This variability of these input variables affects the output variables, or predictions, of the wildfire model. However, the relation between these is currently not well quantified in operational wildfire models. With a move towards ensemble and probabilistic forecast approaches for wildfire predictions quantifying the sensitivity between the variation in the input variables and the resulting outputs in an efficient manner is becoming increasingly important.

A straightforward method of quantifying such sensitivity is through a basic Monte Carlo approach. Given a set of inputs with respective random distributions, an ensemble of simulations can be run with input conditions drawn from these distributions. The aggregation of the ensemble members is then used to determine the distribution of the output variables. However, convergence can be relatively slow and require a large set of ensemble members. A more sophisticated technique is Polynomial Chaos, in which the statistical distribution of the outputs are represented using orthogonal polynomial series expansions. The method allows the output distribution to be reconstructed by picking input values at specific points, corresponding to Gaussian quadrature points, rather than randomly. This allows output distributions to be estimated using fewer computational simulations, and hence much more rapidly, than using a Monte Carlo approach.

In this study we implemented a Polynomial Chaos method using the Python NumPy library. The method provided input values to 'black box' simulations carried out in Spark, a wildfire modelling framework (http://research.csiro.au/spark/). The modelling set up used in this study was a point ignition propagating under a constant wind direction but variable strength and a variable fuel load. The McArthur model was used for the head fire rate of spread and the simulated duration of the fire was six hours from an initial point source. As a comparison, we also used the NumPy library to generate and aggregate ensemble members for a Monte Carlo simulation. The only output variable considered in the study was the arrival time of the fire at points in the spatial domain.

Sensitivity analysis using Polynomial Chaos for one uncertain input variable, wind strength, required just four simulations to reconstruct the distribution of the output variables and to calculate the mean and standard deviation of the arrival time output variable. In comparison, the Monte Carlo method slowly converged to the distribution taking around one hundred times more simulations to approach a comparable value for the mean. For a sensitivity analysis of both wind strength and fuel load the Polynomial Chaos method required sixteen simulations to reconstruct the distribution. The Monte Carlo method showed similar convergence behaviour to the previous test, requiring several hundred simulations to approach a comparable value for the mean. The Polynomial Chaos method clearly provided a far more efficient method for sensitivity analysis in wildfire applications.

Other strengths of the method include the ability to find the distribution of any number of outputs without running any additional simulations. The sensitivity of an entire field in space, such as the distribution in arrival time over an entire spatial domain at each point, can easily be evaluated. The number of simulations scale as the polynomial order to the power of the number of input variables, making the technique computationally intractable for large numbers of uncertain variables. However, more advanced quadrature techniques, not covered in the present study, could resolve this difficulty. We believe the method may be suitable in applications such as operational fire predictions as uncertainty in predictions can be rapidly assessed. The method also does not depend on any particular fire simulation algorithms and can be built as a framework around a 'black box' simulator.

Keywords: *Wildfires, sensitivity, modelling, polynomial chaos*

What are the safety implications of dynamic fire behaviours?

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Abstract: Many firefighters in the world have been injured or killed due to a forest fire entrapment, caught by the fire heat or smoke. Some case studies have pointed out that dynamic fire behaviour may have played a role. We investigate here how changes in wind direction, channelling (i.e. vorticity-driven lateral spread on a leeward slope) and long distance spotting could contribute to entrapments through a process model, simplified in Figure 1. There are three situations likely to entrap firefighters:

- S1. Facing a violent fire front either because of a change in wind direction or not
- S2. Fire channelling, i.e. fire developing an atypical lateral spread
- S3. Fire developing at a long distance because of mass spotting.

We review fire agencies archives in Australasia and Europe from 1979 to 2017 and retrieve 106 entrapments, investigating weather, terrain and location of fire front during entrapment. We also compare the Australasian subset with fires without entrapment using a binomial regression function.

In Australia, changes in wind direction induced by cold front passes is the main factor contributing to entrapment. These sudden changes in wind direction switch long smooth burning flanks of fire in violent fronts and lead to S1 situations. S2, sudden lateral spread, occurs in rough terrain. There, leeward slopes may generate channelling, causing entrapment several hundred meters far away from the fire flank. S3 appears when fire danger index reaches highest values. When fuel drought combines with adverse weather conditions, mass spotting propagates fire at long distance. Then, firefighters may be entrapped whatever the terrain.

This work improves our understanding of the process from dynamic fire behaviour to firefighter entrapment. Identifying three different situations, the model should help fire agencies to adapt their safety warnings regarding the local daily conditions.

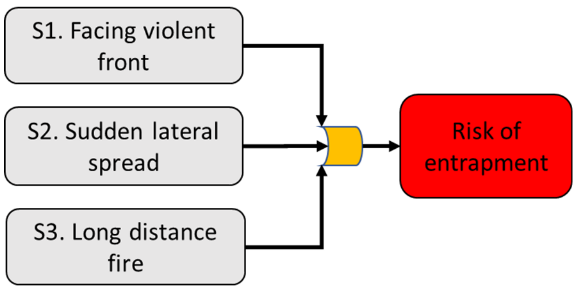

Figure 1. Simplified process model of entrapments.

Keywords: *Entrapments, firefighters' safety, wildfires, extreme behaviours*

EXTENDED ABSTRACT ONLY

A New Index for Determining Fuel Accumulation Using Optical Remote Sensing: Application to Fire Simulations

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Abstract: Predictive fire models rely on fuel conditions such as the state and amount of vegetation. Temporally and spatially high-resolution fuel maps are required for accurate rate-of-spread simulations for operational fire management and risk assessment. Understanding fuel in a forest, particularly in the understorey, is also important for fire management and planning. However, fuels either continuously accumulate or are rapidly depleted in high intensity wildfires. As a consequence, such fire events along with prescribed burns make accurate assessments highly challenging. Optical sensors on-board low Earth orbit satellites offer data at spatial and temporal resolutions ideal for quantifying fuel conditions. A new index, the Vegetation Structure Perpendicular Index (VSPI), has been developed to provide an estimate of fuel load depletion and rate-of-recovery in eucalypt forest stands after a fire. The VSPI represents the difference from a temporally averaged reflectance and is calculated using two infrared spectral bands centered at 1.6 µm and 2.2 µm, available from a number of satellite platforms. Sensors on board Landsat and Sentinel-2 have spatial resolutions ranging from 15-30 m and repeat coverages between acquisitions ranging from 16 to 5 days.

In the current study, the accuracy of dynamic fire spread predictions resulting from the use of VSPI as a descriptor of fuel conditions is investigated. The study event is the 2003 Mount Cooke bushfire in Western Australia which scorched 25,000 ha of jarrah forest. Here, the VSPI was used to provide fuel hazard scores in the Dry Eucalypt rate-of-spread model by matching index recovery curves to experimental curves. The Spark framework was used to simulate fire spread, with VSPI determined directly within Spark from available Landsat data. The simulations qualitatively show high similarities with the actual fire scar and simulations using a spatial map of know fuel age (Fig 1). The use of VSPI provides the possibility of incorporating spatial and temporal fuel variability in high resolution fire rate-of-spread simulations from freely available satellite imagery, rather than subjectively derived fuel age maps. The use of such an index could improve operational forecasts, risk assessments, and guide in the articulation of strategies for locating future fuel reduction burns.

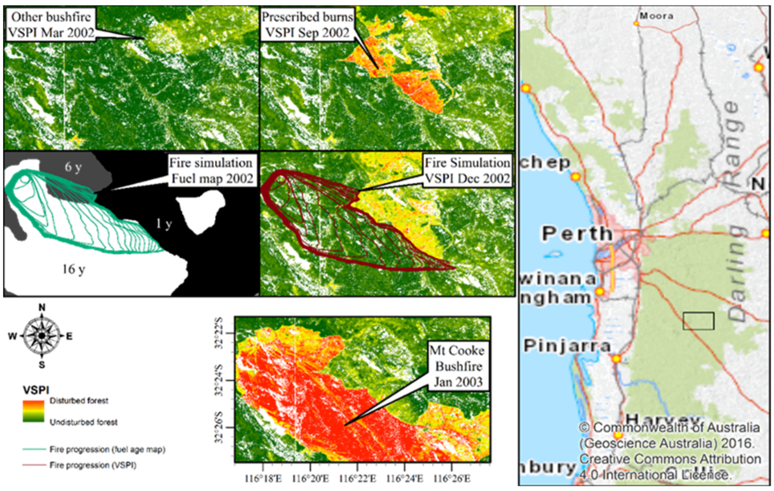

Figure 1: Location of the Mount Cooke bushfire (Jan 2003) in a jarrah forest in WA. The simulation of the first 20 hours of this bushfire approximated well the real fire scar due to the VSPI detection of young fuel patches. The fire disturbance signals are detected at maximum during the fire events (see the 2-month VSPI for a bushfire in January 2002 in the top panel and planned burns in November 2002 in the middle panel) and continue to be detected for 3-7 years after the fire.

Keywords: *Remote sensing, bushfire, Vegetation Structure Perpendicular Index, vegetation recovery*

The Use of Spectrum Width Radar Data for Bushfire Model Verification

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Abstract: In wildland fires, the turbulent motions of air in the convective plume can significantly affect fire spread through processes such as spotting, local wind field modifications and the initiation of pyrocumulus and pyrocumulonimbus (*i.e.,* cumuliform cloud types associated with fire activity). Radar has been used in a variety of studies to gauge the escalation of such processes. However, these studies have relied heavily on the radar moment of reflectivity despite a poor understanding of the nature of the particles producing the back-scatter. In the last decade, many models have emerged capable of simulation of fire-atmosphere interactions. Validation of these models requires observations of the turbulent motions in plumes, but such observations from very large fires, including those that develop pyrocumulonimbus, are very rare.

Doppler velocity can be used to estimate radial windspeeds, but specialised manual interpretation is required to characterise the coherent vortices, which offers little utility to modellers. Reflectivity and Doppler velocity therefore are limited in the modelling of to bushfire. The use of spectrum width, defined as the standard deviation of the Doppler velocity, has received no attention in the literature to date in relation to its potential to quantifiably validate modelling of fire-atmosphere interactions. This variable has long been known to act as a proxy for the sub-grid turbulence in radar sampling volumes.

The Bushfire Convective Plume Experiment (BCPE) involved a 2.5 year field campaign to capture observations of pyroconvection primarily with a mobile X-band Doppler radar, to collect a range of different types of observed fields including spectrum width. This field campaign involved collaborating with agencies responding to wildfires through the bushfire season, as well as attending prescribed burning for bushfire hazard reduction. The mobile radar observations were supported by other field observations, including weather balloons to observe vertical wind and stability structure of the atmosphere, as well as rapid-deployable Automatic Weather Stations (AWS), time-lapse cameras and fire severity reconstructions.

One particular finding from the BCPE relevant to the modelling community is associated with the Doppler velocity and spectrum width results. In effect, it was found that spatial approximations of the turbulence distributions within bushfire plumes can be produced, along with resolving the structures of large vortices within the plume through the two variables. Here we present a summary of some previous radar-based studies of plume dynamics, as well as observations from one of the BCPE fire cases, showing the spectrum width and Doppler analyses of the Mt Bolton bushfire (in Victoria, southeast Australia). The Mt Bolton fire event was captured in high resolution using a portable X-band radar in the course of the BCPE field campaign. The resolution allowed for the calculation of Plume Relative Winds (or PRW). These were calculated by subtracting an estimate of the advection in the wind field from the downwind Doppler returns. The initial results of PRW and spectrum width illustrate a potential new avenue for model validation. The proposed validation includes tying high resolution turbulence parameters and structures in the radar data in bushfire simulators, Large Eddy Simulation and in fire-atmosphere coupled models.

Keywords: *Bushfire, plumes, turbulence, radar, spectrum width*

Predicting pyroCb occurrence: a case study of the 2017 Sir Ivan fire

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Abstract: Pyrocumulonimbus (pyroCb) storms, which form over a significant wildfire, are the most extreme manifestations of violent pyroconvection. The fire behaviour associated with pyroCb occurrence is generally not amenable to suppression; instead of the fire propagating as a contiguous front, it tends to propagate as an ember storm which produces a rolling succession of coalescing spot fires. PyroCb's are also associated with the most significant losses – both economic and societal. Existing methods of assessing the potential for dangerous fire behaviour typically only consider surface weather conditions, and so offer only very limited information on the potential for pyroCb occurrences, which are coupled fire-atmosphere events.

In response to the clear need to improve operational prediction of pyroCb events, a number of authors have proposed ways to improve predictive ability. In one such example, the authors introduced the blow-up fire outlook (BUFO) model. The BUFO model considers the potential for 'deep flaming' to form in an unstable atmospheric setting. BUFO was found to provide valuable guidance in a number of cases during an operational trial of the model in NSW, and has been shown to be useful in retrospective analyses of pyroCb events. In this paper we discuss the performance of the BUFO model, as it was applied operationally to a particular day during the 2016/17 fire season in southeastern Australia.

On February 10th, 2017, there were a significant number of unconfined wildfires burning in north-east New South Wales, with a forecast of significantly elevated fire danger for the next day. The BUFO model was run to see if any of those fires had the potential to develop into blow-up events or to form into extreme wildfires. Based on an initial assessment, three fires were considered for further analysis: one on the coast exposed to a coastal wind change; and two in the Cassilis geocol, exposed to both coastal and interior air masses. One of these inland fires was at higher elevation, on the edge of the Central Tablelands, the other in the river floodplain on extreme outliers of the Sydney sandstone basin. BUFO analyses combined with operational discussions concluded that the greatest risk was at the latter fire, due to the potential for fine-scale vorticity-driven lateral spread to occur along the frequent horizontally bedded sandstone outcrop edges, and produce deep flaming. Instability was expected to peak in the early afternoon, based on detailed forecasts of the Continuous Haines Index. This was associated with a trough-line expected to traverse the area from the south-west. While the other two fires of interest were expected to be challenging wildfires driven by surface weather, terrain and fuel loads, they were seen as unlikely to form deep flaming. As such, the BUFO model did not identify these fires as likely to exhibit blow-up behaviour.

With a forecast in place from the previous evening and generally consistent forecasts in the morning update, the situation was monitored as the afternoon weather evolved. Himawari-8 satellite imagery was the key tool, as the fires were not well covered by weather radar. Active convection was clearly visible from mid-morning, among a widespread cumulus field (4 oktas) with the cloud base at around 2.5 km ASL. Smoke was injected to around 3 km ASL. The sky behind the approaching trough-line was clear. As it passed over the fire, convective intensity escalated rapidly, and this persisted for roughly 2 hours. Satellite imagery from 3 weeks post-fire indicated that three major blow-up events occurred, roughly concurrently. These events were indicated by their uniform, complete burn scarring, independent of terrain. Lightning detection systems indicated hundreds of lightning strikes from the pyroCb as it advected away to the ESE. Infrared satellite imagery showed that the cloud top brightness temperature was -54°C. Radiosonde data put the cloud top at an elevation of 12 km ASL, confirming that this was a major pyroCb event.

Interestingly, the escalation in pyroconvection occurred about an hour before the arrival of the wind change, which counters the common notion that it is the arrival of a wind change that results in blow-up fire activity. As such this case highlights the need to improve understanding of the role of complex frontal dynamics in blow-up fire events

Keywords: *Extreme wildfire, pyrocumulonimbus, pyroconvection, blow-up fire*

Physics based modelling of tree fires and fires transitioning from the forest floor to the canopy

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Abstract: Wildland fires or bushfires can be a surface fire such as a grassfire or an elevated crown fire. Crown fires are often supposed to originate from surface fires spreading either along the bark of the tree trunks or direct flame contact to low branches with leaves and needles. In a previous study, surface fire (grassfire) spread simulation was successfully conducted using a physics based model, Wildland Urban Interface Fire Dynamics Simulator (WFDS). The base open-source code of WFDS was developed by the National Institute of Standard and Technology (NIST), USA from its original building fire model Fire Dynamics Simulator (FDS); but it is being further developed by other researchers. It is important that the capabilities of WFDS for modelling tree and forest canopy fire are explored to develop rate of spread equations for crown fires.

In this study, we have first quantitatively studied a burning single tree and then semi-quantitatively studied forest floor fire transitioning to a crown fire. For tree burning simulations, Douglas fir experiments conducted at NIST are considered, where mass was measured and mass loss rate (MLR) was calculated taking into consideration the moisture content in the samples. We have used two thermal degradation sub-models within the physics-based model to simulate the tree burning experiments the linear and Arrhenius models.

The aim of the first part is twofold: one we seek numerically converged results, which were elusive with the previous version of the model; and secondly we appraise two thermal degradation sub-models. Comparison of MLR results from the simulations shows that grid convergence is not elusive and convergence is deemed to be obtained with 50 mm grid for both thermal degradation sub-models. The grid converged solution agrees well with the experimental result involving burning of a Douglas fir tree.

Then a fire in a hypothetical forest of Douglas Fir trees sitting on a grassland, which can be thought of as a model of a plantation, is simulated using the linear thermal degradation sub-model due to its simpler parameterization requirement. A sensitivity of the domain height and space downstream of the forest is carried out. Final results are obtained with a narrow simulation domain of 124 m long, 8 m wide and 25 m high, which is not sensitive to domain size variation. The result, firstly, shows that the WFDS model is capable of qualitatively predicting propagation of surface fire to this forest canopy. It is also found that upon transitioning to a crown fire, after an adjustment period, a fire propagating with a quasi-steady rate of spread is established. We can therefore be confident that crown fire simulations and studying detailed crown fire dynamics are possible with the physics-based model.

Analysis of the heat release rate (HRR) data shows that the surface fire propagates underneath the crown fire and therefore the fire observed here is a supported crown fire. That is, the surface fire puts energy into the crowns to sustain the burning of the crown material. Overall many features are qualitatively in agreement with other crown fire studies.

By changing the properties and configuration of the fuel material, simulation of native Australian vegetation can be attempted. In the future, similar simulations will lead to greater understanding of the transition of surface fires to crown fires. With further refinement, simulations could be used to construct threshold models of crown fire transition. The largest drawback of physics based simulations remains the large computational time due to the extremely fine grid sizes required. However, a simple linear parameterisation of thermal degradation model along with simple turbulence model can be used to reduce some of the computational effort.

Keywords: *Physics based modelling, crown fire, tree fire, fire transition, rate of spread*

Field-scale testing of a detailed physics-based fire behavior model

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Abstract: Wildland fires are driven by strongly coupled transport processes over a wide range of spatial and temporal scales. The interaction of these processes can be difficult to capture through measurements, and the study and increased understanding of the role of component processes can benefit from the use of numerical modeling. In particular, detailed physics-based models have gained increasing attention in the research community in recent years, especially for parsing the mechanisms that drive fire spread in various scenarios. These models are built on the methods of computational fluid dynamics (CFD) which numerically solve the governing equations of mass, momentum, and energy. The phenomena relevant to fire behavior are either directly resolved or approximated, with an overall aim of limiting empiricism, such that a significant amount of flexibility is afforded for model application. However, the capability of such models to provide reliable outputs is dependent upon their undergoing rigorous testing against appropriate experimental measurements at a variety of scales. This remains a considerable constraint, particularly given the limited availability of sufficiently detailed and comprehensive datasets of fire behavior at the field scale.

In this work, the above challenge is addressed by testing a detailed physics-based fire behavior model – the Wildland-urban interface Fire Dynamics Simulator (WFDS) – against data collected in an experimental fire in a pine forest, located in the Pinelands National Reserve (PNR) of New Jersey, USA. An evaluation of macroscopic fire behavior was made through comparison to experimental measurements of fire spread and fuel consumption. A combination of remote sensing techniques and point measurements were employed. Further, an investigation on the accuracy of the numerical predictions of more fundamental mechanisms driving fire behavior was carried out. This was done through direct comparison to detailed measurements of temperature, flow, and radiative heat flux, which were obtained at specific locations within the burn block (e.g. Figure 1).

In terms of global behavior, the simulations were within the range of experimental observations, for both fire progression and fuel consumption, though tending towards the higher end. However, the global behavior can only go so far in terms of understanding the quality of the model, as the integration of several incorrect representations of physical processes can produce seemingly accurate global trends. Therefore, the comparisons of point measurements of the mechanisms of fire spread, as in Figure 1, are critical. Overall, the simulated trends were qualitatively consistent, with features like fire residence time and the occurrence of an upstream fire-induced in-draft being well reproduced. Some discrepancies were found, particularly with the long distance radiative flux, the peak value of local velocities, and the nature of post-flaming conditions. Most importantly, this work has led to the identification of several clear improvement needs. These relate to measurement procedures, model parameterization, and numerical formulations.

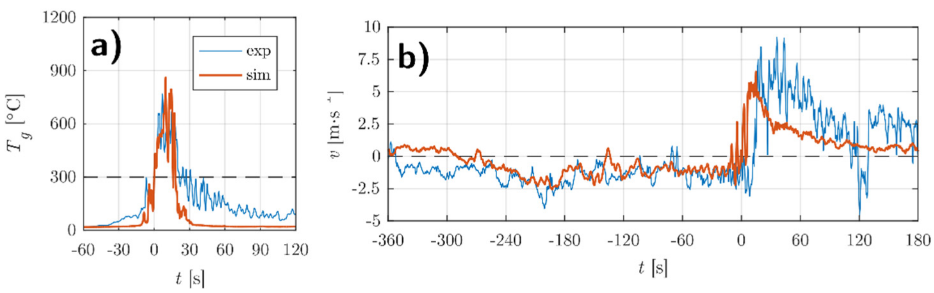

Figure 1. Comparison of experimental and simulated values of (a) gas phase temperature and (b) horizontal entrainment velocity at one of the local fire measurement sites during a fire in the PNR.

Keywords: *Computation fluid dynamics (CFD), fire spread, wildland fire, model testing*

Incorporating ember attack in bushfire risk assessment: a case study of the Ginninderry region

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Abstract: Current methods for assessing the risk of bushfire to built structures are based on the assumption that the majority of structure loss is due to radiant heat exposure. However, data collected in the aftermath of recent destructive bushfires indicates that the impacts of radiant heat are insignificant compared to the impact of ember attack. Recent work by the Bureau of Meteorology has provided fundamental information on how embers are distributed by a convective plume. These ember distributions have subsequently been incorporated into a model that permits estimation of the likelihood of ember attack downwind from an active fire. In this paper we employ the ember load model to incorporate ember attack into bushfire risk assessment. In particular, we consider the case of the Ginninderry region, which is a tract of land currently subject to rezoning for urban development. The Ginninderry region is of interest because it is prone to dynamic modes of fire spread such as eruptive fire spread and vorticity-driven lateral spread, the latter of which is known to result in enhanced production of embers. The ember load model is used to assess the risk of the Ginninderry region to ember attack and compare the inferred risk to that informed by traditional risk assessment methods based on radiant heat thresholds.

The results of this case study indicated that risk of ember attack had a distinct directional signature, which is accounted for in the current approach to bushfire risk assessment. Moreover, the ember load model indicated that many areas at considerable risk of ember attack are further than $100m$ from the urban edge. Such areas are not currently required to have any special resilience to embers. As such the results indicate that current methods of risk assessment could significantly underestimate the risk of house loss from bushfire, and that current requirements for construction standards should be extended further than 100m.

The present analysis contains a number of fairly crude assumptions, and so the results should be considered preliminary. Nevertheless, with some refinement, the ember load model could play an important role in more accurately informing bushfire risk assessment and provide a more quantitative basis for revising and improving the Australian standard for building in bushfire prone areas.

Keywords: *Bushfire risk, Ember attack, Australian standard, dynamic fire spread*

A stochastic differential equation approach to modelling the growth phase of fire spread

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Abstract: From a point source, landscape fires accelerate until they reach a quasi-equilibrium rate of spread. The rate at which a fire accelerates from its ignition affects the time first responders have to attack a fire in its initial stages when it is more easily suppressed. As such, knowledge of the rate of acceleration of a fire from ignition can be valuable from a fire management perspective. However, the majority of studies in wildland fire science have been dedicated to development of models for the quasi-equilibrium rate of spread attained by the fire after its acceleration phase. Comparatively little attention has been given to the development of models that specifically account for the growth phase of a fires development.

The rate of acceleration depends on many factors including variations in ambient and induced wind speed and direction, variation in moisture content of the fuel, fuel stratification and slope variation. Present models of fire growth from a point ignition are expressed as deterministic algebraic equations, thereby neglecting variability. The numerous variables involved make predictions of rate of spread from a point source very difficult.

In this paper we consider two approaches to model the acceleration phase of a fire. The first considers fitting a sigmoidal function to experimental data using a nonlinear curve-fitting procedure. The model takes the following functional form:

$$R(t) = \frac{R_0 R_e}{(R_0 + (R_e - R_0)\exp(-at))},$$

where $R(t)$ is the rate of spread at any time t. The parameters R_0 and R_e are the initial and quasi-equilibrium rate of spread respectively, and a is the growth rate.

In the second approach we propose the use of stochastic differential equations to investigate the growth of a fire to quasi-equilibrium. Specifically, the model is given by the following stochastic differential equation:

$$dR = aR\left(1 - \frac{R}{R_e}\right) dt + \sigma R\, dW,$$

subject to the initial condition $R(0) = R_0$. Here, W is a Wiener process.

In addition to providing a more realistic portrayal of the time series data relating to fire growth, this second approach allows for better discrimination of the mechanisms driving the growth phase of fire spread.

The models are assessed by appealing to observations of experimental fire growth. Specifically the data relate to fires growing from a point ignition under the influence of a uniform wind. The results indicate that both approaches can provide an accurate representation of the observed data, but that the approach based on stochastic differential equations yields 95% confidence bounds that are higher than those obtained from the nonlinear curve-fitting. The difference in confidence bounds indicates that the way stochasticity is incorporated into fire growth models has implications for how models inform decisions about the likelihood of a fire self-extinguishing before it reaches quasi-equilibrium, and the magnitude of the rates of spread it is likely to exhibit during the initial stages of growth.

Keywords: *Fire growth, fire acceleration, rate of spread, stochastic processes, stochastic differential equations*

Dynamic simulation of the Cape Barren Island fire using the Spark framework

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Abstract: The Cape Barren Island fire occurred in December 2016 and ran mostly unsuppressed from the west to the east of the island, burning around 60% of the island's total area. The fire offered valuable opportunities for the evaluation and development of fire spread simulators as it ran through relatively uniform fuels subject to minimal suppression.

In this study we simulated the evolution of the Cape Barren Island fire using the Spark framework. The framework allows rates of spread in different fuel types and new types of dynamic fire behaviour to be easily tested. Here, we incorporate parameterised behaviour models including one that allows for the effect of vorticity-driven lateral spread (VLS). In VLS regions fires are counter-intuitively observed to spread perpendicular to the wind direction on lee slopes due to vortex iteration with the terrain. The VLS sub-model was implemented natively using the Spark framework using a filter criteria and a specialised rate-of-spread model for fire propagation perpendicular to the wind direction. This dynamically-driven mode of fire propagation is not accommodated within the current suite of operational fire spread simulators. Indeed, this work presents the first instance of a two-dimensional fire spread simulator that incorporates VLS dependence.

The simulations were found to closely match observed fire perimeters over a 45 hour duration, apart from regions in which suppression operations had likely occurred. The simulations also served as a validation exercise for the heathland fuel rate-of-spread model used, showing the empirical model has excellent predictive ability. Simulations performed with the VLS sub-model were found to match observed fire perimeters in regions where VLS was predicted to occur. Furthermore, simulations performed without the VLS sub-model were found not to burn these same regions. The accuracy of the simulated fire perimeters were evaluated using the 'threat score' (Faggian *et al*., 2017), which measures how well the simulated burnt area overlaps with the observed burnt areas. The threat score is calculated as:

$$S = \frac{TP}{TP + FP + FN}, \tag{1}$$

where TP represents the total area that the simulated fire correctly identified as burnt (true positives), FP represents the total area that the simulated fire incorrectly identified as burnt when it was observed as unburnt (false positives), and FN represents the total area where the simulated fire did not spread but was observed to have burnt (false negatives).

Threat scores were calculated at two times when observed fire perimeter data was available: 11:30 am on 6$^{\text{th}}$ Dec, and 9:00 am on 7$^{\text{th}}$. At the earlier time the threat scores were $S = 0.4768$ for the simulations without the VLS sub-model, and $S = 0.4788$ for the simulations with the VLS sub-model. At the later time the threat scores were $S = 0.7393$ for the simulations without the VLS sub-model, and $S = 0.7434$ for the simulations with the VLS sub-model. Hence, inclusion of the VLS sub-model resulted in a slight improvement in overall model performance.

Extension of fire spread simulators to accommodate fire behaviours such as VLS offer an enhanced ability to predict critical aspects of fire development, with ensuing benefits to fire managers, firefighter safety and resilience of the broader community.

Keywords: *Wildfires, sensitivity, modelling*

Modelling the dynamic behaviour of small scale junction fires using curvature flows

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Abstract: The merging of two lines of fire is a relatively common occurrence in landscape fire events. For example, it can arise through the coalescence of two wildfires or when a prescribed fire meets a wildfire as part of suppression efforts. When two fires approach one another, the effects of convective and radiative heat transfer are compounded and high rates of spread can arise as a result. This is particularly the case when two lines of fire meet at some oblique angle - the point of intersection on the newly merged fire can advance rapidly. This case was investigated recently by Viegas et al. (2012), who devised an analytical model to emulate the effects of energy concentration between the two merging fire lines. In this paper, we present a more geometric approach by considering the evolution of the merged fire as the flow of a plane curve with a normal speed that depends on the curvature of the fire front. Parametric variation of the curvature dependence is investigated, and the resultant geometric evolutions of the fire front are compared with the experimental observations of Viegas et al. (2012). Further theoretical aspects of plane curvature flows and their more general application to fire front modelling are also discussed.

Junction fires occur when two fire lines meet at an oblique angle. The interaction of the two fire lines means that junction fires can exhibit unexpected fire behaviour, with enhanced rates of spread in the vicinity of the junction point. Junction fires also comprise one of the main fire behaviours involved in spot fire coalescence. Quantifying the interaction between two oblique fire lines is essential for the development of next generation fire spread models, which will allow for prediction of dynamic fire propagation. Previous work considered using fire line curvature as a simple means for modelling the dynamic behaviour of junction fires. However, in this preliminary work the method for modelling the fire spread was based on initial conditions that were not truly representative of merging fire lines. Subsequent work has implemented the curvature based model using a level set method, which allows for more natural boundary conditions. This approach was used to successfully simulate the behaviour of large-scale experimental grassland fires. In this paper we consider the same approach applied to experimental fires that are an order of magnitude smaller than those considered previously. Optimal parameters for the curvature based model applied to the smaller scale fires are derived and compared to the optimal parameters obtained for the larger scale fires. This comparison reveals information about how the dynamic behaviour of junction fires varies across different scales.

Keywords: *Wildfire simulation, fire line merging, level set method, fire line curvature*

Reassessing the validity of AS3959 in the presence of dynamic bushfire propagation

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Abstract: The Australian Standard for construction of buildings in bushfire-prone areas (AS3959) specifies requirements in order to improve the resistance of buildings against bushfire attack from burning embers, radiant heat, direct flame contact, or a combination of these three factors. In particular, AS3959 informs the design and construction of buildings in bushfire-prone areas through the concept of Bushfire Attack Level (BAL). In principle, BAL can be determined through application of the Standard to any site in the landscape, thereby providing the appropriate design and construction measures required to reduce the risk of bushfire igniting a building situated at the site. The calculation of BAL at a site relies on the following four main factors:

- fire danger;
- vegetation type;
- distance of the site from the classified vegetation; and
- the topographic slope on which the vegetation is situated.

Moreover, BAL is calculated based on the assumption that a fire will behave in accordance with the quasi-steady assumption. In this paper we examine the validity of AS3959 in situations where the quasi-steady assumption is violated. In these situations the expectation is that fires will exhibit dynamic modes of fire spread such as vorticity-driven lateral spread, eruptive fire spread and ember storms. As such, this study constitutes a critical review of the current models and methods informing the construction of buildings in bushfire prone regions, and that underpin bushfire risk assessment on the urban interface more broadly.

We find that there are a number of recent insights into dynamic fire behaviour that are not adequately addressed in the modelling framework that underpins AS3959. For example, current calculation of BAL is based on radiation thresholds derived using (scalar) distance to vegetation as a key input, without any acknowledgement of directional influences. A case study is presented that highlights the fact that dynamic modes of propagation could produce a strong directional bias on bushfire attack levels. The overall implication is that construction standards and bushfire risk more generally, as assessed based on the principles espoused in AS3959, is likely to be under-predicted in the presence of dynamic fire propagation. The insights gained from recent dynamic fire modelling efforts provide the basis for further review and refinement of AS3959.

Keywords: *Bushfire risk, Australian Standard, dynamic fire behaviour, AS3959*

Scale dependence of topographic slope and its effect on dynamic bushfire propagation

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Abstract: Topographic slope is well known to have a significant effect on the rate of spread and general behaviour of a bushfire. While there is still no definitive understanding of the physical mechanisms that underpin slope-driven fire spread, there are number of models that quantify the effect of topographic slope on fire propagation. These models range from simple rules of thumb that describe how the head fire rate of spread is affected by slope, to threshold models relating to dynamic fire propagation regimes. Topographic data, as it is applied to the modelling of fire propagation, is typically provided by a digital elevation model (DEM), in which the topography is realized as discrete elevations over a spatial grid of a particular resolution. In practice, DEM grid resolutions employed in operations and research can vary from 1 m to 250 m, or more. The DEM resolution has an inherent effect on the magnitude of slopes that can occur: coarser resolution DEMs do not resolve steeper slopes. This will of course have consequences for the assessment of how fire spread is influenced by slope, but this issue does not appear to have received much attention in the literature. In this study we directly address the issue of how the scale of the DEM influences assessment of fire behaviour. In particular, we consider the topographic slope thresholds relating to vorticity-driven lateral spread (VLS). VLS has been shown to only occur on slopes that are sufficiently steep and lee-facing. Here we consider how the VLS slope threshold scales with DEM resolution and provide a model that permits assessment of VLS likelihood over a range of DEM scales.

Previous work developed a first-order metric based on wind direction and topographic slope, which identified a slope threshold for VLS occurrence of $\sigma \approx 11°$ using a 250 m DEM. To understand how this slope threshold parameter σ might scale as the DEM resolution is changed, we adopted the following approach.

1. Begin with a 30 m resolution DEM, and smooth it to varying degrees, down to a resolution of 250 m. For each of the DEMs fit a Weibull distribution to the histograms of topographic slopes.
2. Take the empirical threshold value of $\sigma \approx 11°$ determined from a 250 m resolution DEM, and calculate the proportion of slopes in the 250 m resolution DEM that are above this threshold value. Let this proportion be $p(\sigma)$. Hence, $p(\sigma) = P(\gamma \geq 11°)$, where γ is topographic slope.
3. For each DEM, say with resolution R metres, calculate the threshold slope σ_{R}, which satisfies $p(\sigma) = P(\gamma \geq \sigma_{\mathrm{R}})$.

Based on this approach, it was found that the slope threshold scaled approximately linearly ($R^2 > 0.99$) as described by the equation:

$$\sigma_R = -0.01865R + 15.6625. \tag{1}$$

This means that to decide if a particular landform is prone to VLS occurrence, a threshold slope value must be chosen as appropriate to the resolution of the DEM being used.

We have also developed a second-order metric that appears to better discriminate parts of the landscape prone to VLS occurrence. However, this metric also depends on the scale of the DEM being used. We analysed the scaling of the second-order metric using a similar methodology as described above. The utility of the second-order metric was evaluated using line-scan data from the 2013 Aberfeldy fire, which exhibited a number of instances of VLS. Some implications of these analyses to fire behaviour analysis will be highlighted and discussed.

Keywords: *Topographic slope, dynamic fire behaviour, VLS*

Modelling Firebreaks in a Two-Dimensional Dynamic Fire Spread Simulator

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Abstract: Wildfires cause damage to infrastructure, houses and ecosystems every year in many countries across the world. Modelling of large-scale wildfire propagation is important for both long-term future planning and operational fire management such as decisions around evacuation and suppression tactics. Disruptions such as firebreaks, roads and rivers can completely halt, partially inhibit or have very little effect on the spread of wildfires. The behaviour of the fire at these disruptions depends on factors such as the width of the disruption, the fire intensity and type and condition of the fuel the wildfire is burning through. However, there is currently limited understanding as to the best method for representing such disruptions in wildfire models and quantifying their effect. Here we investigate a range of potential implementations for linear disruptions, and apply these to a simplified disruption scenario.

In this study, probabilistic and deterministic methods of implementing a disruption within a fire spread simulator are investigated. The methods are implemented in Spark, a two-dimensional, raster-based level set solver. The scenario investigated in this study comprises a fire under constant wind and fuel conditions impacting a disruption, representing a firebreak, running perpendicular to the wind direction. The simulation was started from an ignition with a radius of 10 metres, used a southerly wind with a constant speed of 30 km/h, homogeneous fuel type and load and ran for a one-hour period. McArthur's Mk5 model was used for the rate of spread of the fire. A one metre wide disruption was imposed 100 metres downwind from the ignition point.

For the probabilistic method, the disruption was implemented as a set of un-burnable raster cells, the state of which could be set to burnable (allowing the fire to cross the disruption) dependent on user-defined criteria. This criterion was based on a failure function giving the probability of a cell allowing the fire through at each time-step of the simulation. Care was taken to adjust the failure function for both the spatial resolution of the raster cells, and the dynamically changing simulation time step. Using a constant failure function and probabilities of crossing an individual cell of 0.2 and 0.4 respectively, two sets of 1,000 simulations ensembles were run. These simulations were used to obtain cumulative density functions for the length of time it took the fires to cross the firebreaks.

Several deterministic approaches were investigated for emulating the ensemble behaviour of the probabilistic methods, as ensemble simulations might not be feasible for some time constrained simulations (such as operational fire prediction) especially if one has limited computational resources available. These included treating the firebreak as slowly burnable or with a time delay before the fire was allowed to cross the disruption. These deterministic methods yielded similar results to the median of the probabilistic burn area histograms. However, time delays much longer than the median crossing time were required to achieve this. Overestimation of burn areas using the median crossing time is likely due to the existence of multiple or continuous crossing locations compared to the few discrete crossings in the probabilistic implementation. Despite this, the deterministic methods presented here will be useful to emulate probabilistic methods and could be used in fire simulators to improve predictions involving disruptions.

Keywords: *Wildfire, modelling, firebreak, disruption*

Evaluating the terminal-velocity assumption in simulations of long-range inert ember transport

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Abstract: Ember transport and subsequent spot-fire development is an important mechanism of fire propagation, particularly in extreme conditions, and particularly in the eucalypt forests of Australia. Early modelling of ember transport used a combination of analytical and experimental work with appropriate simplifying assumptions. One of these simplifying assumptions is the so-called terminal-velocity assumption, in which embers are assumed to fall at all times at their terminal velocities with respect to the wind field. With the advent of high-speed computers, more elaborate sets of equations of motion can be solved numerically to model ember transport, and the terminal-velocity assumption has become less important. However, this adds computational cost and the assumption is sometimes still used.

Thurston et al. (2017) used the terminal-velocity assumption to study long-range ember transport in turbulent plumes using a large eddy simulation (LES) model. However, Koo et al. (2012) have modelled surface fire using a high-resolution coupled atmosphere-fire model and showed that simulations of short-range ember transport using the terminal velocity assumption underestimated ember travel distances substantially when compared with simulations in which the assumption was not made.

In this preliminary study the validity of the terminal-velocity assumption was examined in the context of the long-range transport of embers in turbulent plumes. The Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) was used in LES mode to simulate a plume in a turbulent boundary layer. Using the resulting wind field, the transport of embers was modelled under various assumptions, and the results were compared. The effects of combustion were not considered. It was found that if a constant terminal velocity was assumed, then the use of the terminal-velocity assumption overestimated ember travel distances compared with simulations in which the assumption was not made. This effect was attributed partly to variations in atmospheric density, and partly to the fact that embers have momentum, and do not respond instantly to changes in the incident wind field.

Keywords: *Ember transport, firebrands, spot fires, terminal-velocity assumption, turbulent plumes*

Fireline geometry and rate of spread in the output of a coupled atmosphere-fire model

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Abstract: Most current operational fire-spread models use an empirical or semi-empirical one-dimensional rate of spread model. These may perform well in some circumstances but they cannot reproduce dynamic fire behaviour, which may involve rapid changes in fire characteristics with little or no change in ambient conditions. Better models, such as coupled atmosphere-fire models, can reproduce such behaviour, but with current technology they are too computationally expensive for operational use, and researchers are looking for computationally cheap ways to improve the results of simple operational models. A number of studies have canvassed a possible relationship between the rate of spread of a fire and the curvature of its front. For example, a simple curvature-based model of spread rate is able to qualitatively reproduce experimental results on junction fires (in which two firelines merge at an oblique angle), and introducing curvature dependence into a simple model of wind-driven fire spread improves the agreement between model results and landscape-scale experimental grass fires. In a previous study, using a coupled atmosphere-fire model to simulate junction fires, we found no relationship between local fireline curvature and instantaneous rate of spread. In this study we look for such a relationship at larger spatial scales (i.e. in a mean sense); again, no relationship between average curvature and rate of spread is found in the model output. We extend this work by making coupled atmosphere-fire simulations of ignitions along circular arcs of equal radius but varying angular length. In such cases, the meaning of the notion of average curvature is transparent. We do not find a relationship between curvature and rate of spread, but a clear relationship is seen between rate of spread and the angular length of the arc of ignition.

Keywords: *Fire-spread models, coupled atmosphere-fire models, fireline curvature, dynamic fire behaviour*

Experimental and Modeling studies on the downslope fire spread

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Abstract: Terrain slope is always considered as an important factor affecting the wildland fire behavior and has been extensively investigated at laboratory and field scales. In many fire spread models, like those used in the McArthur Forest Fire Danger Rating Systems and the Canadian Forest Fire Behavior Prediction System, slope is regarded as separate multiplicative functions to the wind. However, these models are mainly dedicated to upslope fire or headfire. The models for the downslope backfire are scarce or so simple that the prediction of downslope fire spread rate is of low priority.

The rate of spread (ROS) of downslope fire, observed experimentally in literature, firstly decreases and then increases with the increasing of the downslope angle. The first decrease of ROS is considered due to the decreasing radiation from the flame to the surface of fuel bed, because the flame leans more backward as the slope increases. However, the second increase of ROS is hard to explain and there are two hypotheses. One hypothesis states that as the flame tilts closer to the burned area, the effective thickness of flame increases, enhancing its emissivity and inducing a ROS increase. The other states that the radiation from combustion zone dominated the downslope fire spread and caused the second increase of ROS. The mechanism dominated ROS of downslope fire has not reached a consensus.

In this study, the downslope fire behavior was investigated and the radiation from flame and combustion zone was analyzed. The experiments were carried out in fuel beds of dead Pinus pinaster needles (with a density of 583 kg/m^3) with the slopes of -30°, -20°, -10° (downslope), 0° and 10° (upslope). The fuel load was 1.2 kg/m^2 (dry basis) and the average moisture content of fuel was 12.1%. The shape of combustion interface was reconstructed from the measurements of the temperature histories of a vertical line of five thermocouples, spaced 2 cm apart, with the first one located 2 cm above the base of the fuel bed. Flame base thickness was measured by the temperature profiles of the thermocouples on the top surface of the fuel bed, which was used to calculate the flame emissivity by an empirical formula. It was found that the measured combustion interface was always fallen behind the flame front, which is different from the assumption of Dupuy's model. In this work, a physical model, considering the radiation from the flame and combustion zone, was proposed. The predicted ROS agreed well with the experimental data. The calculated temperature curves and heat flux contributions of four different sources revealed that the flame radiation still dominated the downslope fire spread and the combustion zone radiation also played an important role in the near flame area and could not be neglected.

Keywords: *Downslope fire spread, combustion interface shape, dynamic fire behavior, forest fire behavior modelling*

Assessing SWAT model's sensitivity to fire related changes

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Abstract: Wildfire may affect the hydrological cycle of forested water catchments, both in terms of quantity and quality of the stream water. Two major reasons for this are the effect that wildfire has on surface vegetation and soil organic carbon content. A reduction in surface vegetation effects catchment evapotranspiration, and increases erosion and runoff. Another important but less studied fire effect is the reduction of soil organic carbon content. The soil surface and organic layer are important sources of nutrients and help maintain soil structure, and any reduction can make soil more easily eroded, change infiltration rates and water holding capacity.

While there are many empirical studies that show wildfire impacts on surface vegetation and soil organic carbon, the relative impacts that each of these has on stream water quantity and quality is less clear. Therefore, in this study we propose to use the SWAT (soil and water assessment tool) hydrological model to assess the individual and combined effects of each on stream water quantity and quality.

The case study is the 2002/2003 wildfires around Sydney, New South Wales. Five catchments were used to calibrate the SWAT model with 10 years' pre-fire water quantity and quality data and simulations were then performed for 10 years' post-fire period under four scenarios (i) change in soil carbon, (ii) change in surface vegetation, (iii) change in both, and (iv) no change. The fire severity of these burnt catchments were calculated based on the difference between pre-fire and post-fire Landsat images. The land cover of these catchments were modified according to fire severity to predict the effect of changes in surface vegetation. To investigate the effect of fire on soil carbon, 27 soil samples were collected from 7 prescribed burnt sites in NSW. The control (unburnt) sites were adjacent (within 50 metres) to the burnt plots. Particle size fractions and soil organic carbon were measured on the samples. In addition, the burn severities of these sites were calculated based on Landsat images using the same method as for the water catchments. A regression model was then used to predict the change in soil organic carbon based on the unburnt carbon content and fire severity (adjusted $r^2 = 0.54$). This model was applied to create soil carbon maps for the study catchments based on observed fire severity. The predicted carbon maps were used to run SWAT in the post-fire period. The modelled discharge and water quality data (total suspended soil, total nitrate and total phosphate) output from the four scenarios were then compared with each other and with observed post-fire discharge and water quality observations.

Keywords: *Wildfire, water quality, SWAT, soil carbon, burn severity*

Incorporating environmental uncertainty in fire spread modelling

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Abstract: Bushfire simulators provide fire managers with a means of estimating the likely progression of a fire across a landscape. However, the accuracy of bushfire simulators is confounded by the various forms of uncertainty or variability that are found in the data that informs the simulation. Indeed, given the sensitivity of fire spread models to environmental factors such as wind speed and direction, variability in environmental inputs can result in large differences between the simulated and actual progression of a bushfire. To address these issues recent efforts have been directed at incorporating environmental uncertainty through ensemble fire spread modelling approaches. The approaches currently being explored employ a deterministic fire spread model, which is run multiple time using inputs drawn from a probability distribution that represents the variability in the data. While this approach does provide more information on the range of different fire spread scenarios that may arise, there are doubts about whether such an approach provides a faithful representation of the way environmental variability affects fire spread.

In this paper we consider an alternate approach to incorporating environmental uncertainty in fire spread models. In particular, we consider the problem in terms of stochastic calculus, which incorporates stochasticity in the environmental variables in an intrinsic way. In this initial preliminary work we couple a deterministic fire spread model with simple stochastic differential equations for wind speed and direction, which are considered as state variables.

The results arising from the stochastic model are compared with those arising from a deterministic ensemble approach, in which the variability in wind speed and direction are chosen randomly at each time step of a deterministic model run. In this approach the wind speed and direction are not considered as state variables, but are treated extrinsically as random input variables.

Both approaches were implemented 5000 times to develop an overall picture of the distribution of fire propagation scenarios accommodated by each method. It was found that the stochastic approach resulted in a broader range of possible fire propagation scenarios compared to the ensemble approach. In particular, the stochastic approach indicated that the region impacted by fire with a 99% likelihood extended to 18.2% further downwind than what would be expected using the ensemble approach.

The findings of this study indicate that the way environmental uncertainty is incorporated in fire propagation models can make a considerable difference to their ensuing predictions. This has ramifications for the development of probabilistic approaches to fire impact and risk assessment; in particular it suggests that current approaches may underestimate the likely propagation of a bushfire.

Keywords: *Stochastic calculus, fire spread, bushfire, environmental uncertainty, deterministic process*

Toward a stochastic precipitation generator conditioned on ENSO phase for eastern Australia

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Abstract: Stochastic generation of the required daily precipitation data offers an attractive alternative to the use of observed historical records. Stochastic precipitation generators are typically built on the statistical structure of historical data and thus can produce synthetic daily rainfall series with statistical characteristics similar to those of observed series. Parameters of precipitation generator have been typically estimated using all historical daily data for a given period. This approach, however, fails to capture signals in the precipitation process associated with an El Niño-Southern Oscillation (ENSO) phenomenon. ENSO signals have long been known to influence the precipitation in eastern Australia with high rainfall in a cold (La Niña) phase and low rainfall in a hot (El Niño) phase. Here, models for daily rainfall occurrence and intensity conditioned on each ENSO phase were developed to acknowledge ENSO signals in the precipitation process of eastern Australia. The developed models can be used to construct a stochastic precipitation generator for eastern Australia.

We parameterised first-order two-state Markov chains for occurrence process and gamma distributions for intensity process in each month, using recorded data of all historical years (primary models) or recorded data for years of each ENSO phase (conditional models). The Akaike information criterion (AIC) was used to select the "best" occurrence and intensity models among a range of parameterisation schemes for 3 typical locations in eastern Australia, an important agricultural region with a clear ENSO precipitation signal in July – December. Relative performance of the conditional models compared to the primary models was demonstrated by graphic diagnostics of lengths of dry spells for occurrence process and daily precipitation amounts for intensity process.

AIC values of conditional precipitation models (occurrence, intensity, or both) were significantly smaller than those of primary models in all of 18 location-month combinations, indicating superior performance of the conditional models. Graphic diagnostics showed that conditional occurrence models successfully captured differences in the number and persistence of dry days (dry spell) among ENSO phases. Similarly, conditional intensity models noticeably improved the agreements between theoretical and empirical distributions of daily rainfall amounts. Precipitation generators based on the conditional precipitation models can be linked to other process models (e.g. crop model) to derive realistic assessments of the likely consequences of ENSO-related variability of agricultural production in eastern Australia. Conditional stochastic precipitation generators, therefore, can be useful tools to translate ENSO forecasts into likely regional impacts on sectors of interest.

Keywords: *Precipitation models, Markov chain, weather generators, ENSO, climate variability, Australia*

Future Heatwaves in NSW from the NARCliM ensemble

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Abstract: NARCliM (NSW/ACT Regional Climate Modelling project) is a regional climate modeling project for the Australian area. It provides a comprehensive dynamically downscaled climate dataset for the CORDEX-AustralAsia region at 50km resolution, with a finer 10km resolution across South-East Australia. 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 WRFv3.3 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 South-East Australia and were chosen based on performance and independence. These three RCMs are simulating three different periods: 1990-2009, 2020-2040 and 2060-2080. Four different GCMs (MIROC-medres 3.2, ECHAM5, CGCM 3.1 and CSIRO mk3.0) from CMIP3 provide initial and boundary conditions for the WRF simulations. These GCMs were chosen through a process that considered model performance, independence and diversity in projected future changes. This GCM-RCM matrix gives an ensemble of 12 simulations for each period.

Heatwaves are here defined using the Excess Heat Factor metric. Its characteristics, including duration, frequency and intensity, are examined. Compared to observations, the NARCliM ensemble displays a good ability to simulate heatwaves across NSW with almost all present-day biases being non-significant. By 2070, robust increases in heatwave frequency, duration and peak amplitudes are found across NSW and the ACT. Western NSW is projected to have the most significant increases in peak amplitude. Most of NSW is projected to experience about 20 more heatwave-days a year by 2070 compared to the present. In many locations this is more than a doubling of the current number of heatwave days.

Keywords: *NARCliM, Regional climate downscaling, heatwaves*

EXTENDED ABSTRACT ONLY

Towards CORDEX 2

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Abstract: COordinated Regional climate Downscaling EXperiment (CORDEX) is an initiative 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 Coupled Model Intercomparison Project (CMIP) program. It is anticipated that the CORDEX dataset will provide a link to the impacts and adaptation community through its better resolution 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 RCM simulations performed using the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim re-analysis (Uppala et al., 2008) as "perfect boundary conditions". The climate projection framework within CORDEX is based on CMIP5. CORDEX will focuses on the GCM experiments using emission scenarios known as RCP4.5 and RCP8.5 which represent a mid and a high-level emission scenarios. A number of groups have performed simulations for the CORDEX-AustralAsia domain, with a dozen now available through the Earth System Grid Federation. This ensemble will continue to grow over the next couple of years.

The next phase of CORDEX is currently being planned and will include a similar downscaling experiment for CMIP6 GCMs. CORDEX2 will include an increase in resolution (to ~20km) as well as ensemble size with the establishment of a core set of simulations to be performed for all domains. As well as the future projections CORDEX will also 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 mechanism through which CORDEX will attempt to address these issues.

Keywords: *CORDEX, regional climate downscaling, Australasia*

Opt-out rather than opt-in: the case for using all available climate change projections of regional rainfall

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Abstract: Climate projections are tools for looking at potential future climate change that draw on climate modelling as a primary input. However, model have biases, the uncertainties about future change are not fully understood, and model ensembles are typically not systematic (but are rather "ensembles of opportunity"). For examining projections to regional rainfall in Australia, we can draw on global climate model (GCM) simulations under the CMIP structure as well as various *ad hoc* downscaling studies of those GCMs using dynamical regional climate models (RCMs) or statistical models. Dynamical and statistical downscaling are not available for all GCMs and all emissions scenarios. Each of these inputs has value and produces an estimate of forced climate change, but the collection of model runs put together isn't independent or a systematic sample of uncertainty. Therefore, the collected model runs can't be used in a truly quantitative way, such as for producing a probability distribution function (PDF) of projected change. Given this context, how should climate projections be used and which model simulations should we use as input?

Planning for future climate change amid uncertainties and using imperfect inputs means that the 'predict then act' framework where the simulations are treated as a 'prediction machine' is not appropriate. A robust decision-making framework can be more useful, where modelling is used as 'scenario generators' that inform but not dictate decisions between different options. Decisions can be made that are robust, or as robust as possible, to all potential future change. This framework doesn't rely on the information being perfect and unchanging, it avoids vulnerability to over-confidence in projections, and takes the onus off projections to provide a single 'best' answer. To this end, the climate modelling needs to provide physically plausible cases of possible change, including a plausible 'best' case and 'worst' case (where best and worse are defined by the question at hand). Generating climate scenarios doesn't require the inputs to be a statistical sample of uncertainty; it is more important to cover the full uncertainty space than to get a statistically balanced PDF. The 'best' or 'worst' case of change could come from any model set.

This framework suggests that all suitable projections should be considered. If there is a demonstrable reason that a model simulation is physically implausible or otherwise unsuitable, then it should be rejected. If the coarser resolution of GCMs can be shown to have affected the regional rainfall projection, then the GCM can be discounted, but coarse resolution shouldn't be used *a priori* as a reason to reject models. In this approach, selecting a small subset of 'best' models within all suitable models becomes less relevant, the multi-model mean becomes even less of a focus, and ensemble statistics such as PDFs or percentiles are less appropriate. Here we discuss these issues in terms of Australian rainfall change, with examples from Victoria and New South Wales drawing on various projections from GCMs, RCMs and statistical downscaling (Grose et al. 2015; Ekström et al. 2016). We show that, unless and until sub-sets of models can be demonstrated to be unsuitable, then considering all models provides a more robust set of future scenarios than using subsets of information in isolation. We propose that keeping all simulations unless there is a basis to reject them, which could be described as 'opting out rather than opting in', reduces the chances of mal-adaptation to climate change through overconfidence in a narrow range of projections.

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Keywords: *Climate, projections, uncertainty*

Communicating near term climate variability and change to users of climate projections

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Abstract: Future climate variability and change, along with the associated impacts, are more directly pertinent and tangible to many people at the near-term timeframe (e.g. to 2030) than the longer term (e.g. to 2100). The near term is also more relevant to many planning horizons and practical decisions about climate risk and resilience than the longer term. This timeframe is the domain of near-term or decadal climate prediction, however we can still derive useful insights from climate projections if they are interpreted in the appropriate way and combined with other information. Climate projections are an estimate of the climate change driven by external forcings (such as enhanced greenhouse gas concentrations), independent of internal variability. In a signal to noise framework, the forced climate change is the ‘signal’ and the climate variability is the ‘noise’. The signal to noise ratio is higher at longer timeframes, larger spatial scales and for variables such as temperature and sea level, and is lower at short timescales, regional scales and for variables such as rainfall. For 2030, the signal may be prominent in some cases, but swamped by variability in others.

Here I look at some methods for identifying and communicating climate variability and change appropriate to the 2030 timeframe using climate projections. I look at case studies of Australian temperature, and regional rainfall change, including the case of a strong rainfall signal (south west Western Australian winter rainfall) as well as weaker rainfall signals. The methods use an estimate of the change signal from climate projections using global climate model simulations, and the estimate of climate variability (the noise) draws on model simulations supplemented by additional statistical modelling based on historical observations. This extra modelling is used to more fully sample the possible combinations of change and variability at the regional scale on this short time scale. The results are used to characterise the probability distribution function of climate variables at 2030, to show the limits to change and illustrate plausible time series of the climate variables between now and 2030.

The outputs are used to synthesise and communicate issues of climate variability and change to users of climate projections, and to help them understand the relative strength of the signal and noise in different cases. The outputs are also used to help users have appropriate expectations about climate projections and to pre-empt misconceptions such as a warming climate means it gets warmer year-on-year, or that a drying climate means that every year is dry. This work also provides some context and motivation for efforts to understand and predict climate variability at decadal timescales.

Keywords: *Climate change, variability, communication*

Projected changes in frequency of suitable snowmaking conditions for the Australian Alps

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Abstract: Observations have shown a clear increase in maximum and minimum temperature, and a decrease in rainfall and snow for the Australian Alps. Available future snow projections from different projects also demonstrate decreases in snow cover, snow depth and snow season in the future. In order to adapt to declining natural snow cover, snow making is playing an increasing role to sustain the ski industry.

The viability of conventional snowmaking is determined by the frequency of wet-bulb temperatures suitable for making snow. In this study, we used outputs of 12 historical and future Regional Climate Model (RCM) simulations (each with three time periods: 1990-2009, 2020-2039, and 2060-2079) from the NSW/ACT Regional Climate Modelling (NARCliM) project to investigate changes in frequency of suitable snowmaking condition for the Australia Alps. The number of hours suitable for snowmaking was calculated (based on threshold temperatures, such as -2 ^{o}C) for a historic period (1990-2009) and two future periods (2020-2039 and 2060-2079) for each of the 12 simulations. These time periods were compared to investigate if the frequency of suitable snowmaking changes into the future.

The results show that there is a substantial decrease in the frequency of suitable snowmaking conditions for the Australian Alps, with some areas showing larger decreases than others. The major differences between the projections are associated with the driving GCMs, suggesting that the large scale circulation plays a dominant role in the variation of snowmaking conditions.

Keywords: *Wet bulb temperature, snowmaking, Australian Alps, NARCliM, ensemble mean*

Weather@Home-ANZ simulations for the Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI) project

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Abstract: The Paris Agreement of December 2015 committed signatories to `Holding the increase in the global average temperature to well below 2ºC above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5ºC above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change'. But there has been relatively little study of the differences in climate, climate extremes and impacts between these levels of global warming.

The HAPPI project includes large model ensembles for each of 1.5°C and 2°C global warming, so that we can investigate and quantify some of the potential benefits of limiting global warming to relatively low levels. The Weather@Home-ANZ regional simulations provide a very large ensemble of high-resolution atmosphere-only simulations at stationary climates of 1.5°C and 2°C global warming. Results are compared with the smaller ensemble of global coupled-climate models run for transient emissions scenarios through the 1.5°C and 2°C levels. In this presentation we will outline the contribution we are making to the effort to understand the benefits of limiting global warming to 1.5ºC through our regional model simulations.

We will discuss some analyses we have done comparing temperature and precipitation extremes between the 1.5ºC and 2ºC scenarios in conjunction with investigating changes in associated mechanisms. This will include analysis of changes in local and daily-scale extremes which utilise the fine-scale of our model simulations in comparison to global model runs. We will present analyses of changes in heat and rainfall extremes at 1.5ºC and 2ºC global warming in major cities including Melbourne, Sydney and Auckland. We also investigate how events similar to recent extremes, such as the record hot Australian summer of 2012/2013, would change in frequency and magnitude with 1.5ºC or 2ºC of global warming.

The analysis based on these Weather@Home-ANZ HAPPI simulations will extend our understanding of the climate changes and extremes, especially on the local-scale, that we would expect at 1.5°C and 2°C global warming. It is the only project of its kind, to date, over a southern hemisphere region. It is hoped that this work will contribute to the special report of the Intergovernmental Panel on Climate Change on 1.5ºC following the Paris Agreement.

Keywords: *Climate change, 1.5ºC, 2ºC, Weather@Home, Paris Agreement*

EXTENDED ABSTRACT ONLY

Making waves: using wavelet transforms in a multi-site downscaling model

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Abstract: Hydroclimatic variables obtained from General Circulation Models (GCMs) cannot be directly used for catchment scale climate change risk assessment because of their limited ability to represent local variability. In addition to this, GCMs generally do not reproduce sustained anomalies of rainfall and are therefore not suitable for predicting meteorological and hydrological extremes. To address this problem, a multi-site stochastic downscaling model has been constructed using filtered predictors to ensure accurate representation of sustained hydrological extremes. In a pre- processing step, wavelet transforms are used to enhance the important frequency bands of climate variables and allow sustained rainfall anomalies to be correctly represented. The proposed approach of including filtered climate variables in downscaling has not been examined in this way previously and it provides new insights to improve the representation of drought and wet extremes in the downscaled rainfall.

The downscaling model is a two-stage model includes Modified Markov Model (MMM) and kernel density estimator (KDE) for modelling rainfall occurrence and amount respectively. The model is calibrated for the historical period of 1971-2000, using daily rainfall over the Gwydir catchment in New South Wales, Australia and National Center for Environmental Prediction (NCEP) reanalysis data at the grid points over the catchment. The downscaled rainfall simulations driven by the atmospheric variables from GCM over the historical period are used for model validation.

The model shows reasonable performance in reproducing the rainfall variability and its persistence characteristics for the historical period. Result shows that low frequency i.e. interannual and interdecadal variability of downscaled rainfall is greatly improved when filtered climate variables are used as predictor compared to the corresponding raw climate variables. This suggests that the model has potential for skillful quantification of future drought and wet anomalies at catchment scale where GCM performance is limited.

Keywords: *Downscaling, climate change, drought, wavelets*

High resolution regional climate model simulations available through the ACECRC Climate Futures team: What we have and how they can be used

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Abstract: The Climate Futures for Tasmania Project began in 2007 and has developed into the Climate Futures team within the Antarctic Climate and Ecosystems Cooperative Research Centre. The original project produced a data archive of dynamically downscaled simulations from 6 CMIP3 global climate models, for both the A2 and B1 emissions scenarios using CSIRO's Conformal Cubic Atmospheric Model (CCAM) over Tasmania. The highest resolution outputs were of 14 km spatial resolution with 6 hrly temporal resolution. This has recently grown to include a further 6 CMIP5 global climate models dynamically downscaled simulations over South-East Australia and Tasmania at 1-hourly temporal resolution. This new set of simulations has a range of spatial resolutions (depending on the domain): 50 km spatial resolution over the Australasian region; 10 km spatial resolution over South East Australia (133.95E to 154.05E and -44.05N to -27.95N, which is approximately Baird Bay in the west to the East Coast, and from the Gold Coast in the North to the southern tip of Tasmania); and 5 km targeting the Australian Alpine Region, but including almost all of Victoria.

This data archive has been used by numerous projects in the fields of ecological research, natural disaster management, local government land-use planning, water management, power generation and to provide agriculture with estimates of the future. We will provide a description of the gridded data products available for use now through the ACECRC Climate Futures team and a general description of how to access them. We will provide examples of how these data have been used in the past and describe the archiving paradigm we have found to be the most effective when planning to revisit or query an archive numerous times for various different purposes.

This presentation aims to introduce the research community to this data archive; describe the archiving method selected and demonstrate the advantages of this approach; and provide example use cases.

Keywords: *Regional Climate Model outputs, archive management, Conformal Cubic Atmospheric Model (CCAM), climate futures*

Modelling hydrological changes in coastal catchments of New South Wales under future climate change

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Abstract: The aim of the present study was to assess the impacts of climate change on surface water runoff and groundwater recharge along coastal catchments of New South Wales (NSW). Surface flow and groundwater recharge projections can assist decisions on adaptation options for managing water resources, water quality and waterway health issues that affect the ecosystem services that our state's waterways provide. Adaptation options, for example could be to apply more water sensitive approaches (e.g. stormwater harvesting, sewer mining) to urban development in (southern NSW) catchments where projections indicate there will be more water available as surface runoff in both near-future (2020-2039) and far-future (2060-2079) projections.

We used the NARCliM (NSW / ACT Regional Climate Modelling) ensemble of climate projections for south-east Australia. This ensemble is designed to provide robust projections that span the range of likely future changes in climate (Evans et al., 2014). NARCliM projections over three climate epochs were used as inputs to a water balance model, PERFECT (Littleboy et al., 1992). The three epochs consisted of a baseline 1990-2009, near-future 2020-2039 and far-future 2060-2079 scenarios. PERFECT is a daily time-step, one dimensional model that predicts surface runoff, infiltration, soil evaporation, transpiration, profile drainage and groundwater recharge. We specifically modelled changes to surface flow and groundwater recharge using the 10km resolution for climatic data available from NARCliM and finer resolution spatial data available for land use, foliage cover and soils across the coastal catchments of NSW.

Raster format spatial data, maps and graphs from this modelling form part of the NSW Climate Impact Profile to assess projected biophysical changes across the State. Maps show central estimates or arithmetic means of near and 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.

Using a multi-model ensemble approach, the results of the near and future climate scenarios where compared with baseline 1990-2009 epoch to provide changes in surface runoff and groundwater recharge. The mean annual recharge averaged over the coastal catchments for near-future (2020-2039) scenario shows less recharge across much of the coast. Spatially, considerably less recharge is likely in areas along the higher parts of the Great Dividing Range (Canberra, Tamworth). For some areas along the coastal fringes (Eden to Batemans Bay, Sydney to Byron Bay), a slight increase in recharge is shown but these increases are relatively small. In the far future, recharge is expected to slightly increase across most parts of the coastal regions. Coastal fringes from Port Macquarie to Bryon Bay show a much higher increase. Some areas along the Great Dividing Range are likely to experience less recharge to groundwater. The largest impact spatially is the dramatic reduction in recharge in alpine areas.

Across much of the coastal regions, surface runoff is projected to increase slightly in both the near and far future. Largest increases are evident in the far future, in the regions from Newcastle, Port Macquarie to Byron Bay. Largest reductions in surface runoff are projected in higher ranges towards the south of the state near Canberra, and areas of the Great Dividing Range near Tamworth.

Keywords: *Climate change, hydrology modelling, soil water balance, PERFECT, NARCliM*

Using high resolution remote sensing data to investigate ecohydrology thresholds along a precipitation gradient

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Abstract: Anthropogenic disturbance can lead to changes in the physical and biological characteristics of ecosystems, such as a disruption of the spatial structure of vegetation and increases in landscape hydrologic connectivity, erosion and water losses. Arid and semiarid landscapes are particularly sensitive to climatic or anthropogenic disturbances. Remote sensing techniques have proven to be very useful for documenting changes in ecosystems structure and patterns across landscapes. In fact, remote sensing using satellite imagery can provide the information required to assess changes in ecological conditions over a region, including the effect of disturbances that result in changes in landscape functionality (e.g. Rainfall Use Efficiency, RUE) leading to degradation. Previous work in arid and semiarid regions suggests that ecosystem function tends to display critical degradation thresholds, beyond which rehabilitation efforts are difficult and expensive. This threshold behaviour is linked to coevolving eco-hydrologic processes induced by anthropogenic disturbances, such as the removal of vegetation by grazing and harvesting activities.

In this study, we explore the impact of vegetation disturbances (mostly due to grazing pressure) on ecosystem functionality and connectivity along a precipitation gradient (270 mm to 490 mm annual average rainfall) using a combination of remote sensing observations and Digital Elevation Model (DEM) data. Four study sites were carefully selected in the Mulga landscape in the Northern Territory and Mulga landscapes bioregion (New South Wales, Queensland). These study sites display similar vegetation characteristics and good quality rainfall information. In each study site at least 7 plots (1×1 KM^2) with varying degrees of vegetation disturbance were selected. Rainfall-Use Efficiency was computed based on the relationship between Normalized Difference Vegetation Index (MODIS NDVI 2001-2013) and precipitation as a proxy for vegetation response to rainfall. Vegetation patterns and the percent of fractional cover were obtained from high-resolution remote sensing images (QuickBird, IKONOS, and Pleiades). A multispectral classification was performed using standard supervised classification technique to generate vegetation binary maps. The binary vegetation maps and the DEM data were used to compute flowlength. Mean Flowlength was calculated for each plot as an integrative indicator of landscape hydrologic connectivity. Trends for several sites along the precipitation gradient show that there is a highly nonlinear relationship between hydrological connectivity and fractional cover. Moreover, our results are in agreement with the presence of threshold behaviour following disturbance that substantially modify hydrologic connectivity and landscape functionality. Though this threshold behaviour is observed in all sites, the plots in areas with higher rainfall show evidence of higher resilience.

Keywords: *Remote sensing, landscape functionality, hydrologic connectivity, rainfall gradient*

A review of the current trends in the application of Commercial Microwave Links for hydrology

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Abstract: Earth observations systems are evolving rapidly, and while always in search for improved accuracy and higher spatio-temporal resolutions, the current trend is also for more affordable sensing opportunities, which include the use of signals from secondary instruments to inform upon hydrological processes. In particular, the use of Commercial Microwave Links (CML) to derive rainfall depth through signal attenuation over the path length has seen a growing interest over the last decade, initially in research settings, evolving towards real case applications: to produce countrywide rainfall products in The Netherlands and Israel, to derive rainfall estimates in developing countries with a lack of infrastructure such as weather radar and rain-gauges networks (Burkina Faso, Kenya), or to act as an integrated system for now-casting and warning for flashflooding (Nigeria). However, a number of issues still limit the capability of CML to be used more widely. These issues are currently being resolved combining data from different sources and bringing CML to a mature stage ready to be used more widely. In this study, we review the current state of knowledge, current benefits of the use of these "big data" to the wide discipline of hydrology, in terms of data fusion, assimilation and accuracy. We also discuss the potential role of future CML networks at higher frequencies for hydrological applications.

Keywords: *Attenuation, Commercial Microwave Links (CML), now-casting, rainfall depth*

Advances in Multi-Sensor Systems for In Situ Remote Sensing of Australian Forest Canopy Processes

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Abstract: Remote sensing has been the mainstay of much environmental research for many years. Data acquired from remote sensing systems deployed on spacecraft and aircraft have provided insight into environmental processes that are difficult or impossible to obtain otherwise. However, traditional remote sensing systems are expensive, highly specialised and may lack the ability to be moved or quickly deployed.

Fortunately, the cost of sensors like those used in existing remote sensing systems has decreased over time, and their availability and capability has increased. It is now possible to build and deploy ground-based remote sensing systems with capabilities similar to those on traditional platforms. In this context we define 'in situ remote sensing systems' to be within, above, or otherwise adjacent to the vegetation under study but not in direct contact with it. Such systems typically have a measurement range of a few tens of metres, can be deployed quickly and easily moved to new areas of study when required.

This paper describes the development of in situ remote sensing systems as has occurred in Australia. The paper also outlines some of the challenges that were met during development and use of several generations of in situ remote sensing systems and presents contemporary work being done for the next generation of systems that will further expand our scientific measurement capability.

Initial development of in situ remote sensing systems started in about 2003 with the deployment of the first single pixel multi-angle spectrometer at the CSIRO Tumbarumba field site in south-east New South Wales. Though this was a basic system, it provided much useful data, both in a scientific sense as well as providing information that would be useful in engineering the next generation of sensor systems. Early work in comparing acquired in situ data to satellite sensed data, and radiative modelling was complicated; difficulties included the effects of a non-homogenous forest canopy and the angular distribution of leaves.

In 2013 a much more sophisticated system capable of hyperspectral and thermal *imaging* was installed at the same site, and this system continues to provide detailed and calibrated spectral and thermal time series images of forest canopy dynamics. The ability to examine specific and more uniform regions of interest within the forest canopy is the real value of imaging systems, as opposed to single footprint area-averaged measurements. Because of the high spatial resolution of the acquired data, it is now possible to examine 'within-tree' variability as well as 'between-tree' variability. The system provides much data for scientific analysis, and points to some of the engineering and data handling issues that influence the way future systems are developed.

Building upon these earlier systems, the Australian National University has embarked on a project to build a 'state of the art' sensor system that will extend the range of observed wavelengths and be deployable on various platforms for either short-term or extended observation campaigns. This new system uses a variety of sensors that cover the visible, short- and long-wave infrared wavelengths. In the first instance, scientific applications will focus on in situ remote sensing at the ANU Forest Research Facility at the National Arboretum in Canberra.

Some important lessons have been learnt over the past 15 years. In situ remote sensing systems require careful design and engineering if they are to reach their full potential. Instrument calibration, handling the vast amount of acquired data and efficient data reduction are significant factors in the successful use of such systems. This contribution concludes with a speculative view of the future direction of science infrastructure in this field.

Keywords: *Hyperspectral, thermal, LIDAR, infrared, remote sensing, forest*

Rainfall estimates derived from a dense network of microwave links for the Melbourne area

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Abstract: Accurate and timely rainfall estimates are crucial to produce data for flood early warning systems, but also for various urban hydrological studies. Dense rain gauge networks combined with operational weather radars are widely used as reliable sources of temporal and spatial rainfall estimates. However, deploying such observation systems is costly. Consequently, most urban areas, especially in developing countries, are still inadequately equipped. Furthermore, rain gauges only provide discrete point observations, and radar rainfall products are prone to large uncertainties due to calibration, ground clutter and anomalous propagation. Dense networks of commercial microwave links provide untapped resources at an intermediate scale between point measurements from rain gauges and weather radar volume resolutions. Over the last ten years, the use of microwave signal attenuation between mobile phone towers has seen growing interest and several experiments conducted in various parts of the world (Europe, Africa and Asia) have demonstrated the usefulness of links to improve the accuracy of rainfall estimates. The major advantage of link-derived rainfall estimates is that they can provide path-integrated measurement of rainfall closer to the ground. Although the theoretical basis of this approach is well established, examples of real world applications in operational settings have been limited to a few regions and for a few range of frequencies. In this study, we have used a 30-day data set (4 rainfall events), using 68 microwave links with frequencies higher than 15 GHz from October & November 2016, to estimate rainfall in the Melbourne Central Business District. Received Signal Level (RSL) obtained from the microwave links are converted to path-average rainfall intensities after removing the baseline signal and also considering the attenuation due to wet antennas. Link-based rainfall depths are compared with rain gauges and weather radar measurements as shown in Figure 1. The resulting correlations differs for different links and reaches values of $R^2 = 0.85$ for the link-gauge measurement and $R^2 = 0.60$ for the link radar measurement. These promising results show the potential and feasibility of using commercial microwave link to derive rainfall depths, at an intermediate scale between traditional gauges and radar observations, for data assimilation or fusion to create improved rainfall products.

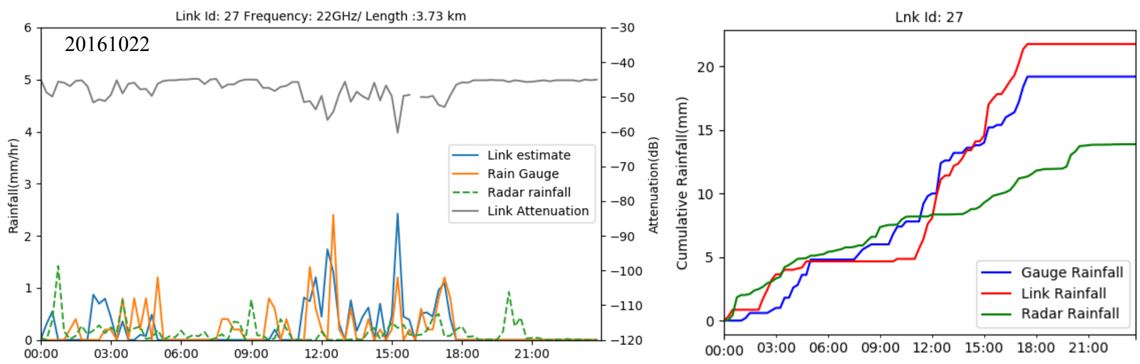

Figure 1. Comparison of link rainfall estimates with rain gauge and radar rainfall for 22nd Oct 2016.

Keywords: *Attenuation, Commercial microwave links (CML), precipitation, rainfall, Received Signal Level (RSL)*

A new optical/radiometer-based downscaling technique for L-band radiometer resolution enhancement

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Abstract: Passive microwave remote sensing at L-band is the most appropriate technique to monitor spatial and temporal soil moisture dynamics globally with 2- to 3-day repeat as it is least affected by vegetation, surface roughness and atmospheric effects. There are currently two operational L-band microwave satellites to monitor near-surface (top 5cm) soil moisture, but both have an approximately 40 km resolution; the Soil Moisture and Ocean Salinity (SMOS), an European Space Agency (ESA) satellite launched in 2009, and the Soil Moisture Active Passive (SMAP) satellite, an National Aeronautics and Space Administration (NASA) satellite launched in 2015. Because of the coarse spatial scale, the SMAP and SMOS radiometer observations do not meet the resolution requirements for soil moisture applications in hydrological forecasting and agricultural production. Consequently, an L-band radar was installed on the SMAP satellite to make combined L-band radar and radiometer observations, for accurate soil moisture mapping at 9 km resolution. However, the SMAP radar sensor ceased operation in July 2015, only 2.5 months after commissioning, rendering this approach no longer applicable. Therefore, alternative downscaling methodologies for the L-band radiometer have required development to produce the higher resolution soil moisture maps that are needed for applications. In this study, a new downscaling technique that combines optical and radiometer data was developed to enhance the resolution of the SMAP and SMOS brightness temperature to ~10 km, from which soil moisture content was then derived. This downscaling model uses the physical relationship between surface temperature and brightness temperature; brightness temperature is a function of the physical temperature of the emitting layer and its emissivity. This research assesses the performance of this new downscaling technique using the soil moisture and brightness temperature measurements collected during SMAPEx-4 field campaign, which was carried out during the Australian autumn (from the 1st to 22nd of May 2015) over the Yanco agricultural area. The Yanco area is representative of the typical landscape and climate of the south-east of Australia. During SMAPEx-4 airborne L-band soil moisture maps were collected by the Polarimetric L-band Multi-beam Radiometer (PLMR) at 1 km resolution concurrent with SMAP and SMOS overpasses, as well as intensive ground measurements of soil moisture. Analyses are based on calculation of Bias, Root Mean Square Error (RMSE), unbiased RMSE (ubRMSE), and Coefficient of determination (R^2) between time series of reference data and the downscaled soil moisture maps.

Keywords: *Soil moisture, Downscaling, Enhanced resolution, Combined optical/radiometer observations*

Buggy-based Soil Moisture Retrieval System

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Abstract: Measuring surface soil moisture in agriculture helps with a number of the most important decisions being made for each cropping rotation. However observations of soil moisture at a point scale are very sparse and observing networks are expensive to maintain. In the past decade soil moisture from remote sensing technology has been increasingly used in hydrological, agricultural, and ecological studies due to its spatial coverage, temporal continuity, and easiness of use. This study took advances of remote sensing techniques in soil moisture measurement and applied them in a different way to achieve the spatio-temporal outcomes required for agriculture. Therefore this study compared various remote sensing-based techniques for soil moisture retrieval, including i) brightness temperature from an L-band radiometer (ELBARA III), ii) GPS signal reflectivity provided by an GNSS-R sensor (LARGO), iii) from the conductivity measured by Electromegnatic-38 (EM38), and iv) from the conductivity measured by Electromagnetic Induction (EMI). In order to evaluate the sensitivity to soil moisture from these different observations, a buggy-based remote sensing platform was developed with those sensors mounted. It was then used for this purpose during the Fourth and Fifth Soil Moisture Active Passive Experiment (SMAPEx-4&-5) field campaigns in south-east Australia. ELBARA brightness temperatures were used to retrieve soil moisture through the *tau-omega* model, while GPS signals reflected over the soil related to the soil moisture using the measurement of the power of the interferent field, and the soil electrical conductivities from EMI or EM38 were converted to soil moisture using the cumulative sensitivity approach. The comparison of these soil moisture retrieval methods is unique as no such research has been conducted before using such a comprehensive experimental data set. These sensors each have a resolution of 1 to 2 m. The buggy was driven within a grassland site along transects that also had intensive ground soil moisture sampling. The observations from each sensor were compared firstly in terms of their patterns and spatial agreement. The soil moisture retrievals from each approach were then comprehensively assessed using point-based soil moisture measurements, and then inter-compared.

Keywords: *Soil moisture, brightness temperature, GPS reflectivity, conductivity*

Towards P-band Passive Microwave Sensing of Soil Moisture

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Abstract: Economic, social and environmental planning for a water-limited future requires a capacity to provide information on soil moisture content in a way that is useful for such applications. Of particular importance is meeting the world's growing demand for food production, which is limited primarily by the soil moisture available for germination and growth of crops and pasture. Timely soil moisture status and forecasts are therefore critical for (i) grain growers to make informed decisions on what and when to plant based on likely germination rates and crop yield, (ii) graziers to be proactive in their management of stocking rates based on likely pasture growth, and (iii) dairy and other high water use agriculture to undertake more efficient irrigation scheduling practices. A fundamental limitation is that current remote sensing technology can only provide moisture information on the top 5 cm layer of soil at most, being one-tenth to one-quarter of the wavelength (21 cm at L-band; 1.4 GHz) using the current SMAP and SMOS soil moisture dedicated missions of NASA and ESA. Consequently, we have developed an airborne passive microwave sensing capability at P-band to develop a new state-of-the-art satellite concept that will provide soil moisture data for the top 15 cm layer of soil using radiometer observations at P-band (40 cm; 750 MHz). Not only would P-band provide soil moisture information on a soil layer thickness that more closely relates to that affecting crop and pasture growth, but it is expected to produce greater spatial coverage with improved accuracy to that from L-band. This is because P-band should be less affected by surface roughness conditions and have a reduced attenuation by the overlaying vegetation. This paper will describe details of a small airborne field experiment, and present some early results of P-band passive microwave observations in comparison with L-band passive microwave and optical observations from initial trial flights.

Keywords: *Soil moisture, brightness temperature, P-band, airborne field experiment*

Disparities in cervical cancer incidence among older women and considerations for screening guideline changes

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Abstract: In US, black women have higher incidence rates, are more likely to be diagnosed at a higher stage, and are more likely to die from cervical cancer than white women. Identifying at-risk groups and trends in incidence is a crucial step in determining the impact of prevention efforts and improving prevention strategies. Our study explores racial, geographic and age-related disparities in cervical cancer incidence and screening.

Surveillance, Epidemiology, and End Results (SEER) 18 Program data were used to calculate incidence rates of cervical cancer from 2000-2012 for four groups: US14-Non-Hispanic White (NHW), US14-Non-Hispanic Black (NHB), South-NHW, and South-NHB, where the South included registries from Georgia and Louisiana. Alabama tumor registry data from 2009-2013 were used to calculate incidence for NHB and NHW women.

Our data demonstrate a decrease in overall cervical cancer incidence rates from 9.6/100,000 in 2000 to 7.4/100,000 in 2012. However, the incidence rates were higher for NHB compared to NHW in the US and in the South. Regional disparity in incidence rates was shown: Age-adjusted incidence rates increased with age for NHB but decreased for NHW after age 50. Age-specific analysis revealed cervical cancer incidence rates for South-NHB compared to US14-NHW were higher as age increases (1.59 times: age 50-64, 2.09 times: age 65-74, 3.88 times: age 75 and older). A similar trend was observed among Alabamians, with 4.07 times higher incidence in NHB age 70-74.

Our results are consistent with previous data showing overall decreasing cervical cancer incidence over time with persistently higher incidence rates in NHB. These racial disparities in incidence rates were most pronounced for older women in the South. Available data have not shown a difference in compliance with cervical cancer screening that would contribute to these differences, and current cervical cancer screening guidelines recommend cessation of Pap and HPV testing after age 65. While the guidelines do not recommend routine cervical cancer screening after age 65, more investigation and policy change may be desirable to determine whether screening should continue for black women over age 65, or if they should discontinue screening.

Keywords: *Cervical cancer, SEER, tumor registry, screening*

Method Comparison for Interrater Reliability of an Image Processing Technique in Epilepsy Subjects

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Abstract: The value of ictal SPECT in the pre-surgical evaluation of epilepsy patients is well established. SISCOM (Subtraction Ictal SPECT Co-registered to MRI) and ISAS (Ictal-Interictal Subtraction Analysis by Statistical Parametric Mapping (SPM)) are two widely evaluated ictal-SPECT processing techniques which have been shown to enhance the interpretability of raw ictal-interictal SPECT image pairs. We sought to apply three strategies of method comparison for the inter-rater reliability of the ISAS technique to simple visual analysis in terms of study localization and overall conclusiveness of this localization. We focus on the Ictal SPECT analysis with SPM (ISAS), since it was observed at the time of this study to be more robust in regard to yield of positive studies and readability.

Our study population consisted of 34 males and 33 females with a mixture of temporal lobe and extra temporal localization. Subjects were identified through medical record review at the UAB (University of Alabama at Birmingham) Epilepsy Center. Patients undergoing inpatient video-EEG monitoring as part of their pre-surgical epilepsy evaluation were intravenously injected with 20 to 40 mCi of the cerebral blood flow tracer Tc-99m hexamethylpropyleneamine-oxime at the first clinical sign of seizure onset. Injected patients were stabilized and scans were acquired within 1 to 3 hours of injection in all cases. As a second radiotracer injection and scan was performed interictally, after a minimum 24 hour EEG confirmed seizure free period. Each scan was performed on a Picker Prism 3000XP (Picker International, Bedford, OH) triple-head gamma camera equipped with low-energy, high-resolution collimators yielding an image resolution of approximately 7 mm full width at half maximum as described in detail previously in Knowlton (2004). Consecutive patients undergoing video-EEG evaluation for their refractory partial epilepsy were included if they had ictal and interictal SPECT scan data, surgically confirmed focal epilepsy, and post-operative follow up of 1 year or more. Since this was a retrospective study, no consent was required. ISAS scans were obtained from 67 consecutive patients as part of their epilepsy pre-surgical evaluation. A panel of 3 blinded experienced reviewers from different institutions evaluated each patient's SPECT data. All scans of the ISAS processing type were evaluated as a group in separate sittings. Each scan was presented in a 16 axial slice (4x4) configuration, and was evaluated based on 1) location of the SPECT abnormality, and 2) the overall localizing value of the study. Localization was identified as the area of most significant activity and its position within one of 30 pre specified brain regions of interest. The localizing value of each study was judged as degree of localization on a continuous Likert scale from 1 to 4 localizing (1- definitely localizing to 4- not localizing) which the authors have simulated from the original data. Methods of agreement were calculated among the 3 reviewers. The methods used were linear with density ellipse visualization, the Bland Altman procedure, and a Bayesian version of the linear methodology. A statistical comparison of the methods was done for reviewers 1 vs. 3 and reviewers 2 vs. 3.

Keywords: *Bayesian, Bland Altman, density ellipse, method comparison*

Effective removal of air pollutions by the electrical discharge

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Abstract: Environmental pollution is one of the greatest man-made problems of our time and happens when the air includes harmful gases, dust or fumes in harmful amounts. It can be serious to human and animals' health or can generate damage to plants and materials.

Air pollutants are strongly associated with diseases, such as, respiratory infections, adverse effect on nervous system and so on. Some forms of air pollution create photochemical smog, greenhouse effect, climate change, ozone layer depletion and acid rain.

Non-thermal plasma is an attractive option for the pollution control due to their high efficiency for producing radicals and oxidizing agents for strong energetic chemical reactions without heating the bulk of the gas. Even if electrons are short lived at atmospheric pressure and collide infrequently with the pollutant molecules, they make many collisions with the dominant background gas molecules and produce radicals through electron-impact dissociation and ionization.

Removal of NOx with a dielectric barrier discharge reactor is conducted in this study. The surface discharges are applied to the reactors and the removal efficiency is compared with different electrode shapes and frequencies. The applied voltage, current, frequency and the electrode shape are applied as main variables.

In general, it has been known that the removal efficiency is decided by the applied power, which is calculated by multiplication of the applied voltage and current. However, it is known in this study that the removal efficiency significantly depends on the composition ratio of the applied voltage and current even though the experimental conditions are not changed even with the same applied power. It means that the removal effectiveness should be considered by the applied voltage and current separately.

The objectives of this study are

- To understand the effects of different electrical and reactor structure parameters on the pollutant removal efficiency
- To optimize reactor parameters to achieve the highest removal efficiency
- To present the technologically feasible and economically attractive discharge system to improve the efficiency

From the experimental and statistical analysis, we found the following results.

- The applied power should be divided into the voltage and current to investigate their individual effects on NOx removal even though the discharge power can be to express the energy efficiency.
- Right decision of the value of the applied voltage, current and frequency is important to maximize the removal efficiency.
- The discharge current is the most important factor to control the removal rate regardless of different types of the reactor.
- The frequency is not the direct function to control the removal rate but is the indirect function to control the removal rate through the effect on the applied voltage and current.

Keywords: *Non-thermal plasma, electrical discharge, air pollution*

The Australian Breast Cancer Screening Simulation (ABACUS)

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Abstract: Breast cancer mortality has been significantly reduced since the introduction of breast cancer screening programs such as the BreastScreen Australia program. This is achieved through biennial mammography (breast x-ray) of asymptomatic women leading to earlier detection – and treatment – of breast disease. Along with mortality reduction, however, screening programs generate cases of overdiagnosis (diagnosis and treatment of cancers that would not otherwise become symptomatic within a woman's lifetime) and investigations of episodes of false positive screening tests. Meanwhile, there is growing interest in tailoring screening strategies according to risk, as well as extending some type of screening to younger women and addressing known issues of poorer screening test accuracy for women with higher mammographic breast density (a measure of radio-dense tissue in mammograms). Screening strategies of interest include personalised screening intervals and selective use of alternative imaging modalities such as ultrasound or MRI.

We aim to evaluate the benefits, costs, and harms of different breast cancer screening strategies in Australia through the development and application of an extensive clinical and health economics population model focused on breast cancer screening, diagnosis, and treatment. To that purpose, we have developed the Australian Breast Cancer screening Simulation (ABACUS), a continuous-time, multi-cohort micro-simulation model. This model has been developed under a collaboration between the University of Melbourne, Monash University, the University of New South Wales, the University of Queensland, the University of Sydney, and the Royal Women's Hospital/Royal Melbourne Hospital.

An extension of an earlier model of a single cohort of screening participants with breast cancer, the current ABACUS model simulates the whole female population eligible for screening, including women with and without cancer. ABACUS simulates the life history of individual subjects, and includes different cancer types and cancer growth models (e.g. invasive cancers and ductal carcinoma in situ). The health economics component includes financial and quality of life measures associated with screening, diagnosis and treatment.

ABACUS is a data-driven model, calibrated and validated against information from a range of sources such as cancer registries, BreastScreen service data, Medicare claims, hospitals data and cohort studies. For all screening strategies explored we evaluate the expected impact on cancer detection rates, recall rates, false positive rates, overdiagnosis, quality-adjusted life years and incremental cost-effectiveness ratios.

Our goal is to use the best available evidence to identify strategies that optimise health benefits while minimising costs and harms. We aim to address current key policy questions to assist decision-makers, and then operate as an ongoing resource to help evaluate new and emerging screening test technologies and to re-evaluate the role screening as the effectiveness of prevention and treatment improves.

In this presentation we will describe the model structure and present some examples of how the model is being used to examine particular health policy questions.

Keywords: *Breast cancer screening, mammography, health systems*

Optimising the service of emergency department in a hospital

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Abstract: Nowadays, the rapidly increasing healthcare cost has become a serious problem because of inefficient usage of medical resources. The Emergency Department (ED) plays a vital role in the hospital system and has critical effects on the overall efficiency in a hospital. The ED deals with patient's arrival, triage, physician assessment, imaging and laboratory studies, treatment planning, nursing procedures, decisions to discharge or admit access to inpatient beds and physicians. These activities generally occur in a sequential manner and the delayed activities of the patient flow can cause bottlenecking and reduce the service level. Optimising the service of the ED is challenging because the arrival times of patients are dynamic and their expected treatment times are volatile. This paper develops a new ED optimisation model using stochastic mathematical programming approach under limited budget and resource capacity. The objectives of the proposed model are for increasing the system efficiency, serving more patients in specific time, or providing the same quality of the service with the use of less medical resources. A numerical investigation is presented and demonstrates that high-quality solutions are obtainable for industry-scale applications in a reasonable time. Computational experiments have been conducted using CPLEX and ExtendSim to solve the ED-Stochastic Optimisation Mixed Integer Programming model and ED-Simulation model sequentially. Real data for Royal Brisbane and Women's Hospital (RBWH) is used in this paper to validate the proposed solution approach.

Keywords: *Emergency department, healthcare optimisation, mathematical programming, simulation*

Automated Wrist Pulse diagnosis of Pancreatitis via Autoregressive Discriminant models

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Abstract: Wrist pulse signals, commonly used in traditional oriental medicine, reflects important pathological changes in the body which may be utilized to characterize an individual's health status. Being one of the 'four pillars of clinical evaluation', pulse diagnosis plays a critical role in traditional Chinese medicine (TCM), informing the physician about crucial information such as the state of balance of the body and the state of internal organs. The traditional method of examination is via palpation in which the practitioner uses fingertips to feel the radial pulse of the patient. It is thus highly subjective and depends heavily on the practitioner's experience. With the aid of technology, modern measurements of pulse signal can be taken in a more objective manner. However, there is a lack of tools and standards for analysing and interpreting these computerized pulse signals. In particular, diagnosis of inflammation is challenging and current clinical approaches via other methods (such as blood test, urine test, and X-ray) are time-consuming and often inaccurate.

This paper proposes an automated procedure for distinguishing patients with inflammation using their digitized wrist pulse signals, based on a two-stage time-series classification technique involving autoregressive models followed by common classification methods such as Linear Discriminant Analysis (AR-LDA) and Logistic regression (AR-LR). We focus on one of the major inflammation symptoms – pancreatitis, a condition that can potentially lead to fatal complications in severe cases. We work with wrist pulse signals captured from patients using a Doppler ultrasonic blood analyser. After pre-processing, features derived from fitted AR models were fed to train a LDA and a LR classifier. The effectiveness of our approach is demonstrated using a subset of the wrist pulse database from Chen et al. (2009), consisting of 100 healthy persons and 54 Pancreatitis patients. To evaluate the classification performance, the models are trained on 50% of the data while the remaining observations were reserved for testing. An overall accuracy of 83% and 91% was achieved from AR-LR and AR-LDA respectively, both with an area under curve of 0.88. AR-LDA achieved a higher sensitivity (81%) and specificity (96%) with a positive predictive value of 92%. These results showed that AR-LDA is a promising approach for classifying time-series wrist pulse signals. It provides a relatively low-cost, easy-to-implement, and reliable tool for modern computerized wrist pulse diagnosis.

Keywords: *Classification, time series, autoregressive model, linear discriminant analysis, logistic regression*

Contribution of smoking during pregnancy to the occurrence of adverse perinatal outcomes

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Abstract: Population Attributable Fractions (PAF) provide estimates of the proportion of linked disease or injury outcomes that could potentially be prevented if exposure to a specific causal risk factor (such as overweight/obesity, smoking or alcohol use) was eliminated or reduced to its theoretical minimum. In this study, based on the Australian Capital Territory (ACT) Maternal and Perinatal Data Collection, population-level effects of smoking on adverse perinatal outcomes were evaluated using a PAF approach. Multilevel regression modelling methods were used to estimate relative risks, adjusting for mother age, previous parity, Aboriginal and Torres Strait Islander status, and Socio-Economic Indexes for Areas (SEIFA). Marginal predictions under different maternal smoking scenarios were made to estimate the number of adverse perinatal outcomes that can be potentially prevented by intervention strategies.

The analysis includes 35,066 singleton births in ACT hospitals between 2009 and 2015 with mother's smoking information available. Pregnant women of young age, identified as Aboriginal and Torres Strait Islander peoples, and from areas with low SEIFA scores were more likely to smoke during pregnancy. Smoking during pregnancy was associated with increased risk of preterm birth (PTB), small for gestational age (SGA), and admission to Special Care Nursery or Neonatal Intensive Care Unit (SCN/NICU). For this study population, the PAFs of maternal smoking were estimated to be 5.2% for PTB, 7.9% for SGA infants, and 4.1% for admission to SCN/NICU. Predictions under different scenarios demonstrated that large number of adverse perinatal outcomes could be prevented by the reduction in smoking rate during pregnancy. This modelling study provided a quantitative estimation of the benefit effect of intervention strategies to improve perinatal health.

Keywords: *Smoking during pregnancy, perinatal outcomes, preterm birth, multilevel modelling*

Gender-specific Study of Cloninger's TCI in relationship to Symptoms of Psychological Distress

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Abstract: The link between personality and depression has long been investigated by researchers and clinicians alike. Insights into the association between personality and depression may contribute to the effective treatment of depression (Turner et al., 2003; Hudson et al., 2015). We examine gender-specific associations between the Cloninger's temperament and character traits (TCI) (Cloninger, 2015; Cloninger et al., 1994) and symp-toms of psychological distress (SCL) (Derogatis, 1983). The four TCI are: novelty seeking, harm avoidance, reward dependence and persistence and the three character traits are self-directedness, cooperativeness and self-transcendence. We investigate gender differences and examine the relationships between the seven TCI and three SCL (depression, anxiety and psychoticism) by using the Beh-Davy non-iterative (BDNI) approach for paramater estimation for the ordinal log-linear model (Beh and Davy, 1999; Zafar et al., 2016). The data analysed comes the NZ Christchurch Psychotherapy of Depression Study (Joyce et al., 2002), first analysed by Turner et al. (2003). We focus on the relationships between the seven TCI and three SCL, and examine changes in direction, and/or difference in magnitude, of the association between the TCI and SCL for males and females. We also analyse doubly ordered $2 \times 2 \times 2$ tables for the association between baseline TCI and Δ SCL (where Δ SCL = post SCL - pre SCL) by gender.

In general, post-treatment, novelty seeking was found to be gender-specific for depression and psychoticism; higher novelty seeking in males was associated with less distress as compared to females who exhibit higher distress with elevated novelty seeking. Therefore, males exhibited more improvement in distress symptoms of depression and psychoticism with elevated novelty seeking, post-treatment in contrast to females. Higher levels of harm avoidance were found to be associated with higher distress in both genders, both pre and post-treatment for all SCLs. Pre-treatment, reward dependence is gender-specific for anxiety; for females, higher reward dependence is related to lower anxiety depicting more improvement in distress, as compared to males who exhibit less improvement. Pre-treatment, persistence is gender-specific for depression. Our findings reveal that for females persistence swaps signs from negative to positive for depression post-treatment. Moreover, for males, persistence changes direction from positive to negative for depression depicting more improvement with elevated persistence. Pre-treatment, cooperativeness is gender-specific for psychoticism as males show more improvement in psychoticism with higher cooperativeness; cooperativeness being a positive trait for males for this SCL. Post-treatment, cooperativeness is gender-specific also for anxiety; with females exhibit-ing reduced improvement in anxiety with higher cooperativeness. Self-transcendence is also gender-specific for anxiety and psychoticism; males being more likely to have higher distress with higher self-transcendence, as compared to females. In summary, for doubly ordered $2 \times 2 \times 2$ tables (baseline TCI by Δ SCL by gender), self-directedness is gender-specific for depression, where increased baseline self-directedness is related to less depression for females. These results agree, in part, with the findings of Zafar et al. (2015) who analysed doubly ordered two-way tables (TCI by SCL) to investigate gender differences. Our findings also give further insights to significant gender interactions for reward dependence, persistence, self-directedness, cooperative-ness and self-transcendence found by Hudson et al. (2017) and support, in part, the findings of Spittlehouse et al. (2010) and Martinottia et al. (2008). These results support new momentum for the creation of gender and patient-specific drugs for the treatment of depression.

Keywords: *Ordinal log-linear models, temperament and character traits, symptom checklist, non-iterative estimation methods, contingency tables*

Size does matter: a simulation study of hospital size and operational efficiency

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Abstract: Hospitals come in different sizes and operate under different conditions. The problem confronting healthcare planners for a long time has been: *How does hospital efficiency relate to its size*? Due to their complex organisational structures, it would be unrealistic, costly and risky for hospitals to conduct field experiments to test the effects of any major organisational change. Mathematical modelling and computer simulations offer an effective and risk-free approach to assess likely impacts of any proposed change.

This study replicates and extends the "Hospital Event Simulation Model: Arrivals to Discharge (HESMAD)" (Ben-Tovim et al., 2016), originally built for the Flinders Medical Centre (SA), to use simulation to model patient flow in another hospital – Nambour on the Sunshine Coast, Queensland. The study will take advantage of the unique opportunity – a natural experiment occurring in the Sunshine Coast, where Nambour hospital has been downsized by more than 50% – for subsequent validation of the HESMAD model, and simulation modelling in general, with data collected before and after the downsizing.

The simulations investigate hospital efficiency by examining the following organisational metrics: (1) length of stay (LOS) by diagnosis-related group (DRG); (2) total hospital utilisation; (3) emergency department (ED) utilisation, where utilisation is synonymous with occupancy rate, that is, number of occupied beds divided by total number of available beds.

The model is used to run experiments on different hospital sizes, especially that of Nambour Hospital before its restructure – 100%, then 50% and 200% of the original size. The base scenario is set to be a reduction/increase in arrivals in line with hospital size while preserving the proportion of ambulance and walk-in (self-presented) patients and the pre-downsizing mix of DRGs. Alternative scenarios tested also include changing the mix of ambulance/walk-in arrivals, as well as DRGs, while maintaining the total rate of arrivals. Such scenarios are realistic because, while ambulance arrivals can be controlled and diverted to other hospitals, self-presentations are much more difficult to control.

Simulation results demonstrate that for the base scenario (proportional reduction) there is no change in average figures of hospital utilisation and LOS (both overall and for individual DRGs). However, there is a dramatic change in variability of the utilisation. A smaller-size hospital has a much greater dispersion in distributions and, consequently, a much higher propensity for becoming overcrowded.

Alternative scenarios (corresponding to disproportional reductions) can be considered as new and very different hospitals. Changing the proportion of ambulance and walk-in patients affects the DRG mix. As a result, the overall LOS, hospital occupancy and waiting times, all change considerably.

The main conclusions are: (1) Smaller size hospitals are operationally more risky; they are at a higher risk of overcrowding, while large hospitals have better ability to absorb spikes in arrivals. This may mean that provision of additional 'surge' capacity may be required when commissioning smaller facilities. (2) While deciding on the size of a hospital, attention should be given to the clinical function that the facility is to perform (i.e. the potential mix of DRGs) rather than just the size of a population that the hospital is serving.

Keywords: *Simulation, hospital size, length of stay (LOS), diagnosis-related group (DRG), efficiency, patient flow*

Dynamic Simulation Modelling to Inform Decision Making for Diabetes in Pregnancy in the Australian Capital Territory

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Abstract: Diabetes in pregnancy (DIP), including gestational and pre-existing type 1 and 2 diabetes, is increasing both in the ACT and Australia, challenging the capacity of diabetes services. The increase in DIP is directly associated with the increasing prevalence of risk factors including overweight, obesity, older maternal age and increasing numbers of women from high-risk ethnic groups. New screening guidelines recommend that women who are at high risk for developing DIP be screened in the first trimester of pregnancy. Consequently, these women are diagnosed with DIP earlier in their pregnancy and require services for a longer time. With increasing prevalence of risk factors, service providers report that women are more frequently presenting with a combination of risk factors resulting in more complex care needs.

The rising prevalence of DIP is having a significant impact on health service demand and resources requiring effective decision support tools to guide policy and program development. The Australian Prevention Partnership Centre in partnership with the Population Health Division, ACT Health, has brought together local, national and international researchers, clinicians and policy makers to collaboratively develop a dynamic simulation model for Diabetes in Pregnancy in the ACT. The participatory dynamic simulation modelling process provided opportunity for diverse stakeholders to explore policy and health service scenarios to prevent and manage DIP. The dynamic simulation model incorporated the complex and interrelated causal factors that contribute to the development of DIP as identified and mapped in participatory workshops and explored a range of intervention options and combinations, spanning the spectrum from clinical to population health interventions. The model drew on a range of evidence including systematic reviews, randomised control trials, health research, existing diabetes models, local population health surveys and administrative data. In addition, expert knowledge of the multidisciplinary team was used to estimate parameters and assumptions where there were evidence gaps. The resulting hybrid model incorporated system dynamics, agent based and discrete events modelling methods. Prevention of risk factors was prioritised in the model as small delays in the development of diabetes will have large implications for the longer-term burden of disease and costs to the health system. The model considered the short, intermediate, and long-term implications of the increasing prevalence of risk factors for DIP.

Keywords: *Participatory modelling, hybrid models, diabetes, pregnancy, health, decision support*

Evaluation of the Major Incident Medical Management and Support (MIMMS) System framework using multi-method modelling and simulation

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Abstract: In this research we outline the design, validation and initial results of a multimethod computational modelling and simulation framework for the evaluation of the effectiveness of medical response systems in prehospital major incident and mass casualty scenarios. We developed a multi-method (Agent Based coupled with Discrete Event) model utilising the previously validated ODD framework describing the design of multi-method computational models. The Major Incident Medical Management and Support (MIMMS) 3rd edition policy was analysed and submodels focussing on three primary areas of organisational and clinical work were constructed – triage, treatment and transport. The submodels were then implemented and merged utilising an iterative modelling cycle approach into the Anylogic™ modelling environment (Figure 1). The construction, basic test and evaluation and baseline testing of these merged hybrid models, in the context of incident site management in a prehospital setting, is reported here. The primary outcomes forming the basis of prehospital system performance and policy evaluation were mortality, morbidity and time to selected defined operational goals. An individual by individual casualty deterioration model was devised that simulated the physiological deterioration of casualties following a range of different wounding patterns consistent with major categories of injuries (airway, breathing, circulation, disability and musculoskeletal), and various severities. Wounding pattern types, mortality rates over time and parameters were obtained from consultation with subject matter experts, and the published literature. Three synthetic casualty populations describing collections of casualties corresponding with three common major incident types – a primarily blunt trauma event (bus crash), penetrating trauma event (lone shooter) and combination blunt and penetrating trauma event (improvised explosive device) were developed parametrised from injury epidemiology reported following historical major incidents. Multiple parameter variation and sensitivity experiments were conducted during the iterative calibration process. We found that outcomes varied considerably across the most common resource and policy setting scenarios, however some parameter settings had more profound effects on outcomes than others. These results suggest that a small set of medical management policy settings and resourcing scenarios have the most significant impact on predicted morbidity and mortality (Figure 2). These differences are outlined most conclusively through comparative survival analysis, supplemented by comparison of overall measures of performance. The potential future integration and extension of this model into more complex incident modelling environments is also described, including integration into geospatially enabled, 3D environments and also the potential incorporation of complex hazards such as HAZMAT, CBRNE and multievent incidents.

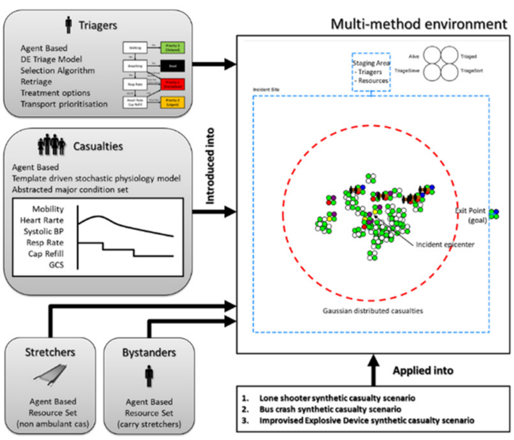

Figure 1. Multimethod Schema

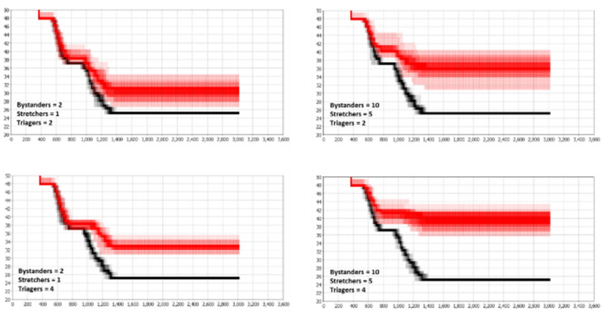

Figure 2. Parameter variation results. Black survival plots indicate survival without intervention. Red indicates survival in various scenarios as indicated. 20 repetitions per run.

Keywords: *Multi-method modelling, simulation, emergency management, major incidents, mass casualty*

Comparing de-congestion scenarios using a hospital event simulation model

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Abstract: The ever increasing demand for hospital services has resulted in more and more congestion episodes occurring in hospital emergency departments (ED). Congestions lead to serious problems such as delayed treatment, increased mortality, as well as stressed hospital staff. It is thus important to explore suitable solutions to manage congestions when they occur. This study seeks to identify effective ways to resolve the serious situation of congestion in a hospital by testing a range of de-congestion strategies using simulated scenarios. All scenarios were investigated through a sophisticated simulation model HESMAD (Hospital Event Simulation Model: Arrivals to Discharge) that captures the characteristics of patient flow based on an existing patient journey database from a large tertiary hospital in South Australia. Simulation models can demonstrate the changes and the impacts of different operational parameters within a complex hospital system before, during and after congestions. In this study, eight scenarios, suggested by senior hospital staff, were investigated using the simulation model, in addition to the base scenario where no intervention was applied. These scenarios include diverting ambulances, postponing elective patients, and discharging certain groups of patients earlier when congestions occur. Parameters such as the number of congestions over a one-year period, the duration of a congestion, and the 10 am hospital occupancy of each scenario were examined. Simulation of each scenario was replicated 20 times under the same conditions to obtain an average behaviour that would allow meaningful comparison of the results from different intervention scenarios. The results show that, for the scale of actions taken, hospital occupancy remained almost the same for all scenarios, while the duration of congestions and the frequency of their occurrence exhibited different levels of reduction. The scenario of temporarily diverting ambulances was most effective in reducing the number of congestion days (from 76.5 days in the base case to 44.2 days; a reduction of over 44%). However, other simulation scenarios, such as removing particularly long-staying patients and postponing the admission of elective patients may be preferable to diverting new emergency admissions when trying to reduce congestion duration and frequency. Although the aim was to shorten the duration of a congestion when it occurred, an important side benefit was observed for all interventions tested, that is, the number of congestion episodes in the long term (over one-year simulation period) was also reduced.

Keywords: *Hospital Event Simulation Model, Congestion Days, De-congestion Scenario Analysis*

Towards a systematic approach to resource optimization management in the healthcare domain

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Abstract: Increasing patient demand, constrained physical resources, and a rising cost of operations are imperative concerns in healthcare management which require improvements to the way medical services are provided to the public. The urgency of the problem in Ontario, Canada has forced the Provincial Government to put a plan in place to increase access and reduce wait times for major health services including cancer surgery, cardiac procedures, cataract surgery, hip and knee replacements, general surgery, paediatric surgery, and MRI and CT exams (Ontario, 2008). The main directives of the plan include four goals:

- significantly increase the number of procedures to reduce the backlog that has developed over the last decade;
- invest in new, more efficient, technology such as MRI machines and provide longer hours of their operation;
- standardize best practices for both medical and administrative functions to improve patient flow and efficiency; and
- collect and report accurate and up-to-date data on wait times to allow better decision making and increase accountability.

In addition, Ontario's health budget for 2017-18 will grow by $1.6 billion, aiming to reduce wait times and ease hospital overcrowding, including program funding for hospitals to be boosted by 3 per cent, or $518 million, as compared to the last year (Boyle, 2017). To achieve the targets, healthcare management at different levels of decision-making should plan effectively to reduce costs, maximize profit, and increase the quality of their services by undergoing a thorough investigation on resource planning, scheduling, and utilization. In this paper, we argue for a systematic approach to resource management in the healthcare domain, focusing on the problem of scheduling medical procedures at the departmental level on the basis of information technology and applicable optimization techniques. The approach is to follow a seven-step exercise itemized in point form:

- a thorough study of the flow of operations and procedures rendered by the healthcare provider;
- identification of all of the actors involved in the operations and management decisions to be made at each hierarchal level (i.e., strategic, tactical, and operational);
- determination of different patient types served by a given provider because their characteristics are important for the selection of optimization methods;
- deciding on the set of applicable performance indicators;
- selecting the most suitable for the task at hand scheduling variables and scheduling types (i.e., in block of resources, open scheduling, allocation or advanced scheduling);
- incorporating uncertainty characteristics of various actors and operations;
- on the basis of the above factors, selecting and applying optimization method(s) or a certain combination thereof, satisfying specific features of the problem at hand in the best way.

Operations of the Image Guided Therapy (IGT) Department of the Hospital for Sick Children ("SickKids"), Toronto, Canada have been taken as a sample object in the study. The IGT department provides valuable diagnostic and therapeutic data using procedures that involve different forms of anesthesia or sedation administered to the patients (Khaiter et al., 2015). The study demonstrated that none of the investigated optimization algorithms was able to minimize the IGT schedules with regard to all selected time-based performance criteria. Each algorithm generated schedules which are more efficient from the perspective of a single performance indicator, but not optimal for the others. It is reasonable to assume that specific features of the IGT department (i.e., multi-server environment and variable-length blocks) make the optimization of heir scheduling a complex non-trivial problem requiring a hybrid approach that combines several optimization techniques.

Keywords: *Healthcare domain, patient type, scheduling variable, performance indicators, optimization*

Design of Cognitive Support for Healthcare

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Abstract: Healthcare work is, to a considerable extent, cognitive. Subsequently, the analysis and the design of supporting technology must be sensitive to the cognitive and adaptive demands of the work and to the cognitive strategies employed by healthcare practitioners. Despite the vital role that cognition plays in healthcare work, current technocentric design approaches for healthcare technology do not explicitly account for it, failing to observe it during analysis and thereby missing opportunities to develop supports for it during design.

Here we describe significant cognitive challenges commonly encountered by staff in high-pressure healthcare settings and observe that the common flow chart analysis used by information technology professionals does not account for any of them. In addition, we describe several design concepts that address the cognitive demands of work. These differ markedly from the rule-based decision supports or procedural interventions preferred by information technology professionals.

We argue for a paradigm shift in the design of healthcare technology and situate our argument within the broader design strategy of functional workspace design. The term *workspace* is preferred to *interface* to emphasize that the worker must remain fully immersed in the work and should not be separated from it by the technology. The term *functional* emphasizes that all transactions, whether they be information access, cognition, or action, carry significant meaning in relation to the work. The aim of functional workspace design is to amplify and extend the human capability to know, perceive, decide, plan, act and collaborate, by integrating system functions with the cognitive processes they need to support. The focus is on the cognitive work with an emphasis on how we might employ technological functionality to support that work.

Keywords: *Healthcare technology, cognitive analysis, cognitive design, functional workspace design*

EXTENDED ABSTRACT ONLY

Optimising Open-Pit Mining Using Multi-Grid Search

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Abstract: Open pit mining requires complex and informed planning (see *Application of optimisation techniques in open pit mining* by Caccetta (2007)). The order in which specific areas of the pit are mined is dependent on many critical factors. We provide a multi-grid method to find a satisfactory mining sequence in a computationally efficient way, using multi thread processing.

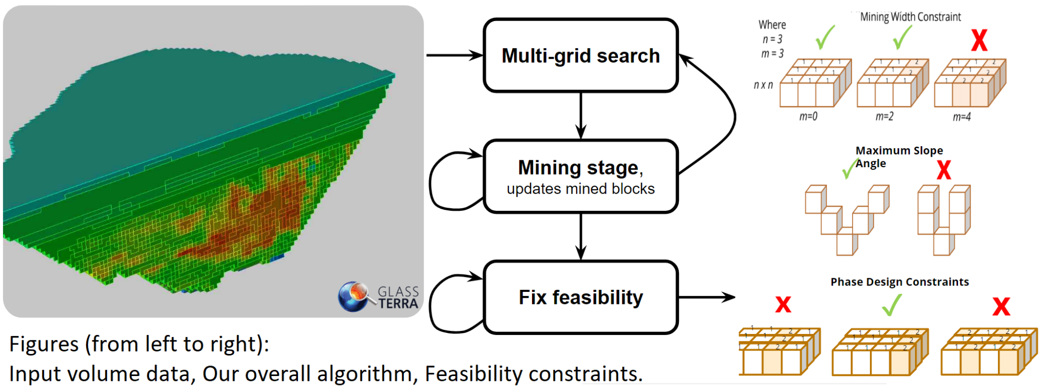
We won the $35K Unearthed BHP Phase-X challenge (*https://portal.unearthed.solutions/9-bhp-billiton-mar-2016*) for optimising open-pit mining phases, using realistic mineral grade distribution data, under many practical mining feasibility constraints such as: maximum mining rate, processing plant capacity, annual discount rate, mining width constraint, maximum slope angle, and connectivity constraints. Our algorithm can deal with over 100,000 3D blocks using a computation time of under 20 minutes. Due to problem complexity, with the need to optimise both the overall net present value (NPV) and the total computational time, we implemented a multi-grid method (see *An ... multigrid methods* by Wesseling (1992)) for open-pit mining planning sequence.

Our method has three components: multi-grid search, full-grid mining update, and fixing feasibility. For the multi-grid search and full-grid mining update, we assume the minable volume to be geometrically convex. Feasibility fixing is needed to account for non-convex minable volume, as certain areas is unmineable due to either man-made features, or natural obstacles.

To mine a certain block, we need to mine at least an inverted-cone due to the maximum slope angle precedence constraint. The effect of mining an inverted-cone has on NPV is computationally costly to calculate, therefore we used a multi-grid search (by mean down-sampling) to estimate the NPV of such cones. Then we scheduled the mining sequence in the full-grid resolution, starting with the cone with best NPV calculated in the last search. The mining sequence would terminate when no positive NPV cone is left, or a set limit is reached.

Since geometrical convexity is not generally true, we need to fix the feasibility of our mining plan, as non-convex minable volume often breaks the feasibility constraints near the edge of the volume. Moreover, fixing one feasibility constraint could violate another feasibility constraint, therefore we fix each feasibility constraint in an iterative loop until all feasibility constraints are meet.

Full scale methods, such as work done by Bienstock and Zuckerberg (Solving LP relaxations of large-scale precedence constrained problems (2010)) are efficient at finding a satisfactory scheduling solution for a deterministic problem with over 100,000 blocks with similar constraints. However, those methods typically search at the full-resolution scale, and therefore do not benefit from the computational efficiency of a multi-grid approach. A fast open-pit planning algorithm allows the testing of different future possibilities, such as changes in mineral price and block mineral content to obtain a suitable decision under uncertainties.



Figures (from left to right):
Input volume data, Our overall algorithm, Feasibility constraints.

Keywords: *Phase scheduling, constraint optimisation, open-pit mining, linear programming, multi-grid*

Resiliency in Pharmaceutical Supply Chains: Collaborative Sourcing under Supply Disruptions and Market Competition

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Abstract: Although outsourcing to Contract Manufacturing Organisations (CMOs) in cheaper locations is a cost-efficient strategy (specially to reduce the manufacturing and material costs) in Pharmaceutical industry, the inherent uncertainty of decentralization and the potential for supply chain disturbances are critical issues that needs to be considered at early design stages. This research studies a Pharmaceutical supply chain problem where two Pharma firms which compete on market share implement a hybrid strategy to source a common core product. The competing firms mainly receive the required units from an independent captive firm which is located in a cheaper location like China and is prone to a certain level of supply disruptions. At the same time, the competing firms can source from a perfectly reliable local/nearshore manufacturer at a higher unit price. Considering the fierce competition in Pharma industry and potential backdrops of disturbance factors, we examine how the recently proposed Pharma SC reconfiguration and recalibration strategies affect the companies' decision making? The main goal is to find the conditions under which the proposed strategy reduces the risk of disruptions, maximizes the individual members' profits, and reduces the negative effects of the competition.

In this research, we first investigate the efficiency benchmark models, by studying a centralized problem and a decentralized problem where there is only a wholesale price contract between the Pharma firms and the local supplier. Considering an insourcing offshore through captives setting, we propose a collaborative hybrid sourcing mechanism where the competing firms can jointly place their orders at the local manufacturer and get a better price, but must commit to always order a minimum quantity under the contract imposed by the local source. In this environment, we reconstruct the optimization problems and sequentially characterize the Pharma firms' pricing and the local manufacturer's contract policies taking the captive sources' disruption risk into account. This study sheds light on the effectiveness of contract-based mitigation strategies enabling Pharmaceutical companies to ensure responsive backup capacity under market competition and supply disruptions at their captive sources.

Keywords: *Pharmaceutical supply chain, collaborative sourcing, supply disruptions*

O2O pricing in dual-channel service supply chains with logistics cost and consumer location considerations

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Abstract: The fierce competitions in retailing industry have resulted in a rapid development in e-commerce systems and logistics services. Many suppliers are engaged in the online and offline market to expand their business, which leads to the online-to-offline mode (O2O) based on dual-channel services. The use of online channels escalates market demand by attracting consumers who purport to reduce the travel costs of getting product. However, the product logistics increases the costs of suppliers by making supplier responsible for the delivery. To optimize the revenue and cost of the O2O mode, pricing policy is a main strategy applied by the suppliers.

The optimal pricing decisions of the supply chain players are engaged in O2O with multi-channel framework, nonetheless major studies overlooked the effects of logistics operations on the revenue and cost of the supplier. The logistics cost is determined by the distance from consumer to supplier, which is various depending on the consumer locations. Additionally, supplier can make profit from the online delivery while no benefit from the travel of offline consumer.

This paper addresses the gap by analysing a supplier's strategic pricing decision in O2O considering the consumer locations and corresponding logistics costs. The individual consumer's logistics cost is ascertained as a travel cost depending on the distance from consumer to supplier. To capture the impacts of the supplier's pricing decisions on consumers' channel choice and expected demand we consider a price sensitive demand function and examine the supplier's optimal pricing policy. The results show that the delivery price determined by supplier is a key factor which affects consumers' choice for online channel and results in influencing supplier's profit. While the consumers' low unit travel cost can increase the supplier profit with providing only offline channel, applying O2O can raise the profit when the supplier employs a low-cost logistics system. Numerical experiments indicate that the consumer travel cost and supplier delivery price jointly affect the online and offline demand. Consumer and supplier can both benefit from the efficient logistics system, which saves consumer travel cost and increases the supplier profit of the delivery. This study sheds light on the effectiveness of inclusive pricing policies in O2O scenarios that improve the service providers' profitability by offering delivery for online consumers with certain distances.

Keywords: *Dual-channel supply chain, electronic commerce, pricing, logistics management, O2O*

Determining optimal intervention strategies for infectious disease control under limited budget

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Abstract: An important aspect of public health strategies is the ability to perform evidence-based mathematical analyses of epidemics, to modify and prioritise intervention strategies with limited available resources. Intervention strategies can be applied in combinations, with varying levels of coverage and hence expenditure for each intervention.

The current approach for deciding on intervention strategies in public health institutions is to undertake scenario analysis, modelling a variety of possible decisions to investigate their outcomes. The aim of this research is to augment these approaches by determining the optimal budget allocation among possible interventions using three separate modelling processes. First, we simulate the spatiotemporal disease transmission dynamics and subsequent impacts of intervention applications. Second, we calculate the associated cost of each intervention that is evaluated in the scenario analysis. Finally, we use optimisation techniques to allocate resources given the budgetary constraints.

In this work, we discuss an optimisation framework tailored to incorporating disease transmission dynamics. The framework discussed builds from the classic susceptible-infectious-removed compartmental model through to more realistic models of disease dynamics.

We analyse the problem by conducting an extensive experimental analysis demonstrating optimal and near-optimal solutions in a variety of potential scenarios. We compare the impact of different objective functions on a number of relevant epidemiological metrics. This comparison provides important insight in to the appropriateness of different objective functions. The key challenges in this work are the nonlinear dynamics, combined with budget allocations between spatial regions.

Keywords: *Epidemiology, infectious diseases, optimisation, budget allocation*

Discrete Time Stochastic Control for Blood Inventories

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Abstract: A robust and reliable supply of fresh blood is a key healthcare imperative for all nations. Centralised blood agencies are tasked with maintaining an adequate population of active donors to ensure that demands for transfusion can be met. Optimal management of blood inventories presents a challenge for both hospitals and centralised blood banks. Both demand for blood from patients and the supply of blood from donors are stochastic and blood itself is a perishable product with red blood cells (RBCs) having a shelf life of 42 days. Perishability encourages smaller order quantities when compared to a non-perishable product. However randomness in both supply and demand have the effect of encouraging larger order quantities. If too few RBCs are ordered a shortage occurs putting patient well-being at risk. If too many are ordered then RBCs that are not used prior to expiry are discarded creating an outdate event. In this case not only have the RBCs not been used, the donors that supplied the blood are unable to donate again until, like all donors, they have served a mandatory 84 day hiatus between donations. The supply chain is further complicated by, negative feedback loops and delivery delays which engender more volatility in the system than is explained by stochastic supply and demand alone. It is within these constraints that effective management of blood inventories requires the determination of an order quantity that minimises both shortages of blood and outdates. The National Blood Authority guidelines suggest that hospitals do this by managing to a desired inventory level based on the number of days stock on hand. The blood service has an Inventory Response Team that is tasked with an analogous objective.

In this talk it is shown how to formulate the problem of how much blood to order using discrete time stochastic control. The method derives the likely impact of a chosen order quantity on the future state of the blood inventory and uses this to find an amount that minimises the weighted sum of expected shortages and outdates. This is a discrete time, infinite state space problem. Since an analytical solution is not tractable, stochastic average approximation (SAA) is used to determine a numerical solution for the optimal order quantity. Results are compared to management of a blood inventory using the approach suggested in guidelines published by the National Blood Authority. Lastly it is shown how the robustness of the blood supply chain can be determined by using the approach to solve for the number of active donors needed to satisfy the demand for blood to meet a desired probability of adequacy.

Keywords: *Discrete time stochastic control, optimal order quantity, blood supply chain*

Blood Transshipment in a Network Hospitals

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Abstract: Managing inventories in the blood supply chain is highly challenging because of the restricted shelf life of blood units and uncertain nature of demand. Lateral transshipment is known as an effective strategy in supply chain management. Despite the importance of transshipment for perishable items, only a few studies have investigated it in the literature. In this study, we propose a proactive transshipment policy to control inventory in the blood supply chain. We consider a finite horizon multi-period inventory system with one main hospital connected to several smaller hospitals. The hospitals face non-negative stochastic demand with general distribution and fulfil it from their own blood inventory that is supplied from a central blood bank. In addition to receiving supplies from the central blood bank, the small hospitals - can transship blood to the main hospital to reduce outdates. We assume that demand fulfillment follows a first-in-first-out (FIFO) policy. We formulate the inventory management problem as an infinite-horizon dynamic program, where the objective is to determine an optimal ordering and transshipment policy that minimizes the total expected cost. The cost function is comprised of ordering cost, transshipment cost, inventory cost, shortage cost and outdate cost. Due to the curse of dimensionality in the state and action space, we use an approximate dynamic programming methodology to solve the problem, where we approximate the value function with a linear combination of basis functions using column generation. We evaluate the performance of our model with different distribution demand (uniform distribution and negative binomial distribution) through a numerical study.

Keywords: *Blood supply chain, transshipment, approximate dynamic programming*

A framework for optimal health worker allocation in under-resourced regions

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Abstract: There are severe health worker shortages globally, with under-resourced regions disproportionality impacted. For example, the estimated health worker shortage in 2011 for South Africa alone was over 80,000. The effectiveness of health systems is dependent on the availability and distribution of these workers across facilities. We propose a decision support framework for optimal health worker allocation, that takes into account geographic, social, and economic differences between facilities. We integrate multiple sources of publicly available data with facility-specific measures to estimate the relationship between staffing levels and facility performance. This statistical model is used in a multi-objective optimisation model to explore how the optimal allocation of health workers changes for different policy scenarios. We compare two different optimisation approaches, constraint programming and mixed integer linear programming. For the latter approach, we linearise multiple nonlinearities that come from the statistical model. The optimisation model allows for practical constraints regarding the movement of existing workers as well as allowing the user to trade-off between the two potentially competing objectives of overall patient treatment and equity between regions.

We use South Africa as a case study to demonstrate the effectiveness and flexibility of our framework with limited data availability. South Africa is an interesting case study given the historic maldistribution of workers, with approximately 44% of the population living in rural areas, but only 12% of the country's doctors working in rural healthcare facilities. The considered case study covers over 150 health care facilities of different types as well as four different types of health care workers. We discuss the key challenges posed due to challenges in under-resourced regions, the outcomes and insights identified by applying our framework, and limitations of our approach.

Keywords: *Human resource allocation, constraint programming, mixed integer programming*

The network maintenance problem

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Abstract: In this research, we describe an optimization problem motivated by the need to maintain infrastructure net-works over time. We consider infrastructure networks in which product is transported between distinct origin-destination pairs, and at the same time the infrastructure assets need to be maintained by resources moving in the network. In order to perform maintenance the assets have to be shut down from time to time thus reduc-ing the system capacity for those time periods. The objective is to maximize the total transported product by aligning the maintenance activities appropriately.

This problem combines flow maximization with maintenance scheduling capturing some important aspects of the motivating practical problem: (1) the interaction between utilization of network assets such as nodes and arcs and their maintenance demands, (2) the limited resources available to perform the maintenance, and (3) the time for moving the maintenance resources between different locations in the network. Depending on the application context, there are a number of natural ways to reflect these in a mathematical model, and this gives rise to a rich and challenging optimization problem which we call the network maintenance problem.

We formally introduce the problem, and present a mixed integer programming formulation. Next, we consider the case of a single commodity and a single maintenance resource when the network is a single path. We describe a polynomial time algorithm which, under some simplifying assumptions, solve the single path case to optimality. The problem becomes more challenging when the simplifying assumptions are dropped.

Keywords: *Flow maximization, maintenance scheduling, special cases, polynomial time algorithms*

Maintenance Scheduling in a Railway Corridor

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Abstract: Australia has a large operational heavy railway network which is approximately 33,355 route-kilometres. This network accounted for approximately 55 percent of all freight transport activity in Australia in the financial year 2013-14, almost 367 billion tonne-kilometres which was up 50 percent from 2011-12 (BITRE (2016)).

To provide a safe and reliable railway network to customers, an effective maintenance regime is a key requirement. Planned maintenance and asset renewal in capital intensive industries such as the railway industry, which has expensive infrastructure, is a common and effective maintenance practice. Infrastructure is of essential importance to maintain a reliable customer service. To prevent long unplanned interruptions in the service to customers, a proper maintenance and renewal program is required. The objective is to schedule planned maintenance and asset renewal jobs in such a way that their impact on the capacity that will be provided to customers is minimised while at the same time keeping the infrastructure in good working condition. A proper maintenance and renewal schedule limits the frequency with which disruptive emergency maintenance is needed.

We investigate a planned maintenance and asset renewal scheduling problem on a railway corridor with train traffic in both directions. Potential train journeys are represented by train paths, where a train path is specified by a sequence of (location,time)-pairs, and we distinguish between up- and down paths, depending on the direction of travel. Necessary maintenance and renewal activities, or work, are specified by a release time, a deadline, a processing time and a location. Scheduling work at a particular time has the consequence that the train paths passing through the corresponding location while the work is carried out have to be cancelled. An instance of the problem is given by a set of train paths and a set of work activities, and the task is to schedule all the work such that the total number of cancelled paths is minimised.

There is a vast literature on scheduling problems and on transportation network problems. However, the interaction of these problems in contexts such as the railway industry have not been studied thoroughly. Boland et al. (2014) study the problem of scheduling maintenance jobs in a network. Each maintenance job causes a loss in the capacity of network while it is being done. The objective is to minimize this loss or equivalently maximize the capacity over time horizon in such a way that all jobs are scheduled. They model the problem as a network flow problem over time. This problem and its variants are investigated in Boland et al. (2013), Boland et al. (2014), Boland et al. (2015), Boland et al. (2016) and Abed et al. (2017). Our work is different from the previous works. The main difference is that we model the capacity by train paths whereas in a network flow model over time the capacity is modelled approximately by flows over time.

The primary purpose of this study is to provide further insight into this problem, to characterize the structural properties of optimal solutions, and to use these properties to develop efficient combinatorial and integer programming based solution algorithms. We present theoretical and computational results on the performance of the developed solution approaches.

Keywords: *Maintenance scheduling, combinatorial optimization, integer programming, computational complexity*

Whey reverse logistics network design: a stochastic hierarchical facility location model

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Abstract: Whey reverse logistics has received a considerable attention due to the recent environmental legis-lation and competitive advantages. In this paper, we study a whey reverse logistics network design problem with stochastic demand, where demand is the amount of raw whey produced by a cheese maker that should be converted into a commercial product. We formulate this problem as a hierarchical facility location problem with two levels of facilities, namely collection centers and plants. Collection centers receive raw whey from cheese makers and convert it to concentrated whey. Then the concentrated whey is sent to plants for further processing. A plant can be established in a potential location if a collection center has already been established in that point. The objective is to determine which facilities to open and to allocate each demand point to the open facilities such that the total expected cost is minimized. The total cost is comprised of transportation cost and fixed cost of opening facilities. The problem with deterministic demand is formulated as a mixed integer linear program. We use this formulation to model the stochastic version of the problem as a two-stage stochastic program, where decisions are made at two sequential stages. At the first stage, we decide which facilities to open and at the second stage, after observing a realization of demands, we decide how to allocate each cheese maker to the open facilities. We use the sample average approximation method to estimate the expected value function. The resulting formulation can be solved using a standard linear solver. Results of a computational study on a set of randomly generated instances will be reported.

Keywords: *Whey reverse logistics, dairy industry, hierarchical facility location, stochastic programming*

The development of the sector risk profiling methodology for Australian civil aviation activity and its application to the small aeroplane transport sector

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Abstract: Sector Risk Profiling (SRP) is a methodology to develop a risk picture for a sector of civil aviation activity using ISO 31000:2009 *Risk Management: Principles and guidelines*. By engaging with sector stakeholders to consult and review all available information on the sector to develop the risk picture, optimal risk responses for risks of significance can be collectively identified and ownership assigned for implementing responses.

Although the SRP methodology is by large a qualitative approach, quantitative data analysis can be integrated into the SRP if relevant data is available. The SRP offers four advantages: (1) It is consultation driven by sector's subject matter experts; (2) It produces a sector risk register which includes all risk attributes such as causes, current controls, future treatments, ownerships, etc.; (3) It suggests an assurance mapping process which contains a gap analysis of the sector risk register and each sector entity's risk register; and (4) It introduces a new concept of the "living risk profile" by implementing and integrating the risk register into the sector entity's Safety Management System (SMS) and into the authority's safety surveillance program to responding to emerging risks.

The SRP process contains three phases. Phase 1 establishes the sector context to assist data collection and analysis. An industry workshop is conducted towards the end of Phase 1. The workshop participants include sector entities (operators), safety authority and other sector stakeholders providing infrastructure and support services. The key outputs from the workshop are: a set of sector objectives, SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis to identify the hazards and associated risks for the sector.

The principal task in Phase 2 is to develop a sector risk register based on the hazards and associated risks at the second workshop. During the workshop the participants engage in a critical assessment of hazards to develop risk statements, impacts from the risks, identify current risk controls and assess current risks using a risk matrix and the developed sector objectives. The information captured in the risk register include causes, impacts, existing controls, current likelihood, consequence and risk rating. When the current risk rating is outside the ALARP (As Low As Reasonably Practicable) limits, additional risk treatments are also identified with accountability assigned to owners best placed to treat the risk. The residual risk is assessed assuming treatments are in place. As part of the collaboration and engagement, the risk register is revised within the workshop participants.

Phase 3 consists of sector assurance mapping, including conducting a gap analysis between the sector risk register and each operator's risk register. This assurance mapping contributes to the authority's sector surveillance program, including the development of Safety Performance Indicators (SPIs) specifically for the sector. Phase 3 also integrates the sector risk register into sector operator's SMS and into the authority's sector surveillance program, hence, forms a living risk profiling process to evaluating the current risk controls and responding to changing operational environment and emerging risks.

The way forward in the 'SRP space' is to 'collaborate more' and 'engage more' with all stakeholders to increase understanding, promote safety improvement opportunities, and work on solutions together. This is underpinned by creating a culture that encourages open and honest communication, listening to others, showing respect and maintaining trust.

The SRP methodology will be demonstrated for a sector in air transport. However, SRP methodology is not limited to aviation, it can be applied to any industry sector.

Keywords: *Sector risk profile, safety regulation, risk management, risk assessment, risk analysis*

Modelling the supply chain of plantation forestry using the Transport Network Strategic Investment Tool (TraNSIT)

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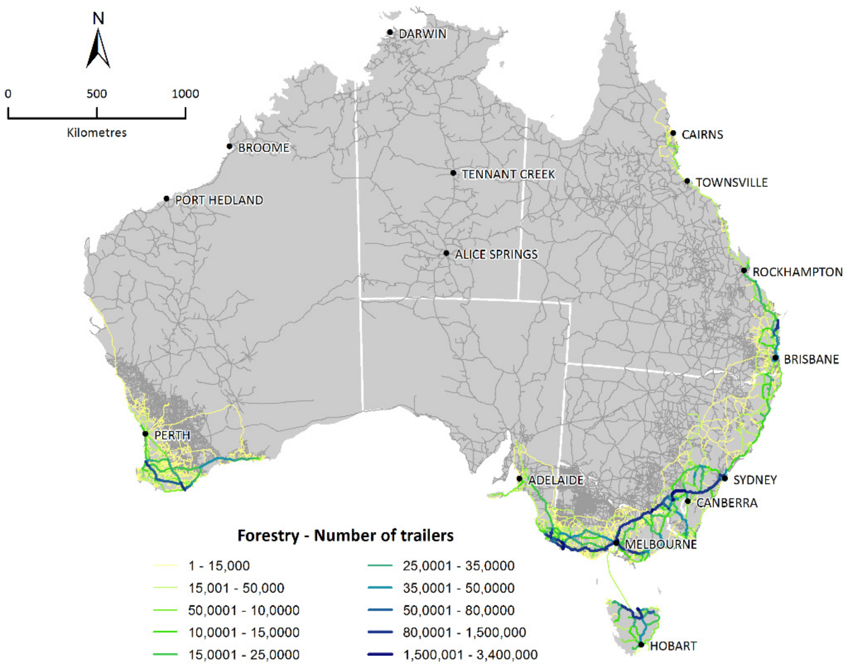
Abstract: In 2015-16 Australia's commercial plantation forestry covered an area of about 2 million ha and the volume of harvested timber logs was at a record level of around 29.5 million m^3. Transport infrastructure is essential to moving these large log volumes from forest plantations to the multitude of processing plants and export ports. While most highways and major roads are sealed, much of the sparse rural road network is unsealed and in poor condition. This substantially reduces average travel speeds and increase maintenance costs of heavy vehicles. To support a national strategic approach into infrastructure investments and to capture the transport implications of potential industry expansion, the Transport Strategic Network Investment Tool (TraNSIT) was adapted to plantation forestry. Current applications of TraNSIT cover over 95% of the transport volume of all agricultural products in Australia. Unlike other agricultural resource commodities, forestry is characterized by much longer harvest rotations as well as interim management cycles which includes the removal of some trees (thinning) so that remaining trees have more room to grow. The TraNSIT application presented here, models the yearly transport volumes of timber logs over a 25 year horizon covering the years 2016 to 2041. It includes long harvest rotations coupled with thinning stages. There were a total of 180,000 unique origin to destination paths included in the model (a path represents the route between two nodes of the supply chain, e.g. between a specific plantation and a saw mill). Along these transport pathways 28 million vehicle trips were modelled over 25 years (2016-2041). The timber transport volume over this period totaled to about 800 million m^3 resulting in a projected average log volume of 32 million m^3 yr^{-1}. The approximate total transport costs over the modelled period was estimated to be around \$23 billion. The figure below shows the resulting transport density on Australia's road network.



The findings of this analysis provide governments, the forest plantation industry and other stakeholders with a baseline of freight transport costs between Australian plantation forestry value chain enterprises. Along with TraNSIT comes the capacity to identify and evaluate scenarios (= changes to the baseline) for example potential road upgrades or regulatory changes and their impacts on costs, travel times and transport densities. This capacity will help to minimise transport costs and maximise long-term profitability.

Keywords: *Supply chain modelling, plantation forestry, Transit*

TraNSIT: Application to Australian agriculture

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Abstract: In Australia over 80 million tonnes of agricultural (including horticultural) output is moved between farms, storage, processors and to markets each year. These movements are characterised by long supply chains; distances between production, processing and markets are often thousands of kilometres, and rarely less than hundreds. To compete, farmers and producers require efficient transport options, which in turn, relies on uninterrupted transport infrastructure and an optimal mix of rail and heavy vehicles enabled by considered policy.

To provide a holistic view of transport logistics costs and benefits due to infrastructure investments and policy changes in agriculture supply chains in Australia, CSIRO developed the Transport Network Strategic Investment Tool (TraNSIT). TraNSIT was identified as the preferred tool to help in unlocking a more efficient agricultural transport system to meet the Australian Government's key objective of the Agricultural Competitiveness White Paper of building the infrastructure of the 21st century. Under this programme of work, TraNSIT was able to provide governments, industry, the farming community and other stakeholders with a baseline of freight transport costs between Australian agricultural value chain enterprises, along with a capacity to identify and evaluate a range of scenarios to minimise transport costs and maximise long-term profitability.

The extension of TraNSIT to broader Australian agricultural commodities was conducted with support, input and validation from over 80 organisations, agencies and associations representing the agricultural/horticultural and transport sectors. Aside from the insights used to ensure the model reflected industry logistic systems and processes, these contributors provided data for 222,000 enterprises across the commodities supply chains including farms, processors, storage facilities, saleyards, abattoirs, export depots, supermarkets and distribution centres which were incorporated into TraNSIT. The enterprises represented supply chain distribution points for the commodities modelled which were livestock, diary, grains, cotton, rice, sugar, stockfeed and horticulture. From this data a set of synthetic trips were created so that annual/monthly total tonnage (or head) transported across the road/rail network were representative of past movements. In total there were 332,000 different origin to destination paths created. This paper highlights the application of TraNSIT to 98% of Australia's Agricultural production and the importance of the industry and government support to identify synergistic efficiency gains in transport. It represents the largest logistics data set assembled and transport modelling ever conducted for Australian agriculture.

Keywords: *TraNSIT, Supply chains, infrastructure investment, transport optimisation*

Iterative train scheduling in networks with tree topologies: a case study for the Hunter Valley Coal Chain

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Abstract: This work describes an optimisation method based on genetic algorithms to generate train schedules for the rail network under the coordinating responsibility of the Hunter Valley Coal Chain Coordinator in NSW. The network connects 3 coal export terminals to 31 load points and haulage distances can extend up to 364 km. The scheduling problem consists of finding a high-quality schedule for trains travelling from a terminal to a load point and back, respecting all constraints imposed by the network itself and the operational environment. Those constraints refer to a mix of single and double tracks, limited parking facilities along the tracks, loading capacity at the load points, as well as minimum spacing (headway) between trains.

The decision variables include the travel speeds at each section of the network and the amount of dwell time for each train at each parking facility along the route. To test our approach, a simplified model of the HVCCC network, with 3 terminals, 11 load points and 40 sections was used. The objective function is the minimization of the total travel times. A lower bound for that objective function was calculated with the trains travelling at maximum speed, and no constraints being applied.

Three scenarios were tested, with 15, 30 and 60 trains; and with different configurations of the genetic algorithm. The results are presented in the form of a table with a number of statistics related to the solutions found, namely average travel time (with standard deviation), plus shortest and longest travel times, and CPU times. Relative to the lower bounds, the gaps for the average trip time range between 14% and 50%, depending of the problem size. These initial results are encouraging, considering the complexity of the system, the number and complexity of constraints, and the CPU time required by the method. Finally, in the discussion section we indicate possible paths of future research.

Keywords: *Train scheduling, supply chain, coal transportation, optimisation, genetic algorithms*

A heuristic algorithm for the Aircraft Landing Problem

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Abstract: The Aircraft Landing Problem is the problem of allocating an airport's runways (processing units) to arriving aircraft (competing tasks) as well as scheduling the landing time of aircraft, with the objective of minimizing total deviations from the target landing times. This work proposes a new approach to solve the Aircraft Landing Problem that includes separating sequencing and scheduling aircraft. While obtaining the optimal sequence of landing is very difficult, particularly for large instances, an optimal schedule for a given sequence can be delivered in polynomial time. We apply the construction algorithm of Salehipour et al. (2013) to construct an initial sequence of landing, and then we improve this sequence by developing a relaxation heuristic, which relaxes and re-optimizes the sequence. Computational experiments over a set of standard instances demonstrate the performance of the proposed approach.

Keywords: *Aircraft Landing Problem, sequencing, heuristic, sequence relaxation*

Optimisation of perishable inventory items with geometric return rate of used product

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Abstract: We present an inventory model for a firm facing a price-sensitive demand rate and in which the deterioration rate of item is constant. For this constant rate of perishable inventory model, we incorporate a return rate of used items which accounts for the impact of reused products on inventory decisions. We broaden the model scope by allowing two cases of purchase payments: payment at the time of delivery and prepayment before delivery. The model is developed and analysed under a cost function which is linear with respect to the firm's order size and the total-item holding cost. The firm seeks to maximise profit-rate by appropriate choice of the price, return rate and cycle length. We present the conditions that guarantee the existence and uniqueness of the optimal solutions to the inventory problem. To investigate the application of the proposed model we conduct a brief numerical study and set up a sensitivity analysis table to assess the effect of changes in the model parameters on the firm's optimal policy. The design serves two purposes. Firstly, it provides an objective way of quantifying how the optimal policy response to changes in the model parameters and, secondly, it helps to identify the set of changes in the input that yields a new optimal.

Keywords: *Optimal policy, order size, return rate, re-use*

Modelling irrigated sugarcane crop under seasonal climate variability: A case study in Burdekin district

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Abstract: Sugarcane industries worldwide are exposed to uncertainty associated with weather and seasonal climate variation. This variability often impacts negatively on crop production, leading to conservative farming strategies that sacrifice productivity in order to reduce the risk of losses in poor years. The situation is especially severe in Australia where sugarcane production is subject to an extremely variable climate. Inter-annual variability in climatic properties in Australia is about 15–18% higher than any other major agricultural nation. In such an extremely variable environment, knowledge of crop performance under different climate conditions and use of seasonal climate forecasts in decision making can play an important role in supporting agricultural risk management.

Here, we quantified the effect of seasonal climate variability on sugarcane performance under rain-fed conditions and irrigation by integrating the long term climate data record into a crop model, the Agricultural Production Systems SIMulator (APSIM) Sugar, which was calibrated using case study information for the Burdekin sugarcane production region. Two irrigation schedules of five and 20 days were simulated for a range of irrigation water volumes applied in each irrigation event to the plant crop and four ratoons to study the effect of irrigation timing. We conducted economic analyses to convert biophysical yield results into economic returns which were classified according to annual precipitation terciles i.e. wet, normal, and dry climate conditions. This framework allowed us to identify optimal irrigation strategies to achieve maximum yield or economic return under different climate conditions.

The results showed that seasonal climate has a strong influence on crop performance and cash flow in both rain-fed and irrigated sugarcane in the Burdekin region. The case study example was not economically viable under normal and dry climate conditions for either the rain-fed or limited water volume simulations, which indicates the significant importance of using seasonal climate forecasts in irrigation scheduling decisions. Different optimal irrigation strategies associated with different climate conditions were observed for all cropping stages (i.e. the plant crop and four ratoons). Results also showed that more regular irrigation resulted in better water use efficiency in terms of both yield and economic benefits. Yield and economic benefit increases for the 5 day irrigation schedule can be up to AUD 40 t ha^{-1} and AUD 1000 ha^{-1}, respectively, compared with those for the 20 days schedule.

Keywords: *Sugarcane, seasonal climate, irrigation, decision support, APSIM Sugar*

The effect of Social licence on Dynamic Decisions making: a Case Study of a Gold Mine

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Abstract: Dynamic decision making can significantly add value to mining projects and deliver more consistent outcomes under conditions of uncertainty. To achieve consistent and better outcomes, decision-makers in industry can benefit from an analytical optimal decision support tool that will help them to formulate and reach the optimal outcomes. The dynamic decision support tool developed at CSIRO is based on novel stochastic optimal control methodologies that can optimise decisions in situations with multiple uncertain variables and decisions. The types of market uncertainties that can be considered include commodity prices, interest rates and exchange rate, while uncertainties considered for mineral ore bodies include reserve levels, boundaries between ore types and even geo-metallurgical parameters. Social license to operate (SLO), the acceptance and approval level, is crutial for mining companies during the mining development. This paper focuses on the impact of social licence in making optimal dynamic decisions, as illustrated by a case study of a gold mine.

The study examines the optimal extraction of gold using the mining characteristics, operating costs and salaries from a stylised gold mine in West Africa. We assume that the company has the operational flexibility to temporarily stop, restart or completely abandon extraction in response to gold price movement. Empirical evidence suggests that closing the mine may meet a very negative response from the local community. This in turn may lead to considerable future difficulties with hiring workers when reopening the mine, which can be viewed as the loss of the social licence to operate. To avoid such difficulties, management may consider paying salaries (full or partial) to local workers during a mine closure. While such a strategy may be expensive, it could help to maintain the community's trust and thus retain the social licence to operate. Consequently, such an expensive strategy will significantly reduce the switching costs when re-opening the mine and the total value of the mine can actually be increased through such an strategy.

This paper is the first attempt (to our best knowledge) to introduce social licence into the optimal flexible management of a mine extraction project. It introduces a simple conceptual model of the social response to managerial actions in the form of switching costs. In addition to maintenance costs, the company is assumed to pay local workers a proportion of their salary in order to prevent negative social response and to maintain its SLO. In the worst case, if no salary is paid to the local workers, the social licence would be lost, preventing the mine from being reopened. If the mine is closed permanently, the company has to pay decommissioning costs. It is also assumed that the company makes a one-off payment to national and international workers when they are laid off. The paper also illustrates how the dynamic decision support tool can assist industry to determine the optimal strategy and determine the optimal proportion of the salary to pay local workers during a mine closure.

Keywords: *Real options, social licence to operate, stochastic optimal control, switching boundaries*

Using GPUs to improve computation time of optimal road design in ecologically-sensitive areas

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Abstract: Heavy vehicle movements along mining haul roads have significant negative impacts on the migration behaviour and survival rates of nearby animal species. As the extinction of certain animal species can have dire consequences for the ecosystem and an entity's license to operate, mine operators need to consider these negative effects at the design and selection stage of new road projects. This necessitates the development of computationally-efficient techniques to optimise the preliminary design of new roads in the presence of ecological uncertainty.

Due to the presence of multiple local optima and non-linear objectives and constraints, the road design problem is typically solved using population-based search techniques such as Genetic Algorithms. Additionally, computing the operating value over the design life of the road requires using Optimal Control (in the form of real options valuation) methods that account for endogenous uncertainty and the ability to alter traffic flow rates. Finally, the evaluation process requires computing the habitat patches and simulating the migration of animals at each step of the optimal control algorithm. Individually, each of these techniques can be computationally challenging but together, they can render even a simple road optimisation through an ecologically-sensitive region intractable.

Existing research has addressed some of the speed limitations through the use of surrogate modelling and dimensionality-reduction techniques. In this paper, we build upon this research by implementing the most computationally-intensive components of the road design process to run on Graphics Processing Units (GPUs) and develop algorithms that take into account the highly-parallel nature of algorithm components (such as Monte Carlo simulation) in the road design optimisation process. In particular, we discuss the implementation of GPUs for three main problem components:

1. A road crossings algorithm to determine the number of road crossings between every pair of habitat patches for which there is a possible transition. This is used to compute the survival probabilities for the patch transitions.
2. A multiple local linear regression that is used at each time step of the optimal control sub-problem to compute the conditional expectations under each available control.
3. A real-options/optimal control scheme with forward path recomputation that incorporates the animal movement and mortality model. This is used to compute the value of the road (with inbuilt ability to alter the traffic flow) in the presence of animal population growth rate uncertainty and commodity price uncertainty.

We show that the speed improvement achieved from implementing these techniques can dramatically increase the ability of road designers to evaluate many alternative options, thus enabling a global search for high value roads in complex regions. We demonstrate this using an example of a typical road encountered when running a global search routine to find a high value road. The improvements presented in this work can be extended to other research using optimal control to value complex systems with endogenous uncertainty.

Keywords: *GPU programming, road design, real options valuation, Monte Carlo simulation, ecological model*

A Weighted Sustainability Index for Selection of Optimal Operating Plans

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Abstract: The Wimmera Mallee Pipeline Project (WMPP) provides reticulated water to 36 towns and about 6000 farms across an area of approximately 2 million hectares and forms part of the Wimmera-Mallee Water Supply System (WMWSS). The WMWSS is a multi-reservoir system located in Western Victoria (Australia) which is operated to meet a range of conflicting interests for water using complex operating rules. Since completion in 2010, the pipeline has vastly improved efficiencies in the supply of water, with water savings being returned to the environment, existing consumptive use and new development. However, one of the major challenges for managers of these water recovery projects is to determine the most effective or *optimal* operational strategy to meet the needs of all water users.

In Victoria, these often conflicting interests to water have traditionally been addressed through a consultative process supported by surface water simulation modelling. Simulation models attempt to represent all the major characteristics of a system and are suited to examine "what if?" scenarios. Whilst such models are highly effective in demonstrating the effect of changes in system operation, the modelling process is limited to finding one solution at a time for a given set of conditions. Optimisation models have also proven to be effective tools but unlike simulation models are characterised by a numeric search technique and are better suited to address "what should be?" questions. In recent times there has been growing interest in linking optimisation techniques with simulation models in order to build on the strengths of both modelling approaches in the search for optimal solutions. The general structure of this combined modelling technique provides for an iterative process; simulation outputs are used to quantify the effect of candidate solutions which are in turn passed to the search engine to find optimal solutions. The process of selecting the most preferred optimal solution brings together two aspects of multi-objective optimisation, namely; (i) the quantitative characteristics of these solutions relative to other solutions; and (ii) the higher level qualitative information in the form of stakeholders' preferences.

The aim of this study is to incorporate stakeholder preferences into a sustainability index which has been previously used to evaluate and compare optimal operating plans for the WMWSS. In that previous study, Godoy et al. (2015) applied a multi-objective optimisation and sustainability assessment approach to an 18-objective function multi-objective optimisation problem (MOOP) which represented a range of interests for water. For the present study, the same interests are described in terms of three broad categories i.e. strong environmental preferences, strong social preferences, and strong preferences for the needs of consumptive users. A weighted sustainability index is presented which incorporates these preferences in the original sustainability index formulation. This weighted sustainability index is used to select preferred optimal operating plans previously found by the optimisation-simulation modelling. The results showed that the weighted sustainability index provided a simple means to incorporate stakeholders' preferences into the selection process and inform the decision maker of a stakeholder's uncertainty about their values and priorities for water.

Keywords: *Multi-objective optimisation, Sustainability Index, REALM, Wimmera-Mallee Water Supply System*

Optimal Harvest Strategies according to a Markov Decision Process applied to a delay-difference model: insights from the tiger prawn fishery in Moreton Bay (Australia)

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Abstract: A Markov Decision Process (MDP) is a mathematical framework to optimize sequential decisions in a probabilistic model. In this poster, we applied a MDP to a delay-difference model calibrated to capture the dynamics of a trawl fishery targeting tiger prawn (*Penaeus esculentus*) in Moreton Bay (Australia). This bio-economic model of the fishery explored harvest control rules that maximized the economic profit of the fleet in response to variable economic and environmental conditions. Accounting for these uncertainties, a MDP suggests that the industry is operating at or near optimal level given the regulatory and environmental constraints they have to deal with. It shows that the Maximum Economic Yield (MEY) is achieved by adapting effort in response to abundance and economic conditions, notably by increasing fishing effort when the resource is abundant. This MDP application to a tiger prawn fishery concludes that economic conditions and regulatory measures currently in place are constraining fishing effort below effort at Maximum Average Yield (MAY): this stock is not at risk of becoming over-exploited. At low levels of abundance, the spawning stock biomass is effectively protected by economic factors because fishermen loose money if they go fishing. Fishing effort at MEY has been at about 21% of effort at MAY during the period 1990 to 2010. Simulations comparing the optimal strategy to other fishing strategies showed that (a) fishing the stock at MAY is un-profitable in the prevailing economic conditions, performing even worst than a random strategy and (b) fishing at a low level of effort return smaller profits than the optimal strategy but still deliver pretty good yields. The notion of a static reference point (MAY and MEY) is contrasted to the notion of dynamic changes in effort in response to stock abundance emerging from applying a MDP to this fishery.

Keywords: *Markov Decision Process, bio-economic model, delay-difference model, brown tiger prawn*

Field exploration: when to start extracting?

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Abstract: For mining companies, mineral exploration processes such as drilling holes are very costly, but are necessary to have more accurate assessment of the potential quality and quantity of certain minerals in a new field before mine development and extraction can start. Extended exploration periods can drastically reduce geological uncertainties but can be prohibitively expensive. By contrast, insufficient exploration process will leave substantial uncertainty in the assessment of ore grade and reserve in the field. For a mining company, choosing the optimal time to stop the exploration process and start mine extraction can significantly add value to a new mining project. Due to the large uncertainties present, adopting dynamic and reactive strategies in the decision-making process can mean the difference between a profitable and a loss-making mining project.

In this paper, we present a mathematical approach for solving the exploration-to-extraction timing problem. More specifically, we model the decision-making process of a mining company which holds a lease to explore a selected land for a limited time, before exercising the option to start a mining operation or cease the lease. This exploration-to-extraction decision-making process is largely determined by two main sources of uncertainties: the current estimated mineral reserve and the future ore price. Mathematically, we formulate this problem as an optimal stopping problem. The decision to start mining or not is chosen so as to maximise the probability that the whole mining project, after deducting exploration costs, would meet a predefined minimum profit target.

In order to solve this mathematical formulation of the exploration-to-extraction problem, we use the simulation-based Regression Monte Carlo method. We assume the mineral ore price follows a mean-reverting process with jumps and the estimated reserve follows a pure jump process with decreasing variance as long as exploration occurs, to account for the uncertainty reduction provided by exploration. We present the output results from the model in the form of intuitive graphical displays, in particular the optimal decisions over time as a function of the two uncertainties. The objective of this paper is to illustrate the feasibility and benefit of using such a mathematical approach for optimally timing the exploration process, and to contribute to the efficient management of mining projects by adopting such innovative decision support tools.

Keywords: *Mining, exploration, optimal stopping, reserve estimation, uncertainty, real option, project valuation*

Optimal policies for aircraft fleet management in the presence of unscheduled maintenance

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Abstract: This paper presents a fleet management model for military aircraft that generates daily flying and maintenance allocations. This model has two novel features that distinguish it from previous models of fleet management in the literature. Most notably, random unscheduled maintenance is integrated with an optimisation approach. This is important, as unscheduled maintenance is a regular occurrence in day-to-day military aircraft fleet management, thus limiting the ability of deterministic models to provide useful guidance. Furthermore, the model is designed to discover policies that dynamically adapt to random events to deliver optimal fleet serviceability. Other features of the model include flying-hour based phased maintenance with variable induction (day when maintenance begins), day-based regular inspections, and separate phased and flight-line maintenance facilities with both manpower and line capacity constraints.

In the model, serviceable aircraft fly up to a specified number of hours per day. Once a certain number of flying hours has been achieved, those aircraft must begin phased maintenance within an allowable induction range. Regular inspections are an additional type of scheduled maintenance based on elapsed time. Phased maintenance typically takes a few hundred maintenance man hours, whereas regular inspections take tens of man hours. Two types of maintenance facilities are included. Phased maintenance can only be undertaken on the phased maintenance line, and regular inspections are typically undertaken on the flight line. If a regular inspection is due at the same time as a phased service, these can be performed concurrently. Unscheduled maintenance is undertaken in flight line maintenance if incurred on serviceable aircraft, or in either facility if discovered during the course of scheduled maintenance.

We use Approximate Dynamic Programming (Powell, 2011) to formulate the decision making model. The objective is to find the policy that maximizes the expected value of the contribution function. Our contribution function seeks to maximize the flying hours achieved and maintenance throughput of the fleet over a time period, with a weighting factor balancing these priorities. Decision variables include the allocation of flying hours and maintenance man hours per aircraft per day, and when aircraft are inducted into phased maintenance. The model consists of 75 sets of constraints describing: the allocation of flying hours to serviceable aircraft and maintenance man hours to aircraft in maintenance; the allocation of different maintenance types to aircraft in different maintenance facilities; and state transition tests to determine when aircraft are eligible or required to begin or end types of maintenance. The unscheduled maintenance constraints include an exogenous stochastic variable that represents the daily amount of new unscheduled maintenance generated randomly from a lognormal probability distribution. Aircraft are allowed to carry forward a limited amount of unscheduled maintenance while remaining serviceable. However, once a specified level of unscheduled maintenance is exceeded, the aircraft must undergo maintenance at an appropriate maintenance facility until the outstanding unscheduled maintenance is reduced to a required level.

In Approximate Dynamic Programming, a policy is a function that returns a decision, given the current state of the fleet (in the present context). We consider a deterministic look-ahead policy that depends on a discount factor and a look-ahead time horizon. We undertake computational experiments with a squadron of 12 aircraft over a 180 day period, with time horizons ranging from 1 to 14 days and discount factors from 0.8 to 1. Indicative simulation results are presented, where the time horizon substantially dominates the discount factor with respect to influence on the mean total flying hours achieved. While longer time horizons produce larger optimal objective values for a given parameter set and random data, simulation results may not significantly differ when compared with shorter time horizons due to random variation. This is apparent in our results, demonstrating the potential for substantial savings in computational time.

Keywords: *Aircraft fleet management, computational stochastic optimization, unscheduled maintenance*

Optimising electricity distribution networks to minimise the risk of powerline-initiated bushfires

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Abstract: Asset failures, human errors and accidents, animals, birds and vegetation can all lead to electrical powerlines causing bushfires. The electrical distribution network has proven to pose the greatest fire risk throughout Australia and overseas. Most of the fatalities in Victoria on Black Saturday 2009 occurred due to powerline-initiated bushfires, and most recently, powerlines are alleged to have ignited fatal bushfires in Chile during February 2017.

By putting powerlines underground, or using insulated conductors and equipment, much of the fire ignition likelihood can be eliminated. These treatments are expensive, and in general cannot be economically applied to a large proportion of developed networks such as those in Australian states. However, smaller-scale targeted powerline replacements can be part of an optimal portfolio of risk mitigations. Various improved electrical protection technologies, which can detect anomalies more rapidly and reliably cut electricity supply before an ignition can occur, are another important and impactful element in a portfolio of risk mitigating investments.

In current Australian best practice, the formulation of a portfolio of risk mitigations has relied on a combination of expert opinion and a ranking of network elements by expected risk reduction benefit. While this approach should lead to portfolios that are satisfactory and quite cost-benefit efficient, we are nevertheless interested in exploring the development of mathematical programming and other optimisation-based approaches that can generate known optimal or near-optimal portfolios.

We describe our experience with various integer programming and heuristic approaches to optimal powerline bushfire risk mitigation portfolio formulation. The base-case MIP formulation is a variant of Roozbahani et al (Proceedings MODSIM 2015) which has been improved in various ways including through a better representation of the rollout of feeder-level electrical protection. A version of the MIP is developed which uses information from pre-solved sub-problems so as to enable avoidance of unnecessary segmentation of asset improvement treatments along a powerline. We also briefly describe the application of the CSIRO SPARK bushfire model in order to compute fire consequence estimates at a fine spatial scale, and the development and use of statistical models of ignition likelihood, as part of the data preparation process for optimisation.

We apply the methods to data from Victoria, and compare the current risk mitigation portfolio adopted by the Victorian government and electricity companies to theoretically optimal portfolios generated by our methods. We also outline realistic use-cases for optimisation in decision-making relating to electricity distribution network operations and planning, where our view has been informed by consulting engagements in Australia and overseas.

Keywords: *Wildfire, electricity distribution, risk optimisation*

Issues for wildfire evacuation modeling

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Abstract: Evacuation is the removal of people from an area at risk, to one at low risk. Stated like this, the concept and modeling seems straightforward. For example, we simply need to know how best to move people out of a building or aircraft on fire. There are some outstanding and widely used models for this purpose.

However, for some hazards, in particular wildfires, the problem can be more complex. There can be a number of key objectives: the main aim might be to minimize disruption to livelihoods and commerce, while also maximizing safety. An overly early or unnecessary evacuation can result in significant loss with or without a fire. Few if any evacuation models consider the costs of the process. Maximising safety is not necessarily simply the task of moving people, and in some circumstances can mean keeping people where they are. Specific and common issues that need consideration include traffic jams stranding people in the path of the hazard – thereby increasing their personal risk, or of other accompanying hazards such as extreme heat. The details of the fire hazard and landscape also need to be included in models. Key evacuation routes can be unavailable at very short notice because of fire or flooding, road crashes or other problems. Some evacuees, and some institutions, need more time to leave because of medical conditions or livelihood constraints. Also, they might not understand the evacuation messages or have the capacity to leave. This argues for a realistic approach to evacuation with cars: fuel, food, medical support and sanitation are all issues typically overlooked by evacuation managers and modelers. Also often ignored is the suitability of car evacuation in some cases where the use of cars can result in fatal delays, in part because of the traffic congestion mentioned above, and in part because there is not enough time to use a car.

In examining the issues surrounding mass evacuation for wildfires, it is helpful to draw on experiences with other hazards. The mass evacuations in the USA for hurricanes over the past few years illustrate some of the potential modeling challenges – including the rationale for not evacuating. We are usually concerned that people do not leave, but sometimes far more leave than expected clogging roads and other facilities, drawing out evacuation times and thereby creating additional demands on all services. One issue with mass evacuation is that there will often be people dependent on various forms of life support, which in turn require power and medical facilities. Medical emergencies during a major evacuation in Texas included births, deaths, insulin issues and dialysis – gridlock prevented delivery of most services. When mass evacuees arrive, the destination will face massive sudden demand for all types of supplies and services. Usually well beyond local capacity, and modern supply chains carry almost no margin. Mass evacuation by air in the US has had issues too. Insistence of full security screening, confiscation of wheelchairs, etc, has meant that flights take off nearly empty when the airports are operating with limited power, and that delays run into days. This approach makes an explicit judgment that normal aviation security protocols are more important than lives threatened by extreme events. Can modeling provide insights into such tradeoffs?

One issue that receives little attention is that mass evacuation for wildfire can lead to increased property, and possibly livelihood, losses. Can modeling assist with such decisions? When should evacuation start, and where should people go, and when shouldn't they go, given the examples of constraints mentioned above?

Keywords: *Evacuation modeling, wildfire, safety*

Prescribed burning and conservation as a landscape design problem

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Abstract: Reducing fuel load through prescribed burning is a common means of mitigating the risk of large wildfires. This has an effect on faunal habitats and from this perspective great care is needed in the spatial and temporal scheduling of fuel treatment. In fire prone landscapes flora generally have a minimum and maximum tolerance for the frequency of fire events. The tolerances differ with the ecological vegetation class (EVC). These considerations constrain the problem of where and when to burn to reduce fuel load. More than that, however, are considerations of fauna. As an EVC ages it becomes suitable habitat for some species while losing its suitability for others.

For some fauna it is necessary to maintain some measure of habitat connectivity over both time and space. Simultaneously we need to address the main objective of undertaking prescribed burns to fragment areas of high fuel as much as possible. Some multi-period mixed integer programming problems have been formulated to solve this problem. This will be discussed and illustrated with examples. But the computational effort required to solve some of these problems over a suitable time horizon is challenging. We consider a new approach to this problem. This talk will focus on the endangered Southern Brown Bandicoot which requires heathland that is between five and fifteen years since the last fire. A landscape mosaic that meets habitat needs on a permanent basis while ensuring low connectivity of high fuel areas.

There is always scope to go some way towards meeting the needs of an animal whose habitat requirements do not completely overlap with high fuel load areas. What if this is not the case? In such cases it is necessary to exploit the fact that connectivity of high fuel load cells from a hazard perspective is not the same as connectivity from a habitat point of view. This means that for each year separate graphs representing connectivity have to be set up: one for high fuel load and one for habitat. The bi-objective problem of minimising connectivity for hazard reduction while maximising connectivity of the same cells for habitat purposes needs to be solved.

A spatio-temporal Mixed Integer Programming model will be formulated for this problem. The landscape is divided up into burn units. The time since the last burn is recorded giving the 'age' of vegetation in each unit. Binary variables are introduced to classify each unit as high fuel load or not depending on age. Two further sets of binary variables are required to determine whether two high fuel load units are connected – one set from a hazard perspective and the other set from a habitat perspective. It will be shown how this is effective in representing landscape level connectivity. Despite the large number of binary variables the model can be solved quite quickly using Gurobi in a Julia environment. Some illustrative solutions will be presented.

Keywords: *Prescribed burning, mixed Integer programming, habitat connectivity*

Stochastic and multicriteria decision making applied to wildfires

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Abstract: Several operational research models can be found in the literature dealing with prevention and preparedness in order to mitigate the effects of wildfires. These models aim to help decision-makers with decisions such as where to perform prescribed burning or resource allocation among others. Most of these models try to integrate different criteria, but often they handle it by adding hard constraints (for instance, on budget or on some environmental metric). However, it is difficult to find models dealing with the response phase, especially taking into account the inherent multicriteria aspect of the problem.

Once a wildfire has started decision-makers have to choose where and when to attempt to contain it, attending to several criteria and a high level of uncertainty. There are a great number of simulators widely used by fire response services that provide them with an estimation of how will the fire front advance. With that estimation these decision-makers have to decide where and when to send their crews and resources to contain the fire.

In this work we develop a mixed integer linear programming model that will attempt to help the decision-makers with such decisions. The model, which includes multiple criteria and stochasticity, works as follows:

- A landscape to be studied is divided into homogeneous cells, some of which are suitable to be controlled by response teams.
- Once a wildfire starts on the landscape a fire simulator is run in order to know when would fire reach each of the cells (possibly allowing different scenarios).
- With these time windows provided, a mixed integer linear programming model determines which are the cells most suitable to be controlled in order to contain the wildfire.

A multiobjective approach is suggested, as multiple conflicting criteria could be considered, such as:

- Cost of suppression
- Affected area (either burnt or evacuated)
- Reliability of operation
- Safety of crews

Keywords: *Wildfires, early response, stochastic optimization, multicriteria decision making*

A heuristic scheme for the Cooperative Orienteering Problem with Time Windows

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Abstract: The Cooperative Orienteering Problem with Time Windows (COPTW) is an extension to team orienteering problem with time windows where synchronised visits are needed to collect the associated rewards at each vertex. In the COPTW each node is characterised by unique coordinates, earliest service time, latest service time, service duration time, associated reward and resource requirements. The resource requirement is the problem specific attribute. It defines the number and type of vehicles that have to be present at a vertex by the latest arrival time to start the service cooperatively and simultaneously in order to collect the associated reward. The objective of the COPTW problem is to maximise the rewards collected while visiting all nodes is infeasible due to the time constraint.

The COPTW is a type of problem with important applications and yet has received relatively little attention. The real-life applications of the COPTW motivate this research. One of the many applications of the COPTW is the asset protection problem during escaped wildfire. In the case of wildfire the fire front can spread so quickly that incident management teams cannot plan to save all assets, like houses, bridges, hospitals and so forth. For a wildfire that is beyond control, incident management team members seek to save the most valuable assets due to the time constraint. To collect the associated reward of each asset, simultaneous visits might be required by an aerial truck for accessing tall structures and a pumper. Others might need a tanker (own water) and a personnel vehicle. Another application of the COPTW may arise in homecare services where some operations require synchronised visits. For example, where heavy lifting and specialist medical expertise is required.

The Orienteering problem is NP-hard so that exact methods are not able to solve large scale instances of the problem at a reasonable time. Moreover, the COPTW takes the cooperation and simultaneous aspects of a service into account which brings in more complexity for solving the problem. In this study developing a solution approach for the COPTW is investigated for the first time. The interdependence of routes motivates developing a fast and efficient heuristic to solve the problem. We handled the complexity of the COPTW by proposing a new robust enhancement to the Clarke and Wright algorithm followed by boosted operators, which allow insertion of nodes within the routes unlike the classical CW heuristic. The main feature of the heuristic algorithm is its simplicity which facilitates easy handling of the problem constraints. The algorithm generates solutions with high quality in short computational time. To carry out extensive computational experiments, a new set of benchmark instances is developed. The proposed solution approach attains an optimality gap of 1.09% for the small size instances for which the optimal results are known and solves realistic size problems in a reasonable time.

Keywords: *Heuristics, team orienteering problem with time windows, savings algorithms, vehicle routing problem*

Locating fuel breaks to minimise the risk of impact of wild fire: a probability approximation approach

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Abstract: Fuel break is a widely used method to limit the spread of wildfires and to manage the induced risk for lives and goods. In this work we consider a specific kind of fuel break called *Fight suPport Zone* (FPZ) that has been developed in Corsica and South of France. A FPZ corresponds to a strip of land of 100 meters width and a length of several kilometres where the fuel load is maintained under a fixed threshold. It is equipped with water tanks and, at the centre, with a road drivable by fire-fighting vehicles and connected to the main road network. The objective is to facilitate and secure the action of firefighters so as to reduce fire spread between two adjacent areas (cells). Since the set-up and maintenance of a FPZ require a significant amount of resources, their location should be determined carefully. The final aim of this research is to develop a model to determine such a FPZs system.

We propose a network approach where nodes represent areas of lands and directed edges represent potential fire spread. Nodes and edge weights represent respectively the probability of ignition and of spread of fire; in addition each area is associated with a value(loss) depending on the density of inhabitants and the presence of specific assets (school, hospital, camping, industry ...).

Each FPZ reduces the probability of spread between two adjacent zones. The aim is to determine an optimal system of FPZ to minimise the risk under budget constraints. The first difficulty is to define a suitable measure to represent the risk associated with such a network in order to compare different configurations assuming that weights are known. Understanding the risk in terms of expected losses, we define the measure as the sum of the node values multiplied by the probability that the node burns. The main problem is to determine these probabilities. Usually, in similar approaches, probabilities are determined for a specific fire scenario; here we propose to estimate them in general for a time period. We propose the following nonlinear system to approximate the probabilities.

N : set of nodes (cells), $i, j \in N$
E : edges of the network, $e(i,j) \in E, i, j \in N$
g_j : probability of ignition of node j
v_j : value/loss of node j
p_{ij} : probability of propagation through edge (i,j) conditioned to node i is burning

Variables

A_j : variable for probability of burning node j

Constraints

$$1 - A_j = (1 - g_j) \prod_{i/e(i,j) \in E} (1 - p_{ij} A_i) \quad \forall j \in N$$
$$0 \leq A_j \leq 1 \quad \forall j \in N$$

We study the properties of this system, proving that there is at least one solution using Groebner basis, or showing that even in the case of independence between spread probabilities, the solution is not exactly the probabilities of burning. We study whether there is a unique solution, and propose a NLP model including binary variables X_{ij}, if a FPZ is built in edge $e(i,j)$, to minimise $\sum_j v_j A_j$ including a budget constraint. The properties of these model are studied, as well as its suitability to obtain an optimal strategy building FPZs.

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Keywords: *Wildfire, fight-support zone, fire-spread network, risk, probability, Groebner basis*

A Hybrid Decision Making Model for Evaluating Land Combat Vehicle System

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Abstract: New Land Combat Vehicles (LCV) are being acquired to improve the fighting capability of the Australian Defence Force (ADF). Combat vehicle design has traditionally focussed on the use of new and improved technologies to provide an appropriate level of survivability and lethality against a range of threats. However, other factors such as sensors, firepower, mobility, tactics, situational awareness and communications also play a role in increasing or decreasing the survivability and lethality of LCV.

For the most part, LCV system interactions between the components are defined by logical or physical links which complicate the evaluation of its capabilities. In addition, the different types of operational scenarios and threats provide a challenge to the Decision Maker (DM) in providing a clear answer to the problem of determining the 'best' combination of LCV system configurations.

This paper utilises two methodologies, Bayesian Network (BN) and Multi-Criteria Decision Analysis (MCDA), and presents a hybrid decision making model for evaluating the operational impact of different LCV system specifications and configurations. BN is employed to establish a qualitative and quantitative representation of the relations between the variables of the model and calculate standard values of uncertain LCV capabilities like survivability, lethality, etc. MCDA is adopted to integrate the influence of LCV capabilities and calculate the utility value of the selected options.

In order to analyse a very large number of model outputs from all possible system components, a prototype tool of the hybrid approach has been developed. This tool conveniently performs inferences over the BN, examines various proposed configurations in a more intuitive and friendly fashion using data analysis, visualisation and sensitivity analysis techniques, and also searches for the 'best' configuration for the LCV system. The tool utilises public-release BN software (GeNIe), statistical packages (R) and a built-in Analytic Hierarchy Process (AHP) to allow the required calculations to be completed automatically and the results captured in both tabular and graphical form.

Keywords: *Bayesian network, multi-criteria decision making, analytic hierarchy process, data visualisation, data analysis*

Using risk equivalence as the negotiating metric when trading draft selections and players in major sports leagues: who won the Dangerfield trade?

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Abstract: In major sports leagues that use an annual draft to assign eligible players to clubs within the league, it is implicitly assumed that the perceived best young players in the draft pool will be chosen with the initial selections in the draft. Various measures of ability, such as salary, games played, and award and ranking points, are used to estimate the value of draft selections. Typically, draft values decrease exponentially with increasing draft selection number. These functions are called Draft Value Indices (DVI). Having a measure associated with a draft selection can allow clubs to anticipate future growth of the player, and perhaps the success of the club.

Recruiting players to clubs is inherently risky. Clubs invest substantial financial resources to manage their player lists. This includes determining players to retain, de-list, trade and recruit through the draft. There is considerable risk that players drafted or traded-in will not meet expectations, and clubs minimise this risk through extensive background research, including tests of character, skill, competitiveness, leadership and injury history. However, there remains a substantial likelihood that a player will not fulfil their own expectations or those of their club.

The decision to trade players or draft selections (or a combination thereof) to another club often leads to protracted negotiations where each club attempts to maximise their potential gains (or perhaps minimise their losses). Such trade negotiations should, ideally, lead to a fair exchange, but will be constrained by the players and selections available to be traded. Measures of draft selection value or player value can be used to assist negotiations. Draft Value Indices have been used to help balance trades in the NFL and more recently in the AFL. The trades, and the DVI upon which they are based, implicitly assume that the exchanges will provide equivalence in mean performance (and in aggregate, if more than one selection is traded). Whether performance of the recruited players meets expectation in reality is purely probabilistic. Distributions of performance are skewed with a high density of zeroes (no games played) for lower draft selections. This immediately leads to questions of whether the measure of central tendency used to compare trades should be the mean. And while the measure of central tendency may be equivalent in a trade, the probability of obtaining players of satisfactory ability may not be.

Here *risk is defined as the probability of the aggregate value of the received draft selections being below a minimum acceptable value*. Using this as the basis for trade negotiations, clubs will then want to ensure that aggregate draft value is above this level with sufficient probability. As with the measure of central tendency, defining a risk probability is subjective, but for illustrative purposes is taken to be the lower 5^{th} percentile of the aggregate density distribution of value, and the player value corresponding to this is the minimum accepted value, *MAV*. This implies that there is a $p = 0.05$ probability (one in twenty) of receiving a worse combination of selections than the *MAV*.

For *risk equivalency*, clubs will seek trades that balance the probability of receiving selections of a minimum (aggregate) draft value. For example, if a club holds a draft selection (or selections) with a 0.05 probability of being less than *MAV*, then trade negotiations with another club will minimally need to meet this requirement. Clubs can achieve this by packaging selections (or players if these have been valued using a similar acceptable metric). Strategies that attempt to balance risk across alternative management options are also known in gambling, finance, medicine and natural resource management.

Examples of risk equivalence strategies are provided using data from the Australian Football League (AFL). A new DVI for the AFL is derived based upon the numbers of games played. It is shown that under this DVI, the number 1 draft selection under mean equivalence is worth approximately two selection 13s, whereas under risk equivalence it is worth approximately two selection 5s. Example past AFL trades are examined to see how mean and risk equivalence compare, including an evaluation of the trade of marquee player Patrick Dangerfield from the Adelaide Crows to the Geelong Cats.

Keywords: *Risk, decision analysis, sports, player trading, competitive balance*

Flood Damages Reduction with Evacuation Plans: Life Safety Model implementation on an Italian Basin

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Abstract: Results of tsunami, earthquake, floods and other natural disasters require a deepened preparedness of population tackling with these natural calamities. Specifically, the analysis of flood-events development and resulting effects highlight the inadequacy of people awareness and preparedness in dealing with this kind of risk. Stakeholders and local authorities are facing these challenges taking into account the increase in urbanization, road networks and human activities expansion in flood-prone areas and consequent sprawl of lifelines risk. Recent researches and studies show that the need of specific flood emergency plans implementation is requested by countries to be get a better preparedness managing population evacuation in affected territory.

A first phase in the achievement of flood emergency plans is given by defining flood hazard and risk maps in the flood-prone territory, identifying which part of the territory could be mainly involved and the related hydraulic values consequent to flood flows.

This paper describes a modelling approach to manage the evacuation process in case of flood emergency: the research has been pursued using the software Life Safety Model (LSM, (BC Hydro, 2006)). The flood event development in the territory is described in terms of time and space expansion occurrences, allowing LSM to get a feasible description of receptors reactions when the flood occurs. LSM produces baseline data to support population and territory management in case of emergency, reducing and, possibly, avoiding loss of lives which is contemplated as the worst potential damage.

The project presented herein studies the applicability of LSM to the Coghinas River lowland valley basin: this has been considered as the pilot basin in the Regional Flood Risk Management Plan for Sardinia, Italy. The study collects information about each receptor located in the area: population (residents and tourists), buildings and infrastructure networks. LSM is developed considering the 2D hydraulic model RFSM-EDA (HR Wallingford Ltd, 2013) in order to describe a flood event of 200 years return period in terms of water depth and velocity evaluation. Flood-event features description on the territory allows LSM to model its evolution, to evaluate potential damages and to easily show, by a visual interface, the emergency development. A proper and detailed representation of the urban network criticalities and social environment during the event should be a safeguard from reaching greater damages: the event simulation verifies the effects of alert/evacuation warnings, as well as activating proper safety actions mainly on crucial points at high level of risk.

Keywords: *Emergency plans, flood risk reduction, Life Safety Model, flood damages prevention*

Development of a Bushfire Evacuation Support Tool Using Workspace

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Abstract: Bushfires are a serious and growing threat to Victorian communities. At present, more than 433,500 Victorians live in 146,750 dwellings in areas impacted by bushfires over the last 50 years. The bushfire risk is increasing due to growing populations in high-risk, rural-urban interface areas and a trend to hotter, drier summers with more extreme fire-weather days. In particular, the Barwon-Otways region is among the highest-risk areas in the country. The tourist-popular towns of Anglesea and Lorne are exposed to bushfires, and the Great Ocean Road, the only main road through the region, carries heavy traffic during the bushfire season. The seriousness of the current situation has brought about the Great Ocean Road Decision Making Support System (DSS) Pilot project that will develop a software tool to support emergency management organisations assess evacuation and risk mitigation options. This partnership, managed by Emergency Management Victoria (EMV), includes CSIRO's Data61, DELWP, the Surfcoast Shire, the Department of Premier and Cabinet (DPC), Victoria Police, VicRoads, and other emergency support agencies. This evacuation support tool will enable users to explore how different mitigation strategies may impact the fire propagation and in turn community evacuations, how infrastructure and resource investments can be expected to improve evacuation, and how new developments or increases in population impact evacuation planning.

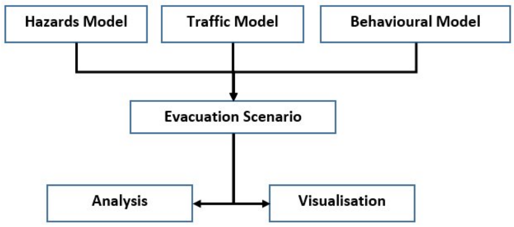

Figure 1. Components of the evacuation support tool.

The initial design of the support tool identified five primary components for evaluating an evacuation scenario, as shown in Figure 1. The Hazards Model will provide estimates of the movement, extent and behaviour of the bushfires involved in the scenario, as well as associated elements such as smoke and ignition points, given a set of fuel, weather and topographic conditions. These estimates are then used to provide risk assessments for population centres, roads and evacuation areas. Data61's own bushfire model, Spark, meets these requirements. The Traffic Model performs one or more MATsim simulations of the movement of people and vehicles along a changing transport network following the specifications of the selected evacuation policy. The Behaviuoral Model, still under discussion, will be tasked with producing estimates of behavioural parameters on population responses to the different evacuation events and directives. The Analysis module performs the aggregations, calculations and queries on the scenario input and simulation output to produce tables, statistics and measures for evaluating the performance of the selected evacuation policy. Similarly, the Visualisation module provides the graphs, charts, thematic maps, and animations that illustrate the significance of the computed statistics and measures.

The evacuation support tool is currently being implemented using Workspace, CSIRO's own workflow-based application development framework. The Workspace GUI provides a catalogue of pre-built Workspace operations implementing basic and enhanced capabilities in flow control, visualisation, modularisation, database access, scripting and parallel execution in order to seamlessly integrate processes from multiple disciplines into a single, rapid, graphical development platform. With Workspace, evacuation modellers can create reusable plug-ins, expose external libraries, design custom user interfaces, call-out other packages such as R, and complete applications that can run on the Linux, Windows and Mac operating systems.

The collaborative nature of the Great Ocean Road DSS project makes Workspace an ideal application development platform for its implementation. Results from the initial case studies indicate a reasonably robust and responsive tool capable of meeting most of the initial performance requirements. With additional workshops to exchange expertise between stakeholders and surveys to obtain new data, the model capabilities are being expanded to deal with new use-cases and behavioural issues.

Keywords: *Bushfire modelling, evacuation planning, emergency management, traffic simulation*

Fusing modelling and engagement practices to support assessment of conjunctive water use opportunities

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Abstract: Effective water resource management requires the consideration of issues at stake within an appropriate coupled human-water systems context. In the case of the Murray-Darling Basin, societal sensitivities mean any approach to progress the management of the system must be defensible and socially acceptable under scrutiny from multiple perspectives (i.e. environmental, social, economic, and scientific). Integrated approaches allow us to elicit, connect and assimilate often-fragmented knowledge and information across sectors and disciplines, and with modelling processes to evaluate the consequences of management options.

We have applied an integrated approach to elicit and explore various conjunctive use options (i.e. managing surface water and groundwater collectively) in the Campaspe catchment. Through disciplinary research – including groundwater and surface water modelling, recharge studies, ecological and social research – and through integrated modelling processes, we have identified and explored the feasibility of conjunctive use options. The approach comprises six key components: 1) identifying issues and conjunctive use options through stakeholder workshops, 2) development of a feasibility assessment methodology for these options, 3) conceptual design of the integrated model, 4) design and development of component models, 5) software implementation of the integrated model and 6) evaluation of the options paying particular attention to uncertainties (Figure 1).

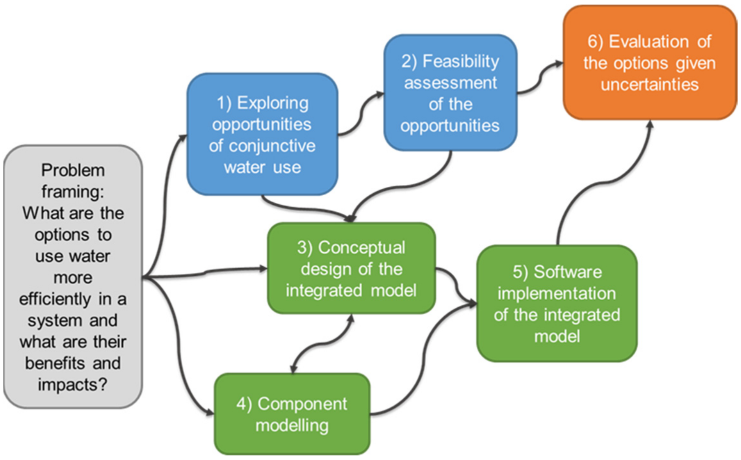

Figure 1. Components of the integrated assessment (blue: social studies; green: modelling) and their connections.

The integrated modelling was designed for generating system understanding and management and decision support. It allows us to investigate the consequences of various possible futures, considering climate, water policy and irrigation opportunities on groundwater sustainability, farm profit, river ecology and recreational values.

In the presentation we describe the approach, and discuss the benefits:

- Engaging irrigators in constructive dialogue about ways to improve water management
- Identifying innovative opportunities that have not been considered or tested by policy managers
- Integrating local knowledge and advanced science to aid decision making
- Highlighting knowledge gaps and uncertainties that need to be addressed to support water management

Keywords: *Integrated assessment, conjunctive water use, feasibility assessment*

What to do when a model is contested? Laying out a modeller's options

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Abstract: Consider a situation where a model has been used to justify a course of action. A stakeholder disagrees and challenges the modelling, model or model results. How should the modeller respond? The answer depends on precisely what the challenger contests, what effort the modeller is willing to make (is more work an option?), and what outcomes the modeller considers both acceptable and feasible. We provide a two-part presentation on this topic. We first describe a generic conceptualisation of the problem to help understand the breadth of options available. We then delve deeper into one aspect, namely how a modeller can adjust the strength of their argument to make it compatible with the stakeholder's own mental model.

We conceptualise the problem of contestation as a difficulty in accommodating each other's mental models of the system, which prevents agreement on a course of action. The contestation may be resolved by the modeler or challenger changing their mind, or by choosing a course of action that allows them to agree to disagree or suspend judgement, i.e. recognizing both perspectives as valid. All cases result in stakeholder acceptance of a (possibly modified) course of action. We see changing positions on an issue as an argumentation problem – but which can draw on a variety of rationalities and modes of reasoning. Resolution of disagreement depends on establishing a common ground (e.g. agreed facts, rationalities) that provides a relationship (an "intersubjectivity") between mental models, allowing them to accommodate each other. Clearly a large range of solutions exist, e.g. depending on whether the challenger questions the actions modelled, the action evaluation criteria, or the modelling assumptions, and whether the modeller wants to make a logical argument or establish trust.

If the modeler wants to make a logical argument regarding modelling assumptions, they still need to consider how it relates to the challenger's mental model, as well as the context and purpose of the modelling. In addition to work that *strengthens* their argumentative position by connecting to evidence acceptable to the challenger, the modeler can argue that the modelling assumptions are fit for purpose. They can *defend* their argumentative position, or *wind back* in order to use the modelling assumptions for a different purpose. Defining strength of the position in terms of four dimensions based on previous work yields a set of twelve responses to contestation (see table) to promote further discussion of the range of strategies a modeler can employ.

	Strengthen position	Defend	Wind back
Maturity	Improve the model	Argue it is already fit for purpose	Use the model for a different purpose within the argument
Scope	Expand the scope of validity of the model	Argue that the challenge is irrelevant to the conclusion	Draw a more limited conclusion
Level of belief	Increase confidence in the conclusion	Defend existing level of confidence	Use an argument relying on a lower level of confidence
Depth of analysis	Explore alternative lines of argument	Defend the depth of analysis	Change interpretation to reflect depth of analysis

Keywords: *Uncertainty, core modelling practices, stakeholder acceptance, model contestation*

Unifying framework for the classification and calculation of robustness metrics

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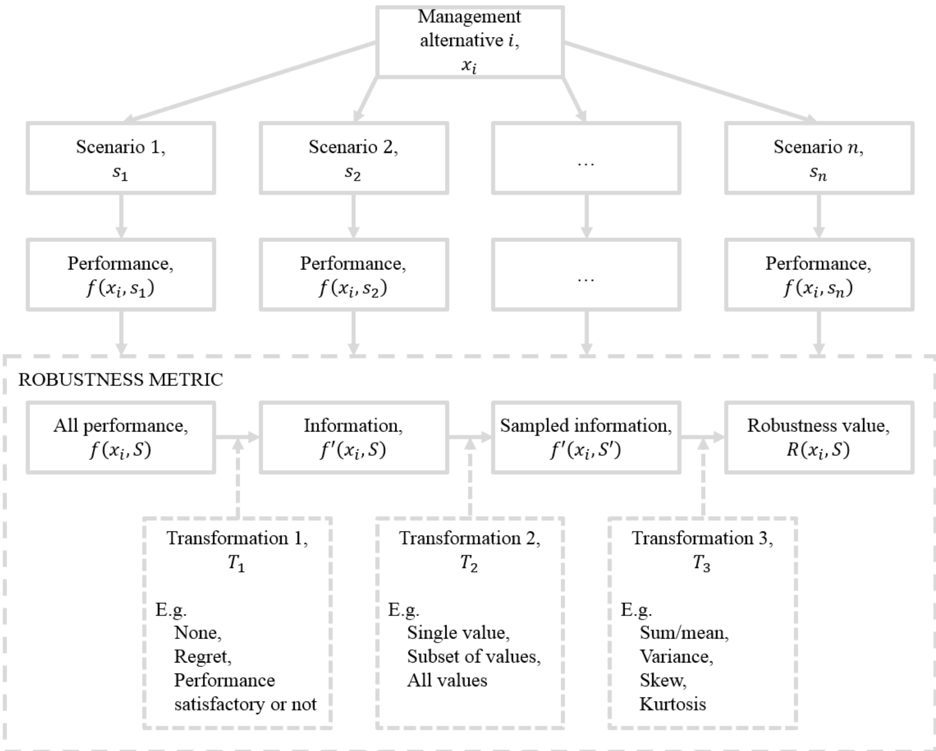
Abstract: There are many metrics in the literature that provide some measure of robustness. Previous categorisations of these metrics have focused on the metrics as a whole, accentuating their differences and sometimes masking their similarities. We proposed breaking down the calculation of robustness metrics into three transformations, which provides a unifying approach (see figure) to calculating a wide range of metrics and enables deeper insights to be gained into the similarities and differences between them. As shown in the figure, the form of the first transformation determines the type of information the robustness metric utilises (e.g. absolute performance values, regret, or satisfaction of constraints), the second transformation reflects the degree of optimism or pessimism of the decision-maker, and the form of the third transformation reflects the decision-maker's preference towards maximising average performance, minimising variance, or some other higher-order moment.



We demonstrate the wide range of applicability of the proposed framework by using it to categorise a number of commonly used metrics, such as the maximin and maximax metrics, Hurwicz optimism-pessimism rule, Laplace's principle of insufficient reason, several regret metrics, and Starr's domain criterion. The unifying framework demystifies robustness metrics for decision-makers, providing guidance as to which metric might be most appropriate in their decision context, and, unlike previous categorisations, provides a computational framework, rather than a conceptual one, allowing users calculate different robustness metrics using three transformations that are common to all metrics.

Keywords: *Deep uncertainty, robustness metrics, unifying framework, decision analysis*

An exploratory modelling and analysis of farm resilience under uncertainty in the lower Campaspe, Victoria

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Abstract: Agriculture is an important industry in Australia, both economically and socially, generating substantial revenues as well as supporting many regional communities. As with any farming enterprise in arid and semi-arid climates, Australian agriculture faces uncertainty about future climate, policy and market conditions. Concerns over changing climates and recent water policy reforms for sustainable development and use of water resources have fueled a growing need to consider and understand the possible impacts of policy changes and (extreme) climate variability. Accordingly, it is necessary to explore the consequences of the various uncertainties for decision making and identify robust adaptation options that influence farm resilience to climate uncertainty whilst maintaining sustainable water use.

Exploratory Modelling and Analysis (EMA) is a specific approach for model-based foresight for systems and problems characterised by deep uncertainty. Rather than attempting to predict the behavior of a system (or systems) of interest, the EMA approach generates an ensemble of modelled outcomes constrained by available data and knowledge. These model results then reflect the effects of a given range of possible actions considering the uncertainties in the modelled representation of a system and its external drivers. Thus it considers scenarios in terms of future drivers like climate and prices, as well as in terms of model structure and parameter uncertainty.

We applied the EMA methodology to a component-based, farm model developed for the lower Campaspe, Victoria. The Campaspe catchment is in north central Victoria and is managed by the North-Central Catchment Management Authority (NC CMA) and the local water corporation, Goulburn Murray Water (GMW). It is a long (150km) and narrow (25km) catchment covering about 4000 sq. km. The lower Campaspe river flows southwards from Lake Eppalock, the major reservoir for the catchment holding 312,000ML, to the River Murray in the north. The Campaspe system is highly developed and regulated and supports extensive irrigation infrastructure. The average annual rainfall is about 550mm, mainly winter dominated and relatively dry in January-February. As a semi-arid region, groundwater resources provide an important source of water. Water is predominantly diverted for agricultural purposes and is the primary consideration herein. However, it is acknowledged that there are other key water users in the basin, including industry, stock and domestic, water for recreational purposes, and the environment.

By applying the EMA methodology, it is possible to determine robust pathways that are beneficial to both farming enterprises, as well as the environmental systems of which they are a part. In other words, it attempts to identify conditions, with respect to futures and model uncertainty that lead to desirable outcomes. Conditions include the adoption of technological and management options in the face of extreme climate variability. Here, technological options refer to the use of more water efficient irrigation systems whilst encouraging the conjunctive use of water resources and changes to water allocation schemes at the policy level to reflect policy changes that affect farm water availability. Results from the modelling will indicate the confidence one can have in a range of future system influences, taking into account the uncertainties in the model itself.

Keywords: *Exploratory Modelling and Analysis, water resources, uncertainty, farm model*

Why pay attention to paths in the practice of environmental modelling?

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Abstract: Recently we have seen rapidly growing interest in behavioural issues related to modelling (Hämäläinen, Luoma and Saarinen 2013; Hämäläinen 2015; Franco and Hämäläinen 2016a, 2016b). This presentation aims to show that the idea of paths in modelling is an important perspective for people working with model supported problem solving and policy decision making. The literature on operations research practice and environmental modelling has discussed processes and best practices. There is, however, a key difference compared to a path, which is defined as the sequence of steps taken in a problem solving case (Hämäläinen and Lahtinen 2016, Lahtinen, Hämäläinen and Guillaume 2017).

The path perspective can be relevant in particular to the environmental modeler. In projects with a prescriptive goal, the consideration of paths is essential. We describe how path related phenomena and effects are pervasive and can lead to poor modelling results. Paying attention to the path perspective challenges modelers to identify critical forks along the modelling path and to be aware of the phenomena influencing their choices at the forks. The number of critical forks can be high in complex policy problems involving deep uncertainties, e.g. climate policy. We provide a path checklist, which can help the practitioners to cope with path dependence and to successfully navigate their paths in a reflective mode.

The term path helps distinguish between a planned modelling process and its actual realization. This distinction helps when discussing and communicating about the practice of modelling. Even if a prescribed 'best practice' process is followed, the resulting path can be influenced by the human biases of modelers, hidden motives, unexpected changes in the modelling environment, and systemic effects.

The concept of path offers an integrative perspective to capture the overall impact of behavioral phenomena in modelling. These phenomena do not occur in isolation of each other and the sociotechnical system of problem solving. The behavioral phenomena interact and their effects can accumulate along the path consisting of sequential modelling steps. The path perspective helps the practitioner to take a systemic big picture view of the problem solving situation. Understanding the role of behavioral effects is critical.

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Keywords: *Path dependence, biases, behavior, decision making, policy making, problem solving*

Optimisation is dead – long live optimisation

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Abstract: Optimisation as we know it today, in the context of finding the extreme control solution to a system, is a fairly recent advance, when considered in the context of mathematics as a discipline that goes as far back as humanity. It gained its status as a method at the same time as Operations Research emerged as a mathematical discipline, in the 1940s. Optimisation has also enjoyed a surge of popularity in the last 40 years, as computational advances made it possible to solve exponentially larger problems with many thousands of variables. Computation also made it possible to explore approximation approaches to solving large problems, getting solutions that are 'good enough' or as close to optimal as possible.

However, the rise of problems from social spheres, where boundaries are fuzzy, stakeholders many and optimality is elusive, means that traditional optimisation approaches start to struggle. Not only can we not assure we have fully understood the problem and its context, the stakeholders can't agree on a solvable formulation. Because all of this, hard operations research including optimisation is facing a decline. We ask the question, have all the mathematically solvable problems been solved, and is hard OR truly dead?

The difficulty of using hard OR methods for messy problems has first been highlighted by Ackoff in his 1979 paper titled *The Future of Operations Research is Past*, which arguably laid the foundations for the rise of soft operations research, and holistic systems methods such as Checkland's Soft Systems Methodology. In this article he claims that Operations Research is dead, and if there is a chance for its resurrection we must approach problem solving differently.

The soft systems analytical approach usually relies on a qualitative or semi-quantitative, analysis of a small number of feasible, acceptable, suitable, and distinguishable (FASD) options. However, the options assessed this way should be selected so that their analysis informs an understanding of the feasible solution space as much as possible. This approach attempts to identify regions of pareto-optimality in the feasible solution space, and delegate the choice between them to the decision makers according to their priorities. In complex contexts, where it is difficult to produce a set of feasible options that spans the entire space of possibilities, there may be a place for optimisation as a fast way of scanning and/or searching through the solution space.

One such case study is presented, from land capability development. In this example, optimisation was used as a tool that scanned large swathes of the solution space to define several capability options that span the set of feasible solutions. This allows for a variety to be selected for further detailed analysis while ensuring only promising options are down-selected, not expending analytical effort on options that are infeasible, clearly dominated or too similar to an option already identified.

This approach helps construct potential solution options based on different paradigms, thus exploring the possible solutions in a systematic manner. Decision makers alone would not be able to achieve such breadth of exploration not only because of the size of the problem, but due to their internal biases and dismissing whole classes of solutions before actually considering them.

The case study demonstrated the utility of such an approach in assisting the decision makers in understanding their decision space and the relationships within it. It also achieved many other positive outcomes, such as the ability to explore preconceived ideas as a result of decision makers' biases and verify their veracity, test various 'constraints' that can be put on the solution set and their implications for the solutions and their comparative utility. The process of developing the optimization model was an important part of the options development process, as it helped clarify stakeholder goals and preferences even in their own minds, and thus avoid prematurely excluding solutions in order to remove complexity from the problem.

When it comes to solving wicked problems, the preferred approach to solving problems should, wherever possible, be a bespoke solution that considers a combination of soft and hard OR methods, that helps the decision-makers understand the implications of the entire solution space.

Keywords: *Optimisation, assignment problem, decision support*

Simple models for complex systems? Equality and equity in modelling social-ecological subsystems

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Abstract: How simple can a model become before it stops being an abstract representation of a system and becomes capable of generating only linear outcomes and outputs? In geomorphic modelling, the inclusion of the two components of sand and waves can simulate the formation of beach cusps through the principle of self-organization. When social elements of a complex system are modelled the minimum number of inputs is higher, but how much higher must it be?

Using an idealised shallow-coastal system (catchment/estuary/barrier) as an example of a social-ecological system, this presentation and a series of forthcoming papers on which it is based follow a novel route of simplifying computational modelling of complex shallow coastal systems using open-source agent-based and system dynamics software. Three conceptual subsystem system dynamics models (social, ecological and geophysical) were developed using Vensim PLE and follow a single template – seven variables in each subsystem with each model developed around a 'core' self-stabilising feedback between two variables. Linking these subsystem models together, a coupled-component model was produced that provided each subsystem with the necessary complexity to represent it effectively (equity), while modelling every system in the same way (equality).

A review of the literature, coupled with ground-truthing of some social components of the model, demonstrated that a majority of stakeholders prefer a visual tool to the arguably more conceptual 'stocks-and-flows' approach of system dynamics modelling. To facilitate this, the coupled-component system dynamics model is subsequently being redeveloped in NetLogo (agent-based modelling software). The variables used in Vensim and any directional interactions between them are being used as a template for developing a rule-based qualitative code that is capable of simulating the form, function and potential futures of estuaries along the north-eastern coast of New Zealand's Te Ika a Maui / North Island, from North Cape to East Cape. The agent-based model redesign will allow for stakeholders to download the NetLogo software and alter both the boundary conditions and external forcing of the model to assist in developing their own understanding of how the full social-ecological system works in their specific locale. Additionally, it allows for individual human and non-human agents in the model to impact upon system form and function, rather than simply viewing their cumulative impacts on any given variable.

However, the agent-based rebuild of the system dynamics coupled-component model necessitated the inclusion of a far larger number of variables to be able to simulate the wicked problems impacting upon such systems. While the primary external forcing remains anthropogenically-driven climate change, the breadth of climate change impacts in shallow coastal systems required the inclusion of 39 variables, with 24 of these being geophysical attributes.

Despite following a different approach to achieving equity and equality between subsystems to the original system dynamics model(s), the agent-based approach continues the quest for equity in modelling the subsystems by giving each subsystem the necessary complexity to model it effectively. It also continues the pursuit of subsystem equality, as the same software and qualitative rule-based coding and interactions between variables are used in the modelling of each subsystem. Our approach facilitates the development of a relatively simple model that is able to investigate potential directions of change in social-ecological systems under changing future environmental conditions and that is also accessible to, and usable by, stakeholders.

Keywords: *Open-source, modelling, shallow-coastal systems, social-ecological modelling, agent-based, system dynamics*

The Effect of Renewable Energy Technology Uptake by the Hotel Sector

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Abstract: Renewable energy technology (RET) is promoted to combat climate change, reduce poverty and reduce reliance on fossil fuels (UNEP, 2011). However, its impacts need to be managed to promote sustainable growth. RET has several impacts, for example on human health through wind turbine syndrome and RET-work related accidents; on social inequality because some RET incentive policies may benefit certain groups in society; on the environment during its production; and on centralised distribution networks.

This research focuses on the hotel sector because of its relatively high energy intensity compared with other commercial buildings; and also because of its embeddedness in local communities and environments. The results of a systematic quantitative literature review reveal that studies about the impact of RET deployment in the hotel sector are currently absent. Moreover, existing studies that explore the effect of RET deployment use a linear approach rather than a holistic systems approach. The systems approach provides a framework for dealing with dynamic complexity, for seeing patterns of change rather than static 'snapshots'. The overall aim of this research is to analyse RET deployment strategies in the hotel sector and to identify suitable strategies that: (a) balance environmental, social and economic risks and benefits; and (b) promote sustainable growth of RET deployment.

This conference paper presents the result of the first stage of this research including the typologies of variables that influence the deployment of RET in the hotel sector in Queensland, Australia. The data were collected from stakeholders, and were analysed using a structural analysis with the MICMAC approach. The results show that the respondents has rated 'the reliability of electricity produced by RET' and 'a tourist comfort' as influential variables and 'whether the hotel has green program' and 'energy storage or not' as dependent variables.

The next step in this research is to develop a causal loop diagram in a stakeholder engagement workshop to identify underlying systems structures likely to influence a hotel deployment decision in RET within Queensland, Australia. Details of this workshop are outlined in this paper. A final causal loop diagram will be used to develop a simulation model to suggest improvement to hotel RET deployment strategies that balance environmental, social and economic risks and benefits.

Keywords: *Renewable energy technology, hotel, impact, deployment, systems thinking*

Portfolio selection of stormwater management projects using multi-stakeholder optimization and visual analytics

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Abstract: An optimization-visual analytics decision-support framework for complex environmental management problems involving multiple stakeholders is presented. The framework is applied to select a portfolio of stormwater management projects for an integrated catchment management plan that is jointly funded by a catchment authority and three local government entities.

Optimization is a computational tool that can be used as part of a decision support approach that attempts to find the best solutions to a complex problem according to some pre-defined objectives. The optimization problem to be solved has generally been represented by a single formulation, including all decision variables, objectives and constraints considered to be relevant. This can result in the inclusion of a large number of objectives and options, making it difficult to identify solutions that represent the best trade-offs between objectives. This is especially the case where multiple stakeholders have their own sets of objectives for a problem. An example of this is the integrated management of a river system and its catchment, where the objectives of stakeholders managing separate sub-areas of the catchment would most likely be different from each other, and different from those managing the catchment as a whole.

A proposed new multi-stakeholder optimization framework that addresses these issues consists of four steps:

1. Multicriteria assessment – identify and evaluate individual projects
2. Multi-stakeholder portfolio optimization – identify the optimal portfolios of projects for each stakeholder
3. Visual analysis – visualise the multi-objective performance trade-offs of jointly-optimal portfolios
4. Selection and negotiation – several portfolios are selected and presented to decision-makers who then make the final selection

Following a multicriteria assessment of individual projects, the stormwater management problem is represented as a series of smaller, interconnected optimization problems, reflecting individual stakeholder interests. These optimization problems are each solved using a multi-objective optimization algorithm, to produce Pareto optimal portfolios for each stakeholder. The optimal portfolios maximise trade-offs between multiple benefits accruing to the individual councils including stormwater harvesting and amenity benefits, and the total catchment benefits including water quality improvement at the catchment outlet. The optimal portfolios that are sub-optimal for one or more stakeholders are eliminated, leaving only the jointly-optimal portfolios for further consideration.

In the third step, the trade-offs between objectives of the jointly-optimal portfolios are presented in a 'multi-stakeholder trade-off space'. This involves a visual analytics software package, which can present large data sets in a form that can be rapidly analysed. The fourth step, involves stakeholders selecting from the optimal portfolios, using the visual analytics package to assist.

To demonstrate the utility of the framework, it is applied to a case study which involves multiple stakeholder groups funding either the capital or operating expenses of stormwater best management practice projects for a catchment in a large Australian city. The framework is used to identify several portfolios of biofilters, swales and wetlands that distribute costs and stormwater harvesting, amenity, and water quality benefits in an equitable fashion among four stakeholders.

A new optimization method for selecting project portfolios for management problems involving multiple stakeholders is presented. The jointly Pareto-optimal portfolios for multiple stakeholders are determined using an optimization algorithm, and are explored, analysed and selected with the aid of a visual analytics package. The approached identifies potentially equitable portfolios of stormwater projects that achieve efficient outcomes in terms of stormwater harvesting, water quality, and amenity benefits and costs for each stakeholder.

Keywords: *Multi-stakeholder analysis, multi-objective optimization, catchment management, multi-criteria assessment*

Structurally aware discretisation for Bayesian networks

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Abstract: Bayesian networks represent a versatile probabilistic modelling technique widely used to tackle a range of problems in many different domains. However, they are discrete models, and a significant decision when designing a BN is how to split the continuous variables into discrete bins. Default options offered in most BN packages include assigning an equal number of cases to each bin or assigning equal sized bins. However, these methods discretise nodes independently of each other. When learning probabilities from data, this can result in conditional probability tables (CPTs) with missing or uninformed probabilities because data for particular bin combinations (scenarios) is either missing or scarce. This can result in poor model performance.

We propose that the structure of the network is an important determinant in node discretisation, and that the best bin allocations for a simple naïve network will be different to those for more complicated networks that attempt to model relationships between the predictor variables. Furthermore, a good discretisation algorithm should not require the model designer to specify the exact number of bins as a target for discretisation. Rather, it should be flexible in determining bin allocations within limits specified by the model designer. BN performance can be improved if discretisation results in CPTs that contain fewer combinations with insufficient evidence to confidently estimate probabilities. We have developed a structure aware discretisation (SAD) algorithm that minimises the number of missing probabilities in CPTs by taking into account network structure. The algorithm requires some parameters to be set, such as the minimum number of cases in each bin, but determines the exact number of bins and their limits based on the data. It consists of two stages: a structurally unaware discretisation stage (SUD) that distributes the cases into bins until each bin has a minimum number of cases, followed by a structure aware discretisation stage (SAD) that further reduces the number of bins to account for incomplete CPTs.

The algorithm was tested on a real life water quality case study, using three different network structures (naïve network, tree augmented network and expert designed network). The results show that both the SUD and SAD stages of the algorithm have potential to improve the discretisation process over equal case discretisation by selecting an appropriate number of bins and their limits. Improvement in performance (area under the receiver operating curve and the true skill statistic) was greatest in non-naïve network structures. A major benefit of SAD is that model designers are not required to specify the exact number of bins, with the algorithm instead balancing the parsimony and precision of the network.

Keywords: *Bayesian networks, structure aware discretisation, water treatment optimisation*

Integrated modelling of contemporaneous multi-utility demand data from intelligent meters

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Abstract: With the advent of smart metering in recent years where water and energy consumption data could be recorded at high resolution, several studies have been undertaken all over the world to unpack various benefits for both consumers and suppliers. Separate analysis and modelling of water or energy data has shown valuable state-of-the-art applications to inform single and multi-utilities and regulatory agencies. This paper suggests a new concept where high resolution multi-utility data is concurrently collected and modelled to allow for enhanced pattern recognition of other resources (e.g. having electricity data assists pattern recognition of water), deeper insight into customer demand and optimal opportunities to manage it. Through using a smart device to capture concurrent water and energy consumption in near real-time, and exploring the correlation between these two consumption activities, the proposed system has helped avoid the need of using Hidden Markov Model and Dynamic Time Warping algorithms in several analysis stages, thus allowed the classification process to be undertaken much faster with higher achieved accuracy. Once finished, the system will result in a wide range of benefits for utilities and regulatory agencies, especially allowing them to have a unique single platform to monitor all water and energy consumption of any particular household or region in near real-time to immediately identify faulty issue with the power system or pipe leakage if it happens. For customer, they will also be immediately alerted when there is any single problem occurring to any water or energy device, or be informed about the current efficiency status of water and power appliance in the house, as well as receiving various incentives when they follow instruction to improve the current supply network.

Keywords: *Water consumption, energy consumption, end use*

Ranking Malaria Risk Factors in East Africa Using Structural Analysis

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Abstract: A key area of concern is how climate change will influence the incidence, and spread of infectious diseases such as malaria. Approximately 3.3 billion, or half of the world's population, are at risk from malaria and under climate change projections; this number is projected to rise under global climate change scenarios. Studies on the impact of climate change on malaria transmission show that even the smallest variation in temperature can have an exponential change in the transmission of the disease. Rainfall is also a driver of malaria transmission and can influence the development of the mosquito by creating suitable habitats for larvae and increasing mosquito abundance. This risk is significant in East Africa whereby rising temperatures and changes in rainfall are projected to expand the transmission range of malaria into geographic areas where communities were previously unexposed to the disease. The malaria transmission cycle is complex and while climate change does influence the global distribution of malaria, the spatial extent within regions will be determined by local land use factors and by other non-climatic factors. At a local level, these factors can influence malaria transmission independently or by modifying the effects of climate change. Therefore, quantifying and understanding the risk of malaria under future climate change scenarios needs consideration of the interactions between these other factors, climate change, and malaria transmission.

Focusing on the East Africa region, this paper suggests a participatory systems approach to identify and rank key variables of climate change, land use, human behavior and interventions, socio-cultural and socio-economic factors influencing malaria transmission. In this process, known as structural analysis, we used systems thinking, literature review and expert consultations to identify a candidate set of influencing variables and to describe the relationships between them. Further, we ranked these identified variables in the order of their influence on the system. From our results, we determined that El Niño, average rainfall, malaria vector control, quality of information and agriculture were the five most influential variables of the system. Current malaria prevention mechanisms have been designed assuming a stable climate. Thus, conducting assessments of future risk of malaria under climate change scenarios is necessary to design the appropriate models, tools, technologies, and policies to enable communities and governments to make informed decisions for sustainable adaptation. Therefore, ranking the variables in order of influence is important when considering priority areas for climate change and malaria risk adaptation and policy creation.

Keywords: *Climate change and malaria risk, complex systems, structural analysis, East Africa, climate change adaptation*

INVITED PAPER

EXTENDED ABSTRACT ONLY

SYSTORY – a story telling system dynamics model for addressing socio-ecological problems

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Abstract: The CCRES (Capturing Coral Reef and related Ecosystem Services) project is a World-Bank, Global Environment Facility (GEF) and University of Queensland funded project that 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). Understanding how communities interact with coastal ecosystems and how these interactions, along with external factors have led to current socio-ecological problems is an important facet that is being undertaken by the Systems Analysis component within CCRES.

The Systems Analysis has been conducted using steps common to systems modelling. The initial step was to identify priority socio-ecological problems (problem articulation) that provide the context for the systems analysis. For El Nido, the socio-ecological problems identified were food insecurity, water pollution, fish catch decline and mangrove loss. For Selayar, the socio-ecological problem identified was coral reef fisheries decline. The greater number of socio-ecological problems identified for El Nido (four) compared to Selayar (one) reflects the comparative modelling resources available for each site.

Focus group discussions (FGDs) with village residence (such as fishers, farmers and local government officials) from each site were carried out to elicit the local knowledge about these socio-ecological problems into rich pictures. Each FGD focused specifically on a single socio-ecological problem (e.g. fish catch decline) to help contain or bound the rich picture being developed. Multiple FGDs (per socio-ecological problem) were carried out with groups of participants from different villages within the case study sites to capture spatial differences in local knowledge. Participants were also separated into practitioners (e.g. fishers) and decision makers to try and account for power asymmetry dynamics.

A purpose-built spatially-explicit (Apple maps) iPad application (SESAMME: Socio-Ecological Systems App for Mental Model Elicitation) was developed and used as the interface to capture these rich pictures during the FGDs. The application of SESAMME was accompanied by a 'script' that provided a detailed, methodological and repeatable process for developing these rich pictures. This process identified *Resources*, *Activities*, *Pressures* and *Decisions* associated with each socio-ecological problem and the causal relationships among them. This is comparable with a DPSIR (Drivers, Pressures, State, Impact, Responses) approach.

These rich pictures were then coalesced into separate causal loop diagrams (CLDs) for each of the socio-ecological problem. These CLDs help to identify and consolidate the important interactions and feedbacks that relate system structure to system behavior.

Finally, we drew upon this participant understanding, along with scientific evidence, to create a system dynamics story-telling model (SYSTORY) that can help practitioners manage the socio-ecological problems that we focused on. The SYSTORY model combines system dynamics modelling with a story telling narrative to help contextualise the model. The model is being developed using dedicated system dynamics software (STELLA Architect) and this model will this be converted to an app (iOS, Android) to increase the accessibility and usability of SYSTORY to a wide range of potential end users.

This presentation will present the stepwise progression of the SYSTORY model from problem articulation to rich picture and CLD development and finally the development and testing of the system dynamics model.

Keywords: *Socio-ecological problems, systems modelling, participant modelling, SESAMME, SYSTORY*

Using SESAMME Apps to Map the Systems Responsible for Coral Reef Fisheries Declines in Selayar, Indonesia

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Abstract: Selayar is a fisher district in Indonesia that suffers from coral reef fisheries decline. The importance of this socio-ecological problem was highlighted during a scoping study that was conducted in 12 coastal villages located throughout Selayar. The aim of this scoping was to identify a key problem or problems (problem articulation) to evaluate, understand and address using systems modelling. The process involved engaging with local stakeholders to identify (a) the resource-use activities conducted within each village, (b) the resources used or affected by these activities, (c) the trends in these activities and resources, (d) the problems associated with these activity and resource trends, (e) the most important or high priority problems, and (f) the stakeholders believed to be directly and indirectly affecting and affected by each of these high priority problems. This was done using hand-drawn rich pictures and stakeholder maps, maps which drawn by participants. The scoping results showed that the decline in fish catch and damage to reef fish habitat from destructive fishing techniques were commonly reported as problems across the Selayar villages dependent on coastal and marine resources.

After the conclusion of the problem articulation process (*coral reef fisheries decline*) 17 Focussed Group Discussions (FGD) were conducted in 9 villages spanning 5 sub-districts of Selayar. The number of participants per FGD was between 15 – 20 people. In general, two FGDs were conducted per village: one FGD with fishermen, their wives and local fish traders; and a second FGD with community representatives, government officials and community surveillance group representatives. This separation was aimed to address potential power asymmetry. The aim of each FGD was to produce a rich picture that reflected the mental model of the system associated with *coral reef fisheries decline* based on the collective knowledge of the stakeholders involved. An iPad app called SESAMME (**S**ocio-**E**cological **S**ystems **A**pp for **M**ental **M**odel **E**licitation), developed by Dr. Russell Richards, Dr. Carl Smith, and Dr. Novie Setianto, was used during the FGDs to help develop and record the participant's rich pictures. SESAMME is based on a drag-and-drop approach where icons representing resources, activities, pressures and decisions can be selected as elements of the rich picture. SESAMME uses Apple Maps to provide an interactive map of the study area so that the icons can be placed at specific locations e.g. a fish boat (activity) can be placed at an important fishing site.

A causal loops diagram (CLD) was developed based on the themes that emerged from comparing the SESAMME rich pictures and supplemented with peer reviewed scientific literature. CLDs are a visualisation tool used in systems modelling to help identify system interrelationships and feedback loops. The feedback loops are essential tools for understanding model behaviour. Specifically, the CLD, constructed using Vensim® software, represents our current hypothesis for the *coral reef fisheries decline* problem in Selayar and attempts to explain the dynamics of the system. A total of twelve feedback loops have been identified; seven reinforcing (R) and five balancing (B) loops. The feedback loops explain the following conclusions: (1) the balancing loops between coral fish stock and fishing activities contain delays, which means that fishing activities do not correct quickly in response to reduced fish stocks. Hence fishing activity remains high even when fish stocks decline; (2) vicious cycles worsen the problem of fish stock decline: low coral fish stocks mean less fish caught, which puts upwards pressure of fish prices, leading to sustained fishing activity and poison fishing, which in turn further declines coral fish stocks; (3) there are many upward pressures on fishing activities: (a) human population increase leading to more demand for fish; (b) upwards pressure on fish price leading to sustained fishing activity; (c) absence of alternative livelihood leaving people with no option but to fish; and (4) presence of poison and bomb fishing that destroys fish habitat (such as coral and seagrass), leading to a slow or no recovery of fish stocks.

Keywords: *Causal loop diagram, destructive fishing, coral reef, poison fishing, traditional fishing*

EXTENDED ABSTRACT ONLY

Participatory modeling: integrating models and stakeholders

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Abstract: Integrated modeling is seen as a way to connect modeling efforts across disciplines and developers, including on-going model development and existing legacy models (Laniak et al., 2013). So far most of the integration is happening at the level of software, when models are presented as software components, which are further connected applying various programming tools. However there is a large category of models that come in form of concepts, the so-called conceptual models. In some cases these are just the first stage of developing more detailed models that eventually do end up as software. In some cases conceptual or mental models never get any further developed, providing important services as is, in the form of conceptual diagrams, cognitive maps, etc. For examples in participatory research, the stage of conceptualization may prove to be sufficient for finding consensus and helping to make the best decision.

However often there is a need to connect such conceptual, qualitative models, with more detailed quantitative models. Models produced with stakeholder participation, first as conceptual ones may need to be further translated into formal languages and eventually converted into computer code to run scenarios and produce quantitative results. In this same process it is equally important to be able to translate the quantitative output of computer models into qualitative terms that can be then brought back to the stakeholders to increase their understanding of the system dynamics and processes involved. We find that this integration of quantitative and qualitative models can be accomplished by means of specialized user interfaces, which, on the one end, help to link the conceptual models to appropriate quantitative modules, and, on the other end, present the quantitative modeling results in terms of appealing and coherent visual content that can be linked back to the stakeholders mental models.

Moreover, such interfaces can become essential to assist stakeholder interaction, helping stakeholders communicate knowledge and information among themselves, by providing a common framework and language to express their individual mental models, ideas and data. This can also help to address another big challenge, which is the need to synchronize our understanding of systems gained from models, with our human perceptions, beliefs, values and preconceived notions about the system. The modeling results may go contrary to our preferences and priorities. We find it then difficult to act based on the models and the logic of the system 2 type of thinking involved, when it clashes with the intuitive system 1 thinking (Kahneman, 2011). Engaging stakeholders in the modeling process in a participatory process can help resolve some of these contradictions, though in many cases it is still difficult to organize and conduct the process properly. New technologies inspired by social media and wide access to the Internet deliver opportunities for broad democratic engagement of the public in science and decision making. However the process is easily compromised by increasing uncertainties associated with information production and sharing, group thinking, and clustering along cultural, educational or party lines (Voinov et al., 2016).

We see a lot of potential in taking model integration beyond the software coupling, and considering mental models developed by stakeholders in addition to computer models. Model integration should then deal with coupling of all sorts of models, including software components and conceptual models produced by stakeholders. However appropriate coupling tools, or interfaces are still missing.

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Keywords: *Modeling interfaces, model integration, mental models*

Using system archetypes for problem framing and a qualitative analysis: a case study in Iranian water resource management

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Abstract: Sustainable decision making about water resources needs contextual understanding and analysis of water resources systems. A systemic approach provides a holistic understanding of issues and facilitates conceptualizing of the problems. Applying the archetype lenses to look into water resource problems in Gorganroud-Gharesu basin, we found out the overall dynamics of the problem can be explained using some archetypes, mainly: limits to growth, attractiveness principle, fixes that fail and shifting the burden.

The Gorganroud-Gharesu Basin is located in Iran in the eastern part of the southern Caspian Sea (Figure 1). The climate is mild and the annual precipitation ranges from 250 to 450 mm, with easterly regions receiving the most rain. The basin area is 13935 Km^2, 60 percent of it is mountainous and the rest is plains (Samareh Hashemi et al., 2014). The main economic sectors in Gorganroud-Gharesu are agriculture, services and industry.

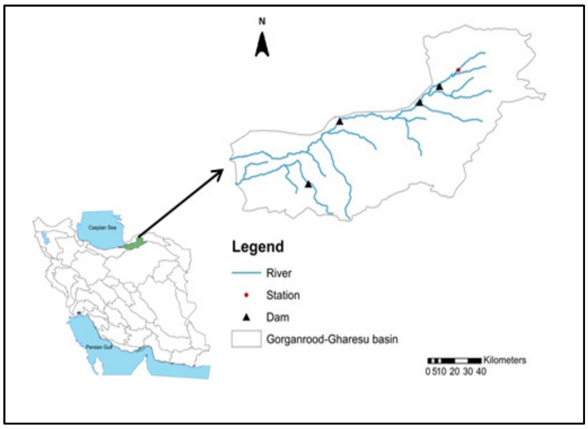

Figure 1. The Gorganroud-Gharesu Basin

The Gorganroud-Gharesu Basin has several problems and each of them has different socioeconomic and environmental impacts. The main problem faced by the Gorganroud-Gharesu Basin is the lack of an integrated management in the face of growing demand. Water management in the basin is based on short-term responses to the problem without paying attention to the consequences. In other words, despite building four large dams and thousands of wells to meet water demands, the problem comes back more intense each time after a while of meeting previous demand. Also, the number of floods and their damage increased dramatically in the past decades. By investigating the Gorganroud-Gharesu basin's issues and problems, its systemic archetypes were recognized based on facts and data.

The story of archetypes started when the growth of industrial, agriculture and services sectors is threated or limited by not having enough water, this fail has been fixed by making dams and wells and provide more water, unfortunately more supply gives the wrong message to consumers of having sufficient water and lead to encouraging more consumption and problems will continue. The first step to breaking the dynamics of an archetype is to recognize them, their causes and consequences. The system archetypes serve as the means for gaining insights into the underlying system structures from which the archetypal behaviours emerge. This research facilitates conceptualization the model and developing the preliminary dynamic hypothesis for the next step.

Keywords: *Limits to growth, attractiveness principle, fixes that fail, shifting the burden, Gorganroud-Gharesu Basin*

A novel integrated assessment framework for exploring possible futures for Australia: the GNOME.3 suite for the Australian National Outlook

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Abstract: A more robust understanding of the implications of future risks and opportunities could improve strategic decision making at different levels. Single sector analyses are likely to simplify key interactions across domains which may limit their ability to identify mechanisms to mitigate risks or harness opportunities. This paper describes an integrated suite of a dozen global and national models for exploring Australia's future through quantitative scenario analysis, GNOME.3 (the Global and National Outlooks for Materials, Economy, Environment & Energy).

The GNOME.3 suite builds on the integrated suite used in the first CSIRO (Commonwealth Scientific and Industrial Research Organisation) National Outlook (Hatfield-Dodds, Adams, et al. (2015)), expanding both its robustness and depth. Expanded modelling capability in the GNOME.3 includes: a new computable general equilibrium model (GTAP-ME.3); a global and local learning (GALLM) model of transport, GALLM-T; improvements to CSIRO's global electricity model GALLM-E; and a global land use and agricultural model, the Global Biosphere Management Model (GLOBIOM), modified to separately identify Australia (GLOBIOM-Aus). GNOME.3 also provides improved ability to analyse pathways for Australia's future energy system through a new Australian energy model, AUS-TIMES. Development of computer scripts to automate interactions across core components of the modelling suite improves the transparency and efficiency of scenario analysis.

This multi-model framework is the most comprehensive scenario capability for Australia to date that connects and integrates across the three interconnected sub-systems: economic-social, environmental earth systems, and food-energy-water nexus. There are several areas—for example, assessing markets for ecosystem services, exploring the complexities of water use, and exploring potential shifts in comparative advantage—where analysis can only be obtained by cross-sector integration associated with the comprehensive model-linking approach possible with GNOME.3 and used in the Australian National Outlooks. We describe the system and identify areas for further development and application.

Keywords: *Scenario modelling, global change, futures, Australia*

Developing a common language for transdisciplinary modelling teams using a generic conceptual framework

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Abstract: In developing countries, problems of poverty and the environment are inextricably intertwined, with any potential resolution requiring underlying political, social and economic causes to be addressed. An integrated research approach to examine such problems should not only involve a transdisciplinary team that covers the broad scope and perspective of relevant issues, but also ensure that interactions between different issues are deliberately explored. Differences in theories, methods, terminologies and research interests of team members, often hinders integration and leads to such complex projects being fragmented by disciplines. This paper describes a template for developing a conceptual framework for a project aimed at promoting socially inclusive and sustainable agricultural intensification in West Bengal (India) and southern Bangladesh. The project involves consideration of the various climate, market, environmental, social, political and health risks that threaten the livelihoods of these rural communities. The proposed template was designed to provide a common framework that the team can readily co-develop and thus overcome some of the challenges of working with transdisciplinary teams. This framework underpins the integrated modelling activities of the team.

In our conceptual framework template, processes are described in terms of a change to resources, the direct and indirect drivers of this change, and the direct and indirect impacts of the change. We selected terms that are unambiguous, yet broadly applicable and neutral, avoiding value-judgments. The use of more neutral terms will enable the framework to be used to represent both opportunities and challenges, as well as positive and negative directions of change. It will also help avoid imposing certain perceptions onto others – for example, what is viewed as a risk or disbenefit by some may be viewed as an opportunity or benefit by others. Therefore, the neutral language is more amenable to cross-cultural contexts and teams. A change in resources can include any increase or decrease in tangible and intangible assets, capabilities, capacities, or behaviours. Additional factors can be any factor that affects the rate of change – i.e. one that increases or reduces the magnitude of change or impact, or the capacity of the subject to avoid, cope with or adapt to the specified change. Examples of the use of the template are provided in this paper.

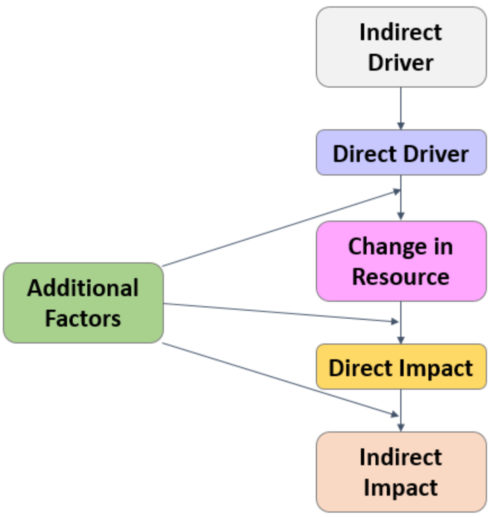

Figure 1. The proposed conceptual framework template for assessing system processes and changes

The template is modular in nature, so that diagrams can be readily combined to capture multiple system processes and complex pathways of influence. As multiple diagrams are combined, impacts from a change in one resource may become drivers for change in another resource. The template allows divergent ideas from the team to be mapped out and linked together in one common framework, facilitating a genuinely transdisciplinary process.

Keywords: *Integrated modelling, integrated assessment frameworks, conceptual model*

Scaling down, scaling up: Development of a framework to understand vulnerability and change potential in the Hauraki, New Zealand

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Abstract: In New Zealand, regional councils are responsible for developing and implementing policy, and realising objectives for natural resource management. Across the country, councils face the challenge of creating policies that will ensure the maintenance of ecosystem services, while future-proofing the social, cultural and economic viability of their regions in the face of multiple uncertainties and drivers of change.

The Hauraki subregion presents a “perfect storm” of interacting environmental, social and economic challenges. While wetland drainage at the turn of the 20th century transformed the landscape, and provided superior land for dairy farming land and associated livelihoods, this low lying coastal area now faces multiple socio-economic and environmental challenges. The legacy effects – drainage, peat shrinkage and land subsidence, salt water intrusion, and biodiversity loss – are exacerbated by changing land use and land management practices. Climate change and the risk of increasing variability and extremes, as well as social and economic drivers, further complicate the scope for policy-, planning- and adaptation solutions. In addition, there are a wide range of stakeholders in a highly complex social and political environment, including settlement claims by Māori, the indigenous people of New Zealand, under the Treaty of Waitangi; a Marine Spatial Plan developed with stakeholders from around the wider Hauraki Gulf; and an upcoming review of the Regional Plan and Regional Coastal Plan.

The Hauraki is diverse and spatially heterogenous, implying that impacts from different driving forces will be felt in different ways by different communities. In the past, integrated assessments for the purpose of policy development have tended to focus on region- or sub-regional scale modelling of high level scenarios. Such assessments can be a useful tool to understand broad scale issues, but from the outset they often limit the scope for understanding local-level vulnerabilities and innovation potential.

In order to develop effective policies, we suggest that vulnerability and innovation potential need to be both considered spatially and understood at different scales. To this end, we propose a framework, developed by Landcare Research together with the Waikato Regional Council (WRC), for an integrated assessment process intended to address the challenges described above and to underpin policy development. We approach the assessment both at the broader scale, through spatial mapping and the development of indices of environmental as well as socio-economic and cultural vulnerability; and at the local scale through the spatial identification of hotspots of vulnerability and local capacity for change, where we are able to explore place-based, adaptive pathways. Based on the premise that change can occur most efficiently, equitably and effectively where the need for such change is recognised across different parts of the community, and where there is a shared vision and direction, we propose that the understanding of vulnerability and innovation potential generated from the development of local-scale, place-based visions that cut across sectors can then be scaled up to help inform broader policy questions and future scenarios.

Keywords: *Scale, integrated assessment, pathways, policy development, vulnerability, adaptation*

Beyond Planning: Implementation, reporting and investment strategies with the CAPER DSS

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Abstract: The Catchment Planning and Estuary Response (CAPER) DSS has been used successfully over the past decade to aid in the development of Water Quality Improvement Plans, including for Sydney Harbour, Botany Bay, Darwin Harbour and the Great Lakes in NSW. More recently the approach was used to develop a comprehensive WQIP for the Tamar estuary and Esk Rivers catchment in northern Tasmania and simpler plans for multiple smaller catchment and estuary systems in Tasmania. These Plans have provided a blueprint for priority actions to improve water quality, as well as feasible and achievable catchment load and estuary concentration targets.

Moving forward there is a need for more detailed investment strategies focused on implementing specific recommendations in the Plan. Increasingly project funding is tied to specified outcomes and there is a need to report not only on the actions undertaken, but also to provide a robust assessment of the likely impacts and benefits of these actions. Given the uncertainties and climatic variations in monitoring data, it is generally not possible to monitor for these changes in the short to medium term (eg. 2 to 10 year period). The CAPER DSS is now being used to fulfil this role, prioritising specific investments in on-ground works considering end goals and desired outcomes as well as the relative costs and benefits of potential investments. A key part of the development of such Investment Plans is developing an understanding of the variety of local priority goals to help focus the implementation of WQIP actions in that region, using a collaborative approach with key stakeholders. The CAPER DSS can then be used to assess investment alternatives against these goals and, in conjunction with discussions about key stakeholder and investor preferences as well as constraints and impediments to adoption, provide a recommended direction for given budget constraints.

This paper outlines the ways in which the CAPER DSS is being used to develop investment strategies, underpin funding applications and support outcome reporting. These are key developments in a strategy to action approach

Keywords: *Water Quality Improvement Plan, Decision Support System, stakeholder engagement*

Putting the personal into risk measurement: exploring the roles of psychological and sociological factors in the perception of risk in the water industry

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Abstract: Risk measurement has predominantly utilised the technical and scientific approach to risk, developed in the 1950s and 1960s. This 'rational' and 'objective' approach to assessing risks has not been updated and is still widely used within the water industry. Furthermore, it has been cemented in risk management standards, and acts as the key model for risk assessments. Risk research in the last forty years has proposed alternate theories that are highly critical of the systematic, 'rational' approach of these old risk practices. This criticism stems from the lack of incorporating psychological, sociological and cultural risk elements in assessments, thus limiting the scope of how risks are actually perceived by assessors. Psychological approaches consider the risk assessor's own affiliations with the risk, based on experience and other psychological factors. Sociological theories, such as those proposed by Mary Douglas and Aaron Wildavsky, argue that the beliefs, or worldviews of the assessor more effectively describes how a risk will be evaluated.

In this paper an approach to test the extent technical risk approaches can be deemed 'rational' and 'objective' and whether psychological or cultural theories of risk may be more effectively describe how risks are actually evaluated, are highlighted. The water sector's existing risk processes are used to test these theories; however, this paper only covers the methods utilised, not the results obtained. The water industry is highly regulated, and also (in most cases) government-led, acting as a good candidate for assessment of risk processes. Water management is also becoming an ever more pertinent issue. In circumstances of declining supply and increased demand, risk assessments act as the decision-making tool in the gateway to implementing new projects. Therefore, whether risks are assessed comprehensively will have long-term ramifications in water management.

Keywords: *Risk, water, assessment, sociology*

Unpacking climate risk management in mining value chains: A building blocks approach to conceptualising decision making for adaptation

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Abstract: The mining industries and related service sectors collectively face enhanced risk from climate change related extremes. The interconnectedness of the sector and their supply/value chains means that risks can often cascade both up and down the chain. While the industry is experienced in risk management, future risks, posed by climate change, are expected to present conditions well beyond existing coping strategies. In order to effectively manage future business risks, cross-cutting strategies must be established that consider the potential for worsening weather extremes. For example, an extreme rainfall event could cause a tailings dam to overflow in turn leading to a range of risks including occupational health and safety, environmental, community, regulatory, production and reputation, as the consequences flow through the chain. To avoid maladaptation and assure that negative impacts can be avoided or suitably addressed, it is important to conceptualise the new climate change related risks to the mining value chains in an integrated way. .

Here we propose an approach where 'building blocks' are used to develop a conceptual framework for adaptation decision making. This has been proposed through recent work by Hamilton *et al.* (2017), which provides a common language for investigating and understanding risks regardless of decision-making perspective (Fig. 1, inset). The building blocks are established to consider direct and indirect drivers of change in the key five capitals (natural, human, social, financial and built capital) (Ellis, 2000), and the resulting direct and indirect impacts, enable viewing and interrogation of risks through multiple perspectives. A similar approach has been used for decision making at the mine-scale by Hodgkinson *et al.* (2013), and its application as a conceptual framework for supporting decision-making in mining value chains under a changing climate. In practice, such conceptual frameworks enable the consideration of multiple and sometimes conflicting priorities to be considered and evaluated, as in the case of adaptation in a mining value chain where objectives and decision-making around natural, human, social, financial and built capital is complex (Fig. 1). The concerns of various decision makers can be taken into account, effectively considering various perspectives of impact and required action. Decision support tools are more relevant when the perspective of the user has been considered, particularly across value chains where perspectives vary greatly. The approach we present shows that value chain strategies can be more accurately informed by decision support tools that incorporate the various drivers, impacts and actors of these complex systems.

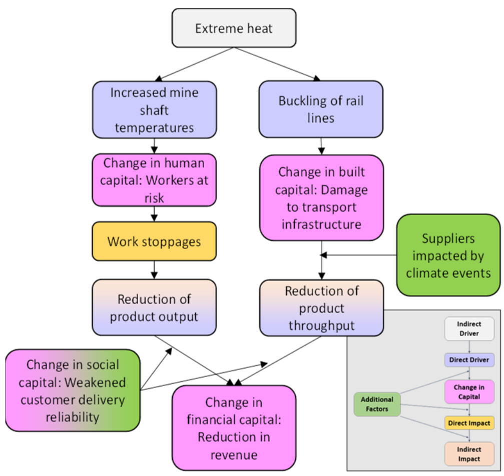

Figure 1. Demonstration of application of a conceptual framework template (inset) to the impacts of climate change on mining value chains as demonstrated by an extreme heat event

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Keywords: *Climate change, integrated modelling, supply chain, conceptual framework, adaptation*

Uncertainty management during conceptual modelling: a cognitive mapping case study

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Abstract: 'Scoping' and 'problem framing' begin the integrated assessment and modelling (IAM) process and result in a conceptual model that frames the system of interest according to a defined problem. A conceptual model is mainly qualitative and provides a basis for the later development of a numerical model. Given the significant complexities of interaction among the cross-disciplinary system components that IAM explores, this process of abstracting reality to a more manageable model requires subjective assumptions and decisions tailored to the specific modelling question and purpose. This abstraction and subjectivity may cause a loss of confidence by policy-makers planning to base decisions on model results. To avoid this, best practice guidance from the literature focuses on process and makes recommendations to engage stakeholders, avoid ambiguity in problem framing, maintain transparency on model decisions, and avoid overly-complex model representations that waste resources. The focus on stakeholder engagement and transparency reflects a belief that, ultimately, model utility is largely defined by the acceptance of its outputs by stakeholders, which will be facilitated by an understanding of the modelling process. What is often not clear is at what point each of these recommendations has been addressed sufficiently for the modelling process to progress. In addition, non-modellers may find it difficult to understand the implications of ambiguous problem framing and a lack of model parsimony. This reduces transparency as well as their ability to contribute on multi-disciplinary, multi-sectoral modelling projects.

This paper suggests that the concept of uncertainty may be a central driver of best practice in the early phases of scoping, problem framing and conceptual modelling. To illustrate, an existing uncertainty management framework (UMF) is used to guide decisions leading towards a conceptual model for a Cambodian groundwater use case study. Two iterations of the UMF application are performed, alternately using the 'scoping' and 'problem framing' phases as sources of uncertainty to be managed. The first iteration triggered the decision to undertake formal stakeholder engagement to collect additional knowledge about the system to be modelled, and the selection of Eden's cognitive mapping approach to structure and analyse this data. This new information helped to reduce or ignore the iteration 1 uncertainties, as well as facilitate the identification of second-iteration uncertainties (only a selection is illustrated).

Strengths of the UMF approach as applied to the case study included the iterative identification and treatment of uncertainties, its structured, action-oriented, step-by-step nature, and the guidance and flexibility on the choice of methods. Implementation challenges were mainly peripheral, such as choosing how uncertainties should be prioritized, choosing how to prompt the *identify* task, and sourcing appropriate methods for a given level and nature of uncertainty. Another challenge was communicating the concept of uncertainty to non-modellers. In terms of handling ambiguity, driving transparency and pursuing parsimony, the uncertainty management approach a) encouraged clarity on what options were available to handle ambiguity and how it might affect problem framing; b) provided transparency through an iterative, structured process that communicated uncertainties about the modelling choices to be made; and c) encouraged questioning of assumptions about model structure, multiple pathways, and which concepts should be made explicit in the conceptual model. The deliberation, transparency, and awareness of resource limits encouraged by the UMF all generated confidence that the resulting system abstraction was defensible and 'enough' to progress through the model-building process. It is hoped that the utility and relative simplicity of this approach as demonstrated with this case study will encourage a stronger and more explicit focus on uncertainty during the scoping, problem framing and conceptualization phases of IAM.

Keywords: *Conceptual model, integrated assessment and modelling, cognitive map, uncertainty*

A framework for the exploration and reduction of disaster risk

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Abstract: Natural hazards are an unavoidable component of life around the world, however with effective risk reduction and management strategies, their impacts can be minimised significantly. The risks into the future, driven by trends in population growth, urbanisation, economic development and climate change – to name but a few, is growing. However tomorrow's risk is a function of today's decisions (e.g. developments allowed, legislation passed) and as such there is scope to limit future losses. To improve decision making in this area, a participatory development process was undertaken to create a framework for the development and utilisation of a decision support system aimed at improved long-term risk understanding and reduction.

The iterative development and use framework combines inputs, qualitative and quantitative, from different actors to develop a decision support system (DSS) and in tangent explore drivers and uncertainties in risk into future through exploratory scenarios. Initially the concept of risk and how to measure it into the future had to be determined between stakeholders' definitions of risk, principles of dynamic exploratory modelling and the metrics required for policy impact assessment in central government organisations. This resulted in the conceptualisation of risk based around the interrelationship between hazards, exposure and vulnerabilities. This allows for modelling risk dynamically via changes to land use and building stock (exposure), building standards and education and awareness (vulnerability), and different hazards impacted by climatic factors. It also allows for the calculation of average annual loss, an important metric for the assessment of future damages due to natural disasters, and one which can be used to compare different scenarios, and the impact of risk treatments across various hazards.

The development process linking inputs from scientists, end users and IT-specialists saw a DSS capable of modelling risk into the future by integrating a land use model, driven by economic and population changes, a building stock model, and various hazard models (earthquake, bushfire, coastal inundation, and riverine flooding). The DSS models the average annual loss across each of these hazards at yearly time-step and at a spatial resolution of 100m grid. The integrated use process focussed on the development of scenarios to explore changes in risk into the future. This process was conducted by the facilitation of views between stakeholders, and modellers using a storyline and simulation approach to develop qualitative and quantitative scenarios of risk. The framework for developing and using the DSS for risk understanding and reduction has been applied to several regions including Greater Adelaide, and Greater and peri-urban Melbourne and Tasmania, and allows for an improved understanding between trade-offs between risk, and socio-economic-environmental objectives for risk treatment options, and build strategic capacity for considering the future challenges of disaster risk reduction in dynamic and growing communities and regions.

This paper explores the process of developing a generic framework for the exploration and reduction of disaster risk while balancing the added value of tailored applications to case-study regions to enhance up-take. Examples will be taken from the development process across three regions to develop a generic system along with the specifics of use cases highlighting the value of these two separate but interconnected processes.

Keywords: *Disaster risk, DSS, stakeholder engagement, exploratory scenarios, integrated modelling*

Using adaptive management to increase the use of scientific input in environmental policy and practice

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Abstract: Scientists need to work with land managers, planners, policy makers, regulators and others to ensure scientific evidence informs environmental policy and practice. However, there is much uncertainty about the process of how these different 'cultures' work together effectively and the factors that affect the use of scientific evidence. We adopted an adaptive management approach to reduce uncertainty about the process. The aim was to increase the likelihood of scientific evidence informing environmental policy and programs.

The first step in adaptive management is to develop a process model to describe how scientific input is used in environmental policy and programs. To do this, we interviewed 13 scientists and 13 practitioners (land managers, park rangers, scientists, and planners from natural resource management agencies) involved in 11 'successful' and four 'challenging' environmental projects. We asked them about the factors that facilitated the use of scientific input during the project, and those that hindered it.

We counted the factors that were mentioned most frequently during interviews. They included scientific rigour and regular communication. The frequently mentioned factors fell into three categories, those relating to: the personal attributes of the individuals involved; how the project and/or relationship was established; and how information was shared during the project.

The frequently mentioned factors were used to inform a process model. The model helped identify parts of the process where outcomes were most certain. In such cases, management actions were being taken to foster the use of scientific input. For example, scientific rigour was frequently mentioned as a factor affecting the contribution of scientific evidence. Therefore, scientific organisations recognise the crucial role of scientific rigour and undertake management actions to embed it.

The model also helped determine parts of the process where outcomes were less certain. In our model, there was most uncertainty about the role of factors related to the way projects and/or relationships were established. Therefore, this part of the process was most amenable to management action.

The next steps will be to intervene during the establishment of environmental projects and/ or relationships, to embed the frequently mentioned factors and test their utility to affect the outcome. The factors that we will test include: involving both practitioners and scientists from inception of a project; ensuring the project team have diverse and complementary skills; developing and articulating a shared purpose; and supporting the team to work collaboratively to define the problem to be addressed and design how the solution will be implemented.

An adaptive management approach enabled us to better understand the process of how scientists and practitioners work together, and identify management actions that can be tested to reduce uncertainty in the process, and increase the contribution of scientific knowledge in environmental policy and practice.

Keywords: *Adaptive management, knowledge exchange, environmental, scientific input*

Accelerating the adoption of knowledge in decision making, policy, and practice

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Abstract: The uptake and use of scientific findings is becoming increasingly important with funders concerned about the impact that research has on policy and practice. Within the health and medical research sector, there is a consistent failure to translate research into useful and usable services. This is increasingly evident across other research disciplines. The slow and haphazard process of moving knowledge to practice and policy is evidenced amongst other things by the 17-year gap to move 14% of medical research into clinical practice. A series of papers in the Lancet, estimated that 85%, or over $US100 million, of research, is wasted, usually, because it asks the wrong questions, is poorly designed, and not published or reported.

Attempts to reduce wastage and improve the movement of research evidence into policy and practice have been increasing over the last decade. This has seen a plethora of models, terminology, and definitions focusing on bridging the research to practice gap. Once such term is knowledge translation (KT), the science of moving evidence to practice. KT involves a complex system of interactions between researchers and research users to ensure research relevance and accelerate the capture of the benefits of research through more effective services and products. With many models and terms, understanding the processes and strategies for beneficial translation can be confusing. For simplicity, this model encompasses translation elements across the research lifecycle. The KT activities in the model are based on existing research from the health and medical literature on KT methodologies.

Phases of research project	**Knowledge Translation (KT) activities**	**Overcoming wastage**
Creation of questions and methods	Involvement of knowledge users, stakeholder discussions, partnerships, project development and design	Ensures researchers are asking the right questions and designing appropriate studies.
Research process	Managing stakeholder relationships, embedding users in research, building capacity, stakeholder feedback, roles of partners and users in the research process.	Ongoing understanding of research relevance to end users.
Outputs	Dissemination and implementation of research knowledge, planning formats for different audiences, media, policy briefs, reports, audio visual tools	Publishing and reporting in appropriate formats for end users.
Activities	Implementation processes, commercialization, policy and practice change, context considerations, working to ensure users know how to use knowledge	Delivery of outputs and products for optimal uptake into policy or practice.
Impacts	Evaluation of dissemination and implementation, feedback to future projects, determining policy or practice changes from your research.	Build in measures of impact at the beginning of projects.

Research in the health and medical sector, has shown that implementing KT elements within the research process increases opportunities to create impact by working closely with key practice and policy stakeholders. Working in partnership with the end users of research from conception has shown that change occurs when the stakeholders are the drivers for change in policy and practice.

This model provides an easy to understand process to help researchers embed KT strategies and processes in any research project and to accelerate the adoption of their research knowledge into policy and practice.

Keywords: *Research impact, knowledge translation, partnership, policy and practice change*

Untangling the Threads of Logic: Analysis in Support of Force Design

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Abstract: Strategic defence planning needs to address an uncertain future, an accelerating present, as well as contend with the weight of the past. Designing a defence force that will serve Australia's future needs is fraught with challenges, including the complexity and interdependencies of the existing force and the influences from lobbyists, political interests as well as service-specific needs. Moreover, a historical focus on optimising individual capabilities often fails to give appropriate resourcing to the underpinning enablers. In such a politically rife world, robust analysis can help untangle the threads of logic that underpin good force design.

In the Australian Government's Department of Defence, force design has been formalised into a centralised, enduring process of translating Government strategic policy into a coherent joint force structure within specified time and budget envelopes. Force design is necessarily an incremental process, with small changes to the existing force being the norm and this creates a significant heuristic bias towards the status quo, acting in favour of maintaining or expanding existing capabilities and precluding serious consideration of whether some functions ought to be abolished or reimagined in an entirely different manner. The accelerating rate of change in the present era, however, renders this approach increasingly problematic.

The newly formed Force Design Division is currently establishing and bedding down its core processes, which affords a unique opportunity to establish sound analysis methodologies into Australia's strategic defence planning. These analytic tools support the force design process through conceptualisation of the force, prioritisation of options, valuing capability, coherence assessment and interdependency analysis.

The traditional role of scientists in this process has been the discipline of operations analysis. However, the role of scientists in force design is expanding through both the application of the scientific method to force design problems - "doing science" - and also by providing an alternative mindset to the force design process, "scientific thinking". This "doing science" includes evaluation of force options through experimentation, countering judgement heuristics and generating ontologies. Characterised by a rigorous methodologic approach, such scientific contributions can broaden the force options and reduce the capability risk.

Five key qualities from these applications of science have been identified as vital to the force design process: collaboration, taking a long-term perspective, being timely, well communicated and relevant. These key qualities, along with the power of a logical, evidence-focused scientific mindset, can provide force designers with the tools necessary to do force design well.

Keywords: *Force design, capability development, planning, operations analysis, strategic planning*

A catchment partnership framework to managing floods, droughts and pollution using Catchment Systems Engineering

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Abstract: Farming plays a key role in increasing local scale runoff and erosion rates, resulting in water quality issues and flooding problems. Increased runoff rates also indirectly give rise to increased drought risk due to a lack of recharge in medium and larger storms. Agricultural intensity and soil degradation are also likely to increase in the future. However, there is a potential for agricultural management and complementary soft engineering (often referred to as Nature Based Solutions) to become a major part for controlling runoff processes. Hence we will establish the nature of the catchments scale problem using case studies and show the overall failure of many land use change and management approaches to date and highlight the key requirement to alter the water balance of the catchment systems.

Here, we will establish a Catchment Systems Engineering (CSE) approach to water balance management. We will explore how the fundamental alteration of hydrological flow pathways are needed to solve the above problem. CSE is an interventionist approach to altering the catchment scale runoff regime through the manipulation of hydrological flow pathways throughout the catchment system, without seriously effecting food production. By identifying and targeting active hydrological flow pathways at source, such as overland flow, drain and ditch flow a significant component of the runoff generation can be slowed and stored which lowers flood risk (referred to as Natural Flood Management in the UK) which in turn reduces soil nutrient losses and agricultural pollution. The role of source and riparian zone management to targeting and mitigating the negative effects of farming will be demonstrated through existing case studies.

Here, a framework for applying a CSE approach to the catchment is shown in a guide to implementing mitigation measures in flood and drought impacted catchments. The framework is based around engagement with many catchment stakeholders operating as a catchment partnership, including local population, NGO's and local environmental policy bodies. The partnership uses evidence arising from hydrological and hydraulic processes, local knowledge, field observations, field visits and the co-design and delivery of full scale demonstration measures. The framework allows the communities to understand the floods, drought and pollution issues and that the problems can be addressed through multiple local interventions. The role of data collection, research monitoring and experimental work at the local site is highlighted as the key to engaging all stakeholders. A series of demonstration features are then created and instrumented, such as woody debris, leaky dams, sediment traps and on-line and off-line ponds (of which some wetlands are included). Subsequent analysis and modelling are also used to show how the approaches can be scaled up and used to convince regulator to invest or at least remain interested whilst the evidence is gathered. Ultimately a few well characterised storm events can prove that soft engineered. Soft evidence and community based observations are is also invaluable. Observations of full temporary ponds and traps full of sediment are powerful images to support the approach.

Once the impact of altering the local processes is recognised by the catchment partnership then wider uptake follows at the catchment scale. Initial findings suggest that attenuating and storing large amounts of flow at many locations across landscapes, during storm events, can alter the water balance at the catchment scale. Initial findings from constructing many runoff attenuation features also show improvements in soil nutrient losses during storm events. We will show case studies from the UK and also highlight several global examples of similar practice where local flooding and drought risk has been reduced. We will argue that as little as 5% of a catchment needs to be managed in order to gain many catchment system level benefits. http://research.ncl.ac.uk/proactive/

Keywords: *Catchment modelling, soft engineering and decision support*

Analytical Hierarchy Process coupled with GIS for land management purposes: A decision-making application

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Abstract: This paper discusses the practical adaptation of a land-use planning methodology in Switzerland as a result of a combined usage of Geographic Information Systems (GIS) and a multiple criteria decision analysis (MCDA) method. The two approaches were integrated in order to help land managers to incorporate the impact of two land-use laws voted by citizens in 2012 and 2013 respectively. The direct democratic system in Switzerland allows citizens to participate actively in the decision-making processes in different fields of interest. In 2012 Swiss people voted in favor of limiting the construction of second homes, this initiative had as slogan "Ending the invasive construction of second homes". The purpose of the initiative is to protect citizens, heritage and the nature as well as the creation and maintenance of cities, habitats and liveable landscapes. According to the initiative, second homes cannot exceed 20 percent of the total community housing of a municipality. Currently this initiative is a federal law adopted by the national council and must be applied by all municipalities. Nevertheless, decision makers (DM) were not provided of an established methodology to determine and justify their choices before the citizens. Furthermore in 2013 Swiss citizens voted for another law on land-use which aims at limiting the size of the areas that will be built. According to this new rule building permit grants will be based on the foreseeable needs for the next fifteen years. In this context municipalities need to make decisions regarding two opposite objectives: How to respect environmental criteria while keeping in mind social-economic issues. Another important question arises: which are the most suitable areas that meet the new legal requirements? These most suitable areas will be freed up at the end of the process.

The main goal of our research was to develop a decision support methodology to help DM to make decisions objectively while minimizing the negative impacts of these choices in the Swiss canton of Valais. For example by identifying the most suitable hectares to be freed up through the zoning process. This was done by using a mathematical psychology method called Analytical Hierarchy Process (AHP) developed by Saaty (1977) which is based on ratio scales derived from pairwise comparisons in this case of spatial criteria. We developed a participatory process where DM and stakeholders with relevant knowledge chose seven spatial criteria. The number of spatial criteria were based on Miller (1956) research which suggested "the magical number seven, plus or minus two" which implies that humans can only process a limited amount of elements in information processes. An applicable solution provided by the integration of AHP and GIS in order to choose the location to be freed up is given by the minimum distance from the theoretical ideal. Thus when the distance from the ideal decreases the criteria are scored higher on the priority scale by the DM and when the distance increases from the ideal, those criteria are scored lower (Carver, 1991). The results were analysed on a GIS with the aim of creating a map series with the visual outcomes. In the first AHP session right before winter (November 2015) DM scored the spatial criteria "distance to the snow removal plan on the roads" was ranked as the most important with a weight of 40.2 percent. In the second AHP session in spring (April 2016) with exactly the same spatial criteria and the same participants the weight of this criteria was only 8.9 percent and was ranked on the fourth place. Other major differences were found among the two AHP sessions in winter and spring.

Results suggest that the timing of the decision-making process might have an impact on the preferences of spatial criteria. At the moment of the first AHP scoring process the city was deploying the snow removal plan. It appears that the relative importance of spatial criteria that are directly influenced by the weather conditions varies considerably if the scoring process is achieved in different seasons. At the end of both sessions in winter and spring respectively DM were satisfied with the two results and discussed openly about it arguing that every result represented their preferences at the moment of each workshop. Important differences were registered in the two AHP iterations so two different spatial scenarios were developed and DM decided to keep both of them. The final decision is currently discussed on a political scheme.

Keywords: *Geo-governance, Analytical Hierarchy Process (AHP), Geographic Information Systems (GIS), decision making, multiple criteria decision analysis (MCDA)*

The Nature Conservation Tool: a decision support system for the NSW National Parks and Wildlife Service

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Abstract: A significant challenge for protected area management agencies is determining priorities for management and ensuring available resources are used in the most effective way. There are many competing conservation priorities, and the risk in not articulating clear priorities and not considering the costs and benefits of actions is that limited resources are not used to the greatest effect.

To help articulate its nature conservation priorities, the NSW National Parks and Wildlife Service (NPWS) has developed a decision support system to guide investment in nature conservation across the State's 871 parks which covers 9% of the state's area. The Nature Conservation Tool (the Tool) has been developed over the last eight years using expert opinion to build and populate computer models with spatially explicit scientific information and other forms of knowledge.

It is the first comprehensive assessment of nature conservation management priorities across the NSW reserve system. It is used by NPWS managers when compiling annual operations plans, when distributing funding for targeted nature conservation projects and when developing park plans of management. It could be adapted for use by other conservation management where suitable information is available for analysis.

The Tool provides information to staff in two formats, as maps and tables of priorities with supporting information. The Tool provides guidance to park managers on where more effort needs to be put into nature conservation management within a park to prevent a loss or degradation of important values. It also provides guidance on where effort could be reduced without leading to a loss or degradation of important values. Guidance is also given on which threats require more resources to reduce the risk to important values.

The Tool uses extensive information from the NSW State of the Parks (SoP) database, a NPWS assessment that since 2004 has collected information every three to four years from NPWS scientists, rangers and managers to monitor and evaluate the condition of and pressures on protected areas and to ascertain how effectively these areas are being managed. The Tool uses information from the most recent 2013 assessment and is designed to be dynamic, with the capacity to be updated after each new SoP assessment.

The Multi-Criteria Analysis Shell for Spatial Decision Support software was used to run three computer models and to combine their outputs to provide the nature conservation management priorities across all NSW parks. The three models used to identify management priorities were: 1) natural conservation values, 2) threats to these values and 3) the condition of these values. These models are primarily based on information from the SoP database, but also incorporate spatial biophysical data from a variety sources. The models are hierarchical, with expert opinion weightings at each level and for each dataset (or indicator).

Experts reviewed, selected and weighted all indicators used in the models. The review of indicators ensured the information used was comprehensive, both its content and coverage, and not correlated with other indicators. The model results were validated with regional NPWS staff at 12 workshops. Expert opinion was also used to combine the values, threats and condition model outputs to provide management priorities.

The nature conservation model contained 24 indicators, the threats model contained 863 indicators and the condition model contained just 7 indicators. The threats model is complex because the SoP database contains consequence and probability assessments for 30 current and 30 emerging threats impacting on ten different nature conservation values. The condition model contained only seven indicators because of a paucity of reliable statewide information on the condition of natural values.

The management priorities have been placed into four nature conservation management categories: critical, very high, high and moderate. Across NSW there are 41 critical parks, 158 very high parks, 495 high parks and 190 moderate parks. The critical parks are scattered throughout NSW from Sturt NP in the north-west to Mimosa Rocks in the south-east, and range in size from under 100 ha to over 200,000 ha, indicating that location and size are not dominating influences in determining nature conservation management priorities.

Keywords: *Decision support system, nature conservation, national park management*

Rapid performance evaluation of government environmental science

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Abstract: The Science Division in the NSW Office of Environment and Heritage (OEH) assessed the performance of 54 sub-programs comprising 144 projects run by the Division in 2015-16. The evaluation was undertaken within approximately six months and included assessment of science projects on climate change, pollution, land and water, biodiversity and community. Termed the Performance Evaluation Framework (PEF), the process used a rapid and rigorous methodology to collect consistent data on the sub-programs and projects to assess their appropriateness, effectiveness, efficiency and impact, against a set of benchmarks.

The Senior Leadership Team (SLT) of Science Division initiated the evaluation and were closely involved throughout the process. A Working Group consisting of two members of the SLT and representatives from across Science Division developed the PEF with support from a small project team and technical experts. The PEF Working Group principally used the then NSW Government Evaluation Framework (2013) to undertake a formative evaluation, informed by published literature.

The SLT and PEF Working Group developed 11 core criteria and nine supplementary criteria to assess performance. Each criterion had five levels to evaluate the: **Worth** (appraisal of appropriateness); and **Value** (appraisal of impact, effectiveness and efficiency). Overall evaluation was described as **Merit** and was determined by the combined consideration of **Worth** and **Value**.

For each of the 11 core criteria, five categories of benchmarks reflecting the different science deliveries we undertake were developed by the Working Group and reviewed by the SLT. The benchmarks categories were: 1. Excellence in delivery and use of relevant, rigorous, accessible, timely science (Project Type 1: **Enhanced Science Delivery**); 2. Foresighting and policy development (Project Type 2: **Inform Policy**); 3. Environmental program delivery (Project Type 3: **Program Delivery**); 4. Public environmental data, information, knowledge (Project Type 4: **Public Information**); and 5. The community acts on and contributes to environmental science (Project Type 5: **Community Action**).

After piloting the PEF on a subset of projects, it was implemented across all 144 projects in Science Division. Project Leaders entered data for each sub-program and project listed in the 2015-16 Science Division Business Plan, under supervision from independent working group members to ensure consistency in scoring and interpretation of questions. Quality assurance was provided by mandating references to evidence used to assign a score and the Project Leaders ranked the Merit of each project or sub-program as **acceptable to outstanding, intermediate** or of **less merit**. The ranking was performed by comparing the sub-program and project score against role-based benchmarks. Results were plotted to facilitate comparison and communication.

The PEF delivered comprehensive, rigorous and consistent information to the Science Division SLT so they could compare performance across 54 sub-programs (made up from the 144 projects). The evaluation guided future strategic directions as well as financial and resource sustainability. Performance against relevant benchmarks also gave clarity to Science Division staff about expectations for project performance. The PEF enabled the SLT to better articulate the value of Science Division work. The ability to provide clear information to the OEH Executive about the merit and performance of Science Division. In addition, to the comparative PEF scores, information was also provided on linkages to OEH goals, science achievements to date and a statement as to why the people of NSW should invest in each sub-program and project.

On reflection, the success of the PEF occurred because the SLT were integrally involved in this initiative, and the PEF Working Group. Project team and technical experts enabled it to be implemented in a practical way. The PEF process demonstrated that rigorous evidence could be efficiently collected and analysed, and effectively communicated in a timely manner to standardise dialogue and data to support decision making.

Keywords: *Environmental science impact, performance assessment, program evaluation, science sustainability, government science*

Innovation policy analysis and decision making: a systems approach

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Abstract: The construction industry is one of the largest and most diverse of the sectors with continuous development. The momentum and impact of the industry's development is highly influenced by a complex system of different elements including innovation. However, the sector is relatively weak at all stages of the innovation process and the strength of collaboration among government, industry and academia is insufficient. It is generally accepted that construction companies invest less in new knowledge and process development as well as engage significantly less in innovation related activities than firms in other sectors. Hence, it is very important to control and manage the significant factors that affect success in innovation taking into account the complexity and the inherent dynamics of the construction innovation diffusion. By doing so, this study addresses the decision making process within the complex innovation process in the construction industry by employing a step-by-step modelling process consisting of a multi-stages analysis, stakeholder-based and modelling approaches. Construction is closely connected to the national social structure and is highly influenced by various institutional actors and interactions among components and, consequently, can be presented as a sectoral system. Hence, the overarching objective of the paper is to introduce a systems approach aiming to conceptualise and formulate an initial simulation model of a complex construction innovation system representing correct and continuous interactions between government, the construction industry and academia. Moreover, the research underpins future development of scenario-generating modelling in order to reveal potential pathways to rational decision-making along with potential policy recommendations and various innovation planning strategies that improve construction innovation performance in the Russian Federation.

Innovation in the construction industry can take various forms and, as a result, is not well represented by official statistics. Therefore, active stakeholder engagement is required to develop appropriate metrics and build the foundations for such a dynamic model, given the level of complexity. As a part of participatory modelling, stakeholder engagement involves: (i) stakeholder identification and stakeholder analysis; (ii) questionnaire-based survey and face-to-face interviews; (iii) consultations with academic and industry professionals; (iv) opinion survey; and (v) facilitated expert workshops. In other words, involvement of stakeholders is an essential requirement given the multi-actor nature of the system under study and lack of data involved. The first research stage aims to identify the most significant barriers, enablers and strategies that most significantly affect construction innovation diffusion in Russia. The results suggest that the construction industry requires assistance and support from the government in order to endure existing impediments and to improve the current lacklustre rate of construction innovation. The next stage determines the degree of influence that the different system's components have on each other. Then, the structural analysis is performed using MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) technique in order to generate the required information about interconnections between the key variables. This stage is effective in building a comprehensive conceptual model, followed by an ongoing dynamic model development, integrating both qualitative and quantitative variables. The model structure highlights that construction companies and academia representatives, along with decision-makers need to acknowledge innovation as a process of development and accumulate innovation capabilities in the whole construction innovation system in order to achieve the benefits of high-level innovation performance. One of the dynamic hypotheses describing the problem under study, centres on how the industry, academia and the government can collaborate to most effectively diffuse innovations throughout the industry.

Keywords: *Systems modelling, stakeholder engagement, construction innovation system, decision making*

The Value of Input Metrics for Assessing Fundamental Research

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Abstract: Fundamental research is high pay-off, high-risk research aimed at game-changing discoveries. These research programs have long-term objectives and may not deliver their outcomes for many years. It has long been understood that small incremental gains in progress are often not a good indicator of the eventual achievement of a program's long-term objectives. So how can governments and corporations ensure that their investment is funding the right research programs?

There has been a significant amount of research into what research programs need to be successful. The findings of such research can be summarised in three points: programming (identifying clear research goals that only fundamental research can solve); ring-fencing (defining a contained program of work which is independent of other short term requirements, parallel income-generating consultancy or intermediate product development); and monitoring (evaluating the outputs and outcomes of research programs). The first two points are relatively easy to achieve, the third can be difficult. While research programs require monitoring to gauge which research groups are performing well and to inform future funding allocations. Output metrics (often called perverse metrics by frustrated researchers) such as the number of journal publications, the impact factors of published papers, or numbers of graduating PhD students, are typical measures used to assess research performance. However, when funding agencies publish the metrics they will use to determine funding allocations, researchers' need to remain competitive for funding results in a shift in their focus. Research focus shifts from meeting the primary objectives (research) to meeting short-term output requirements as dictated by the funding agency's metrics. Significant research shows the negative effect of these metrics on true, forward looking, fundamental research.

We argue that to stimulate fundamental research, performance metrics need to change their focus from monitoring outputs to monitoring inputs. The purpose of assessment is to fund research that is likely to achieve high level objectives. However, with fundamental research, past progress may not indicate future major discoveries. The timing of such discoveries cannot be controlled and therefore performance assessments should not focus on outputs. What can be controlled is the fundamental research-enabling environment; these inputs should be assessed to support future fundamental discoveries. An environment that fosters fundamental research will lead to fundamental research.

In this paper we present four input categories of measures relating to the research environment where assessments should focus. These categories cover various characteristics of the research environment that includes the following: the right people, adequate resourcing, defining the goals, allocating time, putting in place processes to encourage the research and promoting a culture of collaboration. For each of these categories we provide several examples of metrics that could be used.

Keywords: *Metrics, measures, assessing science, assessment of innovation, input metrics, research*

A spreadsheet application for evaluation sub-programs and projects Merit, Worth and Value

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Abstract: Within the NSW Office of Environment and Heritage (OEH), the Science Division undertakes scientific research, investigation, monitoring, analysis, evaluation and reporting on a range of natural resource environmental issues. Covering five broad areas of climate change; land and biodiversity; pollution; water; and community. In 2015, the Science Division managed 54 sub-programs and 144 projects that align to the agencies One Plan services and programs that deliver to the OEH corporate plan.

Summerell et al., introduces the Performance Evaluation Framework (PEF). This is the first time such a process has been used in the Science Division to rapidly access its sub-programs and projects for merit, worth and value. The PEF provides a methodology to capture comprehensive, consistent and rigorous information from sub-program and project leaders. It provides ownership, transparency and a common platform for better understanding of how sub-program and projects deliver to five key benchmarks (i.e. roles of science); strategic organizational management; informing policy; program delivery; public information; and engagement of community in science.

Currently no tool exists within the Science Division other than ad-hoc paper based and non-linked digital format documents. This results in incomplete and inconsistent data, which is difficult to compile and summarise. The result is minimal reporting ability and opportunity for fair assessment and comparison of a sub-program and project outcomes. To overcome these limitations a Microsoft Excel 2013 tool was developed for capture and reporting the PEF information (input/output). PEF information is multi-relational (one sub-program to many projects) and better suited to relational database development; however, Excel was used as an interim simplistic measure. Excel also aligned with other existing OEH financial systems and took into consideration limitations of end user software understanding.

The development of a single tool to provide the capture and delivery of sub-program and project knowledge was crucial to the success of the PEF.

The PEF tool allowed a level of information capture and reporting that has not been provided before within Science Division. The tool was highly accepted and regarded by Senior and Executive Leaders as a pivotal part of providing evidence of the Merit, Worth and Value of current science programs and its funding into the future. The tool allowed staff to evaluate their own projects against set benchmarks. It also provided the Senior and Executive Leaders with rigorous data to support a narrative of the value of science. In the end the tool enabled the Science Division to demonstrate how we deliver science to State, Departmental and community customers.

Keywords: *Environmental science impact, performance assessment, program evaluation, science sustainability, government science*

Assessment of Anxiety on Mathematics for Students in Secondary School in Qatar

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Abstract: Various factors including gender, anxiety, parent socio-economic status and school-specific aspects affect mathematics performance. An analysis of the Program for International Student Assessment (PISA) 2012 data on mathematics performance for secondary school students in Qatar was undertaken. This data includes information on student anxiety and gender among other student and school factors that may potentially impact learning outcomes in the form of mathematics test scores. Results indicate a negative statistically significant relationship between mathematics anxiety and mathematics test scores. This inverse relationship was supported after adjustment was made for other factors that may also potentially affect mathematics performance, indicating lower mathematics scores, on average, among anxious students. It is hypothesised that an attributing factor to the observed association between mathematics anxiety and mathematics performance may be the teaching strategies used that may not adequately attend to the cognitive and psychological needs of students. The degree to which teaching strategies implemented attend to the cognitive and psychological needs of students is a potential area that could be targeted to help improve learning outcomes among students studying mathematics at secondary school. This study assesses the efficacy of various teaching approaches and comparatively assesses their impact on mathematic performance in relation to anxiety levels among students. The implications of this research on suggestions for potential changes to current teaching strategies to acknowledge the potential impact that mathematics anxiety has on outcomes in mathematics is discussed. It is proposed that teaching strategies in Qatar could potentially be reviewed with a view to better cater to the needs of students who are quite anxious about studying mathematics, in an attempt to improve the performance of students nationally as, at present, mathematics performance of students in Qatar is considerably lower than global average standards. Although the average mathematics scores were not significantly different between male and female students, it was observed that males were significantly more anxious compared with females.

Keywords: *Mathematics anxiety, gender, STEM, mathematics education*

Integrating gender dimensions in a model for exploring the implications of agricultural intensification for marginalised communities

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Abstract: The intensification of agriculture is a goal of governments across South Asia, where it is promoted as a means to improve the current and future food security and economic standing of nations, and a way to reduce poverty and improve the livelihoods of rural communities. However, whilst historic agricultural development has undoubtedly led to economic development and increased food security, the social impacts of intensification are not always positive. Within a community some groups are unable to capture the benefits of agricultural intensification and may actually face increased hardship, whilst more affluent or connected people can disproportionately access infrastructure, markets and government incentives. This paper reports on a highly integrative project ("SIAGI") aimed at understanding the drivers of agricultural intensification, and the impacts of these on marginalised households. The project is working with five communities in Bangladesh and India to develop socially inclusive and environmentally and economically sustainable opportunities from agricultural intensification for landless, marginal farmer and women-led households.

The SIAGI project has two study villages in the coastal zone of southern Bangladesh and two major study villages in northern West Bengal, India. Landless, marginal farmers and women-headed households in these communities are heavily reliant on land-and-water based livelihoods. With current agricultural activities unable to provide financial stability to support households, many men seasonally migrate to nearby towns or other areas for labour work. Women have thus taken an increasing role in agriculture despite the many challenges they face in the production and marketing of agricultural commodities. These challenges arise from women's (often) limited power to make decisions or influence others in their home and community, and can be expressed in myriad of ways including lower wages than men, less employment opportunities, a lack of access to resources (land, inputs, credit, extension services, etc.), and inequities in health and well-being. Often women are also time poor as they have to balance their reproductive duties within the households. Consequently, there are expected to be strong gender implications from agricultural intensification in terms of the influence that (e.g.) workloads, resource availability or specialisation may have on inclusion, equality and equity, and ultimately well-being.

The three components of research within SIAGI are: i) institutional, social and economic research (including analyses of value chains, livelihoods, nutrition sensitive agriculture, and the practices of government and non-government organisations), ii) biophysical analyses, and iii) integration. The biophysical component primarily draws upon research from our sister projects, supported with bio-economic household modelling and climate risk analyses. The role of integration is to develop a model that synthesizes and connects the component research. An integrated model can be used, for example, to identify leverage points where a small change can produce high (positive or adverse) impacts on marginalised communities, or to identify and explore potential unintended consequences or counterproductive outcomes.

In this presentation we will report on early progress in incorporating gender into an integrated model for the study villages. We will give consideration to how disciplinary and integrative analytical tools and methods have been used to incorporate gender dimensions into previous development projects. We will then demonstrate tools and techniques that our project team are using to better understand women's influence within local water institutions as well as the power and communication networks that can facilitate rate of change for them. We conclude with a discussion of the implications of gender for our integrated modelling activities.

Keywords: *Integration, agricultural intensification, gender in modelling*

Gender, Water and Modelling: The Manchar Lake Case Study in Pakistan

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Abstract: There is a growing body of literature which considers gender in modelling and simulation, with focuses including women's economic outcomes and dis/empowerment. This paper seeks to contribute to this body of literature by focusing on the nexus between water, gender and social impact, as well as the challenges of making linkages between macro and micro levels of scale. For the purpose of this research, Manchar Lake in Sindh province, Pakistan, was selected for case study through a research partnership between the Pakistan Council of Research on Water Resources (PCRWR), Sindh Irrigation Department, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Australian National University (ANU). Historically, the lake has an ecosystem with diverse flora and fauna, and the local residents had enjoyed prosperity through fishing and agricultural activities as a result. However, due to poor planning in water and irrigation, the lake has now become highly saline with Total Dissolved Solids (TDS) level of the Lake ranges between 3000 - 6500 ppm (high flow – low flow period). Whereas the maximum permissible limit of TDS for drinking purposes is below 1000 ppm, according to the World Health Organisation.

As a result of water pollution, women and men have faced gendered challenges in relation to their health, economic and social outcomes. For instance, traditionally women living by Manchar Lake have enjoyed financial independence through gathering and selling fish and aquatic plants. The lake pollution meant drastic reduction in flora and fauna, which result in women's loss in livelihoods and mobility. Likewise, men also lost livelihoods through fishing and agriculture, and many have migrated to larger cities to pursue low paid, often high-risk jobs such as commercial sea fishing and construction. Poverty also meant parents could no longer afford children's (especially girls) education, while some boys accompany their father as migrant workers. Although ecological assessments have been conducted throughout the years on the impact of lake pollution with some researches including socio-economic and gender-disaggregated, so far there has been no gender integration in modelling and simulation for Manchar Lake. The paper will first outline the context, followed by a case study of how gender was integrated from the beginning: from research design, fieldwork preparation, data collection, and analysis.

Keywords: *Gender, Pakistan, Manchar Lake, water quality, participatory research design*

Quantifying the value of information in reservoir operations

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Abstract: Operating a reservoir requires, at minimum, information about its current state, such as its storage level. In this case, the operation can be considered as purely reactive. Forecasts provide an additional benefit by introducing anticipation in the operation. Forecasts however, come at a cost, therefore it is helpful to know whether the added benefit of forecasts justifies their cost.

This work presents an innovative method for quantifying the value of information in reservoir operations. The method is based on tree-based model predictive control (TB-MPC). TB-MPC is an anticipatory method for controlling systems in real time. TB-MPC accounts for forecast uncertainty by representing forecasted scenarios in a tree structure, made of multiple out-branching. In this work, instead of using tree structures to control a system in real time, this paper proposes the use of tree structures as an analysis tool to estimate the overall operational performance under varying levels of information. This paper proposes the use of tree structures to emulate the decision-making process of a reservoir operator in how they respond to and/or anticipate all possible future conditions (scenarios) that the reservoir may be subjected to considering the information they have available.

Branching points in a tree structure occurs when a scenario can be distinguished by the operator from other scenarios. It represents the time when the reservoir operator is certain that one scenario is occurring instead of another based on the information that they have. Earlier branching points will result in improved operations, because they enable the operator to respond earlier to the occurring scenario and neglect the non-occurring ones. Better information (e.g. availability of forecasts, better measurements etc.) will move the branching point earlier in time.

In this paper, the application of this method is illustrated using simplified test cases. As indicated in the test cases, applying this method will require:

1. A method to generate ensembles of future inflows, such as an ARMA model, with parameters fitted to historical inflow observations. The ensemble size generated can be large and likely to be computationally demanding to process, therefore lumping similar ensemble members together is recommended to reduce computation times
2. A quantification of inflow observation and forecast uncertainty, such as a forecast error covariance matrix. This will influence the branching points of the tree structure, and
3. An objective function to optimise reservoir operations. This is to emulate the decision-making process of the reservoir operator.

The results of the test cases demonstrate that:

1. Better information results in tree structures with earlier branching points, and
2. Tree structures with earlier branching points result in improved reservoir operations

Using the method, the expected value of an information source (e.g. inflow forecasts) can be estimated by creating enough tree structures to sufficiently represent all conditions observed by the operator at present and all ensuing future scenarios the reservoir is subjected to. The overall value of information is then calculated by averaging the 'score' of the operations under all conditions according to their respective probabilities. If the objective function is expressed in monetary terms, this approach can potentially be used compare the value of having information against the cost of procuring and maintaining that information source.

Keywords: *Optimisation, operational water management, forecasting, value of information*

Re-imagining standard timescales in forecasting precipitation events for Queensland's grazing enterprises

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Abstract: The typical presentation of precipitation and climate information is organised according to the Gregorian calendar defined by the months and, in alignment with the temperate, savanna and desert climate zones of Australia, the three monthly seasons. While this is sufficient for many human-centred operations and the currency acceptable norm, grazing land managers (and potentially workers in other agricultural based enterprises) are reportedly restricted in their use of precipitation and climate information presented in this form. Compounding this issue with standard temporal packaging of climate information is the lack of reliability of the forecasts and spatial resolution capacity in the existing precipitation prediction tools that are being promoted to the graziers. Due to a lack of temporally and spatially robust information, graziers are managing their operations in the presence of significant risks, threatening their contributions to Australia's $17 billion red meat and other industries.

Grazing land managers require access to near real-time drought data that will enable the timely and informed decisions to be made about the movement of stock from the cattle stations to the grazing and/or growing properties. Providing graziers with this information having appropriate temporal resolution of the drought status for specific locations will enable the most productive use of the available grazing lands to grow the cattle to specified weights before slaughter. Hence a novel forecasting approach using data driven models of the monthly rainfall decile drought index (RDDI) is being considered in this paper, where the calculation of relative monthly indices are updated on a running weekly basis, providing land managers with spatially and temporally refined information. A similar process is proposed for the determination of relative seasonal rainfall indices, in addition to the consideration of the alternative definitions of Australian seasons as identified in existing literature.

In future development of this research work, this approach will be used to forecast precipitation patterns, where the machine learning models' architecture will be trained and evaluated with historical records of precipitation and other significant climate variables from a selection of sites relevant to the cattle industry around Queensland, Australia. The forecasts are to be derived from the novel implementation of a data intensive hierarchical categorizing support vector machine framework (or alternatively a regression-based data-intelligent model) which is being proposed to deliver the graziers with the appropriate information to plan their operations within the stochastic nature of Australia's climate.

When compared with the seasonal and calendar monthly deciles, the more frequent forecast feeds (i.e., over weekly updated drought status, yet utilizing the concept of decile-based drought) presents a more detailed and robustly reported distribution of rain over the future seasons at specific sites, whilst catering to the graziers' reported decision making processes. The more temporally refined presentation of the predicted rainfall events, for specified sites, has the potential to provide graziers (and other agricultural ventures), with the most relevant information to allow for more confident and profitable management of their enterprises.

***Keywords**:* *Timescale, drought, deciles, month, season*

Victoria's water table over 30 years: Geostatistical approaches for hydrological insights

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Abstract: Groundwater level is the only widely monitored hydrogeological state variable and Australia has over 15,000 currently active monitoring bores and many more bores with good past water level records. The data are primarily used for graphical hydrograph analysis and occasionally for groundwater model calibration. However, the data could be used to inform regional subsurface and runoff processes and we argue that these opportunities have not been fully explored; possibly because of the low frequency and sparsity of monitoring, hydrogeological and forcing complexities and groundwater level data being first and second order non-stationary over space and time. To realise some of these possibilities, herein advanced space and time statistical methods are presented and applied to map the watertable level across Victoria from January 1985 to August 2014.

The statistical methods involve (1) Markov Chain Monte Carlo time-series model calibration of every unconfined groundwater hydrograph in Victoria (n=10,362) using HydroSight (http://peterson-tim-j.github.io/HydroSight/) to interpolate hydrographs at monthly time-step; and (2) geostatistical spatial interpolation of the monthly groundwater level using our R package *GroundwaterMapper*. The geostatistical interpolation comprises of numerous new kriging methods that account for local topographic form, remote sensing of groundwater dependent ecosystems, landuse, land surface elevation and fixed-head conditions (e.g ocean). Furthermore, variograms can be anisotropic and all kriging parameters are set by minimising a cross-validation likelihood function coupled to a mixed data-type global calibration scheme.

In applying the methods, water table maps were produced for all of Victoria for each month from January 1985 to August 2014 (example in Fig. 1). The maps show highly plausible groundwater levels and, relative to existing methods, show significant improvements in the estimation at upland catchments, coastal areas and the area implausibly predicted as artesian. The groundwater flow directions are also highly plausible, with reaches known to be losing and gaining groundwater being identified as such from the groundwater potentiometry. Generalising these findings to other major reaches, the stream-groundwater interaction was characterised based on the tangential curvature of the potentiometry and the fraction of each the reach gaining groundwater was quantified over time; the results from which show the impact and partial recovery from the Millennium Drought. Additionally, regions are identified that were most severely impacted by the Millennium Drought and those that, by 2014, were yet to recover. In summary, our groundwater statistical tools open many opportunities for data-driven insights to regional groundwater dynamics and new opportunities for understanding long-term catchment dynamics.

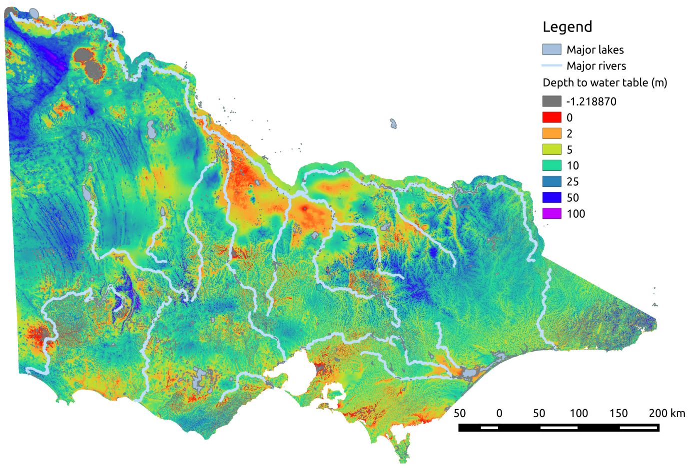

Figure 1. Depth to the water table across Victoria for April 2000 derived using the proposed new approach. Importantly, the interpolated heads were appropriately smooth and this produced very heterogeneous depths, which cannot be achieved using existing approaches.

Keywords: *Geostatistics, interpolation, groundwater, hydrogeology*

Evolution of wetland monitoring from inventory to functional assessment and modelling: a case study from a US catchment

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Abstract: Wetlands provides important ecosystem services. Despite increasing recognition for their importance as a natural resource, wetlands are continuously facing a high risk of loss and degradation. Geographically isolated wetlands (GIWs) and headwaters are most vulnerable. They are temporary water ways with relatively small size. They can be easily filled to support other uses without permits and generally unprotected under the legal framework in the US [US EPA, 2015]. However, there is increasing pressure to consider cumulative influence of certain types of GIWs on downstream water. While debates on protecting temporary waterways continue, improving understanding on the wetland hydrology and stream-wetland connection is crucial. This requires reliable information to update the status and changes on wetlands and rapid assessment tool to investigate the strength and frequency of the wetland connectivity to other water bodies.

The U.S. Fish and Wildlife Service (US FWS) provides information on the extent and status of wetlands, through National Wetlands Inventory (NWI) [Cowardin & Golet, 1995]. The NWI is a spatial dataset that features wetlands and deep water habitats in consistent standardized ecological classification. However, the NWI, similar to other regional land use maps, is a categorical map. It does not provide information on inundation extent. Inundation is highly dynamic and can vary remarkably time to time, in response to multiple drivers and the local hydrological condition. It is a key factor controlling the ecological functioning of a wetland.

In this study, we first demonstrated a practical and effective regional framework to develop long-term wetland inundation record. Using Landsat time records and airborne Light Detection and Ranging (LiDAR) intensity data, we generated a set of temporally consecutive maps of subpixel water fraction (SWF). The SWF maps indicate the percent of surface water within every 30-m Landsat pixel at an annual time basis over 1985-2011. They can provide crucial information on change dynamics and inundation extent of wetlands. When the mapping was demonstrated for the Coastal Plain of the Chesapeake Bay Watershed (CBW), comprehensive accuracy assessments of the SWF maps resulted in an estimated root mean square error (RMSE) of 7.78% for open water area. Moreover, a separate accuracy assessment targeting inundation in wetlands (i.e. presence or absence of water) yielded an overall accuracy of 93%. These results indicated that Landsat data can be calibrated to accurately extract long-term water information at the regional scale.

We then demonstrated how SWF maps and NWI can be used to assess the cumulative impacts of headwater wetlands on downstream water, and how such data could assist us to overcome the challenges in modelling wetland hydrology and assessing the hydrological connection to downstream water at the local landscape level. The study was conducted on the coastal catchment in the upper region of Choptank River in CBW. The study area included a dense network of wetlands, which made up for ~ 30 % of the catchment area in aggregate. When assessed at the local scale, it was evident that the SWF maps showed inundation changed in response to the weather variability, and the change trend was consistent with daily stream flow ($r = 0.81$; p-value < 0.01) and base flow ($r = 0.57$; p-value < 0.1). Furthermore, the change patterns followed the characteristics of the hydrological regimes (i.e., hydroperiod, the seasonal variation of inundation) described by NWI. The catchment-scale, cumulative impacts of GIWs was further investigated using the catchment scale simulation model, Soil and Water Assessment Tool (SWAT), with improved wetland extension. Results showed significant, cumulative, catchment-scale hydrological impacts of GIWs. GIWs changed the partitioning of precipitation between actual evapotranspiration (AET) and stream flow, and the major transport pathway of water delivery into the stream flow. Wetland dominated catchment produced lower AET, but maintained higher streamflow mainly delivered by the groundwater. This study demonstrates the evolution of mapping and monitoring wetlands using remote sensing, and the progress toward modelling wetland function using improved water information and a catchment scale model.

***Keywords**: Wetland classification, spatial data, remote sensing, inundation, wetland modelling*

EXTENDED ABSTRACT ONLY

Evaluation of Australian Water Resources Assessment River (AWRA-R) Model for SEQ Catchments

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Abstract: The Bureau of Meteorology is responsible for producing a range of products and services as federally mandated through the Commonwealth Water Act (2007) including the National Water Account (NWA). It relies on close collaboration with many government agencies and water service providers in Australia. The NWA has been published annually since 2010, reporting on water rights, water stores, flows and water use in a set of regions across Australia including the Murray-Darling Basin, South East Queensland (SEQ), Perth, Ord, Burdekin, Sydney, Adelaide and Melbourne (www.bom.gov.au/water/nwa). This information is compiled based on the available observed data or estimated/modelled data where observed data is not available. At present, a number of river water balance components such as river volume, losses, overbank flooding and return flow, rainfall and evaporation cannot be reported due to lack of suitable quantification approach, which leads to a number of unaccounted components within the water balance.

The AWRA-R is a node-link network based river system model which includes explicit representation of key hydrological processes and anthropogenic water uses developed towards supporting the Bureau's water reporting responsibilities. It was developed with the express purpose of retrospectively estimating the river water balance components to support the NWA. Quantification of these components is useful not only to contribute to the NWA for the region but to assist local water managers and state authorities account for these river fluxes in their water allocation and planning as well as for reservoir operations. It should be noted that AWRA-R inputs are frequently updated in an operational system and these fluxes can therefore be made known by informing users of the amounts of water available and lost within the river system on a daily basis.

The work presents the application and evaluation of AWRA-R to the SEQ region covering six catchments. For this application, the system was divided into 65 reaches. The model was calibrated from 1970 to 2016 individually for each reach using an auto-calibration system where observed data at upstream gauges feeds into the model as well as ungauged runoff from AWRA-L and other water uses within a reach. Model performance was evaluated against observed streamflow using Nash-Sutcliffe efficiency (NSE) and bias. It was found that the model performance is highly satisfactory with median values of daily and monthly NSE are 0.68 and 0.92 respectively, and the bias is almost zero.

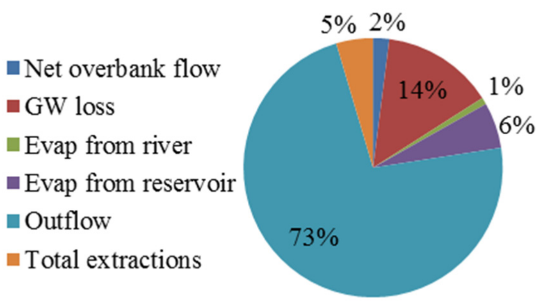

Figure 1. Long-term average of AWRA-R fluxes for the SEQ catchments

Based on the above results, the AWRA-R application to SEQ was deemed suitable for annual water accounting within the catchment, for the first time providing a region wide estimate of the relative amounts of river water balance fluxes such as river groundwater losses, overbank flows and return, and river surface rainfall and evaporation based on a seamless approach. The long-term average of these fluxes over the simulated period is shown in Figure 1. The figure shows that of the total inflows into SEQ rivers, around 73% flows out to the sea, 14% is lost through the riverbed into groundwater, 6% loss from the reservoirs and 2% is the net loss from overbank flow events. To evaluate the impact of AWRA-R application in NWA, these fluxes were used in the past years' NWA (i.e. NWA 2011 – 2016) and found that the inclusion of these river fluxes reduced the unaccounted difference by up to 93%.

Keywords: *River modelling, National Water Account, South East Queensland, AWRA-R*

Urban water sustainability in Australian cities: using the National Water Account to indicate the resilience in water systems

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Abstract: Securing water in Australia is particularly challenging in the context of the country's high natural hydro-climatic variability, population growth and implications from emerging changes of climate pattern. To make informed decisions about Australia's future water security, sound and independent information is needed about the balance of supply and demand across the country.

Under the Water Act 2007, the Bureau of Meteorology (the Bureau) was legislated to provide standardised water information across the country; information that previously was not readily available to the public in Australia. The Bureau's annual National Water Account, with its first publication in 2010, provides water resource management information across ten regions in an independent, accountable and reliable form. The accounts are built through close partnership with reporting partners from a wide range of organisations in each State and Territory, as well as other Australian Government agencies, to gather the best available water related physical and regulatory data.

This paper discloses information on urban water availability, allocation and use in six major cities in Australia from the National Water Account perspective and emphasises the balance between water supply and demand over the past six financial years (2010–11 to 2015–16; 1 July to 30 June). Past accounts have shown that total water use in urban centres has steadily increased at the rate of 2–3 per cent annually. Water security across Australia relies mostly on surface water, particularly for the Canberra, Sydney, Melbourne and South East Queensland regions. In Perth, groundwater and desalinated water supply are now the major sources of water due to low surface water availability. In Adelaide and Melbourne, water supply through inter-regional transfers assist in mitigating poor storage inflows.

Using data from the National Water Account, in an analogy to financial indicators, we have developed a number of indicators for water systems under the themes of sustainability and liquidity. This paper presents these indicators for the six urban centres, and shows how the indicators can be useful for a comparison of water supply stress, flexibility, security and resilience between regions as well as for highlighting emerging issues, prioritising and targeting resources.

Keywords: *National Water Account, water resilience, sustainability indicators, water availability, water use*

Daily gridded evapotranspiration estimates for Australia

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Abstract: There are various Evapotranspiration (ET) estimates/products available for agricultural, engineering, and operational purposes including (a) Evaporative demand (potential ET) and actual evapotranspiration; (b) FAO56 Reference Evapotranspiration from crops and (c) Evaporation from reservoirs, rivers and farm dams.

The Bureau of Meteorology currently provides daily national gridded actual and potential landscape evapotranspiration products via the Australian Landscape Water Balance website www.bom.gov.au/water/landscape. However, while the Bureau produces Daily FAO56 reference ET at 486 automatic weather station sites across Australia (through www.bom.gov.au/watl/eto), there is no equivalent gridded daily product. In terms of evaporation from reservoirs, rivers and farm dams; the Bureau measures Class-A pan evaporation records at 179 locations across the country, and has used these observations over the period 1975-2005 to produce a static set of monthly, seasonal and annual average maps (www.bom.gov.au/jsp/ncc/climate_averages/evaporation). Again, there is no equivalent daily gridded product equivalent to the pan evaporation, or perhaps more importantly a product specifically designed for estimation of evaporation from water bodies. Further, in both of these cases the observational sites locations can often be far from the location of interest, and interpolation of these data, as done to produce the maps, can be strongly biased due to local meteorological effects.

This paper evaluates six daily gridded products including (a) synthetic pan evapotranspiration for operational demand/evaporation monitoring and planning (PenPan), (b) FAO56, (c) ASCE tall crop Reference evapotranspiration for irrigation/agricultural purposes, (d) Penman (as applied by Donohue), (e) Morton areal estimates of ET, and (f) Morton's shallow lake evaporation. The input datasets used to derive these products are compared against available data, and interim (long wave radiation) and derived variables (class A pan evaporation) are compared against observations where available. These products are compared relatively and with available data such as the average maps and for a single site (Fig. 1).

The comparisons show that gridded data inputs were not systematically biased with respect to station climate inputs (temperature, solar radiation, 2m wind) as expected as these data are used in generating the gridded products used. Biases were found in the approach used in FAO56 to transform 10 m observations to 2m wind observations; while the gridded wind 2m product used circumvents this issue. Gridded 2m wind products are recommended to be used in place of transformed 10m wind. Secondly, the PenPan estimate of pan evaporation correctly captured temporal trends (following Donohue) but was biased positively in some locations with further investigation required to understand why this differs from Donohue. Spatial plots of annual maps and site temporal statistics demonstrate the differences between the different methods tested. Further testing is required to evaluate and demonstrate the value of using satellite derived vegetation indices (MODIS as available operationally in the Bureau vs AVHRR used in Donohue). However, the estimates of ET (FAO56, ACSE tall, Morton shallow lake and PenPan) can be implemented immediately on the proviso that there are some differences with pan data, and these will be investigated, with products expected to improve over time with improved inputs and algorithms.

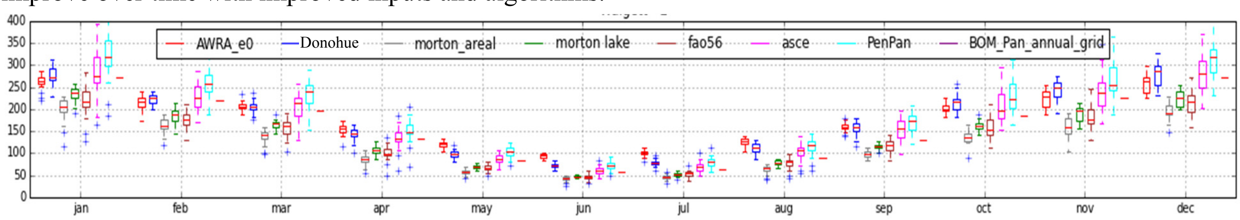

Figure 1. Boxplot of Walgett 1990-2011 monthly ET (mm/month) according to tested methods.

Keywords: *PenPan, FAO56, ASCE tall, Penman, Morton areal, gridded, evapotranspiration, evaporation*

Updating the Atlas of Groundwater Dependent Ecosystems in response to user demand

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Abstract: In many parts of Australia, there is increasing pressure on water resources from various activities including agriculture, mining, urban and commercial developments. Groundwater dependent ecosystems (GDEs) are vulnerable to altered groundwater regimes including flow, pressure, level and/or quality associated with such activities (Eamus et al. 2006). Understanding their locations and groundwater dependency is essential for the management of GDEs. The Atlas of Groundwater Dependent Ecosystems (the Atlas) is the national inventory of mapped GDEs in Australia. By making data easily available, the Atlas ensures GDEs can be considered in natural resource management, water planning processes and environmental impact assessments.

The Atlas was first released on the Bureau website in September 2012. The original data in the Atlas was collected during 2009-10 at the national scale and there has been considerable progress in GDE mapping at the State and regional scale since this time. For example, the Queensland Government has created catchment-scale GDE maps for over half of their State.

Due to an overwhelming request from users and stakeholders, the Bureau of Meteorology has worked with State and Territory water agencies to update the Atlas and maintain its currency. The Atlas has been updated with new regional-scale mapping for parts of New South Wales, Northern Territory, Queensland, South Australia and Victoria. To update the Atlas, the Bureau collated State and regional GDE datasets from a number of agencies for each of the GDE layers: Aquatic, Terrestrial and Subterranean. Coverage was partial for most States, and datasets were created using a range of methods developed for different purposes which are no longer nationally consistent.

To convey information about differences in data source, the attribution of GDEs was updated to clearly distinguish between pre-existing data from the national assessment and new datasets, whilst retaining key national scale information about the GDE potential (the confidence in the identification of an ecosystem as groundwater dependent). New attributes were added to the data model to capture information about the data source. Each dataset required a different approach for integration, and consultation with States and Territories helped in determining this process. The key steps for each State or Territory update were:

1. pre-processing of State and Territory datasets into new data model format
2. attribution of known and potential GDEs according to new rule system
3. mapping of data, which either involved replacing existing data or using precedence rules where overlap occurred
4. populating new data schema using State attributes
5. running Python script to populate national attributes.

In this paper the Queensland Government's GDE data is used as an example of how the Bureau integrated the new State GDE data into the Atlas to ensure that the best available GDE data can be accessed from a central location. Building on the success of the update, the Bureau has established a national GDE Reference Group to continue communication with data custodians, GDE experts and Atlas users. This group will facilitate ongoing access to updated GDE data in order to maintain the currency and relevance of this important product into the future.

Keywords: *Groundwater dependent ecosystem, groundwater, geographic information system*

EXTENDED ABSTRACT ONLY

Reporting groundwater use and availability under the Murray–Darling Basin Plan

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Abstract: Robust water accounting and compliance in any groundwater system ensures that the volume of water actually taken does not exceed the volume of water that is permitted to be taken. This protects investment by governments, corporations and individuals and increases certainty and security for all water uses.

The Murray–Darling Basin Plan (Basin Plan), adopted in November 2012, represents a significant milestone in groundwater management in Australia. It is the first time that a limit of 3,334 GL/y on groundwater use has been established across the Basin. This limit is expressed through the application of sustainable diversion limits (SDLs). The Basin Plan prescribes 22 water resource plan areas and 81 SDL resource units relating to groundwater. Each SDL resource unit has a separate SDL to which the states must manage extraction.

Because the Basin Plan has not yet been fully implemented, groundwater use accounting and compliance in the MDB is in transition. To support compliance with the SDLs after 2019, section 71 of the Water Act 2007 (Cwlth) establishes new groundwater use reporting requirements. Basin states and the Commonwealth Environmental Water Holder (CEWH) are now required to undertake monitoring and reporting of annual water availability and use in accordance with these arrangements.

Given requirements for reporting against all forms of groundwater take, the Authority and Basin states have identified the transition period as an important opportunity to establish and agree, trial arrangements for calculating and reporting actual and permitted take in ways that will support SDL compliance from the 2019/20 water year onward. The Authority and Basin states are currently investigating using the Australian Water Resources Assessment (AWARA) operational modelling system by the Bureau of meteorology to improve the accounting of water available and Water accounting concept as a mechanism for reporting on the basin plan. This will help to ensure that there is continued confidence in the security of water entitlements and the effective operation of water sharing arrangements and trade through the water market.

Keywords: *Groundwater, water accounting, Basin Plan, reporting, AWARA*

Use of AWRA-R model to improve the National Water Account

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Abstract: The National Water Account (NWA: see http://www.bom.gov.au/water/nwa) is a federally mandated report published annually by the Bureau of Meteorology through the Commonwealth Water Act 2007. The NWA is Australia's most comprehensive water information report. The NWA discloses information about water stores and flows, water rights and water use. It also reports on the volumes of water traded and provided for economic, social, cultural and environmental benefit. It provides a picture of water resources management for the previous financial year for ten nationally significant water regions: Adelaide, Burdekin, Canberra, Daly, Melbourne, Murray–Darling Basin (MDB), Ord, Perth, South East Queensland (SEQ) and Sydney. These regions are home to about 75% of Australia's population and represent 70-80% of Australia's water use.

The NWA relies on close collaboration with many government agencies and water service providers in Australia for its information about water rights, water store volumes, flows and water use. This information is compiled based on the available observed data or estimated/modelled data where observed data is not available. The NWA relies for some of its modelled data on the Australian Water Resources Assessment - River (AWRA-R) model. AWRA-R model was developed by CSIRO and the Bureau of Meteorology towards retrospective quantification of surface water items in the NWA and for water resource assessment purposes; using available observed data and inferring other water balance items that are not available. AWRA-R estimates a number of river fluxes and water store volumes such as river volume, river losses, rainfall in and evaporation from the river, water use, and overbank flooding. This paper assesses the improvement in reporting items required for the NWA through the introduction of AWRA-R; in particular assessing the reduction in the unaccounted for difference item. Relatively high unaccounted-for difference was experienced in the past as several reporting items (now estimated through AWRA–R) were partially estimated or not estimated at all.

AWRA-R is a node-link network model developed with explicit representation of key hydrological processes and anthropogenic water uses to quantify various river fluxes and stores at a daily temporal resolution along the river network. The river system is generally conceptualised as nodes at stream gauging stations and connected by river reaches. Runoff from gauged or ungauged tributaries or local contributing area between the two nodes is fed into the connecting reach as an inflow. The river reach is then used to transfer flow between two nodes with routing and transformation of the flow, precipitation and evaporation on/from the river surface, seepage losses, overbank flow, diversion and storage in reservoirs.

At present, the AWRA-R model has been applied for five NWA regions, namely, MDB, SEQ, Melbourne, Perth and Canberra. Outputs from these model applications can be used to produce the relevant reporting items on river fluxes and water store volumes which were not available or partially available in the NWA for past years (i.e. NWA 2011 – 2016). We demonstrate how including relevant reporting items estimated using AWRA-R for past years can reduce the unaccounted for difference and thus improve the NWA. It was found that the use of AWRA-R river fluxes and water store volumes in the NWA contributes considerable improvements across all five regions.

Keywords: *River modelling, National Water Account, AWRA-R*

Bureau's Groundwater Information Suite: National Groundwater Products to Suit a Range of Users

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Abstract: Access to nationally consistent water information is essential to support informed decision-making about Australia's vital groundwater resources. Groundwater data is typically not available in a nationally consistent format because it is managed at a local scale, with local format and terminology. Under the Commonwealth Water Act 2007, the Bureau of Meteorology collects, standardises, stores and analyses groundwater information from lead water agencies around Australia to ensure the best available information is on hand to help understand this complex and largely hidden resource. The Bureau of Meteorology (the Bureau) has adopted a collaborative approach and worked closely with State and Territory governments and other Commonwealth agencies to produce the Groundwater Information Suite, a suite of products designed to inform national groundwater priorities.

The comprehensive set of Bureau groundwater products includes: *Australian Groundwater Insight* – an interactive mapping application that provides hydrogeological information alongside information about licenses, entitlements, bore density, groundwater management areas, and groundwater level and salinity assessments that are easily understood by non-groundwater experts; *Australian Groundwater Explorer* – a sophisticated mapping application for visualising and downloading groundwater data for over 850,000 bores with water level and salinity available as tables and graphs; *National Groundwater Information System* – a spatial database containing standardised groundwater data such as bore purpose, lithology, construction and hydrostratigraphy logs; and *Groundwater Dependent Ecosystems (GDE) Atlas* – an interactive map containing a comprehensive national inventory of ecosystems that depend on groundwater.

The Bureau's groundwater products are used by a range of organisations including government, universities, environmental and engineering consultants as well as mining companies. The Bureau implements a range of methods such as a groundwater mailbox, user surveys, presenting at conferences and industry events, trade stands at conferences, collaborative projects, Groundwater Product Reference Group and GDE Reference Group meetings to identify the user requirements and access local knowledge of groundwater systems. For example, the Bureau is working in collaboration with staff from Southern Rural Water (SRW), who manages groundwater in the Southern half of Victoria and initiated the Victorian Aquifer Framework. This collaboration has updated and improved the national aquifer boundary dataset and linked it to the National Aquifer Framework. Using data provided by Victoria and NSW, the Bureau in collaboration with Department of Environment, Water and Natural Resources from South Australia (SA) also created the 3D hydrostratigraphy model of the Murray Basin.

The strength of the Bureau's Groundwater Information Suite is to provide consistent and easy access to data across state borders. For example, when SRW is assessing a new groundwater licence located in the Victorian South West Limestone Groundwater Management Area (GMA), the Bureau's groundwater products allows access to relevant information from across the state border in SA. This information can be used to inform impacts on nearby users and the environment. Accordingly, entitlement and licenced entitlements for Lower Limestone Coast GMA are obtained from the Groundwater Insight to identify the nearby groundwater licences in SA. Also, the groundwater level status and the trend data for bores are used to understand the groundwater condition such as whether the aquifer is stressed. The salinity levels in the Groundwater Insight are used to assess the suitability of water for use. Using the GDE Atlas, GDEs and groundwater bore information within a 5 km radius of the proposed location of the licence can be identified and used for impact assessments by independent hydrogeologists on behalf of the applicant.

The Groundwater Information Suite was developed to meet the need for groundwater information at a national scale in a consistent format. Our analysis has shown that the products have a broad user base across many sectors. By understanding the users and their needs and collaborating with groundwater experts from state water agencies and water utilities, the Bureau continues to improve the groundwater products.

Keywords: *Groundwater, information, levels, user requirements*

Facilitating improved access and integrated use of data - a case study using the AWRA-L dataset

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Abstract: Availability and publication of data is increasing greatly throughout the scientific community. However, discovery, access and use of the data remain a challenge – in particular, access in modelling and data environments at the user end. On the consumption of data end, scientists are still having to manually access, download, interpret, wrangle, process and clean data prior to any analysis steps relevant for the research activity. Thus access to and use of scientific data needs to be more seamless as research activities become more data-intensive. On the supply of data end, data publishers and providers are publishing data but through heterogeneous platforms, distributions channels, and in a wide range of formats and data models. There seems to be a gap between how data is accessed and how data is published. We argue in this paper that this gap ought to be narrowed.

In this paper, we propose a methodology for assessing the quality of a dataset's publication arrangement and implementing recommendations from an assessment. The assessment component uses a tool called the 5-star data self-assessment tool, which has been developed under the OzNome initiative. The tool implements concrete questions based on the FORCE11 FAIR data guiding principles. This is used in a case study looking at the Bureau of Meteorology's AWRA-L data as a running example. Using the AWRA-L data, we present a summary of this assessment and candidate recommendations to address identified gaps. We then present a summary of implementations to address these gaps. We subsequently show how outputs of these implementations can be leveraged in the modeling environment for AWRA-L via an example using Jupyter-Python notebooks.

This paper also explores specific tools and approaches for improving access and interoperability of datasets in the earth and environmental sciences domain, particularly gridded datasets, as part of examining improvements to recommended parts of the data supply chain. In particular, prior methods used in eReefs were implemented for AWRA-L to improve the binding of reference metadata, controlled vocabularies of the observable and modelled properties referenced, and the actual data. These leveraged tools and approaches such as Linked Data, a vocabulary registry, and web services. Application of these methods resulted in a set of AWRA-L reference metadata that were key components to the integration of data and the conceptual definitions of the modelled properties referenced by the AWRA-L data itself. The governance and operationalization of the AWRA-L reference metadata is being investigated for future work.

The methodology presented in this paper serves as a general approach to assessing and monitoring the quality of a dataset's delivery and access arrangement. It provides data providers with concrete steps that they can take towards improving data provision arrangements. It provides data users with information on the properties of a dataset and an indication of its provision arrangements.

Keywords: *Data integration, AWRA, FAIR data, netCDF, spatial data*

Fitting the Bartlett-Lewis rainfall model using Approximate Bayesian Computation

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Abstract: The Barlett-Lewis (BL) rainfall model is a stochastic model for the rainfall at a single point in space, constructed using a cluster point process. The cluster process is constructed by taking a primary/parent process, called the storm arrival process in our context, and then attaching to each storm point a finite secondary/daughter point process, called a cell arrival process. To each cell arrival point we then attach a rain cell, with an associated rainfall duration and intensity. The total rainfall at time t is then the sum of the intensities from all active cells at that time.

Following Rodriguez-Iturbe et al. (1987), we suppose that the storm arrival process is a Poisson process, and that the cell arrival processes are independent Poisson processes, truncated after an exponentially distributed time (the storm duration). Rain cells are all i.i.d., with independent exponentially distributed duration and intensity.

Because it has an intractible likelihood function, in the past the BL model has been fitted using the Generalized Method of Moments (GMM). The puprose of this paper is to show that Approximate Bayesian Computation (ABC) can also be used to fit this model, and moreover that it gives a better fit than GMM. GMM fitting matches theoretical and observed moments of the process, and thus is restricted to moments for which you have an analytic expression. ABC fitting compares the observed process to simulations, and thus places no restrictions on the statistics used to compare them. The penalty we pay for this increased flexibility is an increase in computational time.

The ABC methodology supposes that we have an observation D from some model $f(\cdot|\boldsymbol{\theta})$, depending on parameters $\boldsymbol{\theta}$, and that we are able to simulate from f. Let π be the prior distribution for $\boldsymbol{\theta}$ and $S = S(D)$ a vector of summary statistics for D, then ABC generates samples from $f(\boldsymbol{\theta}|\rho(S(D^*), S(D)) < \epsilon)$, where $D^* \sim f(\cdot|\boldsymbol{\theta})$, $\boldsymbol{\theta} \sim \pi$, and ρ is some distance function. If S is a sufficient statistic, then as $\epsilon \to 0$ this will converge to the posterior $f(\boldsymbol{\theta}|D)$.

The choice of good summary statistics is important to the success of ABC fitting. To fit the BL model we used rainfall aggregated over six-minute and hourly intervals, and then compared the mean, standard deviation, auto-correlation at lags 1 and 2, probability of no rain, mean length of wet and dry periods, standard deviation of wet and dry periods, and the total number of wet and dry periods We note that for GMM fitting we can only use the first five of these statistics, because we do not have analytic expressions for the others. Using a simulation study we demonstrate that ABC fitting can give less biased and less variable estimates than GMM. We also give an application to rainfall data from Bass River, Victoria, July 2010. Again we see that the ABC fit is better than the GMM fit.

An important advantage of ABC fitting over GMM fitting is that we can use summaries of the data that capture useful information, whether or not we have an expression for their expectation. Moreover, this means that ABC can be used for models for which GMM fitting is not available. For example, if we used a gamma distribution for the duration of a rain cell, rather than an exponential distribution, then we would not be able to calculate the second order statistics of the model, making GMM fitting impossible. However ABC fitting would proceed as before, with the addition of a single parameter. This opens up the possibility of fitting much more realistic stochastic rainfall models.

Keywords: *Bartlett-Lewis process, rainfall, simulation, Generalized Method of Moments, Approximate Bayesian Computation, Markov Chain Monte Carlo*

Non-linear multiple regression analysis for predicting seasonal streamflow using large scale climate mode

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Abstract: New South Wales which is one of the major contributors of Australia's agricultural income, often undergoes extreme climate conditions like droughts and floods due to its geographical location and climatic inconsistency, resulting in high inter-annual variation in streamflow. This study presents a solution to this problem developing streamflow prediction models with long lead time scale using the statistical Multiple Non-Linear Regression (MNLR) techniques. While most of the past studies were concentrated on revealing the relationship between streamflow and single concurrent or lagged climate indices, current endeavour is to explore the combined impacts of large scale climate drivers to forecast seasonal streamflow considering their relationship to be non-linear. Several oceanic and atmospheric climate indices are selected considering their influence on the streamflow of NSW which includes four major climate drivers of this region PDO (Pacific Decadal Oscillation), IPO (Inter Decadal Pacific Oscillation), IOD (Indian Ocean Dipole) and the ENSO (El Nino Southern Oscillation) indices. The developed models with all the possible combinations show significantly good results in terms of Pearson correlation(r), and Root Mean Square Error (RMSE). The outcomes of MNLR models are compared to the best models of Multiple Linear Regression(MLR) analysis which was performed in one of the previous studies of this research. MNLR models are evident to outperform the MLR models in terms of Pearson correlation (r) values in both calibration and validation stages, verifying the non-linear relationship between seasonal streamflow and large-scale climate drivers. The maximum correlations are obtained as 0.46, 0.39, 0.52 in the calibration period and 0.71, 0.85 and 0.79 in the validation period for the Singleton, Coggan and North Cuerindi stations respectively. Though the correlation values are not very high, they are statistically significant. The time series plot of the observed and simulated streamflow for the best developed models, show the limitations of this study as the models fail to predict unusual phenomenon like droughts or floods. Sophisticated non-linear models are expected to provide better predictions; thus, such methods will be attributed to the extension of this research study.

Keywords: *MNLR, MLR, climate indices, streamflow, seasonal forecast*

Seasonal streamflow prediction using large scale climate drivers for NSW region

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Abstract: High inter-annual variability of streamflow resulting from the extensive topographic variation and climatic inconsistency cause immense difficulties to the water planners and managers of New south Wales which is one of the major contributors of Australia's agricultural production. Therefore, in this study an attempt is made to develop a skilful seasonal streamflow forecast method considering four major influential climate variables (ENSO, PDO, IOD, IPO) of south-east New South Wales. Single lagged correlation analysis is performed to identify their individual interactions with spring streamflow till nine lagged months and this is exploited as the basis for developing Multiple Linear Regression (MLR) models to examine the extent of the combined impact of these climate drivers on forecasting spring streamflow several months ahead. Several research works were carried out to forecast streamflow and rainfall for different parts of Australia using the climate indices as potential predictors but none of those apply the Multiple Regression analysis to explore the combined impact of climate indices on long lead seasonal streamflow forecast for New South Wales. Four streamflow stations from south-east New South Wales are selected as a case study based on their recorded data length with fewer missing values. The developed models with all the possible combinations, show significantly good results in terms of Pearson correlation(r), Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Willmott index of agreement (d) where the best models with lower errors give statistically significant correlations as 0.57 for Wee Jasper station, 0.41 Kiosk Station,0.49 for Mittagan station and 0.51 for Gundagai station. The best MLR models are obtained with lagged periods up to 3 months. It is evident that every time the combined model outperforms the model considering single climate variable in terms of Pearson correlation(r) which ascertains the better predictive skills of MLR models to forecast spring streamflow several months ahead for the study region.

Keywords: *MLR, ENSO, PDO, IPO, IOD, streamflow forecast*

Analysing the Effect of Lagged Climate Indices on Rainfall Predictability for Western Australia's North Coast Region

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Abstract: In last few decades, Australia experiences several extreme floods, bushfires and droughts. The consequences of these natural calamities have great social, environmental and economic impacts. Therefore, having a reliable seasonal forecasting of rainfall is highly important to withstand these situations as rainfall is mostly correlated with extreme flood, bushfire and drought incidents. Over decades, scientists and researchers are looking for reliable forecasting systems, which could provide definite predictions of rainfall that is essential for water management, agricultural production and flood management systems and mitigating such destructive situations by proper planning and management. Rainfall forecasting using climate indices has become one of the best ways to predict rainfall variability in many parts of the world. This strategy has also been proved as an effective tool to determine such variability. As Australia is affected by many different weather systems, several studies have been conducted to identify potential climate indices like Indian Ocean Dipole (IOD), El Nino Southern Oscillation (ENSO), Southern Annular Mode (SAM), Blocking highs, MODOKI and their interactions with rainfalls in different parts of Australia. Different regions of Australia have been exposed to different climate indices, so it is often recommended to study different regions separately to understand the effects of climate indices and their effectiveness to predict long-term rainfall. This study explores the seasonal variability of rainfall in Western Australia (WA) considering the effects of dominant climatic indices responsible for this region and develop a rainfall model for predicting Western Australia seasonal rainfall using potential climate indices. Very few studies have ever been found which had a primary concentration in determining rainfall variability in WA. Moreover, most of these studies has evaluated concurrent relationship between rainfall and climate indices. While a very few studies were conducted on concentration of lagged relationship between climate indices and seasonal rainfall. This study explores the significant correlation among lagged climate indices with autumn rainfall for north coast region of Western Australia (NCWA). To do so, two stations (Mingenew and Northampton) from NCWA were considered for this study. From the single statistical correlation analysis, it was found that DMI (IOD indicator), SOI, Nino3.4 and Nino4 (ENSO indicators) and ENSO Modoki Index (EMI) have shown significant correlation with autumn rainfall for these two stations. Several multiple regression analysis were conducted using lagged ENSO and DMI and lagged DMI and EMI as a combined predictor of autumn rainfall. Results showed that multiple regression has significantly increased the correlation between autumn rainfall and climate indices than single correlation analysis. Lagged DMI-Nino4 model showed highest correlation (0.38) for Mingenew and (0.44) for Northampton. Developed models were tested with out of sample dataset and statistically significant models were suggested to forecast long-term rainfall for this region.

Keywords: *Climate indices, rainfall, multiple regression, correlation*

Application of Lagged Climate Indices for Forecasting Autumn Rainfall in South Coast region of Western Australia using ARIMA Model

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Abstract: Climate indices are very effective predictors for forecasting seasonal rainfall. For any rainfall forecasting approach, it is necessary to understand the behavior of potential climate indices with rainfall variability. At present, rainfall forecasting using climate indices is one of the most reliable method to predict rainfall variability in many parts of the world. But, most of the studies have concentration on concurrent relationship between climate indices and seasonal rainfall. While a very few studies were conducted on concentration of lagged relationship between climate indices and seasonal rainfall. This study explores the significant correlation among lagged climate indices with autumn rainfall for south coast of Western Australia. As several climate indices such as Indian Ocean Dipole (IOD), El Nino Southern Oscillation (ENSO), Southern Oscillation Index (SOI), Southern Annular Mode (SAM), Blocking highs, Enso Modoki Index (EMI) are responsible for rainfall variability in Australia; therefore, this study evaluates the major climate indices and their interaction in generating rainfall variability in south coast of Western Australia. In the south coast part of Western Australia, two stations (Albany and Mount Barker) were considered for this study. From the single statistical correlation analysis, it was found that DMI (IOD indicator), SOI, Nino3.4, Nino3 and Nino4 (ENSO indicators) have significant correlation with autumn rainfall in Albany and Mount Barker. However, for these two stations EMI did not show any significant correlation with autumn rainfall. A time series analysis approach (Auto Regressive Integrated Moving Average-ARIMA) was conducted using climate indices, which showed significant correlation with autumn rainfall. In ARIMA model, lagged DMI-Nino3; lagged DMI-Nino4; Lagged DMI-Nino3.4 and Lagged DMI-SOI were chosen as independent variables (predictors) as it has showed significant correlation. From the ARIMA model analysis, it was evident that lagged DMI-Nino3 models showed highest predictability that is 56% and 33% for Albany and Mount Barker respectively. Finally, among those models, statistically significant models that showed high performance in predictability were suggested to forecast long-term rainfall for this region.

Keywords: *Climate Indices, rainfall, correlation, ARIMA*

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Social-hydrology and the Panta Rhei Science Plan: Opportunities and challenges for data-driven hydrologic modelling approaches

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Abstract: Panta Rhei – "Everything Flows" is the science plan for the International Association of Hydrological Sciences scientific decade 2013-2023. This paper presents some of the findings of the Panta Rhei Working Group on Data-Driven Hydrology. These include that the Panta Rhei era provides an exciting opportunity to look at the role of data-driven modelling approaches from a fresh perspective. Rather than simply being used as curve-fitting tools for prediction and forecasting, the increased system complexity and decreased system understanding associated with the consideration of socio-hydrologic systems opens the door for data-driven models to be used as a means for discovering complex relationships from an ever-increasing array of available data, thereby increasing system understanding and enabling the development of different hypotheses that can be encapsulated in mathematical form by conceptual and physical modellers. This mirrors what has happened in the past with the development of hydrological models, where a lack of process understanding resulted in the development of data-driven models in the first instance, with the subsequent development of more process-driven models as system understanding increased.

Data-driven models can also be used to increase predictive performance by using them in combination with other modelling types, as appropriate. In addition, they can be used to support decisions related to specific management questions, as they have a greater focus on the prediction and forecasting of specific model outputs of interest from a decision-making perspective than the accurate representation of system processes.

The realisation that data-driven, conceptual and physical models do not represent competing paradigms, but are part of a continuum of modelling approaches with varying degrees of hypothetic and data influence, and that the relative influence of these drivers is dynamic, depending on system complexity and degree of system understanding, should herald a new era of collaboration between data-driven and more physically-based modellers in order to meet the Panta Rhei targets and improve our ability to model and manage socio-hydrologic systems in the best possible manner.

Keywords: *Data-driven modelling, artificial neural networks, hydrologic modelling, conceptual modelling, knowledge extraction*

Probabilistic Modelling of Water Distribution Networks

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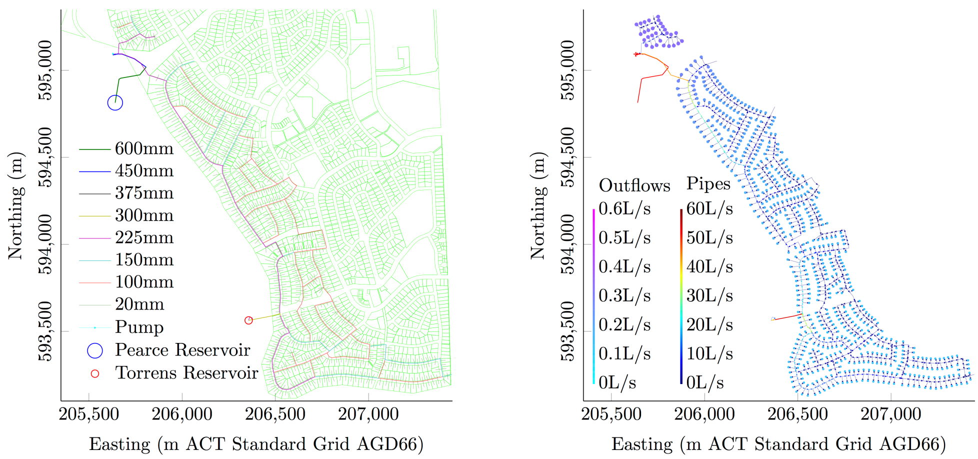
Abstract: For decades, the state of a pipe flow network (e.g. flow rates and pressures) has been analysed by deterministic methods, involving the solution of conservation (Kirchhoff's) laws, along with specified flow rates and/or pressure losses along particular conduits. These have been augmented by dynamical simulation, optimisation and genetic programming methods, for the handling of transient flow states. However, such methods make the fundamental assumption that the network properties are not subject to uncertainty, either due to fluctuations in specified quantities, or due to a lack of information on the properties of the network. To handle such uncertainties, it is necessary to adopt a probabilistic framework.

To address these problems, we have developed probabilistic methods for pipe network analysis, based on the maximum entropy (MaxEnt) method of Jaynes. In this method, an entropy function – defined over the uncertainties in the network – is maximised subject to constraints on the network, to infer the state of the network. The constraints can include "observable" constraints on various flow parameters, "physical" constraints such as conservation laws and frictional properties, and "graphical" constraints arising from uncertainty in the network structure itself. The analysis yields a probability density function which expresses the (probabilistic) state of the network, from which any parameter values of interest (such as mean flow rates and variances) can be extracted. Over the past few years, we have developed the major analytical and numerical tools for this method, including (i) the handling of nonlinear frictional resistances; (ii) physically motivated prior probabilities; (iii) automated integration schemes for the integration of partition functions; (iv) soft constraints imposed in the prior; and (v) a reduced-parameter method for the consistent analysis of pipe flow networks. In parallel, we have also developed Bayesian methods for pipe network analysis. The analyses have been applied to predict mean flows in urban networks, e.g. the 1123-node, 1140-water distribution network in Torrens, ACT, Australia, illustrated in Figure 1. The probabilistic framework is now available for network-scale applications, such as probabilistic network design, metering validation and leak detection.



(a) (b)

Figure 1. Water distribution network, Torrens, ACT, Australia, showing (a) network configuration and (b) MaxEnt-predicted mean water flows for one set of constraints.

Keywords: *Maximum entropy analysis, Bayesian inference, hydraulic network, pipe flow network, non-linear constraints, probabilistic prediction*

Development of an Evaporation - Transpiration product for Australia based on the Maximum Entropy Production theory

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Abstract: For decades, diverse equipment, methods and algorithms have been employed in evaporation and transpiration estimation. Successful accurate regional scale estimation of these important components of the water cycle is highly variable. The most used methods lump evaporation and transpiration together as evapotranspiration (ET) thereby making it unfit for use in applications where the separate contributions of both components are required or only one of the two is required. In recent years, the advent of products derived from remote sensing data based algorithms have become the standard in regional and continental scale ET mapping.

The objective of this study is to create an evapotranspiration (ET) product over Australia using remote sensing data which partitions the evaporation and transpiration into separate components of the water cycle. The algorithm used is based on the Maximum Entropy Production (MEP) method of estimating evapotranspiration. Remote sensing data including land surface temperature, soil moisture and net radiation are used in the computation of the MEP ET. Net radiation data is partitioned between the vegetation and bare soil using fractional vegetation cover. Air temperature and land surface temperature are used in the transpiration and evaporation calculations respectively. The MEP ET is a daily product for the period 2000 – 2015 on a 0.05^{o} grid.

The product will be validated using data from over 30 flux tower sites in Australia. The algorithm performances over various biomes will be evaluated. The validated product will be compared to existing evapotranspiration products such as MOD16 and the CSIRO ET product (CMRSET). The product will identify the contributions of transpiration and evaporation over the conterminous Australia. This contribution will describe the goal, methodology, data and initial results of the MEP ET product.

Keywords: *Evapotranspiration, maximum entropy production, remote sensing*

Using field data to validate MODIS evapotranspiration algorithms in arid floodplain regions

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Abstract: Semi-arid and arid floodplains and their wetlands and riparian forests are important dryland ecosystems. In the Murray-Darling Basin, these ecosystems are susceptible to degradation from alterations of the flow regime related to consumptive use and climate change. Economic, efficient tools are required to aid long-term monitoring of such ecosystems and to ensure future sustainable ecosystem function. Globally, remotely sensed evapotranspiration (ET), has become an effective tool to assist with broad scale landscape and water management decisions. In Australia, MODIS is currently the preferred platform employed to determine ET across such scales. This is directly related to the daily temporal resolution and moderate spatial resolution of MODIS. Previous studies have used flux towers and closed basin water balance to calibrate algorithms that have been developed to produce ET estimates at national scales. However, when these algorithms are applied at more regional and local scales, additional calibration is required to account for local climate inputs and bias generated from national scale development of ET. Without local calibration, the usefulness of the algorithm(s) can be quite diminished in terms of aiding management decisions. In the lower Murray-Darling Basin, ET data collected to understand the water requirements of floodplain trees such as River Red Gum and Black Box, provides suitable field validation data. Field data components include rainfall, soil evaporation, foliage interception and tree transpiration, allowing calculation of plot scaled ET. Seasonal and annual biases in MODIS ET can be identified and corrected using field data, to provide long-term trends in floodplain vegetation ET. With local field ET calibration, remotely sensed ET products provide a means to track the trajectory of change of floodplain vegetation and the creation of new monitoring and predictive tools. Such tools enable water managers to plan in advance where environmental flows might be required in the future to achieve environmental outcomes and to ensure adequate ecosystem function is maintained.

Keywords: *Evapotranspiration, River Red Gum, Murray-Darling Basin*

Parameterization of a physically based transpiration model across global bioclimatic zones for remote sensing ET estimation

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Abstract: A simplified physically based transpiration model (referred to as BTA), with three parameters, was recently developed to represent lumped biophysical controls on plant transpiration. The BTA model has been tested and shown good capacity for transpiration modelling under several different climate conditions. It remains a question whether the model applies at a larger spatial scale with mixed vegetation and over a range of bioclimatic zones. This study examines the BTA model performance across typical bioclimatic zones based on the flux tower data globally. The model parameterization is investigated to understand how the model parameters vary across different ecosystems globally, and how they are associated with the bioclimatic characteristics. Finally, a BTA-based two-source algorithm is proposed to generate a global ET product from remote sensing and climate datasets.

A preliminary test of the model has been done on a grassland site (data provided by HiWATER). MOD16 ET algorithm is used as a reference. MODIS ET radiation energy partitioning is adopted for transpiration calculation using BTA. The result (Figure 1) shows high potential of BTA for remote sensing ET estimation.

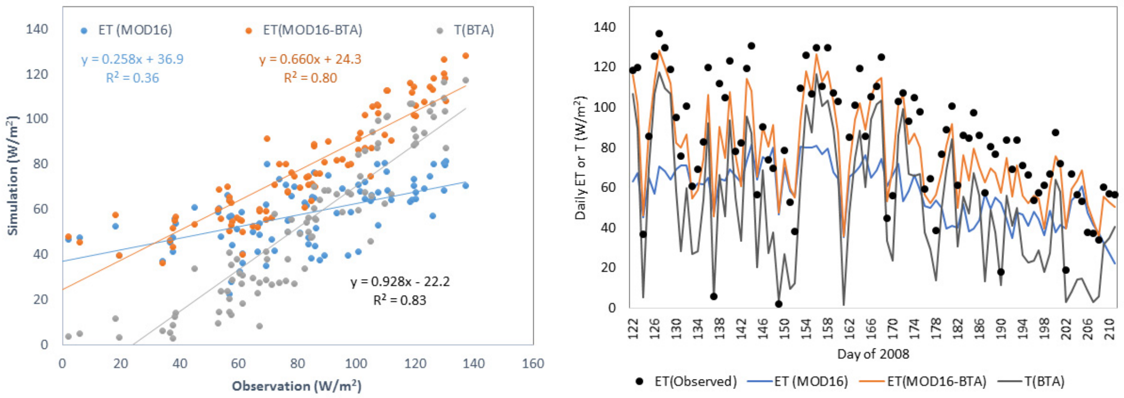

Figure 1. A preliminary test of the BTA model performance for estimating ET at a grassland site, where ET(MOD16) is daily evapotranspiration calculated from MOD16 algorithm, ET(MOD16-BTA) is the sum of MOD16 evaporation and BTA transpiration (T(BTA)).

Keywords: *Transpiration modelling, evapotranspiration*

Transpiration modeling for selected evergreen and deciduous trees in subtropical humid environment

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Abstract: Plant transpiration (Ec) can be estimated by certain functions of environmental factors (e.g. solar radiation (Rs), temperature (T), vapor pressure deficit (D) and soil water potential (ψ)) and physiological controls (e.g. leaf area index (Lc), stomatal/canopy conductance). A previous study shows that the simplified process-based model (BTA model hereafter) does not perform well under a condition of severe water deficit for transpiration simulation. It also raises a question which stress functions are most necessary and effective in the modified Jarvis-Stewart (MJS) model. In our study, we proposed a modified BTA (MBTA) model by adding an empirical stress function of soil water potential to accurately predict transpiration under intensive drought. We also simplified the MJS model by combining a dominant environmental factor (D) and physical control (Lc) for estimating canopy transpiration of a deciduous tree species under sufficient water conditions. The results indicate that the BTA model gives a reasonable accuracy for all target species at daily and hourly scales, but it fails in simulating transpiration in the drought period when large variations root zone moisture condition occurs. This is likely due to the fact that water potential stress is lacking in the BTA formulation. The MBTA provides the improved simulations, and the improvement is more significant in the drought period. The proposed MBTA model can be used for estimating transpiration of mixed forest stands composed of these target species at both hourly and daily scales. For a deciduous species (*L.formosana*) , the MJS model is constructed only by the stress functions of D and Lc, which performed well in fitting the observation data. An empirical regression equation combined with D and Lc (Ec=0.54D*Lc+0.32) gave the highest contribution to Ec, and could explain 83.4 % of the variation in Ec, to show a better simulation result using the MBTA. This indicates that a simpler method can be used to quantify Ec for the deciduous tree species *L. formosana* in this humid region.

Keywords: *Transpiration, modelling, environmental stress, evergreen, deciduous*

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An evapotranspiration (ET) product by "the three-temperature model and infrared remote sensing" for multi-scale and heterogeneous conditions

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Abstract: There are challenges to accurately estimate ET by using many conventional and remote sensing (RS) approaches under multi-scale and heterogeneity conditions. For conventional methods, in addition to fetch requirements, we usually try to extend their point-based measurement to the whole field. This does not work under the multi-scale and heterogeneity conditions. RS algorithms based on Penman-Monteith equation, usually require site specific input parameters, such as wind velocity, humidity, surface and aerodynamic resistances, which are not available in many cases. In this study, we developed a method based on "three-temperature model and infrared RS" to overcome these challenges. This approach was chosen because this method does not require wind velocity, VPD, humidity, and other parameters sensitive to spatial heterogeneity. The main input parameter is surface temperature, which can be accurately measured at over a 100,000 points by thermal sensors on the ground, on airplanes, and on satellites. The model has been successfully tested and applied under many multi-scale and spatially heterogeneous conditions. Recently, it has been integrated into software and can be used for free anywhere in the world. These advantages make it a useful methodology for remote sensing ET estimation under spatially heterogeneous conditions.

Keywords: *Evapotranspiration, infrared remote sensing, three-temperature model, multi-scale*

A satellite-based crop-factor hydrological model for broad-scale estimates of irrigated area, crop-water-requirement and crop phenology

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Abstract: Analysis of satellite derived data to estimate plant performance and crop water requirement (CWR: the minimum water required to maintain crop growth in stress-free conditions) has been used extensively across Victoria. The most commonly applied approach assumes that for a well-watered crop, evapotranspiration can be estimated as the product of a crop factor and a reference potential evapotranspiration. The crop factor is approximated as a linear function of satellite-based Normalised Difference Vegetation Index (NDVI) and the reference potential evapotranspiration is derived from meteorological data. CWR is simply the summed evapotranspiration minus the rainfall over a defined period.

This approach has been shown to be reasonable for specific crop-types within irrigation districts when validated against water supply information, however there remains significant limitations. These include: (1) the methodology only applies to well-watered areas; (2) the application assumes pre-existing knowledge of the location of irrigated land parcels and the duration of irrigation cycles; (3) there is no consideration of stored water in the soil profile at the start of the growing season nor soil drainage characteristics throughout the year; and (4) often satellite data is only processed once during the peak summer period and extrapolated over an assumed irrigation period. These limitations can significantly impact the robustness and precision of the calculations of CWR.

To overcome these constraints the technique outlined in this paper explicitly links satellite derived crop factors with a daily hydrological water-balance model that accounts for rainfall exfiltration, water distribution through a soil profile, surface runoff, subsurface lateral flow, deep drainage and recharge. The approach uses daily interpolated NDVI data, derived from Landsat-8 satellite images (2013-present) captured at 16 day intervals across Victoria and pre-processed to remove cloud and cloud shadow. Crop factors are derived as a function of NDVI from which potential transpiration is estimated. Actual transpiration is based on potential evapotranspiration, root architecture and available water stored in the soil profile. In this study an irrigation event is triggered when the difference between potential and actual transpiration exceeds a threshold amount. During irrigation events, applied irrigation matches transpiration deficit such that transpiration is not limited by available soil water in the root zone. The major advantage of incorporating a hydrological water-balance model is that soil water dynamics impact on transpiration estimates from which irrigation events are triggered. Additionally, time varying NDVI estimates define quantifiable crop factors which when incorporated into a daily water balance model enhances the accuracy of model predictions. This improves on the previous approach whereby irrigation events are simply defined by the difference between rainfall and evapotranspiration over a predefined period.

In this study the linked approach is evaluated by comparing historical survey and irrigation water delivery information with predicted estimates of irrigated area and CWR. Results demonstrate that the integration of satellite imagery data with a biophysical water balance model is capable of estimating CWR in irrigated regions within benchmark survey limits and with a median percentage error of less than 12% relative to water-use licence data. An important advantage of this approach is that it requires no pre-existing knowledge of land use and can be applied consistently across irrigated and non-irrigated areas alike. With the wide-spread availability and low cost of satellite data this approach raises the possibility of predicting crop water requirement globally or aggregated to any spatial scale greater than the pixel resolution of satellite imagery.

Keywords: *Irrigated horticulture water use, satellite data, crop water requirement*

Global variability of transpiration and soil evaporation

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Abstract: As a key component of the global water and energy cycle, land surface actual evapotranspiration has been used to indicate acceleration in the hydrological cycle as a result of global warming and CO_2 fertilisation over past several decades. This paper investigates and quantifies how these main components, associated to ecohydrological links between vegetation and the water and energy cycle, drive the spatio-temporal variation of actual evapotranspiration across the global land surface. We used a well-validated process-based model that estimates evapotranspiration and two of its main components: transpiration and soil evaporation. The results show that transpiration and soil evaporation dominate the variance of actual evapotranspiration in wet and dry regions, respectively. Globally, the relationship between actual evapotranspiration and precipitation are complementary (or contrary) to the relationship between actual evapotranspiration and potential evapotranspiration. In wet regions, particularly in the humid tropics, there are strong correlations between transpiration, actual evapotranspiration and potential evapotranspiration, with precipitation playing a relatively minor role. Therefore there is a strong ecohydrological link between vegetation and the water and energy cycle in wet regions. Conversely in dry regions, there are strong correlations between soil evaporation, actual evapotranspiration and precipitation and the ecohydrological link is weak. To exemplify this, dry southern Hemisphere from 13°S and 27°S contributes to 21% global soil evaporation variance, with only 11% global land area. On the other hand, available radiative energy is the major contributor to the inter-annual variability in transpiration and actual evapotranspiration in Amazonia.

Keywords: *Global, land, evapotranspiration, soil evaporation, transpiration, ecohydrological link*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Sparse multivariate distributions: an alternative to copulas for hydrological applications?

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Abstract: The informal term *sparse multivariate distribution* is introduced here to define a set of lines in N-space, with a univariate distribution defined along each line. Generating a random vector from such distributions is achieved by (i) selecting a line at random (ii) generating a random variable from the univariate distribution concerned, (iii) listing the *N* coordinates which define that point in N-space. This form of multivariate distribution in fact incorporates almost none of the potential N-space, unlike the usual continuous multivariate distributions. However, they have the attraction of simplicity and might be considered as an alternative to copulas for multivariate hydrological applications. For example, joint exceedance probabilities are obtained by integrating the univariate distributions within the region concerned, with accuracy depending on the number of lines involved.

We consider the special case of *data-defined sparse multivariate distributions* as follows: If there are *M* points in N-space then there are $K = C(M, 2)$ possible data pairs, defining a set of *K* lines in N-space. For example, $M = 100$ defines 4950 lines in N-space for any *N*. If the different *K* univariate distributions along the *K* lines all have the same mean and variance as their respective data pairs, then the marginal distributions preserve the means and variances of the N-variate data. In addition, the Pearson correlation coefficient is preserved in all bivariate planes. With similarities to kernel density estimation, we propose for each line defining a finite mixture of two unimodal distributions with common variance σ^2, to collectively reflect arbitrary point patterns in N-space. The user must specify a smoothing parameter $0 \leq \gamma \leq 1$, where $\gamma = 0$ is multivariate bootstrap sampling and $\gamma = 1$ corresponds to the maximum possible value of σ^2 before the two-component finite mixture distribution exceeds the variance of the two data points concerned.

A sense of the method is evident in Figure 1, where (a)-(c) shows the smoothing effect of different γ values for two-component normal distributions and (d) shows a line pattern arising from a bivariate data set. There are obviously limitations such as unnatural appearance when simulating *J* data points when $J >> M$, but there is attraction in ease of use and preservation of correlation for any level of dimensionality.

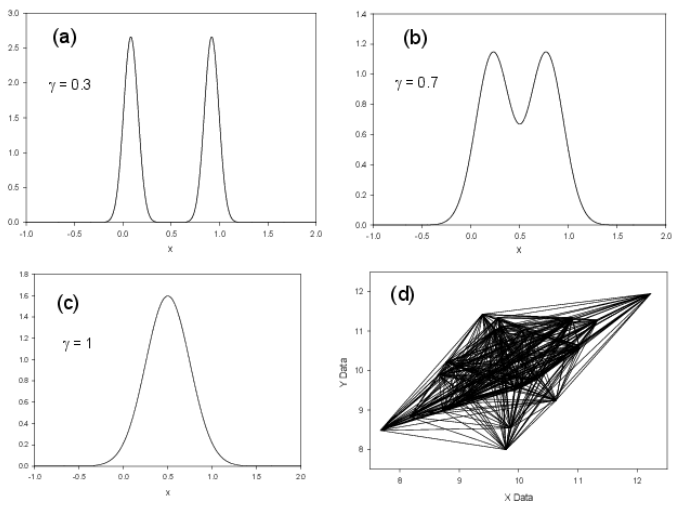

Figure 1. (a)-(c) : varying smoothing with 2-component normal distributions on the line ($x_1 = 0$, $x_2 = 1$). (d) : sparse bivariate distribution for a small bivariate data set (lines not shown extending beyond data pairs).

Keywords: *Multivariate data-based, nonparametric multivariate estimation, correlation preservation*

A comprehensive and systematic evaluation framework for evaluating spatial-temporal rainfall models

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Abstract: The spatial distribution of rainfall has a significant influence on catchment dynamics and the generation of streamflow time series. There are a wide range of rainfall models available for this task and an even wider range of statistics for evaluating these rainfall models against observations. Many previous studies typically have ad hoc descriptive performance assessment (e.g. words such as 'adequate', or 'suitable'). The goal of this study was to develop a comprehensive and systematic evaluation (CASE) framework to identify model strengths and weaknesses. It is comprehensive because it clearly summarises model performance over a wide range of spatial (all sites/fields) and temporal (days/seasons/years) scales. It is systematic because it includes a transparent performance categorisation scheme, which enables comparison of performance over a range of model properties and hence provides a mechanism to clearly identify model strengths and weakness. This included quantitative performance categorisation to provide a systematic, succinct and transparent method to assess and summarise model performance over a range of statistics, sites, scales and seasons.

The CASE framework is demonstrated on two case studies. The first is the evaluation of a new parsimonious daily spatial stochastic model that produces daily rainfall fields across the catchment which was applied to a case study from the Onkaparinga catchment in South Australia. The CASE framework showed the model had many strengths in reproducing the observed rainfall characteristics with the majority of statistics classified as either statistically indistinguishable from the observed or within 5% of the observed across the majority of sites and seasons. These included rainfall occurrences/amounts, wet/dry spell distributions, annual volumes/extremes and spatial patterns, which are important from a hydrological perspective. One of the few weaknesses of the model was that the total annual rainfall in dry years (lower 5%) was over-estimated by 15% on average over all sites. An advantage of the CASE framework was that it was able to identify the source of this over-estimation was poor representation of the annual variability of rainfall occurrences.

The second case study was stochastic generation of multi-site daily precipitation for the assessment of extreme floods in Switzerland. The CASE framework enabled a systematic comparison of three different approaches for modelling spatial extreme rainfall that drives floods in Switzerland. It clearly showed that a model calibrated to 3-day precipitation amounts, for which 3-day simulated amounts are disaggregated at a daily scale, outperformed the models calibrated directly at a daily scale in terms of reproducing spatial extreme precipitation.

Keywords: *Stochastic rainfall, rainfall generation, spatial rainfall, continuous simulation*

The Variable Selection Issue in the Bivariate Frequency Analysis Using Copula Model

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Abstract: Rainfall events can be simplified with the rainfall duration, the total rainfall depth, and mean rainfall intensity. The correlation structure among three variables of rainfall events (i.e., rainfall duration, total rainfall depth, and mean rainfall intensity) can be expected easily both theoretically and empirically. However, the strength of correlation itself among them is not. For example, a negative correlation is expectable for the rainfall duration and rainfall intensity, but the strength of correlation can be weak or strong. It is dependent upon the climate condition, also varies region by region. If only two variables explain a process of interest, these two variables are used for the bivariate analysis; however, if more variables exist for the formation of a process, only two variables should be selected for the bivariate analysis. But a way to properly select the two variables has not been established yet, and the random selection of two variables may affect the results of the bivariate analysis. However, many researchers had performed the bivariate analysis by selecting two variables through their subjective decision. In this study, the selection issue of the two variables of the rainfall events for the bivariate frequency analysis was discussed. As the first step to achieve the study objective, the authors analyzed the synthetic rainfall event, the generation of which is based on a rainfall intensity formula. A total of 200 rainfall events were generated and used for the bivariate frequency analysis. The bivariate frequency analysis was repeated three times with different pairs of the two variables among the three components of the rainfall events, as follows: rainfall duration, total rainfall depth, and mean rainfall intensity. This study considered four copula models (Clayton model, Frank model, Gumbel-Hougaard model, and Gaussian model) for the bivariate frequency analysis. Using these copula models, the results of the bivariate frequency analysis on the synthetic rainfall events and the observed rainfall events were obtained. For both synthetic and observed rainfall events, three results of bivariate frequency analysis from three pairs of two variables were compared with each other. Especially, the results using synthetic rainfall events were compared with the input return period which were considered at generation of data. The findings of this study are summarized as follows: (1) The return period for both synthetic and observed rainfall events were able to calculated and the results were rather different depending on the two variables considered. (2) Among three results, the results considering total rainfall depth and the mean rainfall intensity were found to be the most reasonable.

Keywords: *Bivariate frequency analysis, Copula, annual maximum rainfall event*

A hybrid Wavelet-Lyapunov exponent model for river water quality prediction

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Abstract: River system is an open, complex and non-linear system, and water quantity and quality are often governed by a mix of deterministic and stochastic dynamics. Therefore, chaos theory, with its ability to bridge determinism and stochasticity, is a promising theory to describe and predict river water quality variations. However, only a few studies have, thus far, applied chaos theory to examine and predict the river water quality dynamics.

The goal of the present study is to develop a hybrid model for river water quality dynamics, combining spectral theory and chaos theory. Wavelet transformation is used to filter the noisy signal in the water quality time series. Phase space reconstruction is employed to embed the water quality time series using an appropriate delay time (τ), by partial multiple correlation coefficient method, and determine the trajectory of the underlying dynamics. The presence/absence of chaos in the water quality time series is identified using the largest Lyapunov exponent value (λ_1) and the trends of correlation exponent relative to embedding dimension (m) .

The method is implemented on weekly time series of chemical oxygen demand (COD), dissolved oxygen (DO) and ammonia nitrogen (NH_3-N) from the Aishanxi Bridge station in the Huaihe River, China, observed as part of long-term water quality monitoring programs. The data used covers the period from 2009 to 2014. The water quality time series are first decomposed into subseries by db5 wavelet function. The hybrid model parameters are set based on the previous 5 years of data (from Jan 5, 2009 to Oct 14, 2013), the latest 31 weeks (from Oct 22, 2013 to May 13, 2014) are used for model validation.

The results for the COD time series yield a low dimension (m = 5), small delay time (τ = 3) and a positive largest Lyapunov exponent λ_1 = 0.3955, which suggest that the low-frequency signal is chaotic. The validation results from the hybrid model yield a maximum relative error (MaxRE) of 18.95% and a mean relative error (MeanRE) of 6.54%. When using only the Lyapunov exponent model, the original dataset (covering all the signals) lead to a high dimension (m = 8), small delay time (τ = 3) and λ_1 = 0.4886. The validation results in this case show a MaxRE of 28.20% and a MeanRE of 10.04%, which are larger than that obtained using the hybrid model. Further, the results from the auto-regressive moving average (ARMA) model and the artificial neural network (ANN) model yield MeanRE of 7.11% and 11.98%, respectively. All these results indicate that the hybrid model performs better when compared to the purely Lyapunov exponent model, ARMA model, and ANN model, in forecasting the COD variations.

For the DO time series, the hybrid model predictions have a MaxRE of 26.36% and a MeanRE of 6.55%. For the NH_3-N time series, MeanRE is 14.36%, which is the largest among the three water quality parameters considered in this study. This is reasonable, since sources and dynamics of in-stream NH_3-N process are more complex than those of COD and DO. The many big jumps in the original datasets of NH_3-N also offer some preliminary observations on this. Such jumps probably result from storm water or pollutant discharge and it can be identified as anomalies in practice. DO also has a larger variation among the seasons, which lead to the largest MaxRE.

Efforts are underway to confirm, and possibly verify, the present results on the superiority of the hybrid model, through using water quality data from many other stations in the Huaihe River and also from other rivers in China.

Keywords: *Wavelet, Lyapunov exponents, chaos, water quality prediction, COD*

The next generation: implications of considering sub-daily rainfall event types in weather generators

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Abstract: Synthetically generated sequences of rainfall are required for a variety of flood hydrology applications. Continuous simulation rainfall runoff models are increasingly being promoted as a better way to model floods due to their ability to explicitly model the catchment antecedent conditions. However in many catchments there is not enough recorded rainfall data, particularly at sub-daily resolution, to implement these models without using synthetically generated rainfall sequences. Correctly representing the occurrence and magnitude of extreme rainfall events is vital to ensure that the resulting sequences correctly model flood risk. Most weather generators are constructed to produce time series of daily rainfall. Urban areas are subject to the vast majority of flood risk and infrastructure damage and in many cases the critical duration for these urban catchments is far shorter than one day. Additional effort is required to develop weather generators that can correctly model sub-daily extreme rainfall events.

The atmospheric processes that lead to sub-daily rainfall extremes are quite different from those that lead to daily or multi-day rainfall totals. The atmospheric processes also vary regionally. A climatology of sub-daily extreme rainfalls for Australia and their associated atmospheric condition has recently been developed. Here, the climatology has been used to explore the implications of event types on the sub-daily rainfall data. This is achieved by considering the sensitivity of Intensity-Frequency-Duration data to the types of events used in deriving the relationships (Figure 1). The implications of these findings for engineering design in a non-stationary climate will be discussed.

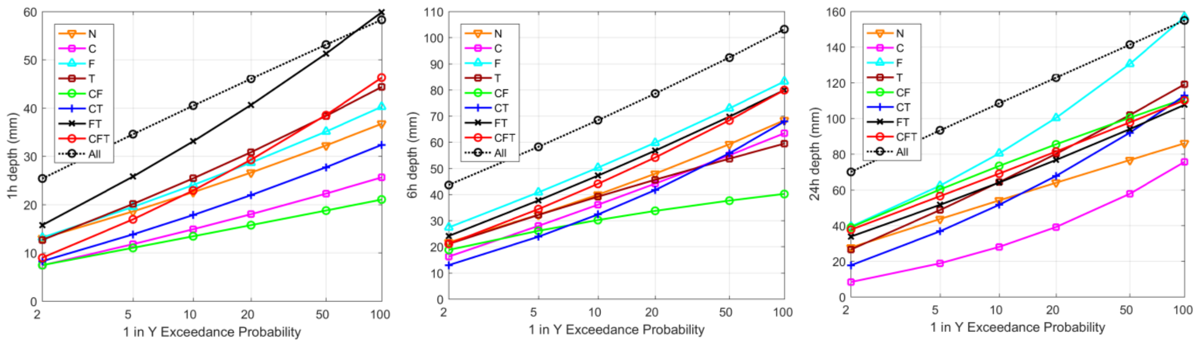

Figure 1. IFD relationships for Sydney estimated using different storm type classifications for a) 1 hour, b) 6 hour and c) 24 hour rainfall depths. Storm types are N:none, C: cyclone, F: front, T: thunderstorm, CF: cyclone-front, CT: cyclone-thunderstorm, FT: front-thunderstorm, CFT: cyclone-front-thunderstorm, All – Annual Maximum Series rainfall

Keywords: *Extreme rainfall, weather generator, climate change, storm types*

Consideration of storm shape in the application of areal reduction factor

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Abstract: The areal reduction factor (ARF) was introduced to consider the spatial characteristics of the rainfall field by converting the point rainfall into areal-average rainfall. In addition, ARF is used in the hydrologic practices to convert the point design rainfall into the areal-average design rainfall, which is used to determine the design flood rate at the exit of a basin. There are many different approaches for deriving ARF; however, only three methods have been developed for the application of ARF. In Method (1) the ARF estimated for the entire basin is applied to all the sub-basins, and in Method (2) the ARF of a sub-basin is independently estimated by considering its sub-basin area. Finally, in Method (3) the ARF is estimated by considering the accumulated area up to the point of determination of the design flood. In this study, these three conventional methods of applying ARF were compared to evaluate their biases. This evaluation and comparison was based on the design flood at the exit of each sub-basin and the entire basin. Also, for this purpose, this study proposed a new method of applying ARF, which considers the shape, orientation and center of a storm. It can be explained as follows: First, a sub-basin is selected randomly within the basin (i.e., the first-level sub-basin), where the storm center will be located. The ARF of this sub-basin is estimated by considering this sub-basin area. Second, among sub-basins surrounding the first-level sub-basin (i.e., the second-level sub-basins), one sub-basin is selected randomly. This study considered the Chungju Dam Basin as a study basin, which is located at the center of the Korean Peninsula. The Chungju Dam Basin was sub-divided according to the Water Resources Unit Map into 50 sub-basins. The HEC-HMS was used for the rainfall-runoff analysis. It is also true that the runoff results derived by applying proposed method are not the truth, but was assumed in this study to be true to be used for evaluating the three conventional methods. The result of estimated ARFs according to method are as follows. As a result, it was found that Method (1) produced the negative bias and Method (2) the positive bias. On the other hand, Method (3) was found to be the most reasonable, with the negative bias of just 5% for the Chungju Dam Basin. However, it should be noted that this result must depend on the study basin as well as the number of sub-basins. If the area of the basin or the number of sub-basins is less than the Chungju Dam Basin, the bias in the estimation of the peak flow may be less than 5%.

Keywords: *ARF, storm shape, Chungju Dam Basin*

EXTENDED ABSTRACT ONLY

Frequency-based Bias Correction: An improved procedure in correcting biases of GCMs in the frequency domain

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Abstract: Statistical bias correction of climate model outputs has become a standard procedure in almost all climate change impact studies. Commonly used bias correction approaches operate in time domain and often correct variables either at a single time scale or at multiple pre-defined time scales. As a result, they do not take into account biases across a range of timescales. Therefore, they may overlook the representation of low-frequency variability or long-term persistence in rainfall and other atmospheric variables.

This study presents a bias correction approach that corrects biases in high- and low-frequency variability of precipitation simulations obtained from the global or regional climate models (GCM and RCMs) in the frequency domain, called a frequency-based bias correction (FBC). We examine the performance of the proposed approach by applying it to the monthly precipitation outputs from GCMs extracted from the most up-to-date CMIP5 and the observation-based Climate Research Unit (CRU) precipitation dataset over the global land surface. The results are also compared with those obtained from commonly used bias correction approaches operated in the time domain (e.g. Simple Monthly Scaling Bias Correction (SMBC), Empirical Quantile Mapping (EQM) and Nested Bias Correction (NBC)).

Cross-validation results showed that the FBC approach mostly led to the smallest root-mean-square error (RMSE) of precipitation characteristics, in particular, those related to low-frequency variability (e.g. Figure 1a). In addition, the FBC approach also led to better agreement (measured by normalized interquartile range – called spread) across the GCMs in simulating persistence attributes of precipitation projections for future simulations (e.g. Figure 1b). Therefore, FBC is recommended as an effective bias correction tool in climate change impact studies on water resources where the low-frequency variability assumes importance. Examples of such situations are many, but the most obviously, the engineering design and management of water storages (for uses in water supply, agriculture, and hydropower, etc.), which are designed to buffer historical variability in precipitation.

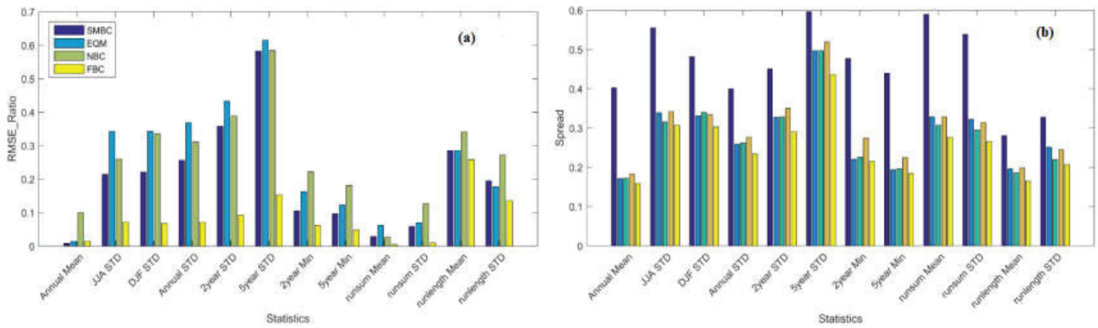

Figure 1. Performance of FBC in simulating current (a) and future precipitation characteristics (b) in comparison with other bias correction approaches.

Keywords: *GCM precipitation, frequency-based bias correction, low-frequency variability, nesting bias correction, quantile mapping bias correction*

EXTENDED ABSTRACT ONLY

Novel combination of radar with raingauges for radar precipitation estimates in cold climates

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Abstract: Weather radars give quantitative precipitation estimates over a large area with high spatial and temporal resolution. However, the weather radar measurements are indirect and they are subjected to many sources of errors. The radar transmits electromagnetic waves and it measures the energy scattered back by hydrometeors in the atmosphere and then the backscattered energy, termed as reflectivity, is converted into rain rate. The errors and uncertainties are during the sampling or measurement of reflectivity as well as in the process of converting them to rain rates. Many studies over the past have focused on estimating these uncertainties for quantitative radar precipitation estimates; however, some of the underlying physical processes are still not well understood.

Typically, radar measurements of reflectivity (Z) are converted into rain rates (R) using parametric Z-R relationship in the form of a power law, $Z = aR^b$. The constant values of a= 200 and b= 1.6 are generally used regardless of climate region. The variability of the power law parameters is related to drop size distribution of hydrometeors. Further, the drop size distribution of snow is very different from rain particles. Several studies investigated different possible parameter sets for snow and rain. Spatial and temporal variation of precipitation phase and rapid changes even within the same event make applying different parameter set for conversion as complicated task and it has led to use constant parameters operationally. However, the bias in the Z-R conversion because of different precipitation phases in cold climates must be addressed to improve quantitative precipitation estimates.

The increasing availability of sufficient number of radar rain rate observations make it possible to apply data based techniques to improve the radar precipitation estimates. For systems where physical relationships are less apparent, and sufficient observational records exist, a range of statistical alternatives can be investigated as a possible way of specifying the underlying form (Sharma and Mehrotra, 2014). The present study assesses temperature as explanatory variable to take different precipitation phases into consideration. Then it uses the non-parametric, k-nearest neighbour method to estimate precipitation by combining radar rain rates with ground precipitation measurements and temperature observations.

Radar rain rate data from C-band Hurum radar station (located at 59.63° latitude and 10.56° longitude) and hourly precipitation records from nearly 100 raingauges within the 50km radar range in the Oslo region of Norway is used in the current study. A preliminary investigation with simple linear regression of radar and gauge pairs shows that, regression slope for rain pairs is greater than regression slope of snow for 80% of the gauging stations under comparison. Further, the non-parametric statistical model with precipitation and temperature as input improves radar precipitation estimates for cold temperatures considerably. This study can contribute scientifically to the growing interest of using precipitation measurements from existing weather radar facilities in the boreal region.

Keywords: *Radar precipitation estimates, cold climate, bias in Z-R conversion, non-parametric method*

Basin Futures: Supporting water planning in data poor basins

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Abstract: Water resources are under growing pressures globally. Sustainable water management requires good understanding of water resources, e.g. where water is stored and used, and how future developments may impact on water availability. Developing this understanding requires investment in data, models, and experts, often over multi-year timeframes.

In the context of developing countries, in particular those with institutional gaps in the water sector, these challenges are difficult to overcome. In this paper we discuss Basin Futures, a response to four issues faced by institutions and water policy makers in developing countries: data availability, capability, capacity and costs.

In Basin Futures, we aim to accelerate the progression toward detailed basin planning by offering access to data sets and models that facilitate the initial stages of basin planning.

Basin Futures is a web based modelling platform that brings together global and local datasets to support water planning in developing countries. The system is designed to leverage investment in existing data (global and local), and then use this to empower decision-makers to understand the opportunities and constraints in managing their water resources. Basin Futures provides an enabling environment for planning, cooperation and participation in water management. It allows defensible decisions to be made at a level that is supported by available data.

With the increasing availability and range of global data, e.g. from satellites, and technologies such as cloud computing, there is an opportunity to perform faster water assessments as an early stage of a large water assessment cycle. We have a developed a cloud-based approach that aims to give users a quicker route to an initial understanding of water resources in basins.

Basin Futures integrates a range of global datasets, include HydroSHEDS, global precipitation, and river discharge observations, with models built for use in a cloud environment. Together with a web-based application, this allows users to make an initial estimate of current water resources. Core to the value of Basin Futures is that it provides user-customisable scenarios that allow dynamic exploration of future scenarios, for example, construction of new storages, changes to irrigation practices, population growth, and climate change scenarios. Users are then able to visualise impacts on water-related security indices.

The model engine is a reach-based model - rather than a node-link model - where the demands are only associated with local (reach) storages and there is no support for upstream ordering of water or for exploring ground and surface water interactions. This is a deliberate choice to create a system that runs fast enough in web time and provides the user with an initial understanding of the water resources in unregulated systems. This streamlined approach to water resource assessments gives users a powerful starting point for positioning future investments in new knowledge and planning activities. The outputs will also guide where more definitive answers, and data, will be required by the appropriate use of more powerful software.

This paper details the driving requirements for the Basin Futures, the underling model, and the implementation using modern web technologies.

Keywords: *Basin planning, global data, cloud processing, decision support systems*

EXTENDED ABSTRACT ONLY

An improved community detection algorithm based on edge betweenness and modularity density for catchment classification

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Abstract: Catchment classification has been gaining increasing interest in hydrologic research in recent years. The main idea behind catchment classification is to streamline catchments into different groups and sub-groups based on their salient characteristics, such as system, process, and data properties. Therefore, catchment classification is useful for a more efficient and effective modeling of hydrologic systems, including in the identification of the appropriate type and complexity of model.

There are many different approaches for catchment classification, with different assumptions, bases, and methods. Application of the concepts of complex networks, and particularly community structure, for classification of catchments is fairly new and an emerging area of research in hydrology. Among the community structure methods, the edge betweenness (EB) algorithm, which applies a hierarchical clustering concept, is one of the basic methods for identification of communities (groups) in large dynamically-evolving networks. The method includes two important steps: (1) iterative removal of edges (i.e. links) from the network based on the value of edge betweenness between vertices (i.e. nodes) calculated via the shortest (geodesic) paths; and (2) recalculation of the betweenness values after each iterative removal. The communities are formed by modularity measure as the maximum value of modularity leads to the best partition of the network.

Although the EB method has been shown to be effective in identifying communities in many synthetic and real-world networks, the modularity function that is used to measure the strength of the community structure is susceptible to network (or data) resolution or scale. As a consequence, communities can change when the size of the network changes. Figure 1, for instance, illustrates the influence of network size on catchment classification, with an example of the classification of catchments in Australia, based on monthly streamflow data observed at 218 stations. Figure 1(a) shows the classification when the edge betweenness method (with modularity function) is applied to all 218 stations, while Figure 1(b) shows the classification when the method is applied to only 100 (randomly selected) stations. The regions marked with red (big) circles show examples of where changes in communities occur.

In the present study, we propose an improved algorithm, by applying modularity density (MD) (rather than modularity) to address the influence of network size on catchment classification. The MD measure is generally defined as the sum of all average degrees of sub-groups by finding the average inner and outer degree of each sub-group. The maximum value of MD represents the best formation of communities in the network. We apply the algorithm to different sizes of streamflow network in Australia, and interpret the results in terms of network size and catchment properties.

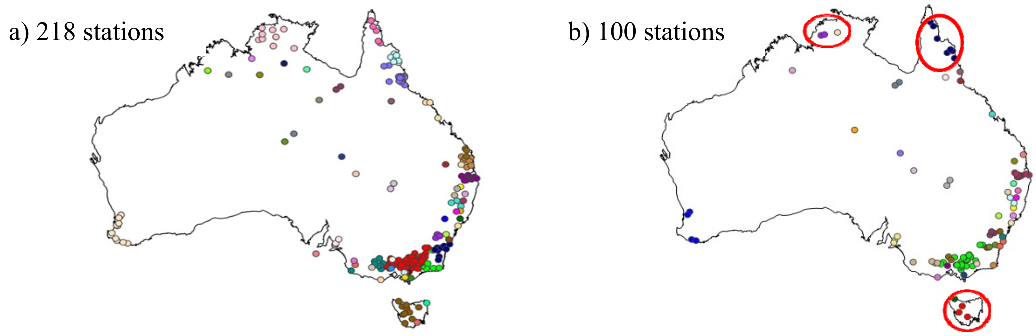

Figure 1. Classification of catchments in Australia using the EB algorithm at correlation threshold, T = 0.8: (a) network of 218 stations; and (b) network of 100 (randomly selected) stations. The different colors are used only to distinguish the communities and hold no meaning when comparing across size of networks.

Keywords: *Catchment classification, complex networks, edge betweenness, modularity density*

Challenges in the development of Current Conditions for the Lachlan River, New South Wales

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Abstract: During the development of the surface Water Sharing Plan (WSP), a long-term IQQM computer model scenario run was developed for Lachlan River System to simulate the patterns of water use in the valley over the full climate record (100 plus years) under plan rules and development conditions. The average annual valley-wide extraction simulated in this scenario run represents the 'long-term extraction limit' or 'Plan Limit'.

As per WSP, the water use in the valley needs to be tested against the Plan Limit model by operating a parallel long-term model under the development conditions at that point in time generally known as the 'Current Conditions' model. This Current Conditions model is intended to include updated infrastructure information, farm level development (e.g. crop areas and cropping mix) and demand patterns (e.g. entitlement share components and planting decisions). The updated Current Conditions model run is then compared to the Plan Limit model run over the full climate record to determine whether overall extraction has increased or not.

If the Current Conditions average annual extraction significantly exceeds the Plan limit, then the maximum annual use permitted for general security entitlement holders will be reduced. The degree of reduction was the amount just sufficient to keep the Current Conditions extraction within the Plan Limit. At WSP commencement the 'annual use limit' was calculated to be 0.75 (or 75%) of entitlement.

The above process is heavily reliant on good quality on-farm data such as planted crop types & areas and planting decisions. The on farm data that were previously collected on an annual basis are no longer regularly collected on a valley-wide basis. In absence of crop types and planted area data, irrigators' surveys were initiated for the determination of crop types and planted areas. In general the response rate of any survey is quite low and therefore the management of irrigators' surveys is a long exhaustive process. An alternative way of estimation of crop areas is the use of satellite imagery data that can be estimated quickly with relative ease.

This paper describes the methods and processes of estimation of planted crop areas irrigated from surface water and the planting decisions using satellite remote sensing as well as sampled survey data and then comparing with each other. The process of estimating the valley planted areas is a complicated exercise as a significant number of irrigators' have both surface as well as ground water entitlements.

Keywords: *Integrated Quantity Quality Model (IQQM), Surface Water Sharing Plan, Current Development conditions, river system modelling, irrigators' surveys*

Adoption of suitable objective functions for auto-calibration in eWater Source: An application to Upper Hunter catchments in Australia

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Abstract: The paper is aimed at exploring the applicability of different objective functions during calibration of a catchment adopting Sacramento rainfall-runoff model in eWater Source platform. A total of 10 objective functions are in-built in eWater Source platform, from where a hydrologist/modeller can choose a particular function from the list. The question is which one would give better calibration results considering the same calibration period and fixed optimisation algorithm for a given catchment. In this study, the testing has been done on two catchments in Upper Hunter region in Australia. In order to obtain a good calibrated parameter set, a modeller has to look for a number of goodness of fit tests (e.g. Nash Sutcliffe Efficiency (NSE), Flow duration curve and volume bias) depending on the applicability of the calibration. It has been found in the testing that no single objective function has been able to generate good results for a combination of goodness of fit tests. For example, if "NSE daily and log flow duration" is used in the calibration, it gives a reasonable NSE values but produces a bigger volume bias. On the other hand, if "Minimise absolute bias" is used, it generates very low volume bias and produces a good match between cumulative volume of simulated flow and observed flow, but it produces very poor flow duration curve. Therefore, a modeller need to carefully check and explore a number of objective functions to produce a good calibration results, sometimes it is often needed to do manual calibration after conducting auto-calibration.

Keywords: *Rainfall-runoff modelling, Sacramento, eWater Source, calibration*

EXTENDED ABSTRACT ONLY

Benefits of a component-based, integrated modelling approach within a participatory process

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Abstract: The assessment and support of environmental issues and policies, such as water management plans, often require the consideration of goals and objectives that span multiple socio-environmental systems. These goals and objectives are often recommended to be developed through engagement with various stakeholder groups that embraces a participatory process. Consequently, they may evolve over time due to previously unknown or unconsidered data, knowledge and information. The model structure, composition, or purpose may then change to reflect the updated goals and objectives. Goals intended for a specific system or sector may adversely affect the ability to satisfy a desired goal in another as these systems are inter-connected. Integrated models are considered as core mechanisms to inform or identify, ideally, a set of pre-emptive or prescriptive actions and conditions in which beneficial results are achieved towards the defined goals and objectives, or failing that, an effective compromise.

In contrast to the fluid specifications which modellers work towards, integrated models are often static in that they are inflexible and relatively difficult to adapt when changes become necessary. In other words, models are tightly coupled to a prescribed set of investigatory goals. Any change to these may be difficult to accomplish and may cause significant delays. Perhaps in consideration of this deficiency, approaches that are not component-oriented prefer that the modelling details are finalised in advance which may place the start of the model development process later in the project timeline.

A component-based approach to integrated model development is reported here. It was adopted for a socio-hydrological system in the lower Campaspe, Victoria, to explore water management scenarios. Component-based approaches compose a collection of compartmentalised models, coupled loosely through a common framework. The developed integrated model represents a sociohydrological-environmental system which, for the Campaspe, includes a (principally cereal cropping) agricultural system model, surface-water representing the lower Campaspe river and tributaries, groundwater hydrology, and a water management policy model. A climate component is also included which serves to provide the necessary rainfall and evapotranspiration data at the requisite spatial and temporal scales. These components were developed iteratively, and are explicitly coupled when required. In other words, component models are coupled as needed, with feedbacks occurring between models through exposed interfaces. In this manner, decisions made in one system, such as water allocation processes, appropriately affect another (dam releases, surface water – groundwater fluxes, etc.). Changes within a component model that do not affect the interface (i.e. the inputs and outputs) are safely abstracted, potentially allowing for a component to be replaced the wholesale replacement of a component with another (new or existing) model should the need arise. While formalised frameworks (e.g. OpenMI and OMS) have many benefits, such as the standardisation of interfaces, the budgetary (both financial, time and other) costs of adoption may outweigh the realisable benefits within the context of this study.

We find the component-based approach advantageous within the context of a participatory modelling context as newly acquired information, data, and stakeholder feedback can be incorporated relatively quickly. As each component is compartmentalised there is little risk of changes in one component flowing through to another, reducing the technical burden on modellers and developers. Compartmentalising each component additionally allows for separate uncertainty and sensitivity analyses to be conducted specific to each component model, in addition to the integrated model as a whole. Finally, the speed at which changes can be incorporated allows development velocity to be maintained, thereby enhancing relevance of the modelling process to stakeholders, which may in turn increase the usability of model results.

Keywords: *Component-based modelling, participatory modelling, integrated model development*

Transition from Water Resource System Modelling towards Integrated Water Modelling: Melbourne Water's Challenges and Experiences

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Abstract: The management options available for balancing water supply and demand in metropolitan Melbourne have expanded significantly over the past two decades. The water supply system has transitioned from one that relied entirely on traditional surface water sources, multiple interconnected storage reservoirs and diversions structures, to one with a mix of water sources including decentralised supplies such as recycled water, storm water and household rainwater tanks, as well as a desalinated seawater supply. This range of 'alternative' water sources is expected to grow further in the future. Coincident to these infrastructure changes have been changes to water management arrangements: retail water companies, regional water authorities and the Victorian Environmental Water Holder are assigned water entitlements from the water supply system of which the assets are owned and operated by Melbourne Water. These water entitlements enable the above organisations to manage their water allocations independently. In its water storage operator role, Melbourne Water needs to ensure optimal management of the water supply system to meet the needs of the above water entitlement holders.

Water resource modelling tools are used at Melbourne Water to inform bulk water supply planning and management, drought response planning, water allocation, environmental flow planning and hydro-climatic impact assessment. In the past, water resource modelling had focused on the behaviour of the centralised bulk water supply system and therefore had limited ability to address new modelling needs. These include assessing: the water availability from centralised and decentralised supply sources, water allocation management options available to individual entitlement holders and the implications of local or centralised supply options on various components of the water cycle.

Melbourne Water, in consultation with its customers and stakeholders, has been developing a modelling tool, using eWater Source, to address the above needs. The comprehensive nature of this modelling tool has also highlighted the need for auxiliary modelling support tools. These include a documentation system for maintaining and sharing the knowledge base, a version control system to manage changes to model and data, a modelling workflow management system and a cloud computing system that enables faster processing of model runs. Development of modelling and auxiliary tools has been staged to ensure a smooth transition from the current modelling approach to the new system.

The paper will outline the historical progression of water resource modelling at Melbourne Water, drivers behind current modelling improvements, challenges faced in implementing new modelling capabilities, identified solutions and future directions.

Keywords: *Water resource modelling, alternative water sources, water allocation, water cycle modelling*

Salinity management strategies to improve Gurra Gurra wetland condition

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Abstract: The Gurra Gurra wetland complex (the wetland) covers an area of 3000 ha that stretches along the eastern bank of the River Murray to the east of Berri. The flow regime of the wetland complex has been significantly changed since construction of Lock 4, located immediately downstream of the wetland, as it maintains a constant water level within the wetland for a large proportion of the time. As a result, the often terminal wetland experiences elevated salinities due to saline groundwater discharge and evapo-concentration processes.

The South Australian Riverland Floodplains Integrated Infrastructure Program (SARFIIP) is planning works on the floodplain on the other side of the river, the Katarapko Floodplain to impound water to meet local ecological objectives. To operate these works effectively, raising of the water level controlled by Lock 4 is required. However, any changes in water level at Lock 4 also affects the salinity within the wetland. In order to understand the future changes in water quality in the wetland from changing the Lock 4 level, as well as assessing a number salinity management strategies to improve salinity within the wetland, a numerical 2D hydrodynamic and advection dispersion numerical modelling has been developed.

The scenarios considered include: 1) regular manipulation of the river water level in an attempt to prevent the build-up of high salinities over time, 2) lowering the sill of an upstream connection between the river and the wetland, to facilitate more frequent flushing of the system, and 3) a combination of both 1) and 2).

The results indicate that under current conditions, very high salinity concentrations in upper parts of the wetland could be expected due to evapo-concentration, and when high flows occur and flush the system, high peak salinities can occur in the outlet from the system. After three years, salinity reached to 16,000 EC in upper parts, which resulted in salinity at lower parts of the wetland where water is extracted for irrigation purposes, peaking to approximately 7000 EC during the high flow event in the fourth year that reset the wetland (shown in Figure 1).

The most effective management scenario was combination of weir pool raising events and deepening Lyrup Creek which resulted in substantial reduction in salinity concentrations across all parts of the wetland with maximum salinity reached approximately 2000 EC during the high flow events (shown in Figure 2).

These results will continue to inform management of weir pool manipulation at Lock 4 for the benefit of outcomes at the reach above the lock, at the Katarapko floodplain as well as the wetland. More broadly, this study provides a methodology for investigating potential changes in floodplain hydraulics and water quality to assess impacts on all water users.

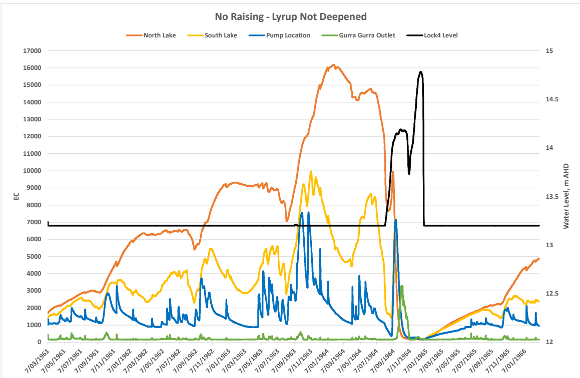

Figure 1. Current Condition

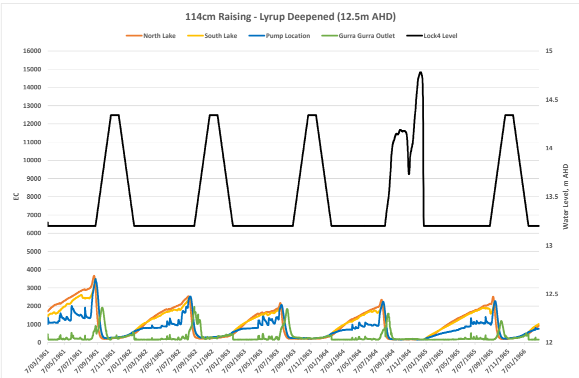

Figure 2. 114cm Raising and Lyrup Deepened

Keywords: *Salinity, hydraulic modelling, river management, River Murray*

Impacts of water transfers on public water supply reliability in South England

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Abstract: In the UK, water utilities are facing challenges including population growth, climate change and abstraction reforms intended to restore sustainable amounts of water for the environment. As the population density increases in the south part of England, one of the possibilities of mitigating water scarcity is to transfer water from the north and west of England. However, droughts are spatially coherent events and the most severe droughts usually result in water shortages over wide areas. Consequently, the question is, does the donor basin have enough water itself during drought or low flows periods to transfer to the other basins?

Here we employ a new large ensemble of climate model projections based on the climate models (HadCM3 +HadRM3) using the weather@home system. Weather@home consists of an atmospheric global climate model and a regional climate model sharing essentially the same physics, which are run on volunteers' computers around the world using the infrastructure of climateprediction.ne [*Guillod et al.*, 2017]. Daily rainfall and potential evapotranspiration time series from the weather@home climate simulations were then run through a semi-distributed hydrological model (Dynamic TOPMODEL) for 45 inflow points in the Thames and Severn-Trent water basins. The model was calibrated to naturalized flows at each of these inflow points to provide naturalized future flow predictions for three sets of climate scenarios including a baseline (1975-2010), near future (2020-2050) and far future (2070-2100) period. Two population growth scenarios were also considered.

We employed WATHNET simulation software [*Kuczera*, 1992] to model two neighboring water companies using flow predictions from the hydrological model, Thames Water and Severn Trent Water, and all of the transfer rules and regulations, including various contractual arrangements, that might govern the transfer of water between neighboring water utilities. WATHNET is a simulation model based on network linear programming. The frequency and duration of imposing restrictions (of different levels of severity) on water users are selected as measures of reliability. They can be combined with the level of service of the two water utilities, which is their target for the maximum frequency of imposing restrictions.

First we assess the impacts of climate change on both water companies' service reliability without any water transfer in place. Then 10 portfolios of options including new water resources and demand management options are evaluated to understand how each of these portfolios make impacts on water companies' reliability, again without any water transfer options included. Next, we assessed the changes of supply reliability for each water company that would result from the construction of water transfers. Two scenarios were defined as follows:

1) Fixed rate transfer. The donor company will guarantee to provide the agreed amount of water in any circumstances.
2) Rule-based transfer. The rule is implied to both sides of donor and receiver companies. The donor company guarantees to transfer water in some situations, i.e. their reservoir level is high enough. The receiver company should decide when they would request water from the other side.

For each of above-mentioned transfer scenarios, the probability of meeting the transfer requirement has been assessed. The results show that climate change reduces the reliability of water transfers, though the donor company may be able to adjust its operational rule to provide water to the receiver company with higher reliability.

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Kuczera, G. (1992), Water supply headworks simulation using network linear programming, *Advances in Engineering Software*, *14*(1), 55-60.

Keywords: *Water supply, reliability, water transfer, climate change*

Assessing residual inflow and loss estimates methods in river reach calibration using the Budyko Framework

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Abstract: River system models are widely used for planning and management in river basins. In highly regulated systems, streamflow volumes in the river from upstream can be far greater than contributions from local runoff and the estimation of localized runoff will have little influence on model performance at the downstream gauge as assessed using metrics such as Bias and Nash-Sutcliffe Efficiency (NSE). However, the local runoff could have significant implications for regional water management. Local runoff, commonly referred to as residual inflows may provide important environmental flows or may supplement irrigation diversions via floodplain harvesting into on farm storages. The estimation of these residual inflows and their corresponding losses can be difficult since different combinations of estimated residual inflows and losses could give similar results at the downstream gauges in term of model performance. It is important that the estimation of both residual inflows and losses are constrained to values that are in line with our understanding on the upper and lower limits for runoff, as the estimated values can have significant management implications and therefore adequate representation of these components of the water balance are required in the river system models used for basin management.

This paper compared a range of schemes that could be applied to estimate losses and residual inflows during model calibration of the river reaches. The outputs from these methods were assessed according to the bounds of local runoff determined from the analysis of observed catchment runoff at the mean annual scale for 213 unimpaired streamflow sites in the Murray Darling Basin.

Three schemes to estimate reach losses based on the difference between the simulated and observed streamflow were tested. The three schemes were different in terms of the data used to derive loss functions, which includes (i) deriving loss function basing on the entire streamflow record, (ii) deriving loss function using only the days where upstream flows exceed downstream flow (losing periods), and (iii) deriving loss function according to periods with the lowest 20% rainfall or weekly rain less than 1 mm. To estimate the residual inflows, a rainfall-runoff model was calibrated to either the gauged streamflow or to the estimated residual flows, and the residual inflows in the reach were estimated either before or after a loss relationship was applied to the river reach model. This resulted in 12 different schemes for estimating residual inflows and the corresponding loss. These schemes were tested across seven regulated reaches, six in the Murray Darling basin and one in North Queensland.

Different schemes have provided different estimates for the magnitude of residual inflows. In order to assess which estimates of residual inflow were more realistic, the estimates were assessed by the mean annual runoff estimated using the Budyko framework (Budyko, 1958) , which assumes that mean annual evapotranspiration (ET) from a catchment will approach total precipitation (P) under very dry conditions (water limit) or potential evapotranspiration (E_0) under very wet conditions (energy limit). The schemes tested did not show a clear best method for the estimation of losses and residual inflows. Particularly, the use of the losing periods to define loss function tended to results in higher runoff coefficients and is potentially unrealistic as assessed via Budyko framework. In this case, the Budyko framework can provide a quick assessment and constrain of the magnitude of the residual inflow estimates.

Keywords: *Reach calibration, rainfall runoff modelling, Budyko framework*

Optimising low flow releases to meet sustainable water management objectives: *A case study of the Angas River catchment in South Australia*

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Abstract: Water resources of the Mount Lofty Ranges have been subject to management under water allocation plans (WAP) since 2013. WAP objectives include achieving triple bottom line outcomes in sustainable resources development. Extraction or use limits defined in the WAPs aim to find a balance between provisions of water for both, (a) consumptive use and (b) maintaining water dependent ecosystems (WDEs) at an acceptable level of risk (environmental targets). Earlier work undertaken to underpin regional water allocation planning identified that allocations could be optimized and environmental targets could be met if low-flows were returned to streams around patterns of farm dam development identified in the WAPs (Vanlaarhoven and van der Wielen, 2009; 2012). Moreover, ensuing work identified preliminary indications that environmental targets may be also met by returning low-flows via a low flow release (LFR) mechanism around different configurations of farm dams, with potential to optimise investments in achieving sustainable water resources management and underpin further policy development (Alcorn *et al*., 2013, Savadamuthu *et al*., 2013). However, this work was conducted on a limited number of small headwater catchments and wasn't able to identify generic patterns which could be used to regionalise decision-making in prioritizing the location of LFRs.

This work describes the methodology and results of the investigation undertaken to extend earlier efforts. Development of a whole of Angas River catchment model in Source platform, containing model nodes for each of its 1060 farm dams and watercourse extractions, enabled assessment of the feasibility of different scenarios for the optimisation of LFR placement, in terms of the total number required (cost) and environmental targets likely to be met by these scenarios (benefit). The scenarios explored considered how the scale and number of LFRs could be effectively reduced while still achieving defined environmental targets. Options for exclusion of farm dams was based on their (i) relative location within a management zone, (ii) size, (iii) type of use and (iv) combinations of the above, for the purpose of LFRs. Scenarios were explored to also develop generic rules of thumb which could be used to inform decision-making.

The resulting flow data from modeled scenarios were compared with the base scenario (WAP scenario), to evaluate their variation from the required environmental targets flow regime. In addition, it was considered essential that the process to define this optimization be transparent and repeatable, and where possible be a rules-based approach. General results confirm the earlier hypothesis that it is feasible to achieve the environmental targets set out in the WAPs with fewer than required LFRs, by strategically locating them across the landscape. However, they also indicate the possibility of more than one suitable (or near-suitable) location strategy for a given area, and that a strategy suitable for one area might not necessarily be suitable for others. Results also indicate it is possible to develop generic rules of thumb for the strategic location of LFRs across the landscape while still meeting environmental targets. Further work across a range of hydrologically diverse catchments is proposed to validate generic rules.

Keywords: *Low flow releases, farm dams, Angas River, Source, environmental targets*

EXTENDED ABSTRACT ONLY

What is ailing the rainfall runoff modelling?

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Abstract: Despite years of research, the state of rainfall runoff modelling is still in an under-developed and fragmented state. There has been a plethora of models available claiming to perform simulation of a range of hydrological phenomena, however most of them are limited to the research papers they are published in. Not a great deal have changed in terms of concepts on which models are based and their usage other than vastly improved user-friendliness of the modelling software. Some of the reasons for this are: unwillingness to working with data, lack of rigorous model testing and assessment, overparameterisation and redundancy in model structure causing equifinality, invalid assumptions, ignoring data quality issues, academic pressure to get research output published and focus on matching the streamflow at catchment outlet rather than a process-based study.

Over the last 30 years computer has made research based in the office more attractive than field-based studies. At the same time, detailed hydrological data gathering is relatively expensive and time consuming and there is a decline in funding for data collection. Many a times researchers struggle to analyse and make sense of data often riddled with noise and other instrument errors as well as vagaries of nature therefore collection and analysis of data are undervalued. Also, much of the hydrological research has been carried out on data from smaller catchments due to the ease of data gathering. These studies have limited benefit as relationship and hydrological processes on small catchments may not be representative of those of larger catchments and their relation varies from region to regions. Recommendations have been made to study of hydrologic processes and patterns at a variety of scales to avoid generation of models with a weak conceptual base.

Subjectivity in assessment of model performance creates a situation where same model calibration/validation can be judged as satisfactory or unsatisfactory for the same outcome. Interpretation of goodness-of-fit values are often subjective biased by perceptions that are often ambiguous. Depending on what is being modelled, the time scale (e.g. daily), ease of relevant data collection, accuracy of a modelling exercise can be decided subjectively.

It has been shown that rainfall runoff data contains just enough information to reliably support model of a very limited complexity with only a handful of parameters. However overparameterisation and redundancy in model is quite common caused by the need to simulate all possible processes. Overparameterisation invariably leads to a non-unique combination of parameters or the "equifinality" and creates a situation where many parameters act as 'error terms' absorbing residual errors during parameter optimization. This results in a loss of the physical significance model parameters. In prediction, when the data characteristics change the parameters continue to predict based on their learned behavior in calibration despite new data regime, causing prediction error.

Simplification without ensuring appropriateness is another issue. The biggest concern of them all is the large scale extrapolation of point data to large scales, i.e. influence of scale. Turning blind eye to the data quality is also a concern. This includes streamflow data affected by measurement errors including the use of old and vastly changed rating curves. Depending on the bed material, the stream cross-sectional profile changes every few years, yet the use of rating curve based on one time measurement is widespread. The use of global climate model in rainfall runoff modelling despite large prediction uncertainty in them is also very common.

Inability to deal with non-stationarity of data has resulted in making the traditional calibration-verification method for prediction/scenario modelling unworkable. For example, model calibrated for a wet epoch may not be suitable for prediction in a dry epoch and vice-versa.

Our understanding of the hydrological processes has not kept pace with increase in our analytical and computational capabilities and this gap in knowledge has limited our ability to advance the science of hydrological modelling. Researchers have highlighted directions for future hydrological modelling that include more field observations and field experiments to capture temporal and spatial heterogeneity of hydrological processes. A systematic approach to formulate models appropriate to the complexity of solution may be worth investigation to creating a tailor-made platform for fabricating a problem/process specific modelling framework.

Keywords: *Rainfall runoff modelling, errors in modelling, equifinality, hydrological processes*

Modelling changing catchment under the climate variability: a case study from a semi-arid catchment in the upper basin of the Goulburn River

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Abstract: Hydrological response of arid and semi-arid regions to climate fluctuations are highly variable and predicting induced hydrological variability is extremely challenging. This study investigated the temporal variability of streamflow (SF), and its relationship with soil moisture (SM) in a semi-arid region at the catchment scale, using SWAT (Soil and Water Assessment Tool). SWAT is a continuous semi-distributed model, which simulates the spatial variability of SM, considering the spatial heterogeneity of a catchment such as land cover, soils, and slope, and predicts SF after the routing process. SWAT has been widely used to evaluate the long term impacts of land management practices on water resources in agricultural landscapes.

Despite its wide application, the capability of SWAT has not been fully realized in the (semi-) arid region. It is largely because the underpinning concept of SWAT in runoff generation lies on the USDA Soil Conservation Service - curve number (SCS-CN) method. The CN method is limited by its empirical origin. Based on the infiltration loss model, it does not consider long term water losses such as evapotranspiration (ET) and evaporation, the most crucial hydrological term in a water limited environment. Several approaches have been made to improve SM estimation for a continuous modeling (William et al., 2012). The main focus was given to improve estimates of the water retention term (S) based on the soil characteristics (known as Direct Soil Moisture Index, DSMI) or relating it to the potential ET (hence varying it with accumulated plant ET) (referred to as Revised Soil Moisture Index, RSMI).

Considering the potential of improved CN methods on estimating SM, we apply SWAT to predict and understand hydrologic behaviors of a semi-arid catchment, located within the Goulburn River catchment in the Upper Hunter Region of NSW. The catchment has experienced an extreme climate variability and shown noticeable changes in hydrologic behaviors, in particular SF pattern over last two decades. We report improved hydrological prediction of a changing catchment by: (1) better accounting for the spatial variability of precipitation, soil characteristics, and antecedent SM condition (using DSMI and RSMI methods), and (2) calibrating model parameters over the period of climate fluctuations (both dry and wet periods) for SF. SWAT was set up at a monthly time scale to simulate SM and SF over the period of 2008-2014 using DSMI and RSMI methods. We used SWAT embedded sensitivity analysis and SUFI-2 to calibrate the model over 2008-2012 and validated it over 2013-2014. Calibration contained both wet and dry climatic conditions, however validation only contained the wet period. Sensitivity analysis revealed that both surface runoff and ET were sensitive processes for both the RSMI and DSMI methods to generate SF. However, soil characteristics became sensitive only for DSMI method.

The calibrated model performance for SF estimation was reasonable based on both methods, but RSMI provided improved overall SM prediction. The calibrated models provided NSE (Nash-Sutcliff efficiency) values of 0.60-0.76 over the calibration and validation periods, with ~ 11 % of RMSE (root mean squared error). Overall, DSMI method predicted SF slightly better during both of wet and dry period, while RSMI provided better estimation of SM for the study period. In addition, we noted the improvement on the spatial variability of precipitation enhanced SM prediction. Most inconsistent results between simulated and observed SM were from those areas with mismatching soil characteristics between available soil information and actual site conditions. This study shows the potential of using a simple, semi-distributed catchment scale model (calibrated based on SF) to predict SM and SF, and to investigate the threshold for SF generation for the catchment with a changing behaviour in a semi-arid region. Accurate representation of precipitation, climate variations and soil characteristics were crucial to reduce the prediction errors.

Keywords: *SWAT, streamflow, soil moisture, semi-arid region, hydrological variability*

The effectiveness of the CN method in areas with saturated soil conditions

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Abstract: The Soil Conservation Service (SCS) Curve Number (CN) method has been widely used by engineers in hydrological modelling. The main advantage of this method is that only a few parameters are needed to calculate the CN. The purpose of this study was to analyse the effectiveness of the regionalized CN method for the analysis of flood vulnerability in saturated soils, commonly located in coastal floodplains.

The study area is located in the Juqueriquere River Basin, on the northern coastline of Sao Paulo, Brazil. It holds the major non-urbanised plains of the northern coastline of the state. It is constrained by the high altitude mountains of Serra do Mar, which causes intense orographic rain in the area. Added to the basin's geophysical features, the influence of tide contributes to the local high vulnerability to floods. Even though the area is not representatively gauged, and scarce runoff data is available, there is high interest to urbanise the plains, due to the recent implantation of the Gas Treatment Unit of Caraguatatuba (UTGCA) of the Brazilian Petroleum Corporation (PETROBRAS) in 2012, and the proximity to the Port of Sao Sebastiao. The City Master Plan of Caraguatatuba Municipality (CMPC) was proposed in 2011. Both the gas pipelines of UTGCA and the part of the Tamoios Highway Complex have been implemented, based on the Environmental Impact Assessment of PETROBRAS (2007), but no macro or micro drainage plans have been developed for this urbanizing area yet. The Foundation of Water Resources of Sao Paulo (Costa Norte 2017) has just approved the macro drainage plan for the downstream area, which is densely urbanised and constantly affected by floods.

In the study, the runoff in each sub-basin was derived from the CN method at the Hydrologic Modeling System (HEC-HMS). The Manning's roughness coefficients of different cross-sections were calibrated at the Hydrologic Engineering Center's River Analysis System (HEC-RAS), where the CN method was also adopted.

The rain gauge of PETROBRAS (EMQAR1), near UTGCA plant, recorded 247.20 mm in a 24h period between 17 and 18 March 2013. This event caused severe floods in the basin, especially in the upstream area. Thus, this rainfall event was used for calibration purposes, taking into consideration the water level of three different cross-sections registered by local farmers.

The CN values of the present scenario were attributed by the land use and land cover (LULC) classification of high-resolution imagery, and were regionalised per sub-basin using the LULC area weighted average approach. The future scenario was based on the collection of similar perviousness-patterned zones of the proposed CMPC. Both scenarios were simulated with the same SCS unit hydrograph, regarding the same calibration event.

The findings of the study revealed that, even though the peak discharge of the future scenario had higher values than the present scenario, they did not represent the significant increase of imperviousness of some of the CMPC zones. It occurred due to: the CN regionalization approach, potential CN losses and underestimation of the rainfall intensity, as the initial abstraction is not related to the soil infiltration.

Keywords: *CN method, soil infiltration, CN regionalisation, CN loss, flood vulnerability evaluation*

Principle of universality in hydrological modelling: a glance into the future of hydrology

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Abstract: The main question to be discussed in the presentation is the principle of universality in hydrological modelling. Can a universal model be developed or it is impossible in principle? How can we assess a model's universality? And how does it relate to the adequate presentation of natural processes? The fundamental laws of physics suggest that the process of runoff formation must be the same in any point of space. This implies the possibility to simulate runoff formation processes in any basin (or any scale) within the framework of a single (or universal) methodological approach, its mathematical realization and unified informational support. The obstacle for such model development is so-called "physically-based" descriptions of the subsurface processes, such as 1) infiltration, water movement in the soil layer, formation of surface and subsurface flow; and 2) slope (surface, subsurface and underground) inflow to the channel network. We consider the use of the following equations widely spread in hydrology – the Richard's equation, the Saint-Venant or kinematic wave equations and the Boussinesq equation – to be wrong approaches. The idea of developing approaches to calculate water movement at slopes, channel network and aquifers using non-existent data about inclinations, morphometry, roughness and etc. is utopic. The methodology of reverse estimation leads to ungrounded beliefs of adequacy since the parameters of models evaluated in such a way are the subject not of systematization, nor generalization, neither normalization; often they are not even realistic (Vinogradov et al., 2011). The reliance on the use of parameter calibration techniques and ignoring the principle of universality in the methodology of model development cause the problems of non-uniqueness and equifinality, and makes James Kirchner's question (are we getting the right results for the right reasons?) very relevant (Semenova & Beven, 2015). We claim that the greater the number and variety of successful testing results of a model over basins of any type, regardless of their scale and landscape/climate characteristics, the more likely it is that the concepts underlying the model are not defective.

Hydrograph is a robust Russian process-based model where the processes have a physical basis and certain strategic conceptual simplifications that give it the ability to be applied successfully in many parts of the world. It has an appropriate physics and level of model complexity for remote, sparsely gauged regions and has ability to use many parameters that can be observed in the field. Its successful application to basins of different scales as well as various geographical zones without change of the model's structure, algorithms and based on unified set of model's parameters has proven the possibility of a general approach in hydrological modelling. By the example of the Hydrograph model it will be shown how 1) the similarity in the earth heterogeneity or, in other words, appropriate general characteristics describing runoff conditions can be found, at the same time accounting for the basin's unique properties; 2) the parameters of the model reflecting objective properties of the watersheds and, therefore, possessing clear physical meaning can be systematized; 3) we can transfer small-scale process parameterization to watershed- and basin-scale modelling; 4) specific studies can be incorporated in the general model; and 5) experimental catchment studies can be used for identification of local conditions of general processes.

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Keywords: *Principle of universality, surface, subsurface and underground flow, parametrization, Hydrograph model*

Interpolation methods for the calibration of rainfall-runoff models in ungauged basins

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Abstract: Meteorological data are essential for the calibration of rainfall-runoff models and the acquisition of reliable outcomes. The rainfall spatial and temporal variability is not easily detected when the number of rain gauges is insufficient or when they are improperly distributed. In addition, the effect of orographic rain near mountainous areas or other local phenomena may not be effectively assessed in a large-scale approach, or by geostationary satellites, such as the Tropical Rainfall Measuring Mission (TRMM). Remote sensing and geoprocessing techniques have been widely used for the spatial analysis of rainfall data, which may come from similar or different sources and formats (vector or raster). Data are commonly integrated and processed by the use of interpolation methods in geographic information systems (GIS). The aim of this study was to achieve properly distributed rainfall data for the calibration of a rainfall-runoff model. The study area is located in the Juqueriquere River Basin, Caraguatatuba municipality, on the northern coastline of Sao Paulo, Brazil. The area is not properly gauged and is influenced by orographic rainfalls due to the nearness to the Serra do Mar Mountains. The analysed precipitation was on the 17th of March, 2013, when the downstream area of the basin was flooded. Data from different sources were assembled to ideally represent the entire area, including the Data Collecting Platform (PCD) 32521, the rain gauges EMQAR1 and EMQAR2 and TRMM. Using GIS techniques and spatial analysis, tests were done for the most intense rainfall period data sets using assorted multivariate interpolators (inverse distance weighting, spline, and kriging). The statistical analysis revealed that the best performance was for the kriging method, taking into consideration the lowest standard deviation for the sample processing. Thus, it was the chosen technique for the rainfall interpolation. A map with rainfall data was generated for the basin with the mean precipitation of every 3h, which was then integrated with the 11 subbasin maps. A 24h period was processed, starting at 3 a.m. (17 to 18 of March 2013), totalling 88 maps with mean precipitation values, and a 24h rainfall hydrograph for each subbasin. The proposed methodology provided more reasonable and well-distributed rainfall data than each separate collecting device, which could not detect the local effect of the orographic rain on the plains in the downstream area.

Keywords: *Interpolation, rainfall-runoff models, kriging, calibration, statistical analysis*

On the benefit of semi-distributed hydrological modelling for better water resources assessment

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Abstract: Developing modelling tools that help to assess the spatial distribution of water resources is a key issue to achieve better solutions for the optimal management of water availability among users. Distributed hydrological models which explicitly consider spatial heterogeneities within catchments are consequently pointed as a solution. However, the analysis of previous studies demonstrates that the benefit of a distributed model over a lumped model is not systematic. In this study, we investigate two main cases where a semi-distributed model is expected to outperform a lumped model. The first one concerns local influence of dams, the second concerns simulation at ungauged locations.

Firstly, for the case of dam influences, we adapted the lumped approach of Payan et al. (2008) to a semi-distributed framework which uses water storage variation of dams as an additional input data. In this way, the specific location of existing reservoirs inside a catchment is explicitly taken into account. A comparison to the lumped strategy demonstrates better performance of the semi- distributed model at influenced locations, especially for reproducing low-flow characteristics.

Secondly, we evaluated the capacity of the model to estimate streamflow at ungauged locations. This is done through a "leave-one-out" evaluation where each gauged catchment is successively considered as ungauged. We evaluated the benefit of a semi-distributed model, which can take advantage of calibrated sub-catchments inside the ungauged one, to outperform a regionalized lumped model.

A large database of over 1270 catchments spread all over France (drainage area between 15 km² and 110 000 km²) enables to explore numerous configurations. The semi-distributed rainfall-runoff model used to investigate those two points is based on the lumped GR5J model (de Lavenne et al. 2016): it runs at the daily time step, and has five parameters for each sub-catchment as well as a streamflow velocity parameter for flow routing. Its structure is based on two stores, one for runoff production and one for routing. The calibration of the model is performed from upstream to downstream sub-catchments, which efficiently uses spatially-distributed streamflow measurements and facilitate regionalization procedure.

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Keywords: *Hydrological modelling, semi-distributed model, large sample, regionalization*

Quantifying groundwater recharge in regional-scale models

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Abstract: For landscapes ranging from prairies to floodplains, wetlands, estuaries and playas, groundwater fluxes at or near the land surface can have significant implications for water management and salinity. Accurate characterisation of recharge and evapotranspiration fluxes is based on accounting for the influence of a broad range of factors, including climate, terrain, soil and vegetation characteristics, as well as depth to groundwater.

Remotely sensed evapotranspiration data is becoming more readily available through products generated from MODIS and Landsat satellites. They have the potential to improve the spatial upscaling of field-based recharge and evapotranspiration estimates, and temporal apportioning of long-term average estimates. They provide information for surrogate or meta-modelling of near-surface groundwater processes and can aid in improving understanding of system behaviours. There is a need, therefore, to reassess how we define groundwater recharge and evapotranspiration processes and represent them in water resources models.

Options for incorporating recharge and evapotranspiration into groundwater flow models range from annual average values and simple conceptualisations, to fully coupled groundwater – surface models and process emulation. This talk will briefly review recharge and evapotranspiration processes in shallow groundwater systems and defines the factors that are important when modelling them. Research from the temperate to semi-arid South East region of South Australia and the tropical regions of Northern Australia is used to give examples of, and suggest methods for, providing the most appropriate spatial and temporal estimations of recharge for a range of problems.

Keywords: *Groundwater modelling, recharge, evapotranspiration*

Stepwise calibration and process verification of continental scale models

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Abstract: Continental and global scale hydrological models have emerged as useful tools for homogenising calculations of hydrological variables across basin boundaries, international and subnational boundaries and climatic regimes. There exist now a large number of different model codes with differing assumptions, inputs, parameterisations of functions and optimisation methods. A large challenge in optimising these models is avoiding equifinality. This study presents a step-wise approach to parameterising and validating a continental hydrological model. Soil-type and landcover specific parameters are set by optimising the relevant parameter in groups of representative gauged basins (RGBs) for each soil-type or landcover. For example, the RGBs for fine soils would be all gauged basins with > 50 % fine soils in their catchments and, < 1% lake or reservoir area. The downstream applicability of these parameters is then validated in more heterogeneous downstream catchments, with promising results. The next step is to optimise routing, lake and anthropogenic (irrigation and reservoir) processes. After optimisation, the same parameter set is then used for the whole model domain. Validation in independent downstream catchments shows this process provides useful predictions in ungauged basins of multiple scales across multiple physiographic regimes.

Continental scale models also provide a workbench to test hypotheses of which atmospheric and land-surface inputs are important for hydrological models, because they combine discharge observations with catchment aggregated inputs for a large number of catchments covering large physiographic gradients. We evaluated the underlying assumptions of 2 very different continental scale hydrological models, HYPE and AWRA-L, by correlating observed flow signatures for the sets of calibration and validation catchments with the physiographic characteristics of the catchments. This verified both existing assumptions and provided new insights. For example, we saw that the chosen of input forcing variables for each model didn't necessarily explain the spatial variability in discharge across the catchments. The Australian model, AWRA, uses the Penman equation for potential evapotranspiration which requires daily net solar radiation as a forcing input. The European model, E-HYPE, uses a modified Hargreaves-Samani algorithm which assumes that the diurnal temperature range together with the extra-terrestrial radiation is a proxy for this. After normalising for the precipitation variability, we saw no discernible correlations to any of the flow signatures for the net radiation used as the input to AWRA-L; however, the diurnal temperature range was shown to explain some of the variability in the runoff response in both Australia and Europe.

Finally, the correlation study was repeated using simulated flow signatures in place of the observed flow signatures to determine if the models were capable of reproducing the observed relationships. The results provide insight into each model, where they work well and where they can be improved. By repeating the study in two continents using two different models, the results also indicate where processes from one model could potentially be transferred to benefit the other.

Keywords: *Continental scale hydrological modelling, regionalization*

The Australian Water Resources Assessment Community Modelling System (AWRA CMS)

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Abstract: The Australian Water Resources Assessment (AWRA) Modelling System has been developed by the CSIRO and the Bureau of Meteorology (the Bureau) as part of fulfilling the Bureau's water information functions under the Water Act (2007). The Bureau's operational AWRA-L model (the gridded landscape water balance component of AWRA) is used in supplying retrospective water balance estimates in the Bureau's Water resource assessments, the National Water Account, and underpins the daily updated Australian Landscape Water Balance Website (www.bom.gov.au/water/landscape). The daily gridded (~5km x 5km) runoff, evapotranspiration, soil moisture and deep drainage outputs (available from 1911 until today) have been adopted by many users and agencies across Australia since the website went live in November 2015; including use for real-time estimation of antecedent soil conditions for flood forecasting purposes, derivation of design flood losses for Australian Rainfall and Runoff, use for monitoring and reporting by various agricultural agencies, and for research into incidence of Ross River virus and bush fire conditions.

To further unlock the potential of the system, the Bureau released AWRA as a Community Modelling System (AWRA CMS) in December 2016, enabling different user applications such as local fine scale application or scenario assessment and further development and improvement of the model and datasets by external users. The AWRA CMS is available publicly through https://github.com/awracms/awra_cms and is a Python based system including the core model; modules for simulation, visualisation, calibration and benchmarking; datasets for testing the model and documentation. Apart from using the system for individual purposes users can submit alterations, allowing the modelling community to benefit jointly from development, and feeding into the Bureau's operational system where appropriate.

This presentation details the AWRA CMS components and recent developments including enabling fully supported MPI based calibration through use of large scale systems such as the National Computational Infrastructure (NCI), sensitivity analysis (see Fig 1), and support for application on arbitrarily sized grids. For further details on the AWRA CMS including training opportunities please contact awracms@bom.gov.au.

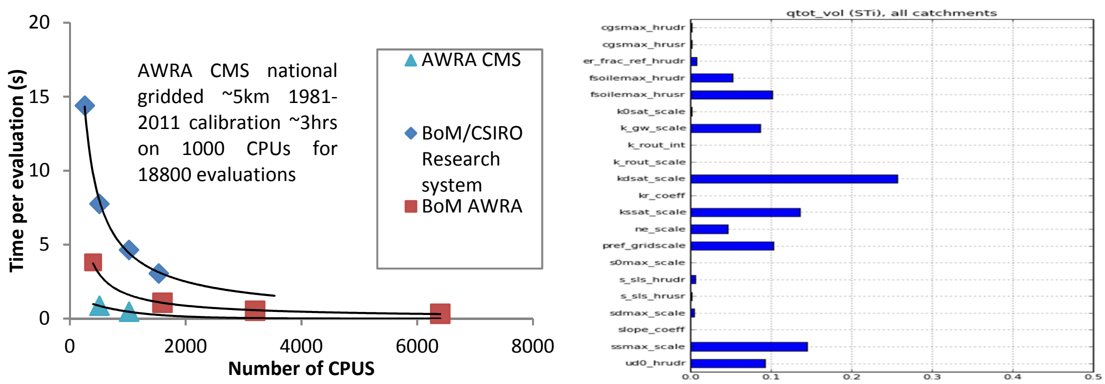

Figure 1. AWRA national ~300 catchments (a) evaluation speed on NCI compared to previous versions and (b) normalised proportion of variance attributed to parameters through Sobol sensitivity analysis

Keywords: *Open source, water balance, Python, MPI, sensitivity analysis*

Bias correction factors for AWRA-L runoff data in Victoria

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Abstract: The Australian Water Resources Assessment Landscape model (AWRA-L) is a water balance model that simulates daily rainfall-runoff, soil moisture and drainage fluxes on a 0.05 degrees (approximately 5 km x 5 km) gridded basis across Australia. AWRA-L model outputs (runoff, soil moisture, evapotranspiration) not only support the Bureau of Meteorology's National Water Accounts and Regional Water Information reports, but also other purposes such as crop yield planning, flood modelling, and catchment condition reporting through regular data feeds to agricultural companies, water utilities, and governmental agencies (state and federal).

The performance of AWRA-L in simulating daily and monthly streamflow was assessed by the Bureau of Meteorology and CSIRO in 2015, and was found to have a similar or better degree of accuracy compared with other landscape water balance models, or globally calibrated rainfall-runoff models. In this study, the performance of the AWRA-L model in simulating monthly run-off across Victoria was assessed in greater detail, using data from the Bureau of Meteorology's Hydrologic Reference Stations. These gauging stations measure flow on unregulated rivers with relatively low levels of upstream land use change and water use. The flow records are therefore a useful benchmark against which the quality of AWRA-L predictions of runoff can be tested. The comparisons with Hydrologic Reference Station records showed that AWRA-L typically overestimates runoff in Victoria. AWRA-L does not simulate lateral flow or routing, and uses one set of global model parameters for all of Australia, so local variability in performance is expected.

Given these local variations in performance, it would be useful to be able to bias-correct the AWRA-L simulated runoff in ungauged catchments based on catchment properties. Initially the differences between predicted and measured monthly runoff appeared to be systematic, and therefore amenable to bias correction (e.g. Figure 1). However, initial attempts to predict the bias at 5%, 25%, 50%, 75% and 95% flow percentiles based on catchment characteristics (i.e. area, mean annual rainfall and flow persistence) were inconclusive. Further work is therefore required, because an effective method to bias-correct the AWRA-L outputs would greatly improve our ability to predict runoff at sites across Victoria.

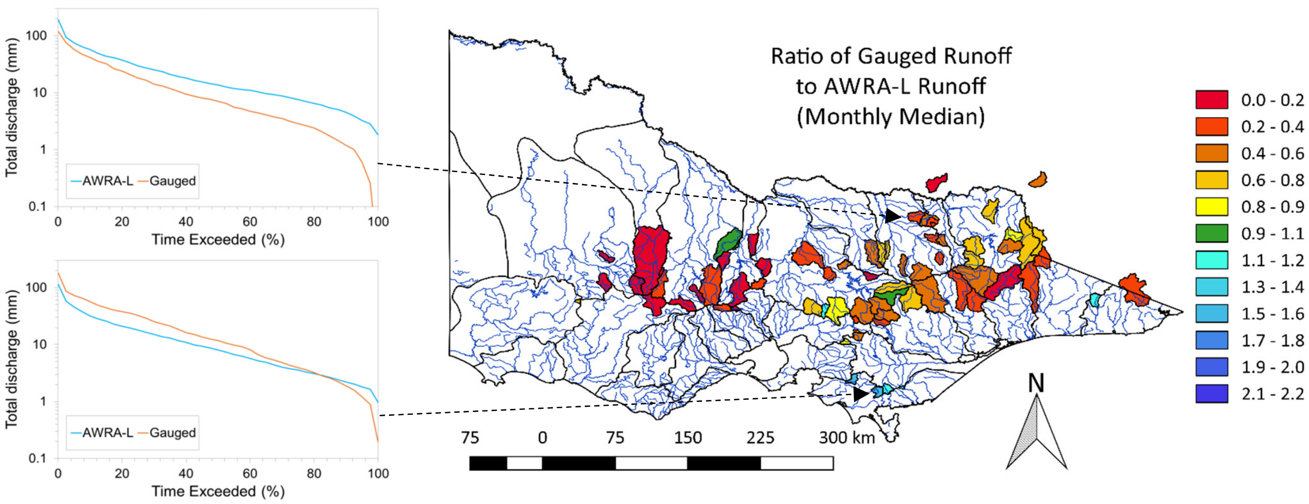

Figure 1. Left: Example monthly flow duration curves of gauged and AWRA-L modelled runoff for Yackandandah Creek (top) and the Tarwin River (bottom). Right: The ratio of the median monthly gauged runoff to AWRA-L predicted runoff for Victorian catchments with Hydrologic Reference Stations.

Keywords: *Australian Water Resources Assessment Landscape model (AWRA-L)*

Continental scale hydraulic properties for hydrological modelling from pedotransfer functions

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Abstract: The measurement of soil hydraulic properties using field sampling techniques over large areas can be prohibitively expensive. The use of empirical regression or pedotransfer functions (PTFs) to derive soil hydraulic properties from secondary data is more practical for unsampled locations across large areas. This study presents the use of the CSIRO (TERN-funded) digital soil mapping of Australian soil properties, selected PTFs, and various aggregation techniques to derive saturated hydraulic conductivities (K_{sat}) and available water content (AWC) across continental Australia for three soil depths (top 10cm, next 90cm and next 5m).

The TERN estimates of sand, silt, and clay for various soil depths are available at 90m spatial grids across Australia. Various aggregation techniques (aggregate soil properties then derive hydraulic properties vs derive hydraulic properties then aggregate; use of geometric means vs arithmetic means) are applied to derive the soil hydraulic properties at 1km and 5km grids. The PTFs used to derive the soil hydraulic properties are selected based on evaluations of published PTFs for predicting K_{sat} and AWC in Australia by Minasny and McBratney (2000) and Minasny et al. (1999), respectively. The K_{sat} for the three soil depths are derived using the PTF of Dane and Puckett (1994) as shown in (1):

$$K_{sat} = 303.84\exp(-0.144P_{<2}) \tag{1}$$

where $P_{<2}$ is the soil particle size fractions of clay. The AWC for the three soil depths are derived using the PTF of Minasny et al., (1999) as shown in (2), (3), and (4):

$$AWC = \theta_{-33} - \theta_{-1500} \tag{2}$$

$$\theta_{-33=}0.3543(1 - \exp(-0.0385P_{<2})) + 0.083 \tag{3}$$

$$\theta_{-1500=}0.4016(1 - exp(-0.0230P_{<2})) + 0.0027 \tag{4}$$

where θ_{-33} is the field capacity of the soil and θ_{-1500} is the plant permanent wilting point of the soil.

The aggregation techniques and the PTFs were implemented in the Murrumbidgee river basin. The maps of AWC for the shallow soil layer based on ASRIS interpretations which is available at 5km grids and those derived using PTFs at 5km and 1km grids are shown in Figure 1. It can be seen that compared to existing soil hydraulic properties based on observations and expert knowledge (ASRIS interpretations) which have sharp discontinuities across class boundaries, the PTF derived maps provide continuous and spatially varying hydraulic properties across large areas. The derived hydraulic properties are expected to perform better in areas where observations are sparse.

When applied to continental Australia, the new spatial layers will be useful for improving estimates of soil water storage in continental models such as the Australian Water Resource Assessment (AWRA) model.

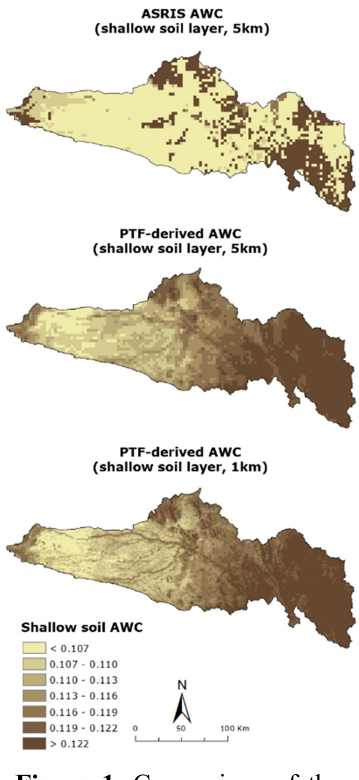

Figure 1. Comparison of the AWC based on ASRIS interpretations (5km) with those derived using PTFs (5km and 1km).

Keywords: *AWRA model, continental scale hydraulic properties, pedotransfer functions*

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EXTENDED ABSTRACT ONLY

Groundwater recharge modelling – a global meta-study

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Abstract: Global statistics indicate that 21 out of 37 major aquifers of the world are progressively undermined. Groundwater recharge plays a vital role in controlling groundwater system dynamics and is one of the most important limiting factors for groundwater sustainable withdrawal. Due to lack of availability of gridded global recharge measurements, large scale recharge are often estimated by water balancing with the help of global hydrological models. All these water balancing are computationally intensive and most of the time lacks direct validation of the groundwater component. In this study we aim to build an empirical groundwater recharge model to study temporal and spatial variations in global recharge at a spatial resolution of $0.5^0 \times 0.5^0$. A multimodel inference approach and information theory are applied to build the groundwater recharge model by considering all potential influential factors with a set of 715 recharge estimates compiled from literature across the globe. The final model developed had a prediction error between -10 mm/yr and 10 mm/yr for 97.2% of cases (Figure 1).

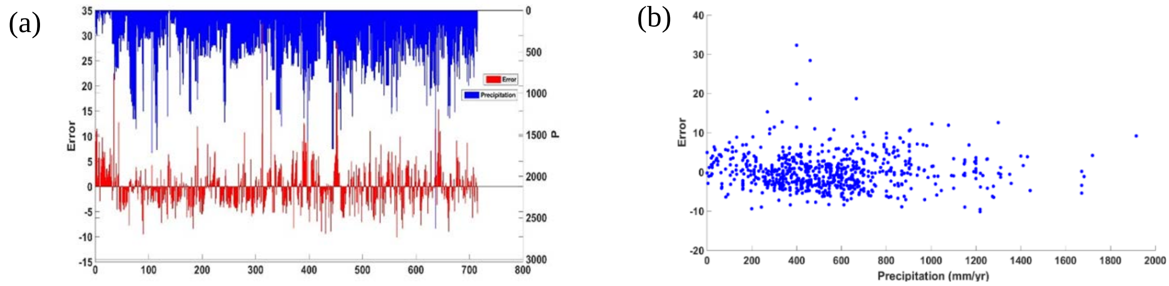

Figure 1. (a) Model prediction error at each data point and (b) Scatter plot between error and precipitation.

Long term average annual recharge was found to be 104.2 mm/yr. The total recharge estimated in this study (13600 km^3/yr) was very close to the existing estimates with the complex hydrological models. It implies that this model can make the reliable recharge assessment with less computational requirement than the existing techniques. Recharge across the globe was found to be highly varying spatially and was analogous to global distribution of climate zones. Humid regions were having very high recharge compared to arid (semi-arid) regions, which is obvious due to the higher availability of water for recharge (Figure 2(a)). Recharge was affected by climate variability and climate extremes at a regional level. However, the effect of climate variability on inter annual recharge at a global scale was not pronounced in our results (Figure 2 (b)). This is because El Nino Southern Oscillations (ENSO), the primary factor that determines climate variability globally, has converse effects on different parts of the world. The effects of increased precipitation in some parts of the world would have counteracted with reduction of precipitation in other parts resulting in relatively less effect on inter annual variation in recharge globally. It is worth mentioning that this study do not include direct anthropogenic effects on groundwater system, which opens a scope of further development of this study.

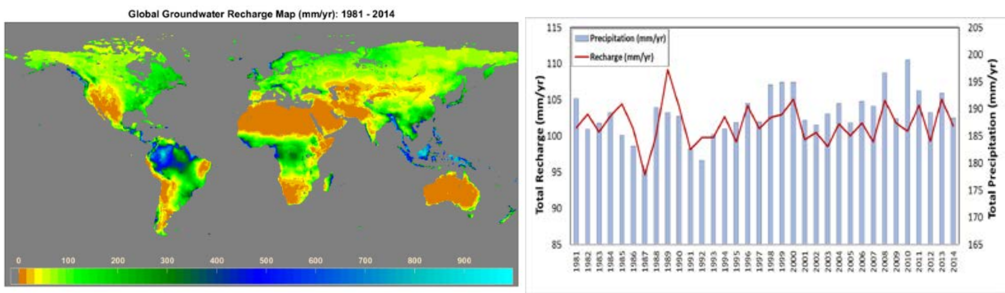

Figure 2. (a) Spatial and (b) temporal distribution of global groundwater recharge fron 1981 to 2014.

***Keywords**: G lobal groundwater recharge, multimodel inference approach, meta study*

A new method of accounting for runoff dams

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Abstract: Runoff dams, sometimes called hillside dams or farm dams, are an essential part of agriculture in Australia, providing water for stock, domestic, and irrigation use. Runoff dams are typically very small at around 2 ML on average, but can be smaller than 1ML or larger than 100 ML depending on the climate, terrain, and intended purpose. Although each dam on average is relatively small, there are vast numbers of them across the country. One study estimated the total capacity of runoff dams in Australia in 2008 to be approximately 1460 GL (SKM/BRS 2010).

Modelling techniques to assess the impact of runoff dams on streamflow were first developed in Australia in the late 1990s, and have been progressively improved since then. Such modelling has primarily focussed on very local scales, such as the impact of all dams in a local catchment, or the impact of individual dams. Over time, there has been increasing recognition of the significance of runoff dams and their impact on surface water hydrology, which has led to an increasing need to formally account for their impact. For example, runoff dams have been included in the Victorian Water Accounts since 2003-04, and starting from 2019 runoff dams will be a key part of the Murray Darling Basin Plan (2012).

In comparison to methods used to estimate runoff dams at a local scale, most methods used to account for runoff dams at a basin or state scale are relatively simple and approximate. In many cases, the capacity of the dams multiplied by a nominal factor is assumed to be a reasonable proxy for their annual impact (SKM/BRS 2010), regardless of agriculture type or annual climate. In the past, this level of simplicity has been unavoidable for two key reasons:

- **Lack of suitable data** – to estimate impacts of runoff dams using current modelling techniques, an essential data requirement is surface runoff. While gauged streamflow data is easily available at small local scales, until recent times a complete set of such data has been virtually impossible to assemble for all areas across a region or jurisdiction. Modelling has been limited to local catchments where stream gauges exist.
- **Difficulty in regionalisation** – impacts of runoff dams seem to vary between wet and dry years, high and low levels of development, climate, and types of agriculture, often without any apparent rhyme or reason. Consistent patterns between catchments have been hard to identify.

This paper will outline a new method for accounting for runoff dams which overcomes these issues. It significantly reduces problems with data availability by only requiring digitised surface areas of all runoff dams and their spatial coordinates. All other data is based either on regional equations and relationships, or obtained directly from the Bureau of Meteorology's publicly available AWRA model outputs. Also, problems with regionalisation are completely avoided by directly calculating a water balance for every dam across a region. As with all hydrology, this method has significant inherent uncertainties, and more work is needed to characterise these.

Using an annual time step, this method allows for regional differences in agriculture type and climate, and can be aggregated at any scale from a small catchment to a large basin or entire state. Testing of the new method was undertaken on 11 small catchments across Victoria, with results indicating that it compares extremely well against more detailed daily models. With simple data inputs, simple calculations, and results which vary with climate, this method represents a practical approach to estimating impacts of runoff dams for accounting purposes.

Keywords: *Runoff dams, farm dams, water accounting*

Assessment of Climate and Land Cover Change on the Hydrological Cycle of North and South Korea

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Abstract: North Korea's economic difficulties in the late 1980s resulted in large-scale of deforestation leading to impact on the hydrological cycle including direct runoff, evapotranspiration, and soil moisture. Due to the climate change and climate variability, North Korea also suffered severe droughts after 2010s. On the contrary, due to the long-term forestry policy of South Korean government, the South Korea's forests cover more than 60% of South Korean territory. In this study, simulation on hydrological cycle within the entire Korean peninsula was carried out from 1981 to 2013 using a land surface model (the VIC model). To reflect the 40 years of land cover change in both nations, the hydrological cycle simulation was conducted based on three different land cover data as a representative ones for each simulation period. The sources of land cover data are NASA (1983), University of Maryland (1995), and ESACCI (2010). The soil parameters for the simulation were derived from the soil data distributed by FAO (1995). The input meteorological records for the simulation of both countries were collected from the WMO observatories within Korean peninsula for consistency. The simulation results are summarized as follows. First, the runoff ratio was estimated as 55% ~ 70% in South Korea and 38 ~ 56% in North Korea. In particular, the variation of runoff ratio of North Korea is about 18%, slightly larger than the South Korea's runoff ratio of 15%. Contrarily, the rate of evapotranspiration of North Korea was larger than that of South Korea. That is, the evapotranspiration ratio in South Korea is 20 ~ 35% of total precipitation, and in North Korea it is 25 ~ 46% of total precipitation. However, the amount of change in evapotranspiration ratio was 21% in the case of North Korea which is slightly larger than 15% of South Korea. It was also noted that during one of the most severe drought periods for North Korea, the evapotranspiration rate reached near 50%. Thirdly, soil moisture estimated in South Korea had an average of 34% and in North Korea 27%. However, unlike the simulated results of the runoff ratio and the evapotranspiration rate, the difference in the variation of soil moisture in South Korea and North Korea over the entire period was moderate with 8%. As a result, the difference in hydrological cycle characteristics between South Korea and North Korea increased since the 1990s, when the forest destruction of North Korea became critical. Particularly, the deforestation of North Korea has resulted in an increase of instability in the direct runoff in major watersheds when compared to those of South Korea. In the case of South Korea, there have been relatively less difference while North Korea had a distinct difference, reflecting the impact of land cover and hydrological cycle change.

Keywords: *Hydrological cycle, land surface model, land cover change*

Estimation of confidence intervals for three different flow naturalization methods

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Abstract: Estimating the natural river flow appears essential in water resources management to quantify the available water, to distinguish human and climate influence and to preserve the ecological status of river. For these reasons, several naturalization methods have been developed to estimate naturalized flows in rivers influenced by human activities. However, up to now, no comparison of these methods and no estimation of their associated uncertainties have been made yet.

Our study proposes a classification of these methods into three main groups and their respective strengths and weaknesses. The first one, namely neighborhood method, is based on a regionalization from geographically close catchments. The second one, namely extension and reconstitution method, implements a hydrological model on the studied basin to estimate its naturalized streamflow time series. The third one is derived from a water balance analysis. In order to facilitate the comparison between methods, a confidence interval around naturalized flow time series is estimated for each of them. The uncertainties of the hydrological model are quantified from the analysis of residuals by flow class (Bourgin et al. 2014). For the first method based on regionalization, a transfer of the global uncertainty from neighbors is made (Bourgin et al. 2015). For the methods based on hydrological model, we used the GR5J model, implemented using the airGR R package (Coron et al. 2017), and a modified version including a dam module.

A comparison of all these methods is carried out using different indicators such as the magnitude, the frequency, the duration, the timing and the rate of change of discharge. These methods are applied on the Seine river basin, mainly influenced by reservoirs. The application of the methods to a larger set of basins, including case studies in Australia and the United-States, with more diverse influences, will allow a generalization of the results.

From this diversity of cases, we discuss situations where each method is more reliable and may therefore be preferred.

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Keywords: *Naturalization methods, influenced catchment, dam, uncertainty, hydrological modelling*

Enhancements to the Australian Water Resources Assessment Landscape (AWRA-L) Model

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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. 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 operational version of the AWRA-L model (v5.0) implemented across the Australian continent at 5km spatial resolution has two hydrological response units (HRU's). The CSIRO and the Bureau have increased the number of hydrological response units from two (representing shallow and deep rooted vegetation) to five (representing shallow and deep rooted vegetation along with impervious areas, large water bodies and irrigated agricultural areas) to better represent the landscape dynamics within an AWRA grid (AWRA-Lv6.0). This was further complemented by increasing the spatial grid resolution from 5km to 1km. A number of modelling experiments were carried out to investigate the influence of number of HRUs (two and five) and spatial grid resolution (5km and 1km) on the water balance flux and store estimates using Murrumbidgee as the test basin. This presentation will provide the comparison between the different sets of results as well as comparison of these results with observations for streamflow, soil moisture, ET and recharge. The overall results from the experiments and comparison with observations suggest that incorporating extra HRUs to explicitly represent impervious areas, large water bodies and irrigated agricultural areas and modelling the associated hydrological processes for each of these HRUs at 1km spatial grid resolution provides AWRA-Lv6.0 with the ability to model actual field representation for the region which in turn provides improved water balance estimates making AWRA-L suitable for catchment and local scale applications.

Keywords: *Australian Water Resources Assessment, AWRA-L, water assessments, water accounting*

Coupled surface water and groundwater model development and calibration using MIKE SHE for the Greater Bunbury region in south-west Western Australia

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Abstract: The Greater Bunbury region in south-west Western Australia is distinguished by low-lying lands, shallow groundwater table, regular winter inundation and extensive network of agricultural drains. Department of Planning, Lands and Heritage released the Greater Bunbury Strategy 2013 which aims to allow the region to grow from 83,598 people (2011 Census) to at least 150,000 people. It assigned Department of Water to develop a Drainage and Water Management Plan (DWMP) to make the growth sustainable. A key component of the DWMP is the development of a fully distributed, physically-based coupled surface water and groundwater interactions model using MIKE SHE hydrologic modelling system. This is to accurately reproduce groundwater levels and aquifer discharge to rivers and drains and understand the hydrological processes. Hence the modelling outcomes will be used in outlining water management and land use change options. This study focuses mainly on the conceptualization, development and calibration of the model. The model covers a study area of 497 km^2 that extends from the Darling Scarp in the east to the coast in the west, and ranges in elevation from 60 mAHD to 0 mAHD. Thirty-five years of distributed daily climate data (1980−2014) were used to calibrate the model. It comprised of process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow and river flow to capture the major processes in the hydrologic cycle. It was built on a 150 m regular grid and the thickness of its saturated zone varies from 160 m in the north to 800 m in the south. The saturated zone was divided into eight computational layers to accommodate the unconfined Superficial Aquifer, and the confined Leederville and Yarragadee Aquifers. The model was calibrated using a total of 62, 13 and 6 bores installed in the Superficial Aquifer, Leederville Aquifer and Yarragadee Aquifer, respectively. The calibration was performed based on comparisons of observed and modelled groundwater heads and river flows. Model results are generally consistent with field observations. An intrinsic difficulty in representing anisotropic Guildford Clay Formation within the Superficial Aquifer limited model performance otherwise excellent agreements are seen in general. The calibration targets outlined were achieved for the Superficial Aquifer with a scaled mean sum of residuals (SMSR) -0.25% (-0.1 m) and a scaled root mean square error of 1.87%. The water balance estimation for the model domain showed an error of 0.01%, which satisfied the criteria of a water balance error<0.05%. These calibration statistics are within the acceptance range as mentioned in the Murray Darling Basin Commission guidelines and illustrate the level of general reliability of the model.

Keywords: *Integrated groundwater and surface water model, MIKE SHE, hydrologic cycle, Greater Bunbury, aquifer*

A comparative assessment of two modelling approaches for simulation of nutrient dynamics in river basins using case studies in Japan and Australia

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Abstract: The modelling of nutrient dynamics in a river basin is a challenging task. This type of modelling requires huge amount of datasets to describe the dominant catchment biogeochemical processes and in-stream nutrient dynamics. In traditional modelling using a conceptual approach, the inherent processes are simplified. On the other hand, the process based modelling approach aims to represent catchment characteristics in a detailed manner. The aim of this study is to evaluate the performance of two modelling approaches, sub-catchment based semi-conceptual approach and raster-based process-oriented distributed modelling approach, for simulation of nutrient dynamics at a river basin scale. The model has been applied in two river basins in Australia and Japan.

In the sub-catchment based modelling, the study area is divided into a number of sub-catchments. The model estimates nutrient export from each sub-catchment in terms of soil bound nutrient associated with soil erosion and dissolved nutrients with runoff. The estimation of soil erosion has been carried out using universally used empirical equations RUSLE and MUSLE. The soil delivery ratio was used to determine the sediment yield from the catchments. The nutrient model takes account of nutrient generation process on the land surface and determine nutrient export via soil erosion and runoff using export functions. The fate of nutrient and transport process in river networks system has been described by solving advection-dispersion equation with chemical reaction.

The raster-based model was configured into a cluster of square grids with appropriate size, where each grid was defined with a set of parameters that represent catchment characteristics. The pollution from land surface to the in-stream release in response to hydro-climatic and land use management practice are modelled. In this modelling approach, the soil erosion model replaced the empirical equations used in sub-catchment based model with process based equations that take into account both rainfall and overland flow impacts on soil erosion. The sediment yield was determined based on transport capacity. The modelling process combined the simulation of surface and river components dynamically. By Describing hydrologic process, hill slope soil erosion and nutrient dynamics in each grid on the land surface, the model estimates catchment nutrient release and its fate during transport in river network system. At the river-surface interface the lateral flow and pollutant load exchange are determined. The model solves the physical transport equation with catchment chemical reaction processes to computes nutrient concentration at each river grid.

The case study area the Saru River in Japan consists of 17 sub-catchments covering a catchment area of 1,350 km^2. The river carried huge amount of sediment and nutrient fluxes during two consecutive flooding events, in 2009, which were modelled in this study. Hourly interval observed data was gathered for the model calibration and validation. On the other hand, the 2nd case study area was located in Latrobe Basin in Gippsland, Australia. The upper catchment of the Latrobe River was modelled in this study for long term simulations of sediment and nutrient fluxes.

The model shows better performance in simulating short term flooding events for the Saru River. Due to lack of data the performance matrix for the Latrobe River are relatively low. It is found that the process based model is highly effective in providing higher resolution modelling outcome. An investigation on the improvement of the process based equations may enhance model performance further.

Keywords: *Nutrient pollutions, lumped and distributed modelling, water quality, hydrologic model, river basin*

Process-based hydrological modelling in different permafrost environments

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Abstract: More than 60% of Russia and 20% of land surface in Northern Hemisphere is covered by permafrost. Hydrological cycle is influenced by time-variable frozen aquiclude, limited connectivity between surface and ground water, long snow season and period of river ice cover. Hydrological models developed for the temperate regions are not applicable in the permafrost river basins. The aim of the study is to make use of historically collected experimental hydrological data for modelling poorly-gauged river basins on larger scales in different Russian permafrost environments using process-based modelling approach.

The Hydrograph model used in the study explicitly simulates heat and water dynamics in the soil profile thus is able to reflect ground thawing/freezing and change of soil storage capacity through the summer in permafrost environments. The key model parameters are vegetation and soil properties that relate to land surface classes. They are assessed based on field observations and literature data, do not need calibration and could be transferred to other basins with similar landscapes. Model time step is daily, meteorological input are air temperature, precipitation and air moisture.

Parameter set is initially developed in the small research basins located in mountains and lowlands. The Hydrograph model was tested against ground thawing and freezing depth, soil moisture, ground temperature and snow characteristics in different permafrost landscapes in Central Yakutia and North-Eastern Siberia.

Shestakovka River basin (area 170 km^2) is a left tributary of the Lena River in the vicinity of Yakutsk city. The climate is very dry and continental. Mean air temperature (MAT) is -9.5°C, precipitation is 240 mm/year. The Kontaktovy Creek basin (area 21.2 km^2) is located in the Upper Kolyma plateau in North-Eastern Siberia. It is characterized by colder (MAT -11.4°C) and wetter (290-460 mm/year) climate. Both of the watersheds have been monitored for several decades. For both Shestakovka and Kontaktvy watersheds simulated soil and snow variable states have satisfactory agreement with observed ones. The river runoff simulation results for the Shestakovka River show very high variability from year to year. Results for mean and wet years are generally better than for dry years. Modelling results for the Kontaktovy Creek are satisfactory. The largest deviations occur in the spring flood period when presumably underground water pathway exist even in the frozen ground but are not accounted for by the model.

Refined set of model parameters was transferred to middle and large river basins characterized by similar landscapes and dominant hydrological processes. Model application to three rivers in Central Yakutia with basin areas between 3 380 and 65 400 km^2 and six river basins in North-Eastern Siberia with areas from 65 to 42600 km^2 suggests that the Hydrograph model is suitable tool for hydrological process investigation in permafrost zone.

We conclude that data about internal catchment processes on the smaller scale is essential for the increasing model realism on small and large scales in the dynamic and vulnerable permafrost environments.

Keywords: *Hydrological modelling, permafrost river basin, the Hydrograph model*

Modelling of urban native bushland reserves with a coupled surface-subsurface hydrological model

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Abstract: Urban expansion and associated land clearing drive habitat loss, creating a fragmented landscape where remaining native vegetation is restricted to small and isolated remnant reserves. These areas create important corridors to maintain high levels of urban biodiversity and provide a collection of environmental and social services essential to the quality of life of urban dwellers. The encroachment of built environment on natural ecosystems, in addition to reducing the extent of these reserves, has the negative effect of decreasing the water available to sustain vegetation growth and health. Increased impervious areas and stormwater drainage network reduce groundwater recharge and the delivery of water to bushland reserves. Therefore, assessing the water balance of urban reserves hosting remnant vegetation is important to guide reserve management to maintain a hydrological regime able to preserve these ecosystems. In the Greater Melbourne area in southeastern Australia, for instance, less than 4% of the pre-European native vegetation cover remains, mainly as pockets of urban bushland reserves managed by government authorities. Reduced water availability associated with urbanization in combination with periods of drought and extreme heat has increased the water stress of these areas.

The aim of this study is to investigate the water dynamics in a small urban reserve (4.1 ha), Napier Park, embedded in a northwestern suburb of Melbourne (Victoria, Australia) (Figure 1a). The reserve is home to valuable remnant vegetation (*Eucalyptus Camaldulensis*) and is highly managed, experiencing passive irrigation in about 85% of the reserve. We use the physically-based spatially-distributed hydrological model CATchment HYdrology (CATHY) to simulate the reserve water dynamics. The model couples the three-dimensional Richards equation for subsurface flow in variably saturated porous media and a path-based one-dimensional diffusion wave approximation of the de Saint-Venant equation for surface water dynamics. Starting from a 5 m x 5 m resolution DEM (Figure 1b), the resulting three-dimensional subsurface grid contains 26,376 nodes and 139,620 tetrahedral elements; based on geological information the soil depth is limited to 2 m for a total of 13 vertical discretization layers (Figure 1c).

Applying such a modeling approach at small spatial scales permits a more detailed description of the variations of land-surface properties, such as topography, soil heterogeneity, and vegetation. The main challenges in simulating Napier Park are the appropriate description of irrigation as a source of water in different locations of the reserve and the selection of proper boundary conditions for a small domain embedded in urban environment. The study showcases the use of a distributed model to potentially support management practices of urban bushland reserves, such as designing irrigation measures.

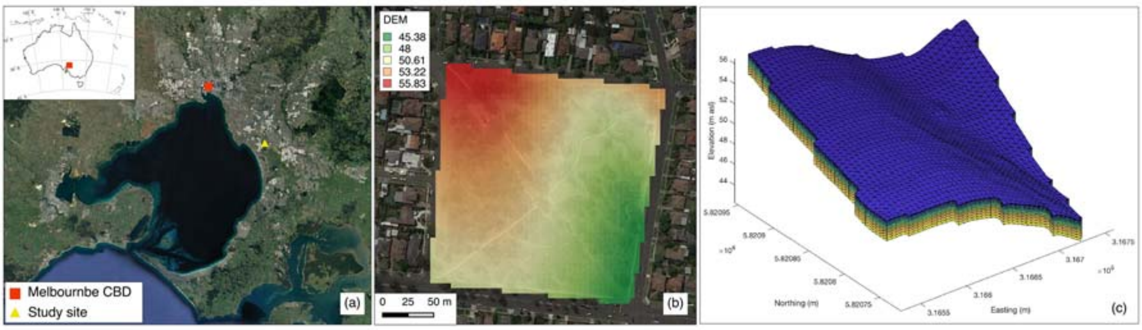

Figure 1. (a) Location of the study site in the Greater Melbourne area in Victoria, Australia. (b) Digital elevation model (5 m x 5 m) of the study area. (c) CATHY 3d grid resulting from the simulation.

Keywords: *Water dynamics, remnant vegetation, urban reserves, soil moisture, coupled surface-subsurface hydrological modelling*

Spatial uncertainty assessment of groundwater recharge at regional scale

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Abstract: Groundwater recharge is one of the several key factors to assessing groundwater availability. It is used as an input into a groundwater model or an independent risk assessment approach, which then determines the maximum volume for extraction. A typical example is groundwater sustainable diversion limits provided in the Murray-Darling Basin Plan. The initial recharge for establishing a sustainable diversion limit in the basin plan was estimated using a biophysically based model (WAVES). Given the role of groundwater recharge, it is of paramount importance to perform a robust assessment of groundwater recharge.

Our prior study suggested that estimated recharge for a particular site could be highly uncertain. But this uncertainty is site-specific, dependent of the uncertainty in input parameters and the uncertainty in observations for model calibration. Despite the site-specific uncertainty, at the regional scale, groundwater recharge and its uncertainty may possess certain trends, as climate, soil and vegetation may have spatial patterns. However, this spatial uncertainty has not been assessed previously. The objective of this study was to evaluate the spatial uncertainty of groundwater recharge at the regional scale.

This study chose the Campaspe catchment in southeast Australia as a study area. The biophysically based modelling code WAter Atmosphere Vegetation Energy and Solutes modelling (WAVES) was used to perform numerical simulations. Based on the conditions of the study area, three weather zones, two soil zones and four land cover zones were used to reclassify the catchment area. In the end, thirteen subareas were considered for recharge estimation. For each subarea, the Monte Carlo method enhanced by the Latin-Hypercube sampling technique was employed to generate 40,000 model realisations. The recharge uncertainty was estimated through WAVES by comparing modelled evapotranspiration to actual evapotranspiration derived from MODIS satellite imagery.

The results show that recharge uncertainty indeed varies from area to area. The largest uncertainty range is 10-240 mm/y in the upland area with the annual average rainfall of 705 mm/y, and the smallest uncertainty range is 0-10 mm/y in the downstream end of the catchment with the annual average rainfall of 410 mm/y. Our study also shows that flood irrigation plays a significant role in recharge. By applying flood irrigation of 20 mm depth once every two weeks between November and next April, recharge increased dramatically. Despite the spatial variation in recharge uncertainty, a clear trend was identified. This recharge pattern generally follows the trend of rainfall, i.e. high rainfall leads to high recharge. Likewise, the recharge uncertainty seems also directly proportional to rainfall. Also, the recharge trend is strongly affected by soil and vegetation as both have similar effects on recharge.

Overall, this study indicates that recharge uncertainty at the regional scale behaves in a similar fashion to mean recharge. Among all the factors, water input including rainfall and irrigation is a major control. For groundwater recharge assessment, we should devote efforts to high water input areas where recharge is expected to be high (i.e. areas with significant rainfall or frequent flood irrigation).

Keywords: *Groundwater recharge, water and energy balance model, spatial uncertainty analysis*

Comparing methods for determining flow routing parameters in models that underpin water resource planning in the Murray Darling Basin

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Abstract: Hydrological models are used to underpin different policy and management decisions in our regulated river systems. Historically, in Australia, different water management agencies have used different modelling platforms and different approaches to calibrate the models the underpin water resource planning. However, recently these agencies have been working collaboratively to build a standard modelling platform (eWater Source) to support water resource planning. As part of this move to a standard modelling platform, it is recognised that it would be useful to compare the different methods used for model calibration. The aim of this comparison is to determine if: (a) the method of calibration impacts on the predictive capability of the model; and (b) if it is possible to recommend a consistent method that can be applied across all river reaches during calibration of river system models in the Murray Darling Basin. The use of an identical approach allows other river modellers to more easily understand how the model parameters are derived. When building a river system model, the parameters of the flow routing component need to be calibrated, these parameters simulate the timing and shape of the hydrograph at the downstream gauge.

This paper compares different methods for setting the parameters (index flows and travel times) of variable parameter Muskingum routing approach within eWater Source. Three methods for selecting index flows and four methods for determining the travel times are compared over 14 catchments within the Murray Darling Basin. Based on the work of Close (1996), a maximum of 10 index flows have been defined for each method for each reach and the inflow bias has been set to 1. The three methods for selecting index flows are:

1. Manual selection of index flows
2. An automated approach based on changes in the slope of the upstream rating curve
3. Fixed interval index flows

The four methods used to determine the travel time are:

1. Optimisation using R (Pearson correlation coefficient) as an objective function
2. Optimisation using the R of the log of the flow values as an objective function
3. Automated selection of travel time based on analysis peaks at the upstream and downstream flow gauges (using the median travel time of the flows with 10% of the index flows)
4. Automated selection of travel time based on analysis peaks at the upstream and downstream flow gauges (using the mean travel time of the flows with 10% of the index flows)

Combined the two sets, results in a total of 12 different methods. The methods were tested using a 2 fold approach and the skill of the methods at making predictions during validation are compared. Using R as a metric, skills scores (Murphy, 1988) were developed to compare the methods to a benchmark model which only considers lag. Comparing the methods using the Student's t-test, we show that at the 0.01 level there is no statistical difference between any of the methods. However, at the 0.05 level, three of the approaches are statically different when compared to the method with the highest skills score (Manual selection of index flow and optimisation using R as an objective). Of these three methods that show a difference at the 0.05 level, two of these methods used fixed intervals for the index flows, while all three are based on an analysis of peaks.

The results indicate that using optimisation makes a marginal difference to the predictive capability based on a comparison of the R values. It also indicates that reasonable predictions can be made via both optimisation or analysis of peaks provides appropriate index flows are selected.

Keywords: *Hydrologic routing, Murray Darling Basin, eWater Source*

A continental scale river system model for water accounting

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Abstract: With increasing competition for finite and often scarce water resources, water information is a critical underpinning of the water reform process both on which to base decisions and against which to measure progress. 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. Existing global and continental scale river models, mainly designed for integrating with global climate models, are of very coarse spatial resolutions and lack many important hydrological processes, such as overbank flow, irrigation diversion, groundwater seepage/recharge, which operate at a much finer resolution. Thus, these models are not suitable for producing water accounts.

The CSIRO and the Bureau of Meteorology have developed a continental scale river system model called Australian Water Resource Assessment River System model (AWRA-R) and implemented it for national water accounting in Australia. The model includes major hydrological processes, anthropogenic water utilisation and storage routing that influence the streamflow in both regulated and unregulated river systems. Two key components of the model are an irrigation model to compute water diversion for irrigation use and associated fluxes and stores and a storage-based floodplain inundation model to compute overbank flow from river to floodplain and associated floodplain fluxes and stores. The AWRA-R model was implemented across 41 large river basins (with median catchment area >15,000 km^2) covering seven different regions with different climatic characteristics across Australia, including the Murray-Darling Basin (MDB). The model included 582 nodes covering a total contributing catchment area of about 1.5 million km^2. Out of the modelled regions, the MDB was the largest region with an area of approximately 1 million km^2. The AWRA-R model was calibrated and validated against the observed streamflow data. Based on the length and quality of the streamflow data at the selected gauges and climatic variability in the MDB region, the period of 1970–1991, covering both wet and dry climate, was selected for calibrating the AWRA-R model. A more recent period of 1992–2014 was selected for validating the model.

The calibration and validation results demonstrated highly satisfactory performance of the model with median daily Nash Sutcliffe Efficiency Coefficient (NSE) of 0.64 and median annual bias of less than 1% for the period of calibration and median daily NSE of 0.69 and median annual bias of 12% for validation period. The model has performed significantly better with the incorporation of dominant hydrological and anthropogenic water use (such as irrigation diversion) in non-headwater catchments and that has contributed to reducing model bias. The model has produced a large number of fluxes and stores for surface water accounts. Where possible, the simulated fluxes were assessed against observed data in a number of areas within the MDB. The simulated evapotranspiration (ET) by AWRA-R irrigation model agreed well with the actual ET (derived from MODIS data, which is called the CSIRO MODIS Reflectance Scaling Actual ET) with a median correlation coefficient of 0.7 for Murrumbidgee and above 0.5 for the all other modelled regions within the MDB. Similarly, the simulated annual irrigated area and diversion in the Murrumbidgee irrigation district agreed well with the observed data.

The AWRA-R model has been operationalised as part of the AWRA modelling system in the Bureau of Meteorology for producing national water accounts.

Keywords: *Water accounting, AWRA-R, Australian Water Resources Assessment, Murray-Darling Basin, AWRA modelling system, river system model*

EXTENDED ABSTRACT ONLY

Reservoir storage and release using proxies of downstream irrigation demand for scenario modelling

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Abstract: Reservoir operations that have the primary objective of supplying water for seasonal irrigated agriculture mainly depend on two factors: (i) storage at the beginning of the irrigation season and (ii) precipitation and potential evaporation fluctuations throughout the season. In this paper we use observed or modelled time-series of reservoir storage, inflows and outflows, and proxies of downstream irrigation demand to calibrate reservoir operations at the daily time-step. A wide range of dam operating conditions are represented as a result of choosing a 30-year (1983–2012) calibration period that included significant dry and wet periods and was performed in a multi-objective fashion against reservoir levels and releases. Two irrigation demand proxies are tested, the first is based on a simple 30-day moving average soil moisture deficit and potential irrigated area; whereas the second uses additional information on crop mix to estimate crop demand via the FAO-56 crop coefficient method. Additional functionality was implemented in the two schemes to emulate aspects of current operational rules which resulted in a total of seven calibrated parameters. The emulated aspects include limits to supply at the beginning of the irrigation season (allocations), limits during times with low storage volumes, minimum and environmental flows. Two river systems in Australia with large within-year multi-purpose dams (> 3 hm^3), all supplying water to austral summer irrigated crops, are used to test the two schemes. The first scheme is implemented in the Hunter River system (21,367 km^2), where two large dams (1,083,000 hm^3) operating in parallel are combined and calibrated as one and then split proportionally in relation to their share of water supply. The second scheme is implemented for two large dams (485,000 hm^3), which were also calibrated combined (but not split because they are operated in series), in the Namoi River system (42,000 km^2). Results showed that both schemes can reasonably reproduce both volumes (r^2>0.8 and error <15%) and releases (r^2>0.7and Nash Sutcliffe Efficiency NSE>0.5) (Figure 1).

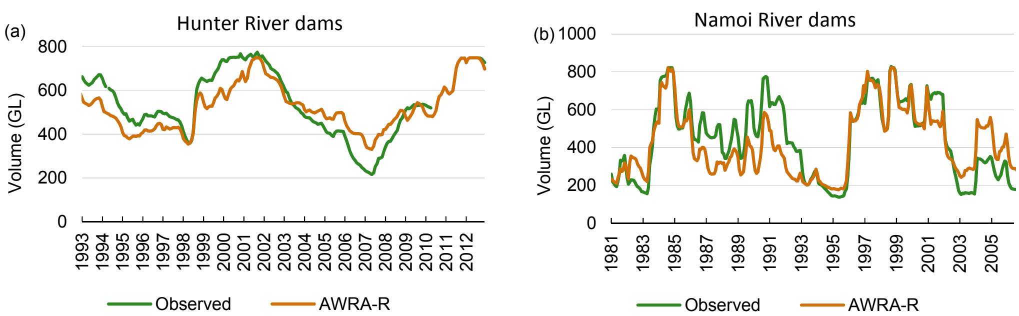

Figure 1. Observed against modelled storage volumes for the Hunter and Namoi River Dams.

Both schemes can be used to simulate the effects of climate change and changes in irrigation and other human demands.

Keywords: *Namoi, Hunter, river system modelling, calibration, dam*

Testing new approaches to river model calibration

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Abstract: River system models are important tools to quantify water storages and fluxes in natural and regulated river systems. They are especially useful for examination of management scenarios and their effects on river dependant water users and ecosystem components. The AWRA-R model was built as a part of the WIRADA to produce various fluxes and stores associated with river systems in regulated and unregulated systems to support the production of the national water accounts (NWA) by the Australian Bureau of Meteorology. One attractive feature of the AWRA-R model are the various auto-calibration options. The most recent of these, denoted "system calibration" shows tremendous promise as a way of extracting the maximum amount of information from all the stream gauge data within a river basin.

Previous studies using system calibration have utilised independently calibrated AWRA-L runoff estimates as part of the model structure. This reduces the dimensionality of system calibration, enabling better system performance relative to reach-by-reach calibration. However, AWRA-L uses a single parameter set calibrated across the region to estimate ungauged runoff (regional calibration). Calibration of ungauged runoff to individual catchments can achieve better goodness of fit than regionally calibrated ungauged runoff calibration. This study investigates the use of four calibration methods in the Fitzroy River catchment of Western Australia; (1) Reach-by-reach calibration using regionally pre-calibrated runoff (from the AWRA-L model), (2) System calibration using regionally pre-calibrated ungauged runoff, (3) Reach-by-reach calibration using individual sub-catchment calibrated GR4J based ungauged runoff, and (4) System calibration using individual sub-catchment calibrated GR4J based ungauged runoff.

System calibration has been demonstrated to perform well in the past using pre-calibrated ungauged runoff. This has been made available from the AWRA-L model that produces gridded runoff based upon a regionally calibrated parameter set. Using these inputs, rather than locally calibrated runoff, system calibration has been shown to improve the performance of river system models relative to reach-by-reach calibration. However, until now system calibration that derives unique parameters for ungauged runoff estimation jointly, has not been attempted.

The results from this study show that the jointly calibrating all river system model parameters including those for ungauged runoff (via the GR4J model) produce superior performance (Figure 1) by reducing error prorogation while simultaneously tuning performance in each sub-catchment.

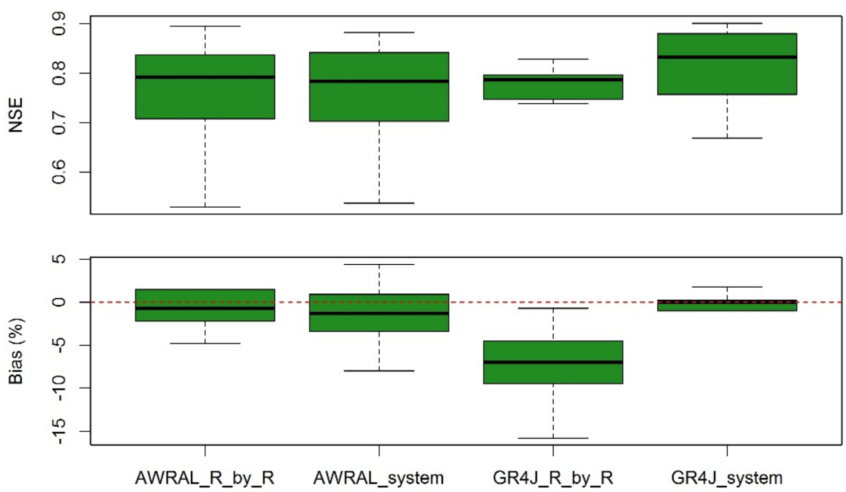

Figure 1. River model goodness of fit for the four tested calibration/ungauged runoff combinations in the Fitzroy River.

Keywords: *River model, system calibration, GR4J, innovative calibration*

EXTENDED ABSTRACT ONLY

Dam behaviour and operation modelling in a data limited environment

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Abstract: Accurately modelling daily reservoir water levels rely on being able to close the reservoir water balance. This requires historical measurements of daily reservoir inflows, releases, losses and gains through evaporation and seepage, reservoir water level and knowledge of the reservoir surface area – volume relationship. Typically, however, one or more of these parameters is unknown, either due to the absence of measurement or the information is considered commercial in-confidence.

This paper describes a novel approach to developing a robust model of an urban water supply reservoir, where due to the sensitive nature of the operation of the reservoir, the only measurements readily available (from a disparity of sources) were daily reservoir volume between 1990 and 2015, annual urban water use between 2006 and 2013, and population estimates between 1911 and 2011.

The approach involved deriving a surface area – volume relationship for the reservoir from the available reservoir volume time series and remotely sensed Landsat imagery. An urban demand model using available population and climate data was then jointly calibrated with a daily lumped conceptual rainfall-runoff model to the reservoir volume observations and the eight years of available annual urban use data.

The model was successfully parameterised and sensitivity analysis indicated that the combination of local climate and reservoir volume/area relationship meant that evaporative losses were high for this dam at dam volumes above 20%. Supplementary water could be pumped into this dam in drought situations, however this was very inefficient when dam volumes were above 20%.

Simulated reservoir volume and Landsat derived reservoir area are shown in Figure 1.

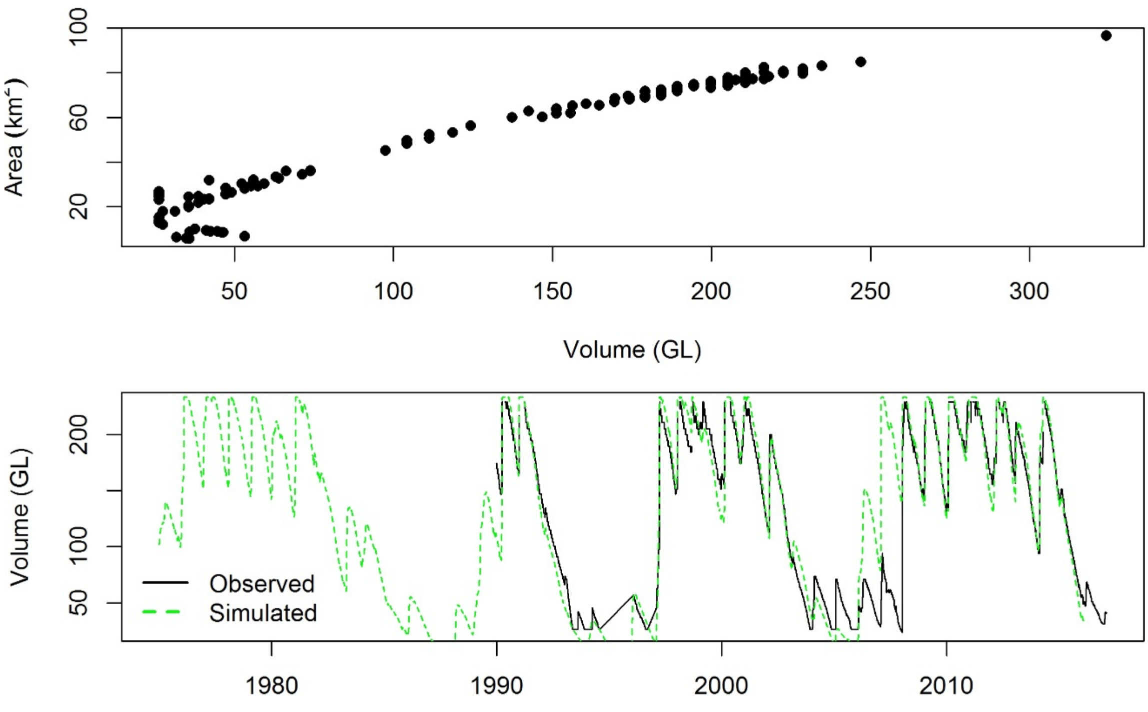

Figure 1. Dam volume and concurrent dam area (derived from Landsat data – top panel), and simulated and observed dam volume.

Keywords: *Landsat, dam water balance, urban water demand, GR4J*

Risk-based water resources planning: Coupling water allocation and water quality management under extreme droughts

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Abstract: The main responsibility of the water sector is to supply reliable and safe water. To fulfil their duty, water companies must consider water quality and quantity issues and challenges. Climate change and population growth will have an impact on water resources in terms of both available water and river water quality. Traditionally, a distinct separation is made between requirements for water quality and quantity in the waterbodies from which water is being withdrawn for public water supply. However, water quality can be a bottleneck in a system since water treatment works can treat water only if it meets certain standards. We present a risk-based approach for incorporating extreme events, based on future climate change scenarios from a large ensemble of climate model realisations, into an integrated water resources model and water quality models. In order to take into account land use and land management effects on water quality, three scenarios were considered: i) LU-baseline: current land use; ii) LU-future: future land use, i.e. expansion of agricultural land due to increased food demand and iii) LU-future+mitigation: future land use with enhanced phosphorus mitigation strategies. Here we employ a more recent large ensemble of climate model projections based on the same climate models (HadCM3 +HadRM3) but with a much larger number of realisations, using the weather@home system [*Guillod et al.*, 2017].

To address water quality concerns in public water supply, we recognise two main factors which pose serious threats to water supply, as modeled in our case study in the River Thames, England: large algal blooms in the water supply reservoirs and high turbidity in the river. With the aim of reproducing these issues, we employed the INCA model to simulate i) suspended sediment concentration in the River Thames, as a proxy measure of turbidity, and ii) phosphorus concentration and water temperature, as a proxy measure of the risk of algal blooms in water supply reservoirs. Subsequently, a set of simulations was carried out with the water resources model WATHNET, in which it was hypothesised that abstractions from the river would be stopped if the water quality was poor. Based on experts' suggestions, the water abstractions were ceased if thresholds of phosphorus concentration, temperature and suspended sediment concentration exceeded the following conditions: 1) Potential high turbidity issue: suspended sediment concentration above 90 mg/l; 2) Potential algal bloom issue: phosphorus concentration above 0.8 mg/l and temperature above 15°C. All of the climatic scenarios from the weather@home dataset were used again to drive the INCA and WATHNET models, under two configurations: (i) no water quality restrictions on abstractions; and (ii) water quality restrictions on abstractions as described above. The risk of not meeting the level of services (LoS) was then computed. Furthermore, the land use and water treatment scenarios described above were also implemented, with the aim of understanding the potential impacts of these measures on the risk of water shortages due to inadequate water quality.

The results indicate an increase of probability of failure (exceeding LoS) of water supplies in future climate change scenarios. This result applies to the current water supply system configurations and does not account for planned interventions in supply and demand, which are expected to be implemented in order to secure water supplies in the future. Having water quality limitations on water abstractions is predicted to cause more restrictions on demand and consequently leads to increases in the probability of LoS exceedance. However, the results of the three land use scenarios highlighted the impact of changing practices in agriculture with improving waste water treatment as a practical means of decreasing the probability of failure. Thus, this outcome shows the potential benefit of cooperation between water companies and farmers and also the benefit of investment in order to upgrade waste water treatment plants.

Guillod, B. P., et al. (2017). A large set of potential past, present and future hydro-meteorological time series for the UK, *Hydrol. Earth Syst. Sci. Discuss.*, *2017*, 1-39.

Keywords: *Water supply, reliability, water quality, land use, climate change*

Estimating diversion components at farm scale in regulated river systems

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Abstract: The Water Management Act 2000 provides for sustainable and integrated management of the water sources within New South Wales (NSW). Under the Act, any water diversions must be taken under the appropriate water access licence, a basic landholder right or a licence exemption. Currently the Floodplain Harvesting (FPH) is the only water extractions that are not licensed. Healthy Floodplains Project rolled out by DPI Water since 2013 is aiming to bring the FPH extractions over the five NSW northern valleys into the licensing framework. This requires licences to be issued to individual eligible landholders with volumetric entitlements to FPH and accounting arrangements that maintain landholders' access to water, while restricting the total diversions to valley scale limits.

These FPH volumetric entitlements were determined using DPI Water's river system models, which have developed and used for water planning and diversion compliance. This required a significant enhancement in the detail of data for and modelling within existing models, which were based on aggregated representations of farm development and on-farm management. The principal factors influencing the entitlement were opportunities to access floodplain water based on the local flow regime; and individual farm characteristics such as pump capacity, capacity of on-farm storages, area developed for cropping, historical areas of crops planted, irrigation practices, and access to other sources of diversions. Data describing all these characteristics were collected using detailed questionnaires completed by landholders, and satellite images of the region. This farm level data was used in the model in conjunction with time series of climate, flow, and diversion data.

The data was used to configure high resolution conceptual models with all water balance components explicitly represented. These were calibrated and validated at individual irrigator, reach and valley scale. To ensure stakeholder acceptance of the outcomes, a high level of quality assurance was factored into the modelling. As well as ensuring that individual farm water availability and usage was realistically represented, rigorous validation steps were done by ensuring that the model could replicate historic key variables, such as river flow, regulated river extractions, and storage behaviour. The calibrated model was then configured with scenarios representing key management and development conditions in order to ensure equitable distribution of entitlements and compliance with valley wide diversion limits. This work has been implemented using both the IQQM and Source modelling platforms in the Gwydir Valley and NSW Border Rivers Valley respectively.

Keywords: *Northern MDB, Floodplain Harvesting, detailed farm models, IQQM, Source*

Modelling climate risk to securing water supply in the Hunter

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Abstract: The Hunter River catchment is an economically important region in New South Wales (Australia). Water demands from agriculture, mining, power generation and urban usage are supplied by regulated releases from headwater storages; which also includes maintenance of flows into the Ramsar listed wetlands associated with the Hunter estuary. Demand patterns have changed in recent years with a shift from agriculture to mining, which is further complicated by the projected increase of urban demands. Water security, especially during drought periods, is vital for these water users. Water availability reached critical low levels during a drought in recent times, and the re-occurrence of more severe droughts such as one that occurred during the 1930s-40s would almost certainly lead to suspension of operation of water dependent enterprises. Thus a forward looking and adaptive water management is required to ensure sustainable water usage and socio-economic growth.

Various options to improve water security have been proposed, some of which entail significant investment. The importance of the water security and the possible scale of the investment necessitated a greater understanding of climate risk. Investigations into climate risk focused on a fuller consideration of drought severity from natural variability, which palaeoclimatic studies indicate have been more significant in the past. These investigations involved the generation of 30,000 years of multi-site stochastic rainfall and evaporation data.

In order to understand current climate risk, DPI Water's Integrated Quantity and Quality Model (IQQM) framework was used to simulate the water security over the historical 120 year climate period with existing infrastructure and current management. Changes to water security from scenarios of varying combinations of the options under consideration were than assessed and compared. Some improvements to the current models were carried out. This required linking independent models of the Upper and Lower Hunter systems and recalibrating headwater inflow models to improve their performance during dry conditions.

Metrics were developed to highlight key water security and supply outcomes for the competing water users and to allow for a clear comparison of performance of different scenarios. Water users in the Hunter operate under rules, regulations and management conditions as set in the current Water Sharing Plan. Different improvement measures of water availability and reliability were developed for users with varying water access. Additionally, the impacts on environment, particularly the Hunter estuary, were assessed externally using changes in the end of system flows from IQQM.

The investigation using historical climate was used to identify effective option(s) by evaluating its incremental benefits using the performance metrics measuring relevant key variables. The IQQM modelling framework was also used with the stochastic inputs to test the options' effectiveness for a larger range of droughts, and to provide information for use in an economic analysis of the options. The successful application of this approach in the Hunter has provided important information and valuable methodology towards understanding how regional water security could be improved via the proposed options.

Keywords: *Hunter, water security, climate risk, IQQM*

Improved Understanding of Dense Jet Dynamics to Guide Management of Desalination Outfalls

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Abstract: With the growing adoption of Seawater Reverse Osmosis desalination technologies, there is a concurrent increase in the production of dense, hypersaline by-products. To minimize environmental impact to benthic biota, these wastes are commonly disposed via submerged diffuser systems in dynamic coastal environments. Traditional diffuser design approaches have relied on empirical techniques derived from small-scale laboratory experiments. This approach has provided a sound basis for preliminary design and regulatory approval of these systems. In practice the coastal receiving environment differs from the idealistic laboratory environments from which empirical scaling functions were derived. With the recent advances in computational power and development of computational fluid dynamics (CFD) approaches, it is now feasible to utilize CFD-based analysis to examine the dynamics of dense brine plumes under conditions representative of in-situ field practices.

For the first time, this study details a high-resolution three-dimensional laboratory-scale numerical simulation of an inclined dense jet diffuser subject to ambient crossflow. The quasi-steady CFD simulations were performed using the Reynolds averaged Navier-Stokes equations with a k-ω shear stress transport turbulence closure scheme. The study compliments existing laboratory studies by assessing CFD simulation results against empirical scaling approaches. Quantitative assessment of diffuser performance with regard to trajectory and dilution for an array of dynamic-crossflow based regimes is presented.

Results show strong agreement with existing small-scale laboratory experiments, with significant potential for upscaling to field-scale applications. Simulated dynamic ambient regimes show the influence of crossflow upon jet trajectory, dilution and lower boundary concentration is significant. The effect of flow structure and the subsequent influence on jet dynamics is discussed. This model poses as an effective strategy for future design of brine outfall systems, with strong potential for application in water quality management for both plant operators and regulators.

Keywords: *Inclined dense jets, desalination, computational fluid dynamics, OpenFOAM*

Advanced hydrodynamic modelling tools for flood inundation simulation in a large and topographically complex river basin

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Abstract: Floodplain inundation modelling is an essential part of river basin management for engineering, ecological and environmental perspectives. Since the mid-sixties, hydrodynamic models of different forms such as one-dimensional (1-D), two-dimensional (2-D) and coupled 1-D and 2-D have been used to simulate river hydraulics and floodplain inundation. While these models are sufficiently accurate for small study areas with fine raster grid size, the results are often distorted for a large floodplain because of coarse grid size in the model. In order to produce the flood mapping necessary to support floodplain management, hydrodynamic models have to be sufficiently detailed and flexible to properly capture the hydraulics of in-stream and overland flows, whilst still being able to capture the full extent of the floodplain. With the rapid advancement in computer technology and computational methods, flexible mesh hydrodynamic models become popular in recent years. One major advantage of flexi-mesh modelling is the ability to represent the area of interest using very fine mesh elements and less important areas using large mesh elements.

This paper presents the results from an analysis undertaken using a 2-D regular grid model (MIKE 21) and flexible-mesh model (MIKE21 FM) for flood inundation simulation in a large and topographically complex river basin. The Fitzroy catchment in Western Australia was selected for the case study. The hydrodynamic modelling domain covers an area of 35,000 km^2 which includes the entire floodplain. The rectangular model consists of approximately 4.3 million model grids with the size of 8100 m^2 (90 m × 90 m). The flexible mesh model consists of approximately 2.0 million grids with minimum and maximum grid size of 93m^2 and 8.1×10^6 m^2, respectively. For a computational time step of 5 sec, the rectangular grid model takes about 16 days of computer time for the simulation of 40-day flood event while the flexible mesh model takes about 2 days for the same flood event. On average, the flexible mesh model runs eight times faster on GPU compared to the rectangular grid model for this case study. It is worth mentioning here that the rectangular grid model is built on a finite-difference implicit scheme and runs on CPU, while the flexible mesh model is built on a finite-volume explicit scheme and is able to run on both CPU and GPU. Simulation on GPU (with GPU cards) is several times faster compared to CPU.

The study evaluates the MIKE21-FM model performances in terms of accuracy of the results compared to the MIKE21 regular grid model. Simulated water levels on the floodplain were compared with observed data at 3 gauging stations on the Fitzroy River. Inundation area were evaluated with respect to satellite imagery (MODIS and Landsat) for the 2011 flood with the magnitude of 25-year average recurrence interval. The results show the MIKE21-FM model better simulates water level and inundation dynamics across the floodplain. We found that the regular grid model grossly overestimates the inundation area during the receding flood. While the flexible mesh model better simulates the receding flood, the overestimation issue is not fully resolved. As the MIKE21-FM model can utilise multi-core parallel computing facilities, the computational time is significantly less compared to the MIKE-21 regular grid model. The main advantage of the flexible mesh model is that it can reproduce the river network much better (with finer mesh sizes) compared to the regular grid model in terms river alignment and depth (due to coarser grid sizes). The findings of this research will facilitate future research in inundation modelling.

Keywords: *MIKE 21, flexible mesh model, floods, Fitzroy catchment, wetland connectivity*

Analysis of runoff production and soil losses at the 1 m^2 plot scale during a long term survey of a small agricultural catchment in Lao PDR

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Abstract: The introduction of cash crops and the evolution of farming practices in the uplands of Southeast Asia has changed drastically the agricultural landscape of the region during these last decades. This evolution has increased significantly soil erosion leading to important on and off-site effects. To assess these effects and propose sustainable land management solutions the French Institut de Recherche pour le Développement (IRD), in association with national partners and the International Water Management Institute (IWMI), undertook a long term multi-scale monitoring of runoff production and soil erosion in the Houay Pano catchment site located near the city of Luang Prabang in the North Lao PDR.

We report here the analysis and the modeling of a 13 years survey of surface runoff and soil losses on 1 m^2 plots for different land uses. This dataset represents more than 300 rainfall events, 254 plots and 18 land uses. The analysis confirm what has been observed over short periods: old fallow promotes infiltration and reduces erosion and, at the opposite, teak increases soil crusting, lowers the infiltration rate and enhances soil detachment. A statistical analysis allowed to determine the correlations between the surface features, the runoff production and the soil loss for each land use. The soil crust, the weed cover and the residues appeared to be the principal and independent features having a protective effect.

The runoff and splash erosion components of the model TEST developed by Van Dijk (2004) for West Java upland terraces was used. This model is based on GUEST model (Yu, 1997) which is the most intensively validated and tested model for tropical regions. The runoff production is described by the Spatially Variable Infiltration (SVI) approach. We showed that, for a given land use, the important spatial and temporal variability of the maximum infiltration rate of the SVI approach may be described in a stochastic framework by a lognormal probability density function (pdf). The splash and wash erosion component of the model TEST predicts that the soil loss during a rainfall event is proportional the product of an effective detachability, the runoff coefficient and attenuation factors linked to surface features. The agreement between the model, computed with experimental runoff coefficients, and experimental results is good and would be probably better if a model of temporal evolution of surface features was included. This agreement also indicates that an application of the splash model to describe inter-rill erosion in the whole basin with its mosaic of plantations would be possible.

As for infiltrability, the variability of soil detachability was described for each land use by a lognormal distribution. Therefore, one perspective would be to compute for each land use and each rainfall event the pdf of the runoff coefficient and the subsequent pdf of the soil loss, and compare this pdf with the experimental results. This type of comparison would permit to assess from a probabilistic point of view the prediction capability of TEST as a global runoff splash erosion model for the plot scale.

Keywords: *South East Asia, runoff production, inter-rill erosion*

EXTENDED ABSTRACT ONLY

Modelling a novel approach to floodplain inundation using HiPIMS to show a nature-based, cost effective solution to downstream flooding

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Abstract: The concept of "Nature-based" solution or "Natural Flood Management" (NFM) has found widespread adoption in recent years. New methods of mitigating against fluvial flooding have been developed that encompass natural materials and construction techniques without resorting to expensive, conventional traditional flood defences. The concept of using temporary offline storage, where flood flows are diverted into a network of constructed features, adds attenuation to the system by optimising floodplain potential. Few studies have determined the effectiveness of these NFM features at the catchment scale. Here, the results of a modelling case study in north-east England are presented. The 2-D High Performance Integrated Modelling System, HiPIMS (www.lukesmith.org) used in this study incorporates a novel algorithm that can distribute the processing load across multiple Central and Graphical Processing Units (CPUs and GPUs), to speed up computations across millions of cells and enable multiple simulations to be performed in a reasonable time frame. HiPIMS incorporates raster data layers to represent the model domain and solves the equations of shallow water flow using a fast, robust, computationally efficient algorithm. A range of numerical schemes are provided for solving the shallow-water equations, including a second-order accurate MUSCL-Hancock approach, a first-order Godunov-type scheme, and a partial inertial approximation. A resilient approach to hydrodynamics is used, which captures shocks, is numerically stable, and prevents the occurrence of negative water depths being computed by the model.

The case study is upstream of the large town of Stockton On Tees (UK), which has suffered severe flooding several times over the past ten years due to its vulnerability to inundation from Lustrum Beck. A NFM scheme was commissioned in 2015 to address this vulnerability by reducing the current 1:100 year event in Lustrum Beck down to a 1:75 year sized event using NFM methods. The modelling case study has used an existing 1m resolution LiDAR Digital Terrain Model (DTM) of the study area, where NFM features are planned to be constructed along 1 km of the existing channel and surrounding floodplain. These features will comprise a series of off-line storage ponds interconnected using swales (vegetated flow channels) in order to provide a cost-effective solution to storing flood flows. These flows will be diverted into constructed swales using draw-off structures in the channel that will be fashioned from natural materials. They will ensure that fish passage will be sustained.

A "baseline" 1:100 year design storm that simulates the "before" case was run using HiPIMS with the unaltered DTM. Subsequently, an altered DTM that contains the ponds and the swales for a number of configurations was created using GIS. Then a "Post NFM" simulation has then been performed to assess the impact of the features on the flood hydrograph. The results show that impact of the roughness changes and the dynamic functioning of the channel, swales and ponds. Hence, we are now able to optimise the design of the final scheme that will lower the peak flow downstream in Stockton itself where previously the worst flooding has occurred. The scheme should achieve the full benefits required at very low cost when compared to the traditional alternatives. Moreover, by having a realistic 2-D hydrodynamic model of the floodplain it is possible to evaluate the local behaviour regarding flow patterns and thus allow many local design issues to be resolved.

Keywords: *Hydrodynamic Modelling, Natural Flood Management, GPU*

Use of Crowd-sourced Data to Assess the Skill of Hydraulic Flood Forecast Models

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Abstract: Floods are considered to be one of the most commonly occurring natural disasters that cause economic damage worth millions of dollars annually in addition to fatalities. Hydrodynamic models used for flood forecasting need to be evaluated and/or constrained using observations of water depth and flood extent. While remote sensing based derivation of these variables have facilitated model evaluation in the past few decades, citizen sensing has emerged as a popular complementary technique to provide flood information in real-time. However, its value for model evaluation still needs to be investigated. This paper demonstrates the use of crowd-sourced flood observations to assess model performance. The model LISFLOOD-FP was set up for the Clarence Catchment at 30 m resolution, with the inflows introduced as the flood hydrograph with hourly measurements of discharge at Lilydale, and the Water Level (WL) observations available at Ulmarra used as the downstream boundary condition. The observation set used for performance assessment consists of 32 distributed high water marks and wrack marks provided by the Clarence Valley Council for the 2013 flood event, whose timing of acquisition was unknown. However, it is reasonable to assume that these provide information on the peak flow. Additionally, flooded locations were identified from event images (6) and news (2) posted on the internet, for which the date of observation was known. The locations were derived from the geo-tags or through manual identification of temporally stable image objects such as named road intersections, bridges, and buildings on Google Earth. The Manning's Roughness Coefficient (n) for the channel was optimized by varying it in increments of 0.005 from 0.020 to 0.035 s/m$^{1/3}$, which is the seasonal range of values for the Clarence River. For each realization of the model, a performance measure was assigned based on the fraction of observation points correctly predicted by the model. The utility of crowd-sourced data for constraining the roughness parameter in the hydraulic model LISFLOOD-FP was assessed though sensitivity analysis. Preliminary results indicate that integrating flood observations from anecdotal data, social media and the internet can generate a dataset useful for hydraulic model evaluation and constraint. As these observations can be made available in real-time through GPS-enabled smartphones and be sent and received from anywhere through the internet, they hold real potential to add value to flood model predictions. Crisis information mobile applications are rapidly becoming ubiquitous across the globe, which will allow users to provide detailed, geotagged flood observations. Additionally, web trawlers that record and analyse all flood mentions on the internet to generate crowd-sourced flood maps are also gaining popularity. It is imperative that the full potential of such data is unleashed to mitigate flood impacts through integrating them into hydraulic models in the future.

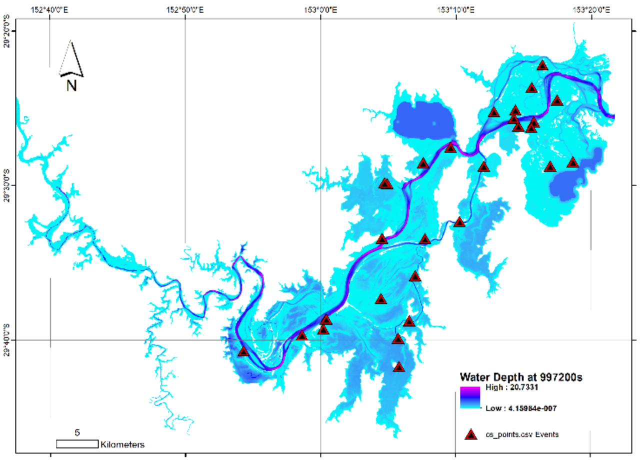

Figure 1. Modelled flood extent at 997200s, for a channel roughness of n=0.025, with anecdotal data points displayed.

Keywords: *LISFLOOD-FP, hydrodynamic modelling, crowd-sourcing, sensitivity analysis, model evaluation*

Building a Comprehensive Spatio-Temporal Database of Floodplain Inundation for Environmental Management in the Murray-Darling Basin, Australia

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Abstract: This paper describes an innovative large-scale floodplain modelling approach that was developed by integrating a suite of models (landscape model, hydrodynamic model and water balance model) and GIS for producing inundation maps at very high temporal and spatial resolutions under different antecedent conditions. A two-dimensional hydrodynamic model was initially calibrated and validated for historical events using observed water levels and flood maps derived from Landsat imagery. The results demonstrate highly satisfactory performance of the model in simulating floods of different magnitudes in a number of floodplains. The hydrodynamic model outputs were then processed using a simplified hydraulic and hydrological water balance model to simulate a range of flood events to produce a comprehensive and very high spatial resolution floodplain inundation database under different flow ranges and antecedent conditions. The model outputs are used by the Murray Darling Basin Authority (MDBA), Australia for decision making process for environmental management. The paper presents the overview of the methodology, the results of calibration and validation of the model and describe the inundation database created for the Lower Balonne floodplain in the Murray Darling Basin.

Keywords: *Hydrodynamic modelling, floodplain inundation, environmental management, Murray-Darling Basin, simplified hydraulic model*

Advances in Continuous Flood Simulation for Design of Linear Infrastructure

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Abstract: Linear transport infrastructure, such as highways and railway lines, represents a challenge for conventional flood estimation practice, where owners and users of this linear infrastructure are interested in understanding the frequency and duration in the closure of individual crossings as well as links and the entire route. Previous authors have demonstrated the application of the eWater Source software to continuous simulation modelling of flood risk for linear infrastructure. They demonstrated that a continuous simulation approach provided significant advantages in modelling the overall time of closure for long sections of linear infrastructure, with multiple waterway crossings.

This paper discusses further advances in applying Source for continuous simulation, for the purposes of design of linear infrastructure. The following advances are discussed in this paper:

- Disaggregation from gridded daily rainfall data sources (AWAP or SILO) to sub-daily timestep using temporal patterns derived from pluviograph data
- Development of a custom objective function, used in model calibration, for tuning the calibration to hydrographs of flood events, rather than moderate and low flows
- Development of a custom objective function, used in model calibration, for tuning model calibration to achieve verification of model parameters to flood frequency analysis (fitted to gauged flows and/or regional flood estimates)
- Adoption of parsimonious rainfall runoff models, to develop models suited to simulation of flood events, which are then more amenable to regionalisation of rainfall runoff parameters from gauged to ungauged catchments

Application of these advances have been demonstrated for one catchment, the Black River to the Bruce Highway, in North Queensland. The model was calibrated to 27 years when there was concurrent gauged streamflow and pluviograph data available. The model calibration was tuned to focus on fitting magnitudes of flood peaks, total flood event volumes and the mean annual duration above defined flow event levels. The model was then re-verified to an independent period of 17 years when there was only streamflow data available, with no pluviograph data.

A lumped conceptual rainfall runoff modelling framework was applied, with calibration performed using both the GR4H and SimHyd rainfall runoff models. For the Black River catchment, the overall performance of GR4H was superior to SimHyd. Both models produced adequate fits to flood frequency curves fitted to flood peaks. GR4H produced an excellent fit to the upper end of the flow duration curve, i.e. GR4H was able to produce an excellent match to the average annual duration of closure for a range of flow rates that would be of interest for flood design (average annual time of closure between 0.1 and 100 hours/year). By contrast, SimHyd produced a poorer fit to the average annual time of closure curve than GR4H.

Both GR4H and SimHyd initially had difficutly in reproducing hydrograph shapes and peaks for particular flood events, when using only the temporal pattern from the pluviograph collocated with the flow gauge. The model calibration process was therefore a good means of identifying particular events for which the temporal pattern at the pluviograph was not representative of the temporal pattern for the catchment. Other pluviographs in the region were then used to identify pluviographs that had a temporal pattern that was more representative of the rainfall for the catchment for these particular events and hence able to better represent the hydrographs for these particular floods.

Keywords: *Floods, continuous simulation, rainfall runoff modelling*

A method for gap filling river channel bathymetry in a high-resolution digital elevation model for use in flood inundation modelling using measured river profile data

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Abstract: A high resolution digital elevation model (DEM) is an essential input into flood inundation modelling. In addition to having an accurate representation of the topography of the floodplains to predict areas prone to flooding, the analysis requires the bathymetry of the river channel to model the river's carrying capacity and the connectivity with the surrounding floodplain. LIDAR derived DEM data provides accurate topographic information for the floodplain but, as LIDAR cannot penetrate deep water, river channel bathymetry can only be obtained by LIDAR when the river is dry. This is problematic when modelling the flooding of permanently full rivers such as the Murray River, where LIDAR returns nodata in the water filled channel and DEM values in this area are either null or interpolated bank heights. To fill this gap in the DEM data, this study sought to utilize known heights from measured cross-sections taken at regular intervals along the river and interpolate these along the channel between the known cross-sections. The serpentine nature of the channel and the clumped distribution of the data points, rendered traditional spatial interpolation techniques unsuitable. Thus, a stepped approach using a mixture of spatial and linear interpolation techniques coupled with vector feature manipulations in a Geographic Information System (GIS) was devised to interpolate in-channel heights along a snaking river channel between known height profiles. The method enabled the interpolation of the known channel profile around river bends and accommodated changes in channel width. The resulting interpolated channel bed was then stitched into the DEM to produce a seamless elevation surface that included in-channel bathymetry. The gap-filled DEM more accurately reflects the capacity of the river channel, especially the volume underwater when the LIDAR elevations were collected. Results of flood inundation modelling were greatly improved when run with the gap-filled DEM.

Keywords: *Flood modelling, Digital Elevation Model, Gap filling*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Integrating reservoir operations in a global flood model

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Abstract: The largest anthropogenic impact on the water cycle arises from construction and operation of reservoirs. To have a better understanding of the interactions between natural and human systems, it is necessary to represent reservoir operations in large scale hydrological and flood models. While the methods for representing reservoir operations at catchment scale have long been studied, integrating reservoir operations in models at large to global scale have only started in the last decade. Existing regional or global studies tend to use geo-referenced and hydrologically-linked global datasets of reservoirs and simplified reservoir operation models to assess the impacts of reservoirs on water supply and the hydrological cycle. Most, if not all, of these studies use virtual representations of reservoirs, which are integrated with global river models, and therefore cannot simulate floodplain inundation dynamics.

This study presents one of the first attempts to physically represent reservoirs and integrate their operation in CaMa-Flood, a flood model that simulate river flow and floodplain inundation dynamics at a continental to global domain. An algorithm for detecting and physically representing the bathymetry of reservoirs in DEMs as well as the methodology for integrating the operations of reservoirs in CaMa-Flood are introduced. The techniques are applied in the Chao Phraya River Basin in Thailand, which is impacted by two large reservoirs, Bhumibol and Sirikit.

Due to the limitations of radar or satellite techniques in detecting the elevation of water-covered areas, the areas inundated by reservoirs are usually represented as flat lands in DEMs. The misrepresentation of the elevation of such areas in DEMs may result to false estimates of the variations of volume, surface water area, and depth of water in reservoirs. Since the accuracy of DEMs greatly affect flow estimates in flood models, such misrepresentations may also lead to biases in simulated flows upstream and downstream of reservoirs. The algorithm developed in the study automatically detects the watershed of the reservoirs, uses the elevation of the surrounding areas to estimate the bathymetry of the reservoirs, and corrects the DEM used in CaMa-Flood. The reservoir areas detected using the automatic algorithm corresponds well with existing water maps as shown in Figure 1.

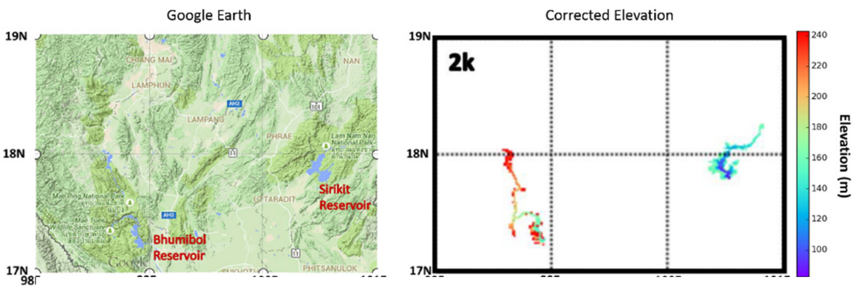

Figure 1. Comparison of the reservoir areas detected and elevation corrected by the developed algorithm with the reservoir area as shown in Google Earth.

The historical operation of the reservoirs is used to develop a reservoir operation algorithm that was built into the CaMa-Flood model. The reservoir algorithm uses empirically-derived water level-storage curves and seasonal means of the historical reservoir release to calculate the amount of water that is released from the reservoirs.

Results after incorporating reservoir bathymetry and operations showed improvements in the simulated river discharge as well as flood inundation patterns downstream of the reservoirs. The physical representation of the bathymetry of the reservoirs also resulted in more realistic simulation of surface water level, storage, and inundation patterns upstream of the reservoirs. While the study presents simplified techniques to physically represent and integrate the operation of reservoirs in a continental to global scale flood model, the new model can be used for a wider range of studies that include the assessment of human impacts on ecosystems, agriculture, and other environmental systems.

Keywords: *Continental to global scale flood model, CaMa-Flood model, reservoir operation, reservoir bathymetry*

Modelling daily water levels derived from multiple satellite datasets in sparsely gauged catchments

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Abstract: River water level is a crucial input data in hydrodynamic models or flood forecasting models. However, *in-situ* river heights are rarely available in remote areas, thus flood inundation predictions in these regions have high uncertainty. Satellite radar altimetry data shows promise in water level monitoring in such areas. However, infrequent observations (often 10 days or 35 days apart) are the largest drawback of satellite altimetry for flood forecasting or hydrodynamic modelling purposes. Previous studies have addressed this by blending satellite altimeter data with *in-situ* water levels to generate higher frequent measurements. However, this approach is not possible in ungauged areas.

To overcome this, we propose a method using the difference in day and night time land surface temperature (ΔLST) extracted from optical Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua daily LST products. We aim to supplement Jason-2 satellite altimeter data to derive daily water levels. Based on the observed correlation between Jason-2 water levels and ΔLST, we develop simple statistical models to predict water levels at three intersections between ground-tracks of satellite altimetry and the upper reaches of the Lower Mekong River (hereafter called virtual station-VS).

We further extend our proposed method by adding satellite precipitation derived from Global Satellite Mapping of Precipitation-Near Real Time (GSMAP-NRT) product and soil moisture from the Soil Moisture and Ocean Salinity (SMOS) mission to improve the daily water level estimates. Here impacts of upstream satellite altimeter on downstream satellite altimeter are considered as a lagged variable.

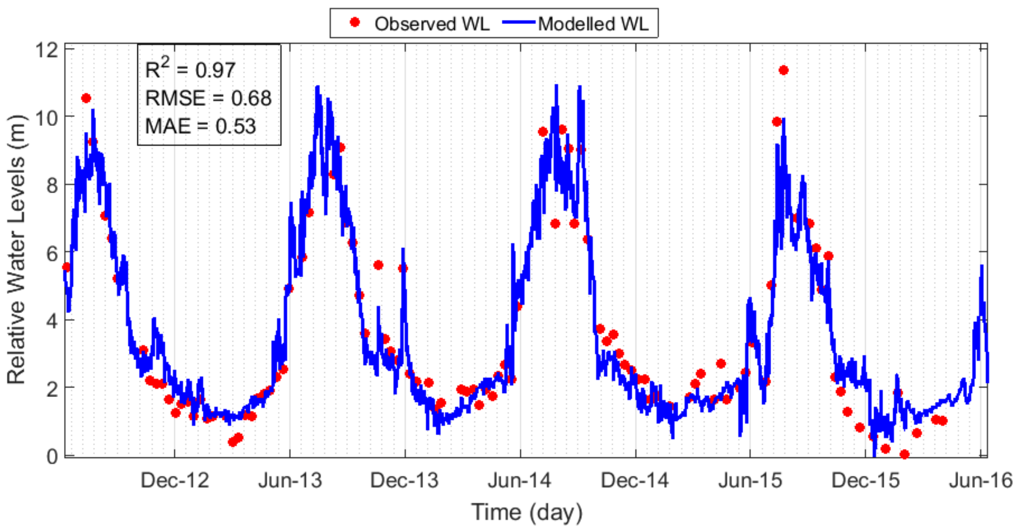

Figure 1. Daily water level derived from multiple satellite datasets at VS#179 in the Lower Mekong River

The results demonstrate that the proposed method using only satellite-based data can successfully estimate daily water levels. The daily modelled water level captures the observed variations in water level in both dry and wet seasons (Figure 1). Validation against *in situ* water levels provided high correlation coefficients ranging from 0.87 to 0.92.

Keywords: *Satellite radar altimetry, land surface temperature, soil moisture, precipitation, Mekong River*

Importance of Dispersion for Shoaling Waves

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Abstract: A tsunami has four main stages of its evolution; in the first stage the tsunami is generated, most commonly by seismic activity near subduction zones. The second stage is the tsunamis propagation through the ocean far from the coast, where variation in bathymetry is slight and gradual. The third stage is the shoaling and interaction of the tsunami with bathymetry as it approaches the coastline. Finally the tsunami reaches and inundates the shore. For our purposes the hydrodynamic models we are interested in deal with the final three stages of the evolution of a tsunami.

The propagation of a tsunami with wavelength λ through water that is H deep is well understood when $\lambda/H \leq 1/20$, which we call shallow water as noted by Sorensen (2006). The wavelengths for tsunamis range from a few to hundreds of kilometres, while the maximum water depth is $11km$ at the Marianas trench, so that most tsunamis occur in shallow water. This stage of tsunami behaviour is adequately modelled using the shallow water wave equations. Current research into tsunamis focuses around more complex approximations to the Euler equations for the third and fourth stages. In this paper we focused on the Serre equations as they are considered a very good model for fluid behaviour up to the shoreline, and they reduce to the shallow water wave equations for large wavelengths.

Although more complicated, the Serre equations provide a better description of the fluid behaviour than the shallow water wave equations and are therefore more computationally expensive to solve numerically. In particular for the methods of this work, we find that the Serre equations have a run-time 50% longer than our equivalent finite volume method for the shallow water wave equations in the one dimensional case. To simulate tsunamis as efficiently as possible it is important to know when using the more complicated Serre equations leads to more accurate predictions of the evolution of a tsunami than the shallow water wave equations. To investigate this we have numerically simulated a laboratory experiment of periodic waves propagating over a submerged bar, and the propagation of a small amplitude wave up a gradual linear slope using both the Serre and the shallow water wave equations.

The results of these simulations demonstrated that the Serre and shallow water wave equations produce similar results for shoaling waves when the wavelength is large compared to the water depth. This is not surprising as this is the regime under which the shallow water wave equations are derived. However, outside this regime the shallow water wave equations are a poor model for wave shoaling and propagation, poorly approximating the shape and maximum height of waves. Furthermore we demonstrate that for steep waves generated by shoaling, the shallow water wave equations can underestimate the arrival time and amplitude of an incoming wave. These results suggest that for a tsunami it is sufficient to use the shallow water wave equations in stages two and some of stage three, even for large changes in bathymetry. Although dispersive equations such as the Serre equations are required to accurately capture fluid behaviour in stages three and four nearer to the coastline, particularly when wavelengths are short or waves are steep. Since the Serre equations represent only a moderate increase in run-times this suggests that our inundation models should be based on them.

Keywords: *Tsunamis, shoaling waves, dispersion, models, shallow water wave equations*

Multifidelity sparse grid surrogate models for uncertainty quantification of flood inundation modelling

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Abstract: We use multi-fidelity sparse grid interpolation to propagate the uncertainty in the flood height at a location based on uncertain rainfall. An important issue with many uncertainty quantification approaches is the curse of dimensionality: the overall computational cost of the uncertainty propagation increases rapidly with the increase in the number of uncertain input parameters. We aim to mitigate the curse of dimensionality by using a multifidelity approach. In the multifidelity approach, we combine results from a small number of accurate and expensive high-fidelity simulations with a large number of less accurate but also less expensive low-fidelity simulations. In this talk we will introduce the method and present results using a case study of the Towradgi Creek 17 August 1998 flood.

Keywords: *Uncertainty quantification, flood modelling, tsunami modelling, sparse grid functions, multi-fidelity, surrogate models*

Flood inundation modelling for decision making

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Abstract: Flooding is a devastating natural disaster that causes loss of lives, property, and social and economic development, but on the other hand relieves drought and has ecological benefits for the environment. It presents a great challenge for planning authorities to formulate management strategies that are scientifically credible but at the same time practically applicable within the available resources. How can end-users' flood management decision making be improved by the prediction of flood frequency, duration and intensity? In what way, and by how much? This research tries to answer these questions by investigating the added value of flood inundation modelling on decision making from both flood risk management and environmental watering perspectives.

Three river reaches in the southern Murray Darling Basin were selected as study areas. These reaches have numerous floodplain wetlands periodically connected to the main channel. The ecosystems there support important species that are listed in international agreements, including some vulnerable and endangered species (MDBA, 2011). The reaches are downstream of large dams or reservoirs and have relatively good flow observations. There are also high resolution LiDAR DEM and Landsat imageries coverage across these reaches, making it possible for flood inundation modelling and validation.

The Environmental Sustainable Level of Take (ESLT) ecological target-flow indicators were used to assess the benefit of a flow regime on the environment in this study (Pollino et al., 2013; MDBA 2011). These indicators have been used by MDBA to achieve the specified ecological targets and flow indicators at the indicator sites. We used these indicators to characterize the timing, frequency, duration, and rate of rise and fall of the flows, as they are essential to determine the ecological responses to flow regimes.

A simple conceptual flood inundation model – the TVD model (Teng et al., 2015) – was used to map the inundation area in order to estimate the benefit to ecological targets and damage to properties. The model had been shown in previous studies to produce predictions of inundation extent that compare well with water maps derived from Landsat TM imageries. The TVD model was adapted and improved for this study by introducing rainfall, evapotranspiration and infiltration to the modelling process to maintain the water balance on the floodplain. The revised model was set up to simulate a number of major flood events on the three selected river reaches. The modelled inundation extents were assessed against remotely sensed water maps. Along with ESLT ecological target-flow indicators, we were able to investigate how a flow regime will impact on the inundation area and whether it is possible to optimize the operation of the system such that damages to the properties are minimized and the benefit to the environment is maximized.

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Keywords: *Murray Darling Basin, floodplain modelling, ecology, environmental flow*

EXTENDED ABSTRACT ONLY

Frequency and variability of floods in the Great Barrier Reef catchments in Australia

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Abstract: Floods are thought to be the driving force for the high biodiversity of river-floodplain ecosystems as they provide an exchange of water, sediments, nutrients and biota between rivers and floodplain. The variability in flood magnitude and frequency influences the spatial and temporal variability of many biophysical processes including the transport of sediment and waterborne pollutants and the recruitment of aquatic animals and plants. This paper presents results from an analysis to assess historical flood frequency and variability in flood magnitudes for the Great Barrier Reef (GBR) lagoon catchments. Flood frequencies were estimated based on number of floods in a specified period of observed flow data. This study used bankfull discharge to identify a flood and to build flood series data. Stage-discharge relationship and river bank elevation were used to estimate bankfull discharge. To quantify flood frequencies across the region, gauges located on or closest to the floodplain areas were selected. For all gauges, stage-discharge relationships were investigated and data were selected that showed a single relationship between stage height and discharge. To avoid any inconsistency in rating curves, pre-1980 data were excluded in subsequent analyses. Finally, gauges having less than 10 years of flow data were excluded. This reduced the number of gauge to 49 that were used to estimate flood frequency and variability. Where available, bankfull discharges were estimated from an inflection point on the stage-discharge rating curve. Once flood series is established, variability in flood magnitude was examined using the flash flood magnitude index (FFMI). The FFMI was calculated as the standard deviation of the logarithm of annual maximum flood series. Flood frequency and variability were estimated for the five regions (i.e. Cape York, Wet Tropics, Burdekin, Fitzroy and Burnet) of the GBR catchment. Results show GBR catchments experience a large variability in flood occurrence across the region, having two to three floods in a year in the wet tropical catchments to less than a flood in a year in the dry tropical catchments. All catchments in the northern part of the GBR lagoon experience more than one flood per year. Variability in flood magnitude across the GBR catchments were found large. The FFMI values varied from 0.15 to 0.94 and 45% of the gauges recorded a FFMI of 0.5 or more.

Table 1. Flood frequency and variability indices across the Great Barrier Reef catchments in Australia

Catchment region	Number of gauges	Data length (years)	Flood frequency (floods/year)	Mean FFMI
Cape York	7	23	1.58	0.36
Wet tropical catchments	11	32	2.22	0.33
Burdekin region	13	28	0.87	0.64
Fitzroy	10	33	0.64	0.76
Burnet	8	27	0.71	0.75

Overall FFMI values for the GBR catchment are similar to mean FFMI of Australian and South African rivers but are large compared to rest of the world. Relatively small FFMI values are observed for the northern rivers, especially in the wet tropical region. Flood variability as measured by the FFMI increases southwards. This information will be useful to ecological impact assessment for any changes in flood flow regime due to anthropogenic or global climate change.

Keywords: *Flood frequency, Great Barrier Reef, ecology, bankfull discharge*

Conditional probability of rainfall extremes across multiple durations

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Abstract: The majority of hydrological engineering design relies on intensity-frequency-duration curves of extreme rainfall, often represented as maps. These maps do not contain information on the conditional probability that extreme rainfall will occur at one location given that it is occurring at another location. Nonetheless, conditional relationships are critical in engineering design and management circumstances such as planning evacuation routes and siting emergency infrastructure. A challenge with conditional simulation is that in many situations the interest is not so much the conditional distributions of rainfall of the *same duration* at two locations, but rather the conditional distribution of flooding in two neighbouring catchments, which may be influenced by rainfall of *different critical durations*. To deal with this challenge, a model that can consider both spatial and duration dependence of extremes is required.

The aim of this research is to develop a model that can take account of both spatial dependence and duration dependence into the dependence structure of extreme rainfalls. This study is a first attempt at combining extreme rainfall for multiple durations within a spatial extreme model framework based on max-stable process theory. Max-stable processes provide a general framework for modelling multivariate extremes with spatial dependence for just a single duration of extreme rainfall. To achieve dependence across multiple timescales, this study proposes a new approach that includes additional elements representing duration dependence of extremes to the covariance matrix of the max-stable model. To improve the efficiency of calculation, a re-parameterization proposed by Koutsoyiannis et al. (1998) is used to reduce the number of parameters necessary to be estimated. This re-parameterization enables the GEV parameters to be represented as a function of timescale. A stepwise framework has been adopted to achieve the overall aims of this research. Firstly, the re-parameterization is used to define a new set of common parameters for marginal distributions across multiple durations. Secondly, spatial interpolation of the new parameter set is used to estimate marginal parameters across the full spatial domain. Finally, dependence parameters are estimated via a likelihood function of the max-stable model for multiple durations.

The Hawkesbury-Nepean catchment near Sydney in Australia was selected as a case study. This catchment has 25 sub-daily rain gauges with the minimum record length of 24 years over a region of 300 km × 300 km area. The re-parameterization is applied for each station for durations from 1 hour to 24 hours and then is evaluated by comparing with the at-site fitted GEV. The evaluation shows that the average R^2 for all station is approximately 0.80 with the range from 0.26 to 1.0. The output of the re-parameterization is used to construct the spatial surface based on covariates including longitude, latitude, and elevation. The dependence model shows good agreement between the empirical extremal coefficient and theoretical extremal coefficient for multiple durations. For the overall model, a leave-one-out cross-validation for all stations shows it works well for 20 out of 25 stations. The potential application of this model framework is illustrated through a conditional map of return period and return level across multiple durations, both of which are important for engineering design and management.

Keywords: *Max-stable process, spatial dependence, duration dependence, linking multiple durations, conditional probability*

Water Quantity Stresses Evaluation under Climate Change on the Han-river, Korea

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Abstract: Water stress with climate change is one of a priority tasks because it has influence to economic growth including capita income and GDP and can lead to local and regional conflicts. The objective of the study, therefore, is to estimate and evaluate the water quantity stress under the drought under climate change on Han River basin. By simulating future runoff and its water resources managements using SLURP and K-WEAP models based on climate change scenarios and models, the Normalized Deficit Cumulative (NDC) and the Normalized Deficit Index (NDI) were estimated and analyzed for medium size basins in Han River basin. The spatial/temporal changes in the water stress under the climate change with three target period - near (2011 to 2039), middle (2040 to 2069), and far future (2070 to 2098) - were analyzed. As the result of the study, overall water stress will be eased under climate change, but several sub-basins need to actual water management to countermeasure for climate change.

The main conclusions are:

1) The present water stress was estimated and analyzed including runoff characteristics, groundwater and water supply system. Several sub-basins were pressured with runoff characteristics, and these basins were identified that the water stress in these basins were eased with groundwater or water supply system. Especially, two sub-basins (1019 and 1201) sub-basin seems to be improved with groundwater than water supply, and four sub-basins (1004, 1013, 1016 and 1018) shows that it only would be improved with water supply system. So, these results could be used as the elementary data for the water resources management.
2) Overall water stress in Han River basin under climate change seems to be decreased in future period, with agricultural and residential water demand decline. However, five (1002, 1004, 1009, 1010, 1016) sub-basins will be dominated by cumulative water deficit, and two of them (1004, 1010) will maintain ‘serious’ or ‘mediocre’ grade for whole future and one of them (1014) are expected as ‘mediocre’ water stress in near future (2011 to 2039 year). Therefore, water management plan for these sub-basins may have to be changed to countermeasure the climate change.

ACKNOWLEDGMENTS

This research was supported by a grant(16AWMP-B121100-01) from the Water Management Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government and this research was supported by a grant (MOIS-DP-2015-05) through the Disaster and Safety Management Institute funded by Ministry of the Interior and Safety of Korean government.

Keywords: *Water Stress, NDI/NDC, SLURP, K-WEAP*

Recent vegetation dynamics and evapotranspiration suggested a risk of drought

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Abstract: The past decade has been the warmest in the instrumental record (2000-2014). Under the impact of global climate change, the vulnerability of ecology system and uncertainty of water resources are increasing. It indicates some moisture deficit between available water demand and supply for evapotranspiration. Drought indices and precipitation-minus-evaporation suggested an increased risk of drought in the present century.

- Terrestrial net primary production (NPP), defines as the amount of photosynthetically fixed carbon available to the first heterotrophic level in an ecosystem, links terrestrial biota with the atmosphere system. Overall, the global inter-annual series of net primary production (NPP) slightly increased in 2000-2014 at a rate of 0.06 PgC/yr^2. More than 64% of vegetated land in the Northern Hemisphere showed increased net primary production, while 60.3% of vegetated land in the Southern Hemisphere showed decreased trend. Vegetation feeds back to the spatio-temporal characteristics of climate through evapotranspiration.

- NPP correlates positively with land actual evapotranspiration (ET), especially in the Northern Hemisphere, where the increased vegetation productivity (0.13 PgC/yr^2) promotes decadal rises of ET (0.61 mm/yr^2). However, anomalous dry conditions led to reduced vegetation productivity (-0.18 PgC/yr^2) and nearly ceased growth in ET in the Southern Hemisphere (0.41 mm/yr^2).

- To understand why climates in the northern and southern hemispheres respond differently to NPP, the results showed that temperature is the dominant control on vegetation growth in the high latitude in the Northern Hemisphere, while net radiation is the main effect factors to NPP in the mid latitude, and in arid and semi-arid biomes also mainly driven by precipitation. While in the Southern Hemisphere, NPP decreased because of warming associated drying trends of Palmer Drought Severity Index (PDSI). In addition, potential evapotranspiration (PET) as a surrogate measure of atmospheric moisture demand, with an increasing trend overpassed the precipitation in the past 15-year record.

- Central Asia, which consists of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan and the arid region of Northwest China, is located in the hinterland of the Eurasian continent, plays a key role of the Silk Road Economic Belt. It is one of the most arid areas in the world, with a unique landscape that features expansive but very fragile ecosystems. The temperature in Central Asia experienced a sharp increase in 1997, and since then has been in a state of high volatility, making the last decade the warmest period on record. Global warming and vegetation greening accelerate evaporation in soil moisture, thus reducing the amount of soil water storage. Over the past 15 years, precipitation increases cannot offset evaporative demand, indicating a potential moisture deficit for water supplies constrained by ET. Vegetation dynamics are highly sensitive to climate change, especially in arid region. 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, The grasslands in northern Kazakhstan have been dramatically reduced and the open shrub lands in Uzbekistan, Turkmenistan and the Tarim Basin in Northwest China have increased substantially, highlighting shrub encroachment into grassland. The phenomenon of shrub encroachment implies some mesophyte plants are turning to xerophilous plants, and the shallow roots of desert plants to die, which will lead to the water-based ecosystem becoming much more fragile in Central Asia.

Keywords: *Climate change, net primary production, evapotranspiration, soil moisture, PDSI*

Preliminary study on the correspondence of turning points between global flood occurrences and polar motion

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Abstract: Floods, as one of the extreme hydrological events, develop at the Earth's surface much often than before, most of which have brought big losses to our society. Polar motion, as one of the Earth's motion factors, is largely excited by mass redistribution on earth, including flooding. The relationship between global flood occurrences and polar motion is explored from the correspondence of turning points. A moving average method with a subset size, which is equal to the prominent period, is suggested to acquire the turning point of polar motion. The combined method of moving t-test and accumulated anomaly is used to acquire the turning points of global flood occurrences. It is seen that the moving average method is more efficient to display the turning points in polhody than the method of removing periods as used elsewhere popularly. 2006 is a most obvious turning point both at polhody and the evolution of global flood occurrence. The variation in 1990s in polar motion also corresponds to that of global flood occurrence. These established relationships found between polar motion and flood occurrence in turning point encourages us to explore the role of excitation of floods to polar motion at least in the turning points in flood occurrences.

Keywords: *Polar motion, flood occurrences, moving average, period*

EXTENDED ABSTRACT ONLY

Impacts of Three Gorges Reservoir on Streamflow of middle Yangtze River

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Abstract: This study was aimed to quantify the effects of the hydrologic alteration of the middle Yangtze River due to the operation of the Three Gorges Reservoir (TGR), the largest dam in China. The streamflows of three downstream stations, Yichang, Shashi and Luoshan were studied to analyze the TGR impacts. Three schemes, including without TGR operation, with conventional and optimal TGR operating rules respectively, were implemented to simulate the streamflow at Yichang station. The multi-input single-output systems models (MISO) were used to simulate the streamflows at Shashi and Luoshan stations with these three inputs of Yichang station, respectively. These streamflows were then analyzed by using the Indicators of Hydrologic Alteration (IHA) and the Range of Variability Approach (RVA) to evaluate the hydrologic changes associated with TGR operation. Based on the IHA method, the RVA consists of following steps: (1) The natural range of streamflow is calculated using the 33 parameters of IHA method. (2) The RVA targets for each 33 IHA parameters are set. For example, the 75th percentile and 25th percentile of ranked daily discharges are often used. (3) The values of 33 parameters are calculated with TGR operation. (4) Based on the difference of the RVA target and calculated values, i.e., (2) and (3), the measure of hydrologic alteration is obtained as a percentage D_i as follows:

$$D_i = \left| \frac{Y_{0i} - Y_f}{Y_f} \right| \quad \textbf{(1)}$$

where Y_{0i} is the calculated or observed frequency, Y_f is the targeted frequency.

Results indicate that:

(1) With the TGR operation, the streamflows of Yichang and Shashi stations are decreased during the flood seasons.

(2) Unlike Yichang and Shashi stations, the annual 1-day maximum flow of Luoshan station could be increased during the flood seasons, which results from the flood peak encountering between the intervening flood and the post-flood release of the TGR (Figure 1). This point can be justified by using a hydrological modelling.

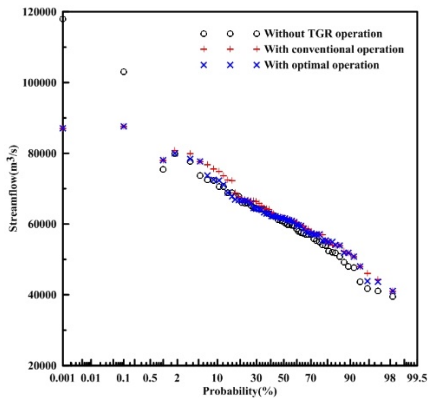

Figure 1. The empirical frequency of annual maximum flow in Luoshan station without TGR operation, with conventional and optimal TGR operating rules

These results are not only beneficial to evaluate the hydrologic systems in the middle Yangtze River after the TGR construction, but also useful for derivation of reservoir operating rules.

***Keywords*:** *Hydrologic alteration, impacts of Three Gorges Reservoir, MISO, hydrologic changes*

A Space Odyssey? Developing a framework to correct GCM spatial biases at multiple scales

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Abstract: General Circulation Model (GCM) simulations are useful tools to understand the large scale effects of anthropogenic climate change on human and natural systems. However biases in GCMs and the scale mismatch between the GCM resolution and the catchment scale preclude their direct use for many water resources impact assessments. Many downscaling and bias correction approaches have been developed to overcome these issues but the issue of spatial dependence in GCM biases has received limited attention. In this work we present two different methods have recently been developed to address this problem.

The first method is as Independent Component Analysis (ICA) based bias correction method which uses a two stage approach to correct biases in spatial correlations followed by a traditional point based bias correction. The ICA bias correction has been demonstrated to provide better assessments of drought areal extent using both GCM simulations and regional climate model (RCM) simulations from CORDEX over Australia. To further address the issue of the spatial scale mismatch between the typical resolution of GCMs and RCMs with the catchment scale, modifications of the popular Bias Correction Spatial Disaggregation (BCSD) method have been proposed that provide better representations of the upper and lower tails of monthly rainfall distributions. This presentation provides a summary of these two new developments and discusses how a spatial bias correction framework is possible through their combination.

Keywords: *General Circulation Models, bias correction, disaggregation, spatial dependence*

Precipitation changes in the water towers of the dry Pacific Basin in Peru

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Abstract: The Peruvian Central Andes is a natural water tower of the dry Peruvian coastal region, where the majority of the population lives (about 28 million). The arid but fertile coastal region has about two-thirds of Peru's irrigation infrastructure (11,900 km^2, or about half of that of Australia). It relies almost exclusively on water supplied by 53 rivers - which form the Pacific Basin - and aquifers originating in the highlands of the Central Andes. Precipitation and temperature are highly variable spatially due to the mountainous topography and steep gradients. In addition, precipitation is strongly seasonal, mostly occurring during the austral summer months (December to February) mainly as a result of convective events. In contrast, the austral winter months (June to August) have very low precipitation. In the Andean highlands (>2500 m.a.s.l.), precipitation can reach up to 2500 mm per year on average; whereas the lowland parts of the basin (<1000 m.a.s.l.) receive around 250 mm per year, and there is almost no precipitation along the coastline. Precipitation characteristics alongside steep gradients and short concentration times result in fast responsive catchments, with only about 30% of them being perennial. There has been considerable investment in the construction of dams and inter-basin transfer schemes to buffer the shortage of resources during the dry months, however year-round irrigation water supply for about 40% of the irrigated area does not have much regulatory storage and is thus unreliable.

This study investigated the long-term changes of precipitation in the water towers of the Pacific Basin in Peru using the PISCO (Peruvian Interpolated data of the SENAMHIs Climatological and hydrological Observations) precipitation dataset for the period 1981–2016. In addition to the change in annual and seasonal precipitation; the duration, frequency and intensity of meteorological droughts is investigated using the Standard Precipitation Index (SPI). Future changes in precipitation and SPI are estimated using an ensemble of 21st century IPCC AR5 CMIP5 GCM projections for a mid-range global warming scenario and a seasonal scaling method that considers future changes in mean seasonal precipitation and potential evapotranspiration. Although uncertainty exists in the projections, the majority of the climate models show a decrease in annual and summer precipitation. Considering ongoing regional socioeconomic development, results indicate that the management of the already stressed water resources in the Pacific Basin is expected to become more challenging due to climate change, and that a range of structural and non-structural measures need to be considered to mitigate its impacts.

Keywords: *Global warming, drought, irrigation, water supply, Andes, arid climate*

Statistical technique for assessing trends in drought occurrence – a case study

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Abstract: Drought is an extreme weather event affecting human wellbeing and the natural environments. In addition, climate change is exacerbating the situations by making drought conditions more common. Identifying and quantifying trends in drought events thus pose a real challenge in managing water resources systems. This study evaluated the trends in the frequency of occurrence of drought events in the Yarra River catchment in south-east Victoria, Australia. The Standardized Precipitation Index (SPI) and the Standardized Hydrological Drought Index (SHDI) were applied for 6-months timescale to identify meteorological as well as hydrological drought events, respectively. Drought indices are the most common and effective tools for the detection of drought periods. This study considered a drought event to commence as soon as the SPI/SHDI value becomes less than zero. Generally, trends in any data series are investigated by non-parametric statistical techniques. However, the time series of rare and extreme weather events are not suited to these traditional approaches due to the presence of zero values and non-normality of data. In this study, the changing pattern in the inter-arrival time of successive drought events were assessed with a statistical parametric method resulting from the concepts of Poisson Process and standard linear regression technique. The SPI and the SHDI were employed to detect drought incidences for two rainfall and two streamflow stations, respectively, within the study area. Overall, all the stations showed statistically insignificant decreasing trends in the rate of inter-arrival times of drought events which indicates that the drought events are becoming more frequent. This study will assist water managers to assess and develop appropriate mitigation strategies to overcome the future drought impacts.

Keywords: *Drought, trend, frequency, parametric method, linear regression*

Aggregating climate drivers to model sustained rainfall anomalies: What is the best scale?

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Abstract: Skillful long-term predictions of year to multi-year sustained anomalies of rainfall are of interest for water resource management. Climate drivers estimated from sea surface temperature anomalies in the tropical Pacific and Indian Ocean have been found useful for this purpose. We have examined whether aggregating climate drivers over different window lengths improves our ability to predict sustained anomalies of rainfall. Rainfall anomalies are represented by the Standardized Precipitation Index (SPI) calculated at 12-month and 36-month time scales. Niño3.4 and DMI, representing sea surface temperature anomalies (SSTA) over the Pacific and Indian Oceans respectively, are considered for prediction of SPI. The aim is to enhance the modelling of relationships between SPI and selected climate indices by isolating the frequency of interest using the aggregation technique. These aggregated climate indices are then used as predictors in a number of different models to predict SPI. The advantage of using a range of models with unique combinations of predictors is that allows the extent of uncertainty associated with predictor selection to be explored. Significant predictors are identified using a nonparametric approach based on Partial Mutual Information (PIC) and a K-nearest-neighbor (KNN) regression formulation based on Partial Weight (PW) is used for prediction of SPI. Finally, a model combination approach based on weights estimated from error-covariance matrix is used to reduce the structural uncertainty of SPI prediction.

The optimum aggregation window lengths vary across Australia and significant improvements in the prediction of SPI are clearly evident for all time scales at almost all grid cells across Australia when aggregated climate indices are used as predictors. The multimodel prediction reduces the structural uncertainty and further improves the prediction efficiency. Given the continuing improvement in prediction of sea surface temperatures, the model developed in this study offers a new method for long term prediction of prolonged drought and wet anomalies.

Keywords: *Droughts, climate teleconnections, standardized precipitation index, aggregation*

Generating perturbed hydroclimate time series for use in scenario-neutral climate impact assessments

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Abstract: A new R-package is presented here that generates perturbed hydroclimatological time series for scenario-neutral climate impact assessments. A scenario-neutral approach 'stress-tests' the performance of a modelled system by applying a wide range of plausible hydroclimate conditions. This approach allows critical variables that affect the vulnerability of the system to hydroclimate variation and change to be identified. The approach further enables the identification of threshold conditions for critical system variables at which the system is pushed beyond acceptable operating conditions. The identification of these key climate variables and the thresholds at which the system is pushed beyond acceptable operating conditions provide practical guidance on what information on projected change should be sought and considered by climate change adaptation planners and system operators.

Effective application of the scenario-neutral approach hinges on the availability of suitable sets of plausible hydroclimate variable time series (e.g. rainfall, temperature and potential evapotranspiration). Considerable technical effort may be required to generate perturbed hydroclimate variable time series that are capable of strategically 'stress-testing' a system. This poses a significant challenge for the wide scale adoption of a scenario-neutral approach for climate impact assessment.

In answer to this a prototype R-package has been developed to produce perturbed time series using a range of approaches (e.g. simple scaling of observed time series, stochastic simulation of perturbed time series via an inverse approach). The software incorporates a number of stochastic models to generate a variety of different hydroclimate variables on a daily basis (e.g. precipitation, temperature) and allows a variety of different hydroclimate variable properties, herein called attributes, to be perturbed. Guidance is provided on the suitability of the chosen models to perturb the chosen hydroclimate variable attributes and combinations of attributes that can perturbed simultaneously. Step-by-step demonstrations of each perturbation approach and comprehensive help documentation are included as part of the software. The software automatically generates a comprehensive range of output diagnostics and graphics which can be used to evaluate the produced time series prior to 'stress-testing' a system. As further developments occur in the field of scenario-neutral climate impact assessment the software will be updated to incorporate these advances.

Keywords: *Climate change impact assessment, scenario-neutral, bottom-up, inverse approach, stochastic rainfall*

Hydrological impacts of climate change and its implication for water management in the Brahmani and Baitarni Basin

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Abstract: The Brahmani-Baitarni Basin extends over the Indian states of Chhattisgarh, Jharkhand, and Odisha with a population of 16.7 million. Agriculture plays a critical role in food security and livelihoods in the Basin. The upper part of the Basin suffers from low crop yield owing to water shortage, while the downstream part of the basin near the delta area is subject to floods. The river system may become more vulnerable under climate change, which includes the changes of magnitude, frequency, duration and timing of the streamflow. To investigate the hydrological responses to climate change, hydrological simulations have been conducted for both the past decades (1901-2013) and the future (2046-2075). With respect to model uncertainty, three hydrological models (GR4J, SIMHYD and Sacramento) are used concurrently with different parameterization approaches. According to the simulation of the past decades, the long-term trend of the hydrological metrics (e.g. annual total, high flow, low flow, dry-spell, etc.) are assessed and the sensitivities to climate change are assessed. To project the future hydrological changes in the region, the scaling factors informed by 40 CMIP5 GCMs are used to provide the future climate forcings to the hydrological model. The results show that the hydrological models perform reasonably well in the region but uncertainty exists particularly when the parameter sets are regionalized. Nevertheless, the overall projection suggests that the dry area in the basin may become drier, while the flooding risk in the lower reaches may increase. The potential changes of the hydrological metrics together with the local socio-economic development indicate that water resources management in the basin is becoming more challenging. Climate adaptation and mitigation strategies including both structural (e.g. new dams) and non-structural (e.g. more efficient water use technology) approaches need to be further explored to ensure the sustainable development of the region.

Keywords: *Water resources, hydrological model, climate change, Brahmani and Baitarni Basin*

Future runoff projections for Australia and science challenges in producing next generation projections

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Abstract: This paper presents future runoff projections across Australia, modelled using climate change projections from 42 CMIP5 global climate models (GCMs) used in the most recent Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5). The empirical delta scaling method is used to scale the observed historical climate data, informed by the change signal in the GCM (for 2046–2075 relative to 1976–2005 for RCP8.5), to reflect a future climate series. The historical and future runoffs are simulated using a daily hydrological model at 0.05° grid cells, using parameter values from the geographically nearest calibration catchment (the model is calibrated against streamflow data from more than 700 catchments).

The plots in Figure 1 show the median and 10th to 90th percentile range of projections for mean summer, winter and annual runoffs. The median projection for Northern Australia is about 5% reduction in mean annual runoff, with a 10th to 90th percentile uncertainty range of –40% to +30%. The median projection for eastern Australia is about 15% reduction in mean annual runoff with an uncertainty range of –40% to +20%. There is stronger agreement in the projections for declining runoff in the far south-west and far south-east where the large majority of GCMs project a drier future winter when most of the runoff in these regions occur. In the far south-west, the median projection is a decline of mean annual runoff of 50% (with an extreme dry projection of –70%), and in the far south-east, the median projection is a decline of mean annual runoff of 20% (with an extreme dry projection of –40%).

The paper also discusses the limitations, science challenges and opportunities in producing the next generation hydroclimate projections.

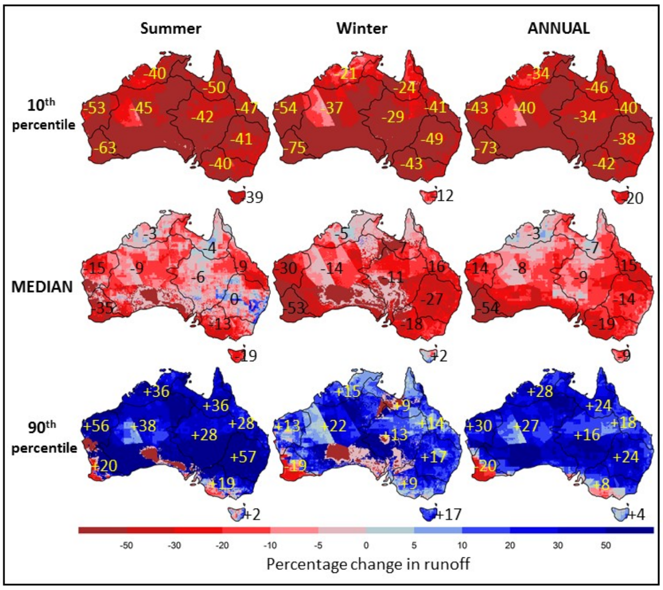

Figure 1. Projected percentage change in mean annual, summer (Dec-Jan-Feb) and winter (Jun-Jul-Aug) runoff (median and the 10th and 90th percentile values from hydrological modelling informed by climate change projections from the 42 CMIP5 GCMs) for RCP8.5 for 2046–2075 relative to 1976–2005.

Keywords: *Climate change, runoff, projections, CMIP5 GCMs, Australia*

Improved rainfall runoff modelling under a drying climate

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Abstract: Rainfall runoff models are useful tools in water planning for future variability in climate. They are commonly used to quantify the impact of changes in climatic variables, such as rainfall, on water availability for human consumption or environmental needs. Many regions of the world are likely to be drier in the future than in the past. Given the importance of water to security, the economy and social wellbeing, reliable tools for understanding future water availability are vital.

However, it appears that the current generation of rainfall runoff models are not reliable when applied in changing climatic conditions. Simulations of historic case studies such as recent droughts in southern Australia indicate that the models often perform poorly, underestimating the sensitivity of runoff to a given change in rainfall. Many hydrologists have assumed that these deficiencies are due to the model structures themselves - that is, the underlying model equations. However, it is possible that the explanation is broader, and can only be understood via holistic approaches examining the entire modelling process. Accordingly, this research, presented in three parts, aims to understand and improve various elements of rainfall runoff modelling in changing climates, with a focus on calibration methods.

Part 1 investigates whether the poor model performance is due to insufficient model calibration and evaluation techniques. An approach based on Pareto optimality is used to explore trade-offs between model performance in different climatic conditions, focusing on a case study in south west Australia and two model structures. Comparison of Pareto results with a commonly used calibration method reveal that the latter misses potentially promising parameter sets within a given model structure, giving a false negative impression of the capabilities of the model. This suggests that existing model structures may be more capable under changing climatic conditions than previously thought. The aim of Part 1 is to critically assess commonly used methods of model calibration and evaluation, rather than develop an alternative calibration strategy. The results indicate that caution is needed when interpreting split sample results.

Having demonstrated deficiencies in commonly used calibration methods, Part 2 examines alternative calibration strategies. The aim is to find calibration metrics capable of identifying parameter sets with robust performance, even if climatic conditions change compared to the calibration period. The merits of various objective functions are discussed, using the same case study as Part 1. With reference to a wider set of results from 86 Australian catchments, we show considerable scope for improved calibration, relative to commonly used 'least squares' approaches. Metrics that consider dynamics over a variety of timescales (eg. annual, not just daily) are more promising, as are objective functions using the sum of absolute errors rather than the sum of squared errors. The key recommendations of Part 2 are to avoid 'least squares' approaches and adopt these alternative methods, wherever simulations of a drying climate are required.

Parts 1 and 2 confirm the importance of calibration methods when modelling under changing climates. This raises the question: in what circumstances should the focus be on improving calibration methods versus improving model structures, or alternatively on other issues such as poor data quality? Although recent literature has presented various evaluation tools – usually variants of the Differential Split Sample Test (DSST) – a modeller whose model has failed the DSST is largely without guidance as to next steps. In Part 3, we explore how the shape of the Pareto Curve (Part 1) can guide whether structural changes are required, as opposed to improved calibration methods. Limitations of inferring future hydrologic processes from historic data are also discussed.

This research underscores the joint importance of model structures and calibration methods, providing practical guidance for holistic improvement of the modelling process. It is hoped this prompts and guides more robust runoff estimates and leads to greater confidence in hydrological projections.

Keywords: *Rainfall-runoff modelling, climate change, calibration, Pareto approaches*

Accounting for uncertainty in modelling hydrological impacts of land use change

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Abstract: Often in modelling of hydrological impacts of land use change, only two scenarios are compared (i) a reference scenario and (ii) a scenario with the altered land use/land cover (LULC), each having a fixed set of LULC-based parameters. However, rarely is the question asked whether the inferred LULC impacts, by comparing only two scenarios, are representative and/or reliable. This study investigated the level of uncertainty in estimates of hydrological impacts of LULC change by modelling two adjacent catchments (i) pasture farm (144 ha) and (ii) tree plantation (299 ha). To investigate the likely impacts of land use change from pasture to tree plantations on streamflow and evapotranspiration in southeast Australia, we used the "Soil and Water Assessment Tool" (SWAT) and a regression methodology, the later relating model parameters to catchment characteristics. We tested relationships between the SWAT curve number (used in the calculation of surface runoff) and catchment characteristics (*area, soil available water capacity, slope, time of concentration and manning's n*) to enable the transfer of parameters from one catchment to another in order to assess the impacts of land use change.

SWAT was calibrated against daily streamflow measured at the catchment outlet from year 2011 to 2013 while 2014 and 2015 were used to evaluate model performance. The years 2005 to 2010 were the model's warm-up period. The model parameters included in the calibration were ESCO (Soil evaporation compensation factor), EPCO (Plant uptake compensation factor), CN2 (SCS Curve number), SURLAG (Surface runoff lag coefficient), CNOEFF (Plant ET curve number coefficient) and SOL_AWC (soil available water capacity). The SWAT model performance was evaluated both graphically and statistically (Nash-Sutcliffe efficiency, NSE) by comparing measured with simulated streamflow.

To quantify uncertainty in model outputs, we combined the Latin Hypercube Sampling (LHS) and Null Space Monte Carlo (NSMC) approaches using the parameter estimation tool, PEST. A total of 5000 parameter sets for each catchment model were generated, and the parameter sets that resulted in a calibrated model with NSE >= 0.6 were selected. The regression relationships derived between catchment characteristics and model parameters using the selected parameter sets for the plantation catchment were used to predict new vegetation-related parameters at the farm catchment. The selected calibrated farm models were then run with these new (regression-derived plantation) parameters to quantify the impact of land use change.

The best plantation regression models with coefficient of determination greater than 0.5 were selected, with *slope* emerging as the most important catchment characteristic in estimation of the curve number.

Overall, streamflow at the plantation was about 25% less than at the farm and this was attributed to the differences in vegetation since the climate and soils were similar in both catchments. On the other hand, annual ET at the plantation was generally higher than at the farm. However, there was little difference in annual ET in the dry years compared to the wet years.

Comparable performance between the plantation and farm-to-plantation models showed that the transfer of parameters using catchment characteristics is a promising approach to land use impacts modelling. There was overlap in simulated streamflow prediction intervals between the farm and farm-to-plantation models, suggesting weak evidence for impact of land use change. However, most models exhibited a decrease in streamflow due to the land use change. Accounting for uncertainty in the regression models greatly increased the uncertainty in model predictions of streamflow in the farm-to-plantation model. Thus, there is need for approaches that reduce regression-model-based uncertainty in LULC change model predictions through robust selection of appropriate catchment characteristics that strongly control the dominant catchment hydrological processes.

Keywords: *SWAT, regression*

How does climate change impact rainfall temporal patterns

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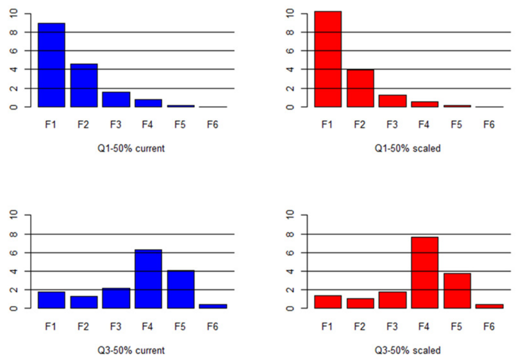
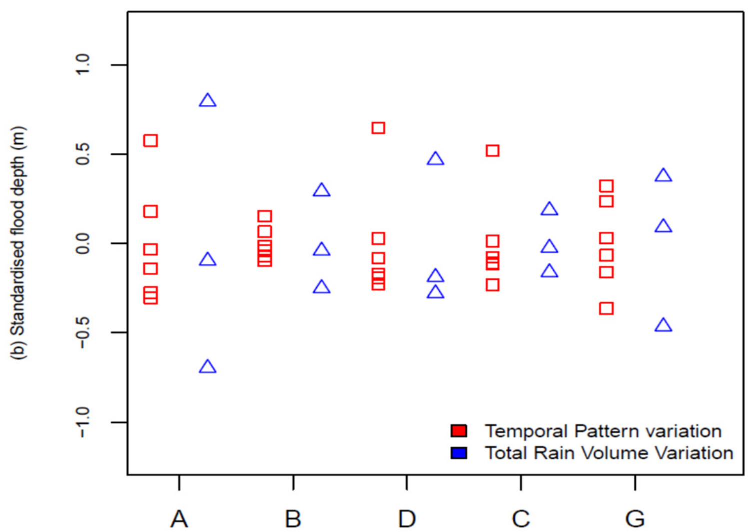
Abstract: Warming temperatures are causing extreme rainfall to intensify resulting in increased risk of flooding in developed areas. Quantifying this increased risk is of critical importance for the protection of life and property as well as for infrastructure planning and design. The study presented in this manuscript uses a comprehensive hydrologic and hydraulic model of a fully developed urban/suburban catchment to explore two primary questions related to climate change impacts on flood risk: (1) How does climate change effects on storm temporal patterns and rainfall volumes impact flooding in a developed complex watershed? (2) Is the storm temporal pattern as critical as the total volume of rainfall when evaluating urban flood risk? The updated NOAA Atlas 14 intensity-duration-frequency (IDF) relationships and temporal patterns, widely used in design and planning modelling in the USA, form the basis of the assessment reported here. Current literature shows that a rise in temperature will result in intensification of rainfall. These impacts are not explicitly included in the NOAA temporal patterns, which can have consequences on the design and planning of adaptation measures. We use the expected increase in temperature for the RCP8.5 scenario for 2081-2100, to project temporal patterns and rainfall volumes to reflect future climatic change. The figure to the left shows an example of the changes in temporal pattern when projected to reflect temperature increase.



The modelling analysis for a 22 km^2 developed watershed show that temporal patterns cause substantial variability in flood depths during a storm event. The changes in the projected temporal patterns alone increase the risk of flood magnitude between 1 to 35 % with the cumulative impacts of temperature rise on temporal pattern and the storm volume increasing flood risk by between 10 to 170 % across the locations that were referenced for a 50 year return period storm. The figure below shows an example of the level of variability in peak flood depth purely due to different temporal patterns compared to peak flood depths resulting from different total rainfall volumes. The variability in catchment response to temporal patterns show that regional storage facilities are sensitive to rainfall patterns that are loaded at the latter part of the storm duration while the short duration extremely intense storms will cause extensive flooding at all locations. This study shows that changes in temporal patterns will have a significant impact on urban/suburban catchment response and need to be carefully considered and adjusted to account for climate change when used for design and planning future stormwater systems.



Keywords: *Storm temporal patterns, urban hydrology, climate change, urban flood risk*

Catchment Systems Engineering: a holistic, interventionist approach to catchment management

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Abstract: Catchments today are largely the product of human activity. They have been engineered and as a result catchments now function in a less resilient way and are more vulnerable to climate change. The negative impacts of some of this historical 'engineering' such as agriculture intensification and deforestation needs to be urgently addressed. However, the answer is not simply a matter of going back to nature. Nor is non-intervention an option. Nature based solutions do hold the key to future sustainable management but only if the interventions are carefully targeted and yield the results we require at the catchment scale.

Here, we propose a Catchment Systems Engineering (CSE) approach that incorporates and expands on existing approaches including Natural Flood Management, Green infrastructure, Sustainable Drainage Systems, Nature-Based Solutions and 'Working with Natural Processes'. However, these methods are then combined with the traditional problem solving engineering approach, that is, to provide a practical outcome of resolving the catchment scale water balance in the future. The approach is predicated on the need to take a holistic view of the whole catchment system and to make proactive interventions that provide system scale process improvements. As the world intensifies its resource use and the pressure for food water and living space increases we must mitigate for these impacts. Obvious options are to have lower intensity farming land use change better soil management. Here we argue that this may not be the most effective approach and we propose a CSE methodology based on soft engineering and mitigation technologies.

The problems CSE seeks to address are international in reach with impacts that cannot be overstated. The CSE approach recognizes the need to understand how the catchment hydrological water balance has changed and what the impact is of those changes. The approach embodies *how we can act* to engineer catchment systems to a safer, functionally appropriate level.

Here, we set out the philosophy behind CSE, proposing a mitigation and adaptation approach for intensively exploited landscapes undergoing climate change. Altering the capacity to holding water in catchments (attenuation) is the primary strategy underpinning CSE. It is primarily the attenuation capacity of catchments that has been lost in the soil and channel network, and we will show case studies to demonstrate this issue. The CSE aim is to create infiltration zones, flood storage, sediment traps, wetlands, changing roughness, change flow pathway length and make best use of floodplains through managed inundation. A variety of methods that act at all scales are employed to change attenuation by adding new attenuation capacity to a catchment. These include features such as swales, bunds, ponds and grassy filters, buffer strips, ditches that hold water and trap top soil lost through erosion, small headwater floodplains that store water, wetlands and woodland. Here we address, at a catchment system level, the required degree of intervention and ask how, where, when and who should intervene? The key role of runoff management at source and in ditches and riparian areas is highlighted. A series of examples are presented where these methods have been successfully applied to reduce flood and drought risk and provide multiple benefits from reduction of sediment and pollutant export to creation of habitats and recreation opportunities.

Keywords: *Catchment management, soft engineering, water balance*

International investigation of climate-runoff response long-term dynamics

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Abstract: This paper presents outcomes of a collaborative project investigating long-term dynamics of climate-runoff response across several countries. Previous research in south-eastern Australia revealed that some catchments are prone to shift their functioning under prolonged change in climatic conditions such as a decade-long drought. This raises the question – are such shifts in catchment behaviour specific to dry catchments of south-eastern Australia, or can such shifts occur in other parts of the world? We explore this question through regression and trend analysis applied to a large international dataset comprising North American (US, Canada), European (France, Austria, and UK), and Australian catchments. The study is focused on investigating long-term changes in the link between catchment climate and runoff response. We hypothesise that long-term changes in climate (~interdecadal variability) can result in significantly different precipitation-runoff or aridity-runoff elasticities than those characteristic of shorter changes (~interannual variability).

Our analysis reveals that changes in both precipitation-runoff and aridity-runoff relationships occur in catchments around the world, but frequency, direction, and likely physical explanation of these changes differ between regions, and between water-limited and energy-limited environments. When significant changes occur in precipitation-runoff relationship, typically less runoff is generated for a given precipitation over time. For aridity-runoff relationship, there is more variability in long-term runoff response to changing climatic conditions, partially because of increasing potential evapotranspiration, partially because of different dominant factors of catchment response in different types of environments. For example, in Australia aridity-runoff elasticity increases over time, while in the UK it declines. We interpret combined results of a number of climate characteristics and runoff response signatures and argue that three main mechanisms appear to be responsible for shifts in catchment response in different environments: 1) changes in potential evapotranspiration 2) changes in vegetation water consumption 3) changes in storage-runoff relationship.

Significant changes in climate-runoff relationship, such as those detected in this study, imply that typical runoff response to given climatic conditions can vary over decades even in near-natural catchments. The outcomes of this analysis have implications for long term water resource assessment, management, and prediction.

Keywords: *Hydrologic change, long-term adaptation, catchment resilience, streamflow, runoff response*

Impact of land use changes on hydrologic processes and the water quality in the Three Gorges Reservoir Area

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Abstract: Land use is considered as the one of the most significant factors influencing the hydrologic processes and water quality at local and regional scales. With the continuous expansion of human development, dramatic changes have taken place on a global scale in land use patterns in catchments. Evaluation of the land use change impacts on the water quantity and quality is necessary to manage the environment sustainably in basin scales.

As one of the most ecologically sensitive areas of China, the Three Gorges Reservoir Area (TGRA) is strongly influenced by the Three Gorges Project. The TGRA covers a total area of 64000 km2 and stretches over a distance of more than 600 km. The construction of the Three Gorges Dam on the Yangtze River led to the resettlement of more than one million people according to official numbers, including the relocation of agriculturally used areas from the valley bottoms to steep, formerly forested slopes, which has resulted in continuously changing land use patterns since 2000. Forest, cropland, pasture, settlements and water are the dominant land use in the study area, and their land use pattern status have direct connection with hydrologic processes and nonpoint source (NPS) pollutant loading.

In this study, four land use data (2000, 2004, 2010 and 2015) were acquired from available Landsat Thematic Mapper images and were classified through the maximum likelihood digital image classification using the supervised classification approach, from which the changes of land use in the TGRA can be interpreted and calculated. After that, the four land use scenarios were used to evaluate the impact of land use changes on hydrologic processes and NPS pollutants loading in the whole TGRA, using a calibrated and validated version of the soil and water assessment tool (SWAT) model. During the 16-year study period, the land use changed markedly with the obvious increase in forestland, settlements and water at the expense of cropland. The land use change showed a significant influence both on the NPS pollutant loading and runoff. Results of this study can improve our understanding of hydrological consequences of land use changes, and have implications for effectively developing and managing land use for sustainability and productivity in the TGRA.

Keywords: *Land use change, hydrologic processes, water quality, NPS pollutants, Three Gorges Reservoir, SWAT*

Development and application of a compensative regulation linear programming model for reservoir flood-control

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Abstract: Optimal reservoir flood-control regulation can significantly improve the overall benefits of flood control. In a flood-control system composed of reservoirs and embankments, reservoirs are usually regulated in compensative mode to protect upstream and downstream areas, where the protected areas are far away from the dam sites but with cross-area flow relationship. The selection of reservoir regulation mode has been made according to experiences in practical operation, which is lack of scientific basis.

Many successful studies of optimization techniques have been done in reservoir operation model since 1980s. The optimal reservoir regulation models they proposed can be summarized into two categories: programming comparison method and optimization method. Although these approaches are useful, they have limitations: different outflow processes of the reservoir can lead to the same discharge process in the flood control section. To ensure the reservoir outflow process is operational under the multi-solution background, the reservoir decision and river flood routing are analyzed separately which cannot promise an overall optimal solution. Due to aftereffect caused by the flood routing characteristic and downstream river storage impact law, mature multi-stage decision optimization methods cannot perform well, meanwhile intelligent algorithms cannot prove to get the optimal solution, when applied to the compensative regulation for reservoir flood-control. And the "optimal solution" calculated by these model shows huge difference to actual decision in real-time reservoir operation.

Taking a basic flood-control system composed of a reservoir and a downstream flood control section as the object, this work considered real-time reservoir operation rules in China, and added the outflow upper limit besides the traditional constraints, then proposed a linear programming model for compensative regulation linear programming model for reservoir flood-control(RFCR-LP). Due to the global optimum can be obtained in the linear programming model, RFCR-LP avoided the aftereffect accompanying conventional methods for a multi-stage decision, coupled the operational decisions and downstream routing methods. It can unify the optimal mathematical models between flood-control planning and real-time operation, promote an stable and efficient solution for complex system modeling. Furthermore, it provides a scientific basis for the selection of reservoir operation methods.

The RFCR-LP has been verified/tested with different types of flood process in Tingzikou reservoir in Jialing River, this suggested that it was a feasible, flexible and stable flood control model.

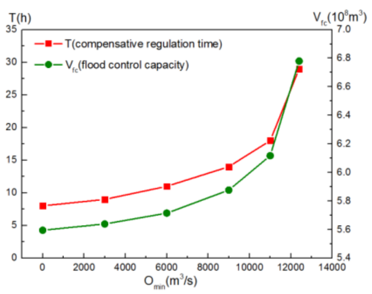

Figure 1. Compensative time and flood-control volume with different lower limit on outflow

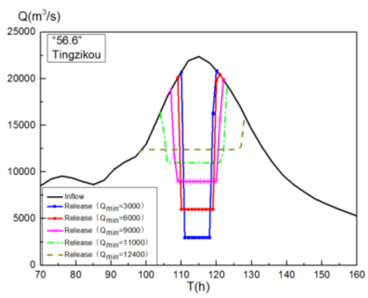

Figure 2. Outflow process of Tingzikou reservoir with different lower limit on outflow

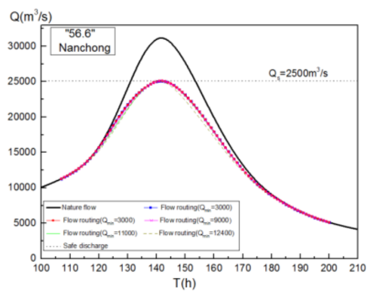

Figure 3. Outflow process of Nanchong station with different lower limit on outflow

Keywords: *Compensative regulation, linear programming, aftereffect, couple, global optimum*

Non-stationarity in base flow recession induced by vegetation changes: insights from paired experimental catchment observations

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Abstract: It is widely recognized that vegetation changes can lead to significant changes in the catchment water balance. However, predicting such changes across different spatio-temporal scales is still uncertain. In this study, daily streamflow observations of paired experimental catchments are used to demonstrate that whether vegetation can induce significant changes in base flow recession dynamics. Results show that catchment base flow recession dynamics of the treated catchments (either afforestation or deforestation) have changed significantly after the treatments, while those of the control catchments are kept stationary (see Figure 1). It suggests that vegetation changes can lead to significant changes in catchment low flow recession dynamics, which can be one of important mechanisms that is responsible for the changes in total streamflow. Furthermore, the power law relationship for describing catchment storage-discharge dynamics is reformulated to capture and quantify the changes in storage-discharge relationship resulting from vegetation changes. This study demonstrates that change in discharges from catchment groundwater storage is one of important mechanisms responsible for changes in catchment water yield after vegetation changes and will improve our predictability about the impacts of vegetation changes on catchment water yields.

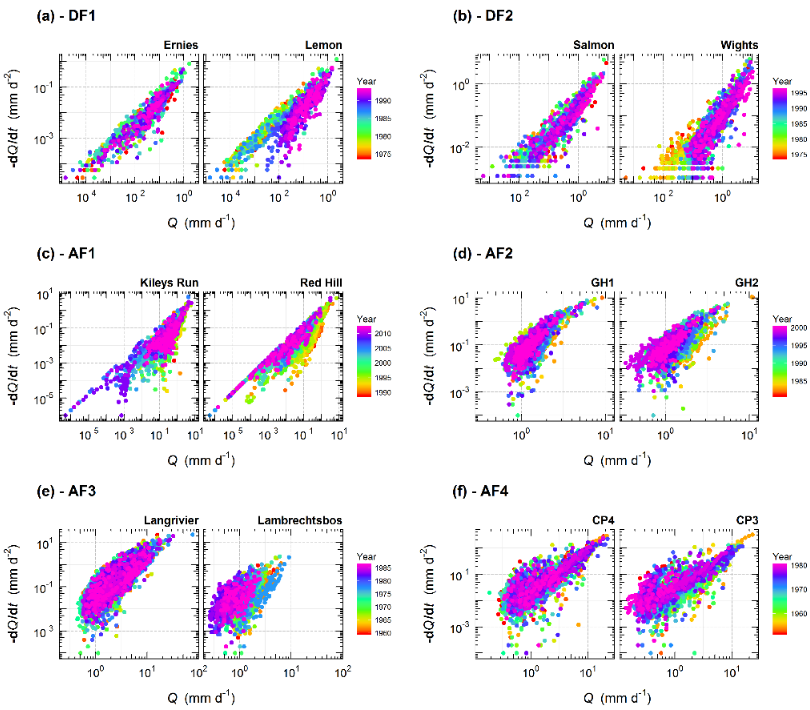

Figure 1. Changes in daily flow recession rates of the six paired catchments grouped by year. In all subplots, the left part is for control catchment and the right part is for treated catchment. "DF" is for deforestation sites and "AF" is for afforestation sites.

Keywords: *Vegetation change, non-stationarity, flow recession, storage-discharge, paired catchments*

Large-scale flood risk management planning: an exploratory modelling exercise

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Abstract: Most large river systems around the world are protected by dikes and it's well recognized that the presence of such structural defences alters the hydrological regime. Raising the dikes at upstream locations exacerbates high water levels downstream and, in contrast, dike failures upstream produce an unloading effect on downstream dikes, which are then less likely to fail. These effects clearly show the existence of hydraulic interdependencies between upstream and downstream locations, i.e. the change in the hydraulic loads at one location as a consequence of the response (e.g. failure) of dikes elsewhere, and shift the focus of flood risk analysis and management on understanding the behavior of the system of dikes as a whole ('*system behavior*', in the following). Previous risk analysis studies have shown the importance of considering system behavior, which affects e.g. the flood frequency curve, the number of expected dike failures as well as the estimated economic damage and casualties. However, a due consideration of system behavior in the design and planning of flood risk management strategies is still lacking. Current flood risk management plans are usually based on worst-case scenarios where all dikes are designed as if their flooding probability were independent from those of nearby or upstream embankments, leading to an overestimation of the risk and to inefficient allocations of economic resources. This is mainly because considering system behavior requires dealing with many uncertain factors. Uncertain are e.g. the actual breach locations ('which dikes will fail and in what order'?), the moments of breach and the final breach widths ('what will be the actual unloading effect?'), against which expert judgment or upfront assumptions about probability distribution functions may prove to be wrong. This requires flood risk management plans to be developed by seeking strategies that perform well under a wide range of plausible system behaviors.

A way of dealing with problems of decision-making under uncertainty is by using Exploratory Modelling and Analysis (EMA), where analysts hypothesize about possible configurations of the system under study and test the performance of multiple strategies in each configuration.

The current work introduces an exploratory model for the study of large-scale flood risk systems with the aim of developing large-scale flood risk management strategies. The model serves analysts in exploring a multiplicity of plausible system behaviors under different choices of management strategies (e.g. system configurations) and aids stakeholders and policy makers in exploring trade-offs among such strategies. In the model, uncertainties in system behavior relate to both structural and parameter uncertainties. Structural uncertainties are explored by using multiple flood damage models. Parameter uncertainties are assigned a plausible range of values, each value being equally likely, and relate to: the peak discharge and the flood wave shape at the upstream location; and the breach width, the breach growth rate and the probability of failure at each dike location. Strategies include: raising and strengthening the dikes; increasing the river conveyance capacity; decreasing the community vulnerability; and establishing upstream-downstream cooperation on regulating the river flow. Strategies are evaluated in terms of costs and expected economic and social (e.g. casualties) losses.

The analysis is conducted on a fictitious case-study with and without considering the effect of system behavior. The aim is to study if and under what conditions considering system behavior influence the final choice of flood risk management strategies. Results show that, in general, when system behavior is taken into account dikes fail less frequently and, therefore, the estimated losses are lower. As a consequence, one would expect lower design standards. However, the actual response to system behavior's effects is highly dependent on how the uncertain factors unfold. For this reason, data-mining techniques are applied in order to discover scenarios (i.e. ranges of uncertain factors) under which system behavior is of relevance, whose understanding is crucial for designing strategies which are considered optimal for the whole system. Future research will focus on the design of strategies on the Rhine and Po rivers.

Keywords: *Flood risk management, exploratory modelling, system behavior*

Identifying changing patterns of reservoir operating rules under various inflow alteration scenarios

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Abstract: Operating rules are important in the long-term operation of reservoirs for its capability of coping with inflow uncertainty. The characteristics of inflow vary as a result of climate change and human activities, and using stationary operating rules would lead to inefficient reservoir operation. This study focuses on identifying changing patterns of operating rules under various inflow alteration scenarios. Two hydrological simulation methods, the simple adjustment method (SAM) and the stochastic reconstruction method (SRM), are used to generate three inflow alteration scenarios: shifts of mean, coefficient of variation (C_V), and seasonality. A deterministic reservoir optimization model is established and then resolved using discrete differential dynamic programming. Finally, the operating rules under each scenario are derived using the linear fitting method. China's Three Gorges Reservoir is used as a case study. The results show that the SAM and SRM produce similar operating rules, which are sensitive to inflow changes during refill and drawdown periods. It is shown that (1) the increase (decrease) of inflow mean changes the operating rules, resulting in the increase (decrease) of the water releases while the shift of C_V has little impact on operating rules; (2) the seasonality changes operating rules in opposite directions during refill and drawdown periods; (3) the changing patterns of operating rules would be superimposed by the superposition of various inflow alteration scenarios whereas the effects might be not obvious. These findings are helpful for adaptive operation of reservoirs under changing environment.

***Keywords**:* *Reservoir, operating rules, adaption, changing environment*

Climatic and anthropogenic stresses on runoff reduction from the Loess Plateau, China

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Abstract: Human intervention has strongly altered patterns of river runoff. Yet, few studies have addressed the complexity and nonlinearity of the anthropogenic stresses on runoff or their interaction with climate.

The Loess Plateau in China, is a typical human and nature coupled system, with 6.7 percent of national land area supporting 8.5 percent of the national population. River runoff in the Loess Plateau contributes 65% of the discharge to the middle reach of the Yellow River; this landscape has been shaped by human activity and is intensively managed. Terrace construction peaked in the 1990s; however, terraces served as an important soil conservation measure in the 1960s–1970s. Revegetation began in 1999, with both grass and tree plantation peaking in the 2000s. Dam construction occupied the smallest area of the CM, while tree planting occupied the largest area. Note that soil conservation measures other than terrace construction decreased sharply in the 1990s. Furthermore, tree and grass plantation prior to 1999 did not cause a statistically significant change in the leaf area index (LAI) in the CM. The significant LAI increase (slope = 0.04, P = 0.002) occurred as a result of the massive revegetation after 2000.

Applying a transient analysis to discover the time-varying runoff trend and impact factors, we found that the average runoff in the Loess Plateau decreased continuously during the period 1961-2009 (average rate of −0.9 mm yr^{-1}, $P < 0.001$). This long-term decrease in runoff mainly occurred in three stages, with transitions in 1970, 1981 and 1996. Reduced precipitation was the main reason for the decrease in runoff over the entire study period. However, human intervention played a dominant role in creating the transition points. Water yield (i.e., the ratio of runoff to precipitation) decreased following each anthropogenic transition, causing a 56% reduction in available freshwater resources during the period 1961-2009.

Climatic and anthropogenic stresses in water-limited Loess Plateau create potentially conflicting demands for water between the ecosystem and humans. From currently revegetated areas and human water demand, we estimate a threshold of net primary production (NPP) of 400±5g C m-2 yr-1above which the population will suffer water shortages. NPP in this region is found to be already close to this limit. The threshold of NPP could change by-36% in the worst case of climate drying and high human withdrawals, to +43% in the best case.

These findings highlight the need for studies that address the dynamic and nonlinear processes controlling the availability of freshwater resources in the light of anthropogenic influences applied under a changing climate.

Keywords: *Climate change, anthropogenic stresses, water resource, human-nature coupled system*

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EXTENDED ABSTRACT ONLY

Water and Ecosystem under Climate Change and Human Activities in Northwest China

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Abstract: Water is the most important constraint factor for the economic development of Northwest China and also is the dominant factor for the ecological environment of Northwest China. Under the influence of climate change and human activities, the irrational allocation of water and soil resources and the shortage of water resources in northwest China are becoming more and more severer, and the ecological and environmental problems are becoming more and more serious, including glacier area decreasing, expanding in land desertification and salinization, vegetation degradation, river drying, groundwater level decline and lakes dried up and so on. In view of the above problems, China has adopted a series of treatment measures for the Tarim River, Shule River, Heihe River and Shiyang River Basin. It has invested nearly 25 billion yuan for ecological restoration, river regulation and water resources management. Although some progress has been achieved, it is still faced with problems such as the arduous task of ecological water conveyance, the slow process of water saving, and hard to build the long-term mechanism of ecological compensation. With water as the main line, this study emphasizes the integration study of water-soil-air-biology-human activity, and solves the key problem of improving the output value of water per unit for mountainous areas, piedmont plains and downstream area, respectively. The specific solutions are: (1) to set up agricultural water-saving integration system which includes reasonable exploitation and utilization of water resources, water saving technology system, water-saving agriculture and water-saving management measures; (2) to coordinate ternary structure of the grain crop, industrial crop and forage crop, (3) to couple the grassland agroecosystem of Mountainous-Desert-Oasis. The aim of this study is to provide a support for gradually increasing the output value of water per unit, to promote the optimal allocation of regional water resources and efficient use, and to solve the problem of moderate economic development and ecological restoration in arid areas of northwest China.

Keywords: *Climate change, human activities, water and ecosystem, Northwest China*

Stochastic Gradient Approach for Energy and Supply Optimisation in Water Systems Management

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Abstract: Under conditions of water scarcity, energy saving in operation of water pumping plants and the minimisation of water deficit for users and activities are frequently contrasting requirements, which should be considered when optimising large-scale multi-reservoirs and multi-users water supply systems. Undoubtedly, a high uncertainty level in predicted water resources due to hydrologic input variability and water demand behaviour characterizes this problem.

The aim of this paper is to provide an efficient decision support system considering emergency water pumping plants activation schedules. The obtained results should allow the water system's authority to adopt a robust decision policy, minimising the risk of harmful future decisions concerning the water resource management. The model has been here developed to manage this problem, in order to reduce the damages due to shortage of water and the energy-cost requirements of pumping plants. Particularly, in optimisation, we look for optimal rules considering both historical and generated synthetic scenarios of hydrologic inputs to reservoirs. Hence, using synthetic series, we can analyse climate change impacts and optimise the activation rules considering future hydrologic occurrences.

A simulation model has been coupled with an optimization module using the stochastic gradient method to get robust pumping activation thresholds. This method allows to solve complex problems, solving efficiently large size real cases due to high number of data and variables. Thresholds values are identified in terms of critical storage levels in supply-reservoirs.

Application of the modelling approach has been developed on a real case study in a water-shortage prone area in south-Sardinia (Italy), characterized by Mediterranean climate and high annual variability in hydrological input to reservoirs. By applying the combined simulation procedure, a robust decision strategy in pumping activation was obtained. Developing the stochastic gradient model, a main programming supports has been built by MATLAB efficiently interfaced with CPLEX for optimisation and Excel for inputs and results representation.

Keywords: *Energy and water supply optimisation, water pumping schedules optimisation, stochastic gradient method*

Incorporating reservoir impacts on flood frequency distribution function's derivation

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Abstract: Assessing the flood frequency in watershed is pivotal for hydrology, with implications in many fields ranging from river science to insurance industry. Reservoir regulations may alter the characteristics of flood frequency distribution function. This paper incorporates reservoir impacts as inherent variable to derive outflow discharge and propose new flood frequency distribution. Steps are as follows: (1) the original flood without reservoir impacts is assumed to follow a Pearson type three distribution, (2) the relationships between inflow and outflow are assumed in three models, (3) the flood distributions under reservoir impacts are derived using updated flood discharge. Triangle simplification method is proposed to derive the outflow discharge based on the inflow observations. Linear reservoir model and nonlinear models are also used to compare the calculation errors and the fitting performance. The Shuibuya basin and Wuqiangxi basin are chosen for the case study, with daily inflow and outflow observations. Results show that reservoir regulations change the original flood frequency distribution function and induce the magnitude of flood peaks. It is indicated that alter the parameters of the flood frequency distribution is not always feasible to tackle the changing environment. Furthermore, the nonlinear reservoir model is the most accurate estimation method, while the triangle simplification method is more applicable in practice.

Keywords: *Flood, frequency distribution, reservoir impacts, linear and nonlinear models*

Unnegligible Nitrogen Pollution of Inland Water in China: Interaction of Nitrogen Deposition and Dam

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Abstract: In the last two decades China has become the largest creator and emitter of Nr worldwide. Nr deposition in China has been estimated at 13.2 kg N. $ha^{-1}.yr^{-1}$ in 1980s, which further increased to 21.1 kg N. $ha^{-1}.yr^{-1}$ in the 2000s. However, there is still a lack of information about the special patterns of the change of Nr deposition in past decades caused by the limitation of national observation dataset. Quantifying Nr deposition to freshwater ecosystem is essential to better understand the global N cycle because its reactor functions for Nr and transport to the sea. So far, estimates of Nr deposition to inland waters and associated contribution to N water eutrophication and transport seas in China are not available, which will be an important step to provide the policy support on controlling Nr not-point source emission. In addition, large numbers of dams have been built across China in the last decades, increasing the water surface areas while decreasing streamflow. This has led to significantly aggravating the water N pollution in China. Here we evaluate spatial and temporal patterns of Nr deposition during the 1990s to the 2010s in China, and assess how the significant extension of the water surface area following the construction of dams might have contributed to the increased eutrophication of inland waters in China.

During the 1990s to the 2000s, the total surface area of inland water in China, including river, lake and reservoir (does not include ephemeral and intermittent stream fraction), has increased from 140001 km^2 and ends with 145747km^2 , which is mainly from reservoirs. In the last three decades, China has built more than 87000 dams with a storage capacity of approx. 700 billion m^3. While the reservoir water surface area significantly increased, the surface area of natural lakes was gradually shrinking from 75286km^2 to 74795km^2 and rivers surface area slightly increasing by 232 km^2 during the 1990s to the 2010s. In China, the Nr deposition exhibits significant differences in magnitude and spatial pattern for the different hydroclimatic zones. From the 1990s to the 2010s, the Nr deposition shows a decreasing trend from southern to western and northern China. While in Southern and Southeastern China, the Nr deposition is > 25 kg. $ha^{-1}.yr^{-1}$, the atmospheric Nr deposition in northern and northwestern China ranges from 15 to 20 kg.$ha^{-1}.yr^{-1}$ and from 0 to 10 kg.$ha^{-1}.yr^{-1}$, respectively. During the 1990s and the 2010s, the annual Nr deposition over China increased by approximately 25%. The amounts of the Nr deposition in the 1990s and 2010s are 11.1 kg.$ha^{-1}.yr^{-1}$ and 15.3 kg.$ha^{-1}.yr^{-1}$, respectively, which is close to the estimation of 9.88 ~ 13.87 kg N ha^{-1} yr^{-1}.

Nr deposition is significantly higher in the humid zone than that in arid zone, and the Nr deposition in subtropical zone is higher than in temperate zone. This could be easily explained by the fact that the Nr deposition is closely linked to the amount of precipitation in most cases. In addition, because of the variation of the Nr emission and water surface area during the 1990s and the 2010s, there are about $2.0 \sim 2.5 \times 10^8$ kg $N.yr^{-1}$ by the Nr deposition input into inland water, of which rivers, lakes and reservoirs account for 28%, 39% and 33%, respectively. Dam constructions in rivers, lakes and reservoirs greatly change the region's geomorphology, enhance the water level, and increase the water surface area. Therefore, the water body would have a larger tendency to receive and detain the Nr deposition regardless the dam's interference on flood control, water resource optimization and soil erosion. Given the fact that China is still facing the dilemma of promoting economic growth and mitigating water shortage, more dams are very likely to be constructed. As a consequence, water flows in China will continue to decrease while water eutrophication problems will increase.

In China, there are total of 87873 dams located in different watersheds dated to 2013, dividing rivers and lakes into many large and small reservoirs. The separation of water bodies seriously obstructs the water naturally flow paths, increases water retention times, and results in increased rates of deposition of many pollutants and nutrients to the sediments of rivers, lakes and reservoirs. The total volume of Chinese water resource was estimated by 28412×10^8 m^3, wherein rivers, lakes and reservoirs reach 26510×108 m3, so the dams would store close to one third of water source for rivers, lakes and reservoirs. This study shows the Nr deposition is also an important N source in the water eutrophication process due to dams' effect.

Keywords: *Nitrogen deposition, dam, eutrophication, inland water, emission*

Modelling the joint-operation of water quantity and quality with multiple dams and floodgates in Shaying River

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Abstract: Poor operations of dams and floodgates have been considered as one of main reasons that are responsible for several serious pollution events in the Huai River Basin (HRB). The HRB not only has very series water pollution issues in many tributaries but also faces increasing effluent load and demand of water quality improvement due to rapid urbanization. Therefore, study of joint-operation of water quantity and quality with multiple dams and floodgates to meet the basic living standards are very important and urgent for the HRB. In this study, the Shaying River, the most seriously polluted tributary of the HRB with six dams and floodgates (as shown in Figure 1), was chosen as study area. A numerical model was developed to simulate the water quality and quantity jointly in the Shaying River. The developed model was applied to simulate one of the most serious water pollution events that happened in 2004. Results show that the developed model can well capture the water quantity and quality of this events under actual operation of all the dams and floodgates. Meanwhile, we demonstrate that the COD_{Mn} at Jieshou, Lutaizi and Bengbu stations can be reduced by 37.3%, 33.3% and 26.9% (as shown in Figure 2) under optimal operation scenario, respectively. To facilitate joint-operation of water quantity and quality in the future, 288 scenarios are further developed based on different combinations of rainfall amounts, water quality, operation rules and targets, which can be used as guides for operation of the dams and floodgates in the Shaying River to meet different water quantity and quality targets.

Figure 1. Schematic diagram of dams and floodgates in Shaying River Basin

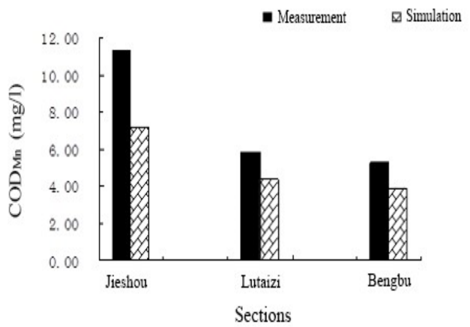

Figure 2. Comparison of optimal dispatching of water quality concentration and measured concentration

Keywords: *The Huai River, dams and floodgates, quality and quantity, joint-operation, Shaying River*

A case study on a combination NDVI forecasting model based on the entropy weight method

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Abstract: It is critically meaningful to accurately predict NDVI (Normalized Difference Vegetation Index), which helps to guide regional ecological remediation and environmental management. Since conventional individual forecasting models having their own strengths and disadvantages, a combination forecasting model (CFM) was proposed in this study to improve the performance of predicting NDVI in the Yellow River Basin (YRB) based on three individual forecasting models including Multiple Linear Regression (MLR), Artificial Neural Network (ANN), and Support Vector Machine (SVM) models. Meanwhile, the entropy weight method was employed to determine the weight coefficient of various individual forecasting models depending on their respective predictive effects. Results indicated that: (1) ANN has the best fitting ability among the four forecasting models in the calibration period, whilst its generalization ability is weak in the validation period; MLR has a poor performance in both calibration and validation periods; the predictive results of CFM in the calibration period have the highest stability; (2) CFM generally outperforms all individual forecasting models in the validation period, it therefore can improve the reliability and stability of predictive results through exploiting the strengths and making up the weaknesses of various individual forecasting models, thus reducing the uncertainty of predictions; (3) the performances of all forecasting models in dense vegetation areas are better than those in sparse vegetation areas. The findings of this study help to shed new light on vegetational cover prediction.

Keywords: *Combination forecasting model, NDVI, the entropy weight method, SVM, the Yellow River Basin*

Investigation of sustainable national water resources management of India in a changing climate

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Abstract: Freshwater scarcity and unsustainable water use is a growing concern in many developing countries including India. Increasing water demand coupled with rainfall variability associated with climate change exacerbates water scarcity. The increase in water demand is attributed to population and economic growth as well as technological change, and the gap between the actual water available and the demand continues to widen. This study aims to develop a large-scale assessment model of sustainable water use in India during the period 1970 – 2010 at a spatial resolution of 50 km x 50 km and a temporal resolution of monthly timescale.

A Community Land Model CLM 4.0, developed by the National Centre for Atmospheric Research (NCAR) of the US, and census-based statistical database are used in this study to quantify and assess the sustainable water use in India. We define the measure of sustainable water use as the difference between the total water available and the total water demand. For each grid cell, the total water available is modelled as the sum of surface runoff and groundwater. The total water demand is estimated as the sum of irrigation, industrial, domestic and environmental water demand in each grid cell. Among the demands, the irrigation water demand is modelled based on census data sets of irrigated areas and irrigation water withdrawal while the domestic and industrial water demand is modelled as a function of population, economic and technological indicators such as gross domestic product, electricity, fuel consumption and industrial outputs. However, the environmental water demand is modelled as a function of total water available, following hydrology based approach, with seasonal variation of water demand to meet the various ecosystem services considered.

Based on preliminary analysis, the rate of increase in industrial water demand (~2% increase per annum) and domestic water demand (~1.2% increase per annum) is higher than the rate of increase in irrigation water demand, thus increasing contribution to the water scarcity in the country (~54% of total population). This rapid growth in industrial and domestic water demand highlights the importance of accurate projection of the future demand. Modelled results of industrial and domestic water demand closely match the observations obtained from the National Commission on Integrated Water Resources Development (NCIWRD) of India. The modelled results are shown to be superior to FAO (Food and Agriculture Organization) estimates of industrial water demand. The difference may be associated with the fact that the FAO estimates do not consider the water requirement for power production in the quantification of industrial water demand.

Keywords: *Sustainable water use, water scarcity, water demand, environmental water requirement*

Derivation and application of analytic method for reservoir mid-long term optimal operation

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Abstract: The reservoir mid-long term optimal operation is a significant measure to improve the utilization rate of hydropower resources. So far many optimization models based on the Bellman's Optimality Theory associated with reservoir operation have been developed. Most of them have aimed to practical and efficient power generation policies for hydropower generation and in order to improve hydropower benefits. Due to the discrete mathematical description of the reservoir characteristic curve, the model and the solution for the optimal power generation rules is mainly based on numerical computation method, which is low efficiency and difficult for us to recognize the responding mechanism between the optimal rules and reservoir inflow. Because of the classic 'multistage decision' models having a discrete nature, the solving methods, such as, Dynamic Programming (DP), Discrete Differential Dynamic Programming (DDDP), Progressive Optimality Algorithm (POA), etc. are highly relied on the discretization of the state variables.

To address these problems, this study proposes a new analytical optimal operation model and its analytical computation algorithm. With the mathematical derivations, the writers propose an analytical model to describe the reservoir characteristic curve, so that the dynamic behavior indexes of the hydropower station can be described by the function expression, and then the writers develop a two stages analytical model and put forward the all stages optimization model and its solve algorithm -- Analytical Progressive Optimality Algorithm (APOA) based on the thoughts of iterative progressive optimality.

The Shizitan reservoir and Muyangxi cascade reservoirs are chosen for the case studies, with the inflows of different representative years and long-time series. The results are compared with the results of a classic Progressive Optimality Algorithm(POA) model. Results show that:

- the optimal trajectories of the water storage with different inflows obtained using the proposed model and algorithm are very consistent with the optimal trajectories solved by the traditional POA.
- for the cases of single reservoir and the cascade reservoirs the computing time of the APOA only 6-10% of the traditional POA algorithm.
- The computational performance is demonstrated by the case studies of long-term hydropower scheduling, which shows that the computation time of APOA increases slowly with the increment of the dispersed precision of state variables, meanwhile the runtime of the classic POA shows a rapid increase.

The proposed models and algorithm can significantly reduce the computing time thereby mitigate the effects of the dimensionality problems. The feasibility and efficiency of the APOA are testified by the case study as well, and the insightful findings of this study suggest that APOA can be useful tool to solve the reservoir mid-long term optimal operation model.

Keywords: *Generation operation, analytic model, computation efficiency, Analytical Progressive Optimality Algorithm (APOA)*

Modelling the effect of land use change on environmental flow in East River, South China

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Abstract: Land use change directly reflects the degree of influence of human activity, which can affect the water cycle and directly lead to changes in water resources supply and demand. The East River basin, is a typical humid area in south China, which is also a key fresh water source for the Pearl River Delta (one of the most developed areas in China), and supplies 80% of fresh water for Hong Kong. Due to fast and persistent economic development and urbanization, this region has experienced rapid land use changes since the 1980's, which has resulted in altered hydrological response. The objectives of this study is to study the effect of land use change on environmental flow in East River, South China, by a hydrological model called XAJ-CN (Xinanjiang model combined with Curve Number) model. Three sub-basins, located in the middle and lower East River basin, were selected as case studies. Firstly, based on the land use and soil properties, the XAJ-CN model was calibrated and validated using 10 years of data, and then it was applied to simulate the effect of land use changes on runoff variations under six specific scenarios. Finally, the impact of urbanization on environmental flow was analyzed using the IHA (Indicators of hydrologic alteration) and HMA (Histogram matching approach) methods. Results showed that: (1) The XAJ-CN model simulates runoff within the range of acceptable accuracy, which is reflected by the goodness-of-fit measure. For model results, the efficiency of Nash and Sutcliffe for daily discharge of the three study basins are greater than 0.7, in both the calibration and validation periods. This indicates that the XAJ-CN method based on the Xinanjiang and SCS models is suitable for rainfall-runoff simulation. (2) The scenario analysis indicates that compared with the influence in the dry season, the change in CN has a greater influence on runoff during the flood season. The effect of change in CN on surface runoff is the greatest in the flood season. The change in the CN value only affects groundwater runoff in the dry season. (3) The average of monthly flows and high flow frequencies in the flood period all increase under the urbanization scenario, and the annual maximum flow of 1-day, 3-day, 7-day, 30-day and 90-day periods are larger than those in the baseline period, and the frequency and duration of high and low pulses has great alteration. These changes will affect the ecosystem of the study area to some degree. As a key fact causing the change in runoff, the land-use change should not be neglected, especially for its impact in the flood season. The role played by land-use change should be appropriately considered due to its impact on water resources and ecosystem health in the East River basin. In this study, we use the same precipitation and evaporation data for all simulations. In fact, climate change should be taken into account when assessing the impacts of LULC (Land Use and Land Cover) change in the future. However, the compound effect of climate and LULC change is complicated and beyond the scope of this paper. In the future research, a land use projection model based on cellular automata and Markov chain, and the regional future climate scenarios would be considered together to quantitatively predict streamflow in response to possible future land use and climate changes.

Keywords: *Land use, environmental flow, Xinanjiang model, curve number, East River*

Reservoirs Adaptive Operation under Changing Environment

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Abstract: Operating rules are important in the long-term operation of reservoirs for its capability of coping with inflow uncertainty. Inflow varies as a result of climate change and human activities, and using stationary operating rules would lead to inefficient reservoir operation. This study focuses on identifying changing patterns of operating rules under various inflow alteration scenarios. Various functional reservoirs, including hydropower, irrigation and flood control, are used to clarify the operating rules coevolution under changing environment.

(1) For hydropower reservoir, it is shown that the increase of inflow mean changes the operating rules, resulting in the increase of the water releases while the shift of CV has little impact on operating rules, and the seasonality changes operating rules in opposite directions during refill and drawdown periods (Figure 1).

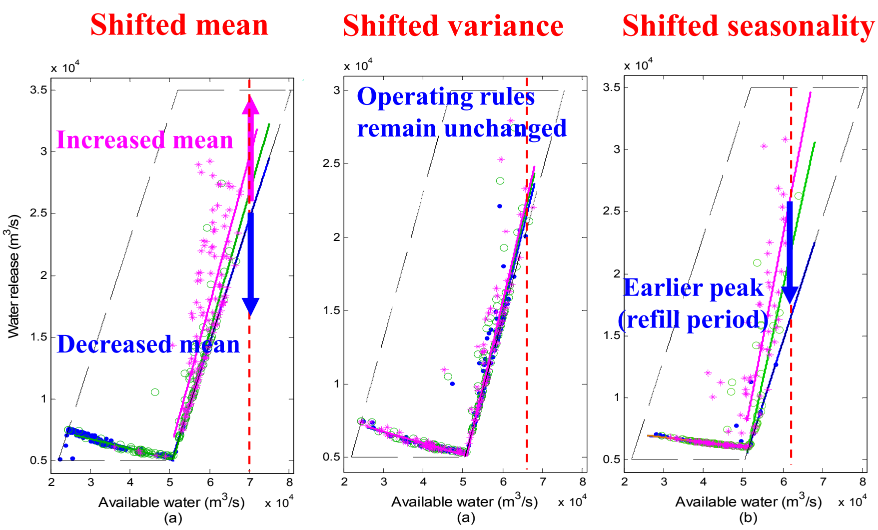

Figure 1. Changes of reservoir operating rules due to varied inflow alteration.

(2) For irrigation reservoir, it is shown that adaptive operating rules can reduce profits loss resulting from climate change, and improve field soil water storages, and the decrement of agricultural profits is less than that of precipitation, which indicates agricultural crops have the resilience to resist the adverse influence from precipitation decrease.

(3) For flood control reservoir, the flood limited water level is sensitive to the design flood, and hence, it needs to be re-established without increasing the cumulative flood risk probability when streamflow changes.

These findings are helpful for adaptive operation of reservoirs under changing environmental conditions.

Keywords: *Adaptive operation, changing environment, operating rules, inflow uncertainty*

Evaluation of flood season segmentation using seasonal exceedance probability measurement after outlier identification

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Abstract: The flood season segmentation, which partitions the entire flood season into multiple sub-seasons, is a significant task for water resources management. Various segmentation schemes of the flood season should be assessed the risks, which has seldom been addressed in the literature. For a preliminary analysis, the PCOut algorithm is firstly used to identify the possible outlying observations to decrease the uncertainty involved in flood season segmentation. A quantitative measurement, the seasonal exceedance probability (SEP), is then proposed to evaluate various segmentation schemes. The SEP measurement quantifies the risk that the maximum observations occur in a non-main flood season. A case study of the China's Three Gorges Reservoir (TGR) and the daily streamflow records from 1882 to 2010 is applied. Since that only the large flood events are of our interest in the flood season segmentation, the seasonal maximum (SM) sampling method is applied for sampling in the main flood and post-flood seasons, respectively. For all segmentation schemes, the SM observations in two sub-seasons are sampling, respectively. The results shown that:

(1) the PCOut algorithm is effective to identify outliers, and the contaminated effect on the segmentation evaluation due to outliers decreases when the end date of main flood season (EDMFS) is postponed. When the EDMFS is after September 8 in the TGR, the effect on the evaluation of flood season segmentation could be negligible. Since those extreme observations (saying outliers) may be involved uncertainty, the outlier identification method could be used to avoid misleading.

(2) the SEP measurement is capable of quantitatively evaluating the segmentation schemes of the flood season. The evaluation results verify that the current flood seasonality scheme with the EDMFS of September 10 is sufficient safety for the TGR. Furthermore, it is suggested that the EDMFS of the TGR is able to be moved from September 10 to August 24. The advance of the EDMFS can help to increase operation benefits of the TGR significantly.

In this study, the seasonal exceedance probability (SEP) has been used to quantitatively evaluate the flood season segmentation schemes under stationary conditions. However, it is still not clear that (i) the variations in the scheme of flood season segmentation under changing environmental conditions, and (ii) the physical mechanisms causing the outliers, which require further research.

Keywords: *Flood season segmentation, evaluation method, seasonal exceedance probability, PCOut algorithm, outlier identification*

Initial Analysis of Water Budget in Koshi Basin, Nepal: Assumptions and limitations

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Abstract: A growing number of studies use hydrological and cryospheric models to understand the water budget of the Himalayan basins of Nepal. These studies are important because they inform strategic basin development and investment in infrastructure; e.g. the proposed storage-based hydropower schemes for the Dudh Koshi River, currently under assessment by the Asian Development Bank. For large infrastructure schemes, understanding the development options requires hydrological models to explain how one proposed scheme may affect others, and the cumulated impacts of proposed schemes on downstream riparian water access and ecological function. These models also need to provide insights on the resilience of the system to the changing climate, and the climate's effect on water stored in glaciers.

This paper provides an initial water budget of the Koshi Basin region. It discusses the assumptions that are made, and how estimated water availability under climate change is sensitive to these assumptions. The contribution of this paper is to highlight known model limitations and provide a reasonable synthesis of available hydrological information.

The method for undertaking the analysis includes: modelling of rainfall and snow extents; developing a hydrologic model with snow and glacier components; regional calibration of snow parameters, and local calibration of hydrological parameters; and sensitivity analysis of selected parameters. We estimated daily rainfall at locations below 3000mASL using observations from 288 rainfall stations. Independent cross-validation showed average of 20% bias, which was sufficient for the regional scale analysis. However, the lack of data at higher elevations allowed erroneous trends to emerge, so we relied on global reanalysis datasets above 3000mASL (0.5 degree grid) because the outputs were constrained by the modelled physics. Despite being better, the global datasets have limitations of resolution and accuracy. MODIS snow cover products allowed the snow processes to be constrained in the hydrological modelling, but they suffered from cloud cover issues. These were partially addressed through the use of Hidden Markov Model approaches to filter noise and provide a daily time-series of snow extent.

A GR4J model with additional snow and glacier melt model (GR4JSG) was applied to six alpine catchments (Nepal et al, 2017). The model was able to reflect stream-flow (median 10% bias) and snow-extent characteristics (median 18% bias). Some parameter values did not make conceptual sense for the catchment (low degree day factors, large conceptual soil storage ~ x_1, large groundwater exchange term ~ x_2) and probably represent poor input data. For the Tibetan Plateau, many assumptions were required about the correct model structure and parameterisation given poor input climate records and no streamflow measurements on the Plateau itself.

Our initial analysis is strongly affected by assumptions of glacial change. This study estimated that snow contributes around 7% (3500 MCM) of the annual streamflow of the Koshi River as it exits Nepal at the border and ice melt contributes a further 3% (1500 MCM). The major carriers of water are the Arun (33%) and Sun Koshi Rivers (49%). Runoff is being generated predominantly at elevations between 2000mASL and 4000mASL – around the same elevation as snow fall is greatest. The greatest uncertainty remains the rainfall at high elevations and the appropriate parameterisation and conceptualisation of snow and glacier models.

Keywords: *Himalayan water budget, cryosphere, Koshi Basin*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Catchment drought response and recovery across Victoria II: Do catchments recover from prolonged drought?

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Abstract: The previous paper in this companion series showed that many Victorian catchments experience major shifts in their rainfall-runoff relationship during multiyear droughts, such as the Millennium drought. This paper focuses on catchment recovery after multiyear droughts, with the broader objective of using droughts as a natural experiment to test the widely held implicit assumption in hydrology that catchments always recover from disturbances.

Currently, almost all hydrological and groundwater models behave so that after a disturbance of any magnitude the system eventually recovers. The system is hence simulated as infinitely resilience. Recently, deterministic hydrological models have been developed that challenge this assumption and it has been theoretically shown that disturbances can displace hydrological systems into a self-reinforcing new stable regime (formally called an attractor); and hence have a finite resilience. The question of whether real catchment can have a finite resilience has however remained open.

This paper makes the first known contribution to identifying real catchment with a finite resilience. Novel Hidden Markov Models have been developed to statistically quantify when catchment runoff relationships shift during meteorological droughts and if and when they recover. The analysis is applied to all unregulated Victorian streamflow gauges, and it used to identify those catchments that are resilient to drought (i.e. slow to switch to a hydrological drought state and quick to recover) and those that have a low resilience (i.e. quick to switch to a hydrological drought state and have not yet recovered). Fig. 1 shows preliminary results for the Bureau of Metrology Hydrological Reference stations in south-eastern mainland Australia. The spatial consistency of the results is then investigated and nested catchments are used to being to understand the role of catchment size in hydrological resilience. Finally, by reflecting on hydrological resilience theory, a framework is presented for the future analysis of those catchments that will eventually recover and those that will only recover once a significant wet period occurs.

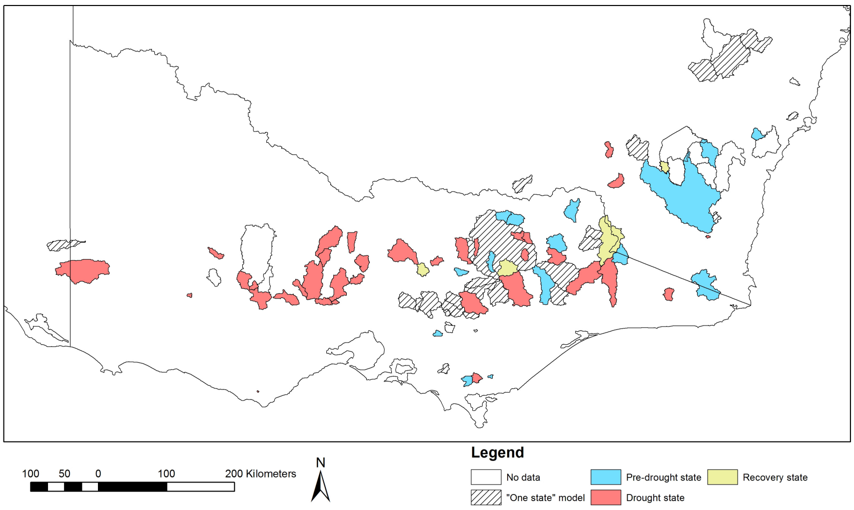

Figure 1. Hidden Markov Model estimates of the rainfall-runoff state at the end of 2015 at the Bureau of Metrology Hydrological Reference stations in south-eastern mainland Australia. At the end of 2015, 73% of the shown Victoria catchments remained within a drought state.

Keywords: *Resilience, hydrology, Hidden Markov Modelling, Victoria*

Catchment drought response and recovery across Victoria

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Abstract: Multiyear droughts, such as the Millennium drought, present colossal challenges to water managers, which can be exacerbated by the cumulative impact of the drought on runoff generation processes. These cumulative effects, primarily related to catchment biophysical characteristics, are currently problematic to account for, which in turn can lead to incorrect estimates of water availability in some areas during long dry periods. Previous research revealed a large range of catchment responses to the Millennium drought, with some catchments responding similarly to previous shorter droughts, and some catchments exhibiting shifts in hydrological functioning so that these catchments produced significantly lower runoff than during similarly dry but shorter droughts.

This study analyses Victorian catchments to detect which streams experienced shifts in their rainfall-runoff relationship signature through formal statistical testing, assuming a null hypothesis that the rainfall-runoff relationship remained stable during and after the drought. The current study extends previous research on changes in the rainfall-runoff response:

- Enhanced regional analysis: we employ a substantially larger number of catchments than earlier studies (~all gauged and unregulated streams with reasonably long records), while limiting the study spatially to Victoria. A large number of catchments concentrated in a relatively compact region allows further analysis of spatiotemporal dynamics of drought propagation and recovery;

- Explicit inclusion of potential evapotranspiration into analysis: we investigate both rainfall-runoff and aridity-runoff relationships; and

- Rainfall-runoff relationship after drought recovery analysis: we explore whether rainfall-runoff relationships return back to their pre-drought state in catchments where significant shifts occurred during the drought, and if so, how long did the recovery of the rainfall-runoff response take.

This study improves our understanding of climate-runoff response long-term dynamics. Making hydrologic predictions in areas experiencing shifts in rainfall-runoff response remains a major challenge, and better understanding is crucial for improvement. Therefore this research has implications for making water management decisions, especially for drought preparedness and infrastructure design and operation.

Keywords: *Drought, rainfall-runoff relationship, hydrologic change, long-term adaptation, catchment resilience*

How many streamflow data are needed to calibrate physically-based distributed hydrological models?

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Abstract: Physically based distributed hydrological models are widely used for hydrological simulations in various environments. As with conceptual models, they are limited in data-sparse basins by the lack of streamflow data for calibration. Short periods of observational data (less than 1 year) may be obtained from fragmentary historical records of previously existing gauging stations or from temporary gauging during field surveys, which might be of value for model calibration. However, unlike lumped conceptual models, such an approach has not been explored sufficiently for physically based distributed models. This study explored how the use of limited continuous daily streamflow data might support the application of a physically based distributed model in data-sparse basins. The influence of the length of the observation period on the calibration of the widely applied soil and water assessment tool model was evaluated in four Chinese basins with differing climatic and geophysical characteristics. The evaluations were conducted by comparing calibrations based on short periods of data with calibrations based on data from a 3-year period, which were treated as benchmark calibrations of the four basins, respectively. To ensure the differences in the model simulations solely come from differences in the calibration data, the generalized likelihood uncertainty analysis scheme was employed for the automatic calibration and uncertainty analysis. In the four basins, contrary to the common understanding of the need for observations over a period of several years, data records with lengths of less than 1 year were shown to calibrate the model effectively, i.e., performances similar to the benchmark calibrations were achieved. The models of the wet Jinjiang and Donghe basins could be effectively calibrated using a shorter data record (1 month), compared with the dry Heihe and upstream Yalongjiang basins (6 months). Even though the four basins are very different, when using 1-year or 6-month (covering a whole dry season or rainy season) data, the results show that data from wet seasons and wet years are generally more reliable than data from dry seasons and dry years, especially for the two dry basins. The results demonstrated that this idea could be a promising approach to the problem of calibration of physically based distributed hydrological models in data-sparse basins, and findings from the discussion in this study are valuable for assessing the effectiveness of short-period data for model calibration in real-world applications.

Keywords: *Physically-based distributed hydrological model, length of observations data, model calibration, data-sparse basin*

Study and Application of Improved Dynamic Programming in Optimizing Hydropower System Operation

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Abstract: Under changing environment, hydropower as clean energy cannot be ignored, so does the optimization of hydropower system operation. Hydropower operation is a typical multi-stage decision-making process, dynamic programming (DP) served as a traditional effective approach is employed to optimize the operation of reservoir. It's an effective technology method to maximize the benefit of hydropower generation. However, traversing all state combinations and "curse of dimensionality" leads to the low efficiency and hardly refines state discrete step-length of DP precisely.

When searching for the best decision, traditional dynamic programming will search all the feasible solutions without considering the relationship between the optimal decisions of different discrete state variables. Actually, the optimal of adjacent discrete state variables have a certain connection. This paper takes Qinshan-Zhouning reservoirs as an example, trying to find the relationship between the optimal solutions of different discrete state variables, which finds that

- the amount of generated energy depends on hydraulic head and discharge, so the optimal decision point does not necessarily have monotonicity, it can be searched upward or downward at random;
- at the same stage, the optimization searching process mostly turn to where the storage is more larger range from the first state variable to the last;
- there is no giant difference between the optimal decision points of two adjacent discrete state variables, and the difference is usually between one to three, mostly zero.

Based on these, an improved dynamic programming (IDP) has been proposed. It can greatly decrease the number of iteration. Case studied in Mianhuatan reservoir located in Fujian Province of China validates the IDP approach. Taking maximum of power output as the optimal criterion, the results compared with DP are more promising and show:

- no matter the optimization searching process turn upward or downward, there is no giant difference between the optimal decision points of two adjacent discrete state variables;
- under the condition that they have same discrete step-length, there is no diffidence in the optimization result, but the calculating time can be reduced at least by 97%;
- in the case where the calculating time is approximately close, the accuracy of the state discrete step-length is improved obviously.

Therefore, the IDP and it has potential as an alternative to dynamic programming approaches in optimizing hydropower system operation.

Keywords: *Hydropower generation, state combinations, step-length accuracy, improved dynamic programming*

Effect of Changes in groundwater level on the Desert Riparian Forest Ecosystem in Ejina Oasis, Northwest China

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Abstract: Groundwater is a key factor controlling the growth of vegetation in riparian systems. It is important to recognize the effects of changes to depth to groundwater in an unconfined riparian aquifer on the riparian forest ecosystem. This will not only help us to understand the ecological and hydrological process of riparian forests, but also provide a scientific basis for ecological restoration of riparian forests and water resources management of arid inland river basins. This study aims to estimate the suitability of the WAVES model to simulate the Ejina desert riparian forest, China, to assess effects of changes in groundwater depth on canopy leaf area index (LAI) and water budgets, and to discuss an appropriate groundwater depth for preserving the stability and structure of desert riparian forest. Results demonstrated that the WAVES model can preferable simulate changes to ecological and hydrological processes. The annual mean water consumption of *T. chinensis* riparian forest was less than *P. euphratica* riparian forest and the canopy LAI of the desert riparian forest will increase with decreasing the depth to groundwater. Changes to groundwater levels could significantly influence a shift in the water budgets for *T. chinensis* and *P. euphratica* riparian forests and show both positive and negative effects on vegetation growth and water budgets of riparian forests. Maintaining the annual mean groundwater depth at 1.7–2.7m below ground is critical for healthy riparian forest growth. This study highlights (i) the importance of considering the impacts of groundwater change on desert riparian vegetation and (ii) on water balance applications in carrying out ecological restoration and maintaining efficient water resource management in the Heihe River Basin.

Keywords: *Groundwater changes, desert riparian forest, Ejina Oasis, WAVES, Leaf area index (LAI), water budgets*

A comparative study of the methods for estimating streamflow at ungauged sites

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Abstract: Streamflow records are most fundamental data for water resources planning, hydropower design and management, water supply, irrigation, flood control, and maintaining ecosystem health. However, gauged streamflow data usually are not available to conduct such applications at rural or remote areas. Although many methods have been developed to estimate streamflow at ungauged sites, such as hydrological drainage area ratio method and regional flow duration curves (FDC) method, accuracy of estimated streamflow is still poor. In this study, an improved FDC method was developed and applied to an ungauged basin in the central south of China. Results show that the improved FDC have better performances than other traditional methods in the study area. Meanwhile, the proposed method in this study is more reasonable and interpretable than other methods in predicting regional streamflow at ungauged sites. By considering three more smaller percentiles, i.e. 1%, 2% and 5%, further analysis shows that derived empirical FDC has a better performance in the ungauged sites in this study. It suggests that inclusion of smaller quantiles can improve the accuracy of estimated streamflow both in high or low flow regimes.

Keywords: *Ungauged site, index gauge, flow duration curve, streamflow prediction*

Scientific Assessment on Ecological Effects of National Integrated Management Project in Heihe River Basin, NW China

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Abstract: The Heihe River is the second largest inland river in northwest China, where the national integrated management project was executed in 2001. Based on the research results and periodicity understanding on the hydrologic cycle, process of nature-society system, and eco-environmental changes of the Heihe River Basin, the scientific assessment on the ecological and environmental effects is carried out. Generally, the water resources of the river are influenced by the Westerlies, and the alp and sub-alp are the main runoff producing area. The last decade and last century are the high flow periods of the instrumental records and on the millennium scale in the Heihe River. This above normal water resources level provided a powerful guarantee for the water division and the integrated management of watershed. Nevertheless, the pressure from increasing water demand of the local socioeconomic system is the main cause of the conflict between the water use by the middle and the lower reaches of Heihe River, and between the economic development and ecological water utilization. Under the effective control of water utilization volume in the middle reaches, the water utilization structure of the socioeconomic system has changed significantly. Because of the limited water resources and the continued increasing farmland area, the grounder water level and volume reserve presents locally decreased tendency in the middle reaches, and it will face serious overloading of water resources in the future lower runoff period. The quantity of water flowed into the lower reaches closes to the request of the water division, the deteriorated tendency of ecology and water environment got restrained, but it has not recovered and has stronger spatial heterogeneity. More elaborated adjustment measures and space time administration of the limited water resources are needed, because the increasing farmland from the reclaimed riparian forestland will bring more pressure between the farmland and ecologic water utilization. In the possible lower runoff future, the water resources management of Heihe River Basin will face greater challenge under the sustainable development aim of society-economy-ecology in the whole watershed.

Keywords: *Heihe River Basin, integrated management of river basin, ecological effects, scientific assessment, problems and proposal*

Optimal design of seasonal flood limited water levels by jointing operation of the reservoir and floodplains

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Abstract: Reservoirs play an important role in the exploitation and utilization of water resources, and the flood limited water level (FLWL) is a key parameter to balance flood control and conservation in reservoir operation. Specifically, as a part of flood control system components, the function of floodplains can not be ignored. However, few cases were reported considering floodplains in reservoir operation.

This study is aimed at joint operation of the reservoir and floodplains to improve floodwater utilization and enhance economic benefits. The net profits, namely the benefits from power generation and water supply minus the losses from the flood volume diverted to floodplains, are set as the objective function. To maximize the net profits, an optimization model is then proposed. Finally, a nonlinear optimization technique, the complex method, is used to find the optimal seasonal FLWL.

The China's Danjiangkou Reservoir (DR), a multipurpose reservoir and the water source for the middle route of the South-to-North Water Diversion Project, is selected as a case study. The results show that the joint use of floodplains enables 2.0m and 0.5m increment of FLWLs in summer and autumn, respectively, compared to the conventional FLWLs. Since the increment of the FLWL decreases the reservoir flood storage by 0.44 billion m^3, the flood volume need to be diverted to floodplains is increased by 0.54 billion m^3 per year. Meanwhile, the power generation and water diversion are increased by 0.59% and 2.99%, respectively. The assurance probabilities of power generation, water diversion and minimum flow are also increased by 1.1%, 0.96% and 0.70%, respectively. As a result, the economic benefits can be increased by 0.25 billion CNY per year. It is concluded that the reservoir seasonal FLWL can be improved by joint operation of reservoirs and floodplains, which is able to enhance economic benefits without increasing flood risks.

Moreover, the increment of economic benefits could be shared by reservoir managers and residents that live in floodplains. This novel operating approach is helpful to the integrated water resources management.

Keywords: *Floodwater utilization, flood limited water level, reservoir operation*

Compensation optimal operation on compound reservoir group considering the ecological flow

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Abstract: Combining with the ecological flow, joint scheduling research on small and medium-sized rivers of compound hydropower stations is an important means of enhancing the management level of current small-medium power stations. Based on compound reservoir group of Lushui River, tributary of the Ganjiang River, in jiangxi province as the research object, the reservoir compound group comprised by two yearly reservoirs and a series of runoff reservoirs through the parallel and cascade form. The position of reservoirs and hydropower stations on Lushui basin can be seen in Figure 1.

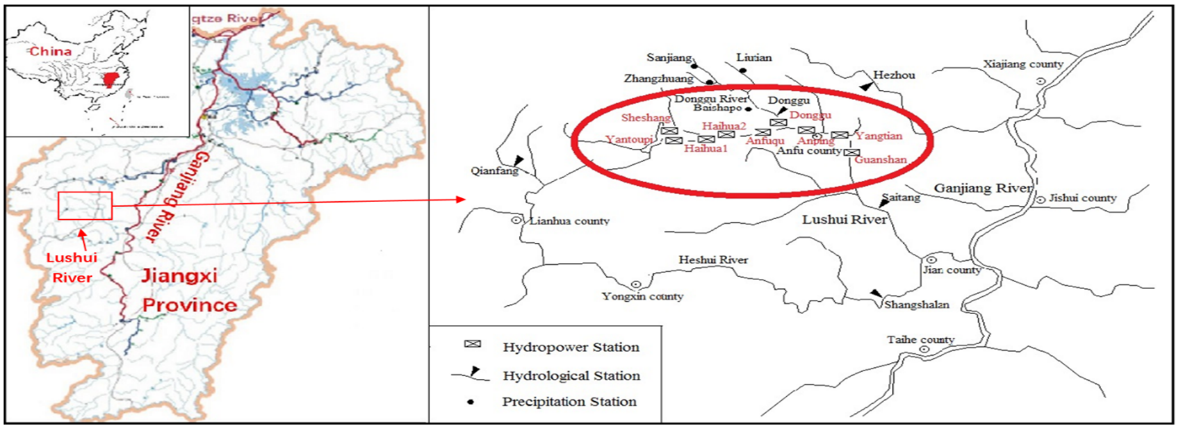

Figure 1. The position of reservoirs and hydropower stations on Lushui basin

Based on the characteristics of the reservoir group, under the premise of considering the requirement of ecological flow for each control point, conducted in three calculation modes of routine operation, single optimization of the leading reservoir with adjustment ability and compensate optimization in a ten-day period. using DP - DDDP algorithm optimization on single reservoir operation, in the multi-reservoir compensation operation, compensated power station is operated with DP-DDDP just as a single reservoir optimization first, and compensation power plant is operated later, the maximize of the cascade power generation is selected as the index function. Table 1 shows the comparison of the results of optimal operation by each single yearly reservoir and compensative optimal operation for the reservoir group.

Table 1. The results of optimal operation for each single yearly reservoir

Year	Shesh.	Yantp	Haih.1	Haih.2	Anf.	Dongg.	Anp.	Yangt.	Guansh.	total
Single	3371.0	1896.1	253.9	525.2	436.1	4341.1	104.7	762.7	907.8	12598.6
compensation	3375.0	1690.6	451.1	535.2	804.3	4355.1	608.3	641.7	862.8	13324.2
difference	4.0	-205.5	197.2	10.0	368.2	14.0	503.6	-121.0	-45.0	725.6
percent	0.1	-10.8	77.7	1.9	84.4	0.3	481.0	-15.9	-5.0	5.8

The results show that under the condition of meeting minimum ecological flow process in the control points, the hydropower generation of compensate optimization method gets 14.105 million kWh more than those of routine operation method in annual power generation, up 11.8%, and 7.256 million kWh more than those of leading reservoir optimization separately method , up 5.8%. Thus, compensation optimization method in multi-reservoir optimal operation is not complicated, easy understand, and global solution got, It can be popularization and application in small and medium-sized hydropower station group.

Keywords: *Ecological flow, compensation optimal operation, compound reservoir group, DP - DDDP, reservoir operation*

Conditional value-at-risk (CVaR) for non-stationary streamflow and its application for derivation of the adaptive reservoir flood limited water level

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Abstract: Streamflow of most river basins becomes non-stationary due to the effect of climate change and human activities, thus adaptive reservoir management in this changing environment is of significant importance. Specifically, the flood limited water level (FLWL), which is the key parameter for trade-off between flood control and water conservation, needs to be re-established to ensure flood safety when the reservoir inflow is altered. This study proposes and applies an approach that incorporates the conditional value-at-risk (CVaR) in quantifying the flood damage loss under non-stationary streamflow conditions, and then the CVaR value associated with flood risk over a specified time horizon is deduced. Finally, the optimal adaptive FLWL is derived to maximize the average annual hydropower generation without increasing flood risk probability and CVaR values under non-stationary streamflow conditions. With China's Three Gorges Reservoir (TGR) as a case study, the changing pattern of FLWL is quantified by using a linear model when statistical parameters of design floods are regressed with time under a non-stationary streamflow condition. The results indicate that (1) the CVaR value of the TGR over the time horizon from 2020 to 2039 is equal to 33.06 c billion yuan (where c represents a unit cost for flood volume needs to be diverted into the downstream floodplain) at 98% confidence level under stationary conditions. Therefore, the CVaR value not only can represent the possible flood damage loss over a time horizon in the future, but also can reflect the flood risk probability by choosing a suitable confidence level α, and (2) the adaptive reservoir FLWL needs to be optimized under non-stationary conditions, and three schemes used in the comparative analysis are presented: (i) the conventional FLWL scheme under stationary conditions (Scheme A), (ii) the optimal adaptive FLWL scheme with the flood risk probability as a constraint under non-stationary conditions (Scheme B1), and (iii) the optimal adaptive FLWL scheme with the CVaR value incorporated for non-stationary conditions (Scheme B2). It is more reliable to take account of the CVaR value as a constraint when studying the adaptive FLWL optimization problem. These findings are helpful to derive the adaptive reservoir FLWL under non-stationary streamflow.

Keywords: *Non-stationary, flood limited water level, flood risk, conditional value-at-risk*

Error correction-based forecasting of reservoir water levels: improving accuracy over multiple lead times

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Abstract: Reliable forecasts of water levels support efficient reservoir operation and management. We present a forecasting model for reservoir water levels that consists of a hydrological model to simulate inflow, a reservoir routing model to simulate water levels, and an autoregressive model for error correction.

The parameters of the hydrological model are calibrated with the objective of forecasting water levels over multiple lead times, while the back-fitting algorithm is used to recalibrate the parameters of the hydrological and autoregressive models in sequence. Finally, seven schemes are developed for comparative purposes, including the conventional integrated hydrological and reservoir routing model and various extensions:

- the conventional integrated hydrologic and reservoir routing (IHRR) model
- the IHRR with the objective function considering multiple lead times (IHRROF)
- the IHRR with the back-fitting based error correction using the most recently known errors (IHRR&BF-1)the IHRR with the objective function considering multiple lead times (IHRROF)
- the IHRR with the back-fitting based error correction using the recursively estimated errors (IHRR&BF-2)the IHRR with the objective function considering multiple lead times (IHRROF)
- the IHRR with both the objective function considering multiple lead times and the back-fitting based error correction using the most recently known errors (IHRROF&BF-1)
- the IHRR with both the objective function considering multiple lead times and the back-fitting based error correction using the recursively estimated errors (IHRROF&BF-2)
- IHRR with both the objective function considering multiple lead times and the joint inference based error correction using the most recently known errors (IHRROF&JI-1)

The results of a case study on China's Shuibuya reservoir show that: (1) the forecasting performance of effective lead times can be enhanced by using the modified objective function, i.e., minimizing the difference between the forecasted and observed water levels for multiple lead times, (2) the most recent errors are better than the one-step-ahead recursive prediction for the error-correction of multiple lead times, and (3) the back-fitting algorithm is superior to the conventional joint inference method. These results indicate that the proposed method improves the forecasting accuracy of water levels over multiple lead times.

Keywords: *Flood forecasting, lead time, objective function, Xinanjiang model*

The indicator system for assessing the cumulative risk of algal blooms in the Three Gorges Reservoir

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Abstract: The operation of the Three Gorges Reservoir (TGR) has a great impact on the appearance of algal bloom in tributaries of the Yangtze River by disturbing key factors for algal propagation. The emergence of cumulative risk problems of algal blooms has become more frequent with changes of nutrition conditions, hydrodynamic conditions and climatic conditions in tributaries of TGR. Algal blooms threaten the water safety and aquatic ecosystem of TGR. While model approaches have been put forward to predict or forecast algal blooms in tributaries of TGR, the approach on assessment of cumulative risk of algal blooms at TGR is limited for lack of consideration on the vulnerability and sensitivity of the target area. Few studies have addressed the risk level of algal blooms with integrative indicators in TGR.

In order to grade the risk level of algal bloom in the TGR, a comprehensive indicator assessment system was developed in this study. In the system, comprehensive indicators were composed of impact indicators and target indicators. Impact indicators reflect the harmful features of algal blooms. The concentration of chlorophyll-a, the spatial distribution and the duration time of an algal bloom event were the most frequently used indicators in assessing the harmfulness of algal blooms. Target indicators represent the vulnerability and sensitivity of research area, including the water function regionalization, the population density of impacted area and the proximity of bloom event to sensitive target.

To fully and accurately assess the changing process of algal, a basin scale Hydro-ecological model was introduced as a tool. The material cycle of nitrogen, phosphorus, silicon and oxygen involving 22 crucial variables in algal dynamics were considered in this model. The model permits the simulation up to three functional algal groups with the same kinetic framework but different model coefficients. To realize fine-scale river management, the research area was divided into several river reaches, coordinating with the control section of monitoring of river water quality. The water area was rasterized as uniformly spaced grid for the eco-dynamic calculation. With the analysis of investigation data and model result, the information needed for indicators can be acquired. These indicators were classified into five grades to confirm the degree of harmfulness, vulnerability and sensitivity, after that a calculation considering impact and target indicators was employed to rank the alert level of algal bloom.

The indicator assessment system was applied in the Pengxi River, one of the typical tributaries of TGR. The risk level was relatively higher of the Pengxi River up-stream than that of down-stream. The impact indicators were more sensitive than target indicators in determining the risk level. The proposed assessment methodology with integrative indicators showed a good application in the TGR, which could provide technical support for the algal bloom risk management and implementing the decision-makings on the algal bloom risk warning in the TGR.

Keywords: *Cumulative risk, indicator assessment system, hydro-ecological model, Three Gorges Reservoir (TGR)*

Short-term Optimization Operation of Hydropower Station based on Daily Load Model

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Abstract: As a kind of new renewable and clean resource, hydropower has become a hotspot of water conservancy development in recent decade. However, with the completion of large-scale hydropower stations in China, the short-time scheduling of hydropower system has been facing many fundamental scientific and technical problems, such as the unclear spatial-temporal characteristics of daily load, the curse of dimension, etc. Based on the hydropower station, the unit-to-overall (generator unit-stations-cascade reservoirs) research idea is proposed to carry out short-term hydropower optimal operation research. The dissertation comprises the following four parts:

Firstly, the concept of "Unit Commitment Model (UCM)" is proposed based on examinations of units' operating characteristics, which contributes to solve the problem of probable frequent load changing or even high-frequency commitment of the generating unit during a day, under the current scheduling approaches.

Secondly, the concept of "Daily Load Model (DLM)" is proposed based on examinations of daily load process of certain hydropower stations. Then, centered on the key problems, i.e. the structure and parameters of the DLM; the transform mechanism between the DLM and daily load process; this project will try to analyse the spatial-temporal variations of daily load, construct the DLM, and the transformation mechanism between daily load process and the DLM of a power station.

Thirdly, the practical application research of the UCM and the DLM in a single Hydropower is conducted. According to the building method of DLM and through comprehensive analysis of daily load process, the certain DLM sets is achieved. Taking total daily power generation and DLM as constraints, a short-term optimal operation model objective to minimize water consumption of the plant is established, and the algorithm based on UCM is proposed.

Fourthly, the practical application research of the UCM and the DLM in cascade hydropower station is carried out. Considering the inflow lag among cascade reservoirs, and taking the total daily water consumption and DLM as constraints, an optimal operation model aiming at maximizing total power generation of the cascade reservoir is established. Then an algorithm taking the DLM type and the peak amplitude as optimizing variables is proposed. Taking Qinshan-Zhouning cascade hydropower station as the research instance, three typical DLM set are taken to be preferred, while the relationship between electricity and DLM type, peak amplitude of the station is respectively studied, and a compare with the DDDP algorithm is conducted. Results show that the optimization benefits ranges from 2.42% to 5.42% under different DLM type combination of two reservoirs, and the relationship between electricity and peak amplitude is not a single trend, last of all, there is a little decrease of optimization benefits, while the optimized process is more in line with actual demand.

Keywords: *Cascaded hydropower plants, unit commitment model, daily load model of a hydropower, short-term optimal operation, daily optimal operation*

The development of preliminary "Irrigator" demand models for key irrigation areas in Northern Victoria

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Abstract: The availability of water to irrigators in Northern Victoria has been highly variable over the last twenty years, due to extremely variable inflows experienced during the Millennium drought, subsequent floods, the maturation of the water market and other factors. Therefore, models of water demand for irrigated agriculture need to be able to represent demand elasticity in response to water availability.

The poster presents the preliminary calibration of demand models representing parts of the Goulburn-Murray Irrigation District using the “Irrigator” module in the “Source” modelling platform. The Victorian Department of Environment Land Water and Planning (DELWP) and other agencies managing water resources in the Murray-Darling Basin are transitioning to the “Source” modelling platform for their policy and planning needs. “Irrigator” has a better capability to represent water demand elasticity compared with other demand models that have been historically used by DELWP and other agencies.

“Irrigator” represents the daily irrigation requirements of a district. Each district can be configured to have as many different planted areas (i.e. irrigated culture types, such as pasture, crops and horticulture) as desired. Each planted area is configurable to represent crop-specific characteristics (e.g. crop factor) and planting decisions (e.g. planting date, harvest date) that impact on water use. “Irrigator” maintains a daily water balance for each planted area during its growing season to calculate the daily soil water deficit by considering water losses (evapotranspiration) and gains (rainfall, irrigation water applied). The total irrigation requirement is the sum of the water requirements for all planted areas.

A standard calibration method has been developed previously. The current work focused on testing the applicability of the calibration method to two Irrigation Areas characterised by different farming enterprises: (1) the Central Goulburn Irrigation Area where dairy and deciduous horticulture are major irrigated enterprises and, (2) the Loddon Valley (Pyramid-Boort) Irrigation Area where annual cropping is a major irrigated enterprise and olive groves are the dominant form of perennial horticulture.

The calibration method involves fitting Planted Area – Available Water relationships for different culture types in the study area. Observed planted area data were obtained from the Irrigated Land Use Database — a purpose-built database that combines satellite observations of vegetation growth (as an indicator of irrigation) with data on farm enterprise type. Time series of available water data were obtained from the Victorian Water Register.

The calibration period is limited by the availability of these datasets. Despite that, the calibration period still covers a range of conditions, from years with very low water availability at the end of the Millennium drought, and years with very high water availability following the 2010/11 flooding in Northern Victoria.

Five culture types are modelled: one representing perennial horticulture, four representing pasture and annual cropping. The non-horticultural culture types are categorised by active growth period: spring active; summer active; summer-autumn active or autumn active. This temporal categorisation of irrigated culture enables the area of irrigated culture to vary throughout the year in response to changes in water availability.

The model outputs were compared with observed demand data at the farm gate. The calibrated models provide satisfactory representations of observed demands. There is still scope for improvement in calibrating the models for autumn crops and drier years by introducing additional adjustments to the standard method such as introducing dynamic planting dates for autumn crops, dynamic soil moisture depletion targets, and better fitted autumn annual water budget.

Keywords: *Irrigation demand modelling, Source modelling, water resources management*

Optimising water treatment operations with prediction modelling and smart technologies

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Abstract: Optimising the raw water intake selection is a critical task for multiple source water treatment plants, as this depends on, among others, water quality, pumping costs, and safety considerations. In case of the Mudgeeraba treatment plant in South-East Queensland (Australia), the raw water can be withdrawn by gravity from the small Little Nerang dam, or pumped from the larger Hinze dam. Intake towers with different gates also allow for the plant operators to withdraw the raw water from different depths. Often though, decision on the optimal intake location is taken based on operators' experience, without a real scientific method relying on in-depth considerations on e.g. current water quality at multiple locations and electricity costs. Nevertheless, the large amount of data collected daily at the treatment plant, and at higher frequency in the two reservoirs by remote vertical profilers, provides an opportunity to link water quality with treatment costs and provide numerical evidence for the operators to take a more informed decision.

As a consequence, a number of data-driven, chemical and mathematical models linking raw water quality with required chemicals dosages, as well as a model estimating the pumping costs, were developed. As a consequence, it was possible to predict the overall daily variable treatment costs based on raw water quality. Given that the water quality is monitored in real time in the two reservoirs for the whole water column, it was also possible to provide advice on a daily basis on which withdrawal depth and reservoir would lead to the lowest treatment cost.

By running the model with historical data, it was found that for almost any given day, withdrawing water from Little Nerang dam would have been a cheaper option due to the associated energy costs (i.e. no pumping required) being much lower than potential extra treatment costs due to poorer raw water quality; however, traditionally operators prefer to keep it as a backup reservoir in cases of, for instance, power outages and inability to use the Hinze dam pumps. Given that Little Nerang dam, despite smaller, would be able to provide enough water for few months, an increased use of this water source was still recommended, especially around wet seasons. Based on this, a medium-term storage volume prediction model was developed, able to forecast the risk of depletion and spill for Little Nerang dam for the upcoming six weeks based on, among others, proposed daily withdrawal rates and weather forecasts. In this way, plant operators would be able to plan the future withdrawals in a way to reduce the costs, but also to avoid excessive spill or depletion risks; thus effectively achieving a better planning and management of water treatment operations.

Despite the predicted benefits, it is critical to engage with the relevant stakeholders and potential end-users in order to incentivise the deployment of the end products of research projects; often, lack of proper communication and engagement can lead to the majority of the research outcomes to be largely wasted. This can be a major challenge with water planning and management research. For this research project, the engagement process started during the model development stage, by organising meetings and presentations to show the status of the model and ask for feedback and suggestions to improve it. In addition, a graphical user interface was developed, whose graphical contents (e.g. output charts) were decided based on operators' and managers' suggestions.

Finally, given that such interface was still underutilised because it was installed only on a specific computer at the treatment plant (while several operators usually spend most of their working hours conducting field work), a smartphone application with similar contents to the computer interface was also developed. This can finally lead to a regular deployment of the optimisation models, therefore transforming the research outputs in real quantifiable benefits for the water utility.

Keywords: *Decision support system, smartphone application, water treatment optimisation*

Incorporating Economic Cost Data in Water Resources Modelling

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Abstract: Victoria's water plan presents a number of challenges and opportunities relating to the planning and management of water resources. One such opportunity is to incorporate the cost impact on the community resulting from urban water restrictions. Water restrictions are a management tool commonly employed by urban water corporations to ration supplies during low water availability and therefore reduce water demands in a system. In Victoria, the implementation of restrictions is described within a Drought Preparedness Plan developed by each urban water corporation, which is system-specific depending upon local catchment climate, storage capacity and dead storage assumptions, seasonal demands and the assumed level of service over a long term planning period.

The Victorian Government has long used water resources models to inform long-term water resources planning and short-term drought response but the economic assessment of such scenarios to-date has been implemented using post-processed modelling results. The lack of integration between costs and flow means that the ability to evaluate alternative management options is tedious and does not provide a reliable and convenient approach for repeating cost-flow calculations, particularly in cases when multiple model runs are required. Moreover, as water resources models become more sophisticated and are developed over time by different modellers, the flow attributes that were once relied upon in previous economic assessments may no longer be appropriate given changes in the cost-flow assumptions.

This paper presents a case study in which an integrated hydrology-economics model has been developed in order to exploit urban customers' willingness to pay (WTP) to forego water restrictions. This work is presented as a proof-of-concept as applied to the REsource ALlocation Model (REALM) modelling package and demonstrated using a long-term planning case study in the Lance Creek Water Supply System. South Gippsland Water (SGW) currently operates the Lance Creek system to supply a number of small Victorian coastal towns using surface water resources harvested from Lance Creek. To date, the planning efforts have focused solely on this local resource but soon these efforts will need to consider additional hydrologic and economic considerations once the system is connected to the Melbourne Water Supply System. For instance, one consideration would be assessing the cost of foregoing water restrictions against the cost of supply from Melbourne.

A REALM model of the Lance Creek system was recently updated to support the preparation of SGW's Urban Water Strategy and is used for this case study. The REALM model runs over a 103-year period on a monthly time step assuming medium climate change hydro-climatic conditions projected at 2040. The unit cost values have been sourced from a review of Australian urban centres that assessed household WTP to avoid water restrictions. Five modelling scenarios are examined which consider different levels of access to the Melbourne system. The results show the marginal change in economic cost in terms of urban water restrictions, cost of water from Melbourne, and environmental cost in each case. The key finding from this work is that there is a cross-over point between the cost of restrictions and cost of water from Melbourne which will be a critical factor in future water resources planning. In general, the study shows that REALM is capable of incorporating economic cost data and providing valuable hydro-economic insights in the management of water resources.

***Keywords**:* *Cost of urban water restrictions, integrated hydrology-economics model, REALM*

Multi-Criteria Decision Analysis for Hybrid Water Supply Systems

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Abstract: Traditional urban water systems based on centralised only water supply are facing challenges to meet the increasing water demand due to increasing population in urban centres. These systems are also vulnerable to periodic drought and flooding due to climate change. For this reason, urban water managers around the world have been supporting the adoption of decentralised water supply options such as wastewater reuse, greywater reuse, rainwater harvesting and stormwater harvesting in combination with centralised system to aid with meeting water demand as well as flood mitigation and stream health restoration. In this paper, the combination of centralised water supply system (WSS) with the decentralised system is termed as hybrid water systems. These systems are relatively new and need to be evaluated using a comprehensive framework that can account for multiple aspects of hybrid water supply systems including interaction between centralised and decentralised system.

Integration of multiple objectives (such as supplying fit for purpose water, supply reliability of fit for purpose water, wastewater and stormwater discharge and contaminant loads in wastewater and stormwater) to evaluate the hybrid water supply systems can be effectively accomplished by multi-criteria decision aid techniques. Multi-criteria decision analysis (MCDA) requires users to assign the weights to considered criteria to reflect their relative importance. This paper describes weight elicitations in evaluating the various combinations of decentralised and centralised water supply systems.

Six performance measures (PMs) were identified in consultation with Victorian water utilities to evaluate the system performance. The identified PMs are: i) Reduction in potable water demand from centralised water supply system, ii) Reduction in wastewater discharges both flow rate and volume, iii) Reduction in contaminant concentration of wastewater flow, iv) Reduction in stormwater flows both intensity and volume, v) Reduction in contaminant loads from stormwater and vi) Improvement of supply reliability of fit for purpose water. Then, a questionnaire survey was conducted among three major stakeholder groups namely, water resource managers, water professionals, and consultants to derive the weights of the selected performance measures.

A simple usual preference function was deemed most suitable by the surveyors in order to assess various aspects of hybrid water supply scenarios. Also, it was found that preference measures became more complicated requiring knowledge from diverse disciplines. To overcome this challenge, the use of simple usual preference function was most suitable. Further, the survey results provided almost similar weights to each criterion, varying between 0.15 and 0.18. This indicates the similar importance of all criteria. Also, none of the criteria was deemed as unimportant demonstrating the robustness of all the selected criteria. The elicited weights and preference function of the performance measures in this paper, provide necessary data required to model and evaluate the interactions between hybrid water supply systems.

Keywords: *Hybrid water supply system, Multi-Criteria Decision Analysis (MCDA), weight elicitation, Performance measures (PMs)*

Quantification and control of seepage losses using linear anionic polyacrylamide (LA-PAM) in unlined canals in Maule, Chile

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Abstract: Seepage from earthen irrigation canals represents substantial water loss in irrigation districts. In Chile, water for irrigation and hydropower generation is mostly delivered through unlined canals, which have high seepage losses. The Chilean National Irrigation Commission (CNR, 2012) estimates losses of water during transport through canals at more than 30 percent on average. Traditional seepage-abatement technologies, including concrete, membranes, masonry and other solutions, are very expensive. Polyacrylamide (PAM) has been suggested as a means of sealing unlined water delivery canals to reduce seepage or infiltration losses (Zhu & Young, 2009). PAM is a synthetic organic polymer used globally in a number of important industries. It also has several valuable applications in irrigated agriculture, including a growing use in reducing seepage losses from unlined irrigation canals and reservoirs, and a use in field furrows to reduce infiltration while controlling erosion and sediment loss in runoff (Lentz, 2009). Different formulations vary in molecular weight, charge (cationic, anionic or neutral) and structure if the molecules are linear or branched resulting in a large number of alternatives to be used (Sojka et al., 2007). The granular form of linear anionic polyacrylamide (LA-PAM) has been identified as capable of cost-effectively reducing seepage rates from unlined water delivery canals (Susfalk et al., 2008). It is one type in a broader family of polyacrylamides that have a variety of uses, including as flocculants in wastewater treatment, in food packaging, and paper manufacturing. In contrast to traditional seepage-abatement technologies, LA-PAM is relatively inexpensive. The goals of this work were to quantify seepage losses in unlined canals and to evaluate the use of LA-PAM to reduce these losses in previously selected sections. The study was carried out in the Maule Region, central Chile, where the canal network is more than 7250 km in length and the average flow is estimated to be 680 m^3 s^{-1}. Under these conditions, seepage losses can represent a significant proportion of the total water consumed by the irrigation and hydropower generation, up to 30%. To study water losses, first, the water users indicated canal sections with potential seepage losses, whose flow varied between 1.9 and 23 m^3 s^{-1}. After that, according to flow measurements, 4 sections, extending 4.6 km in total, were selected for LA-PAM application. The sections received 2 to 4 LA-PAM applications, in total, more than 11 km canals were treated with LA-PAM at rates of 11 kg ha^{-1}, based on wet perimeter area. Because of environmental restrictions, no more than two applications per year were permitted in each section. Big canals were selected for study, allowing a motorboat moving against the current to carry out LA-PAM application, but walking application is also possible in small canals. For application, a seeder machine was used to evenly distribute granulated polymer on the water surface. Using an acoustic Doppler current profiler (StreamPro ADCP), water flow was measured at both ends of 4 selected sections to calculate losses with and without LA-PAM treatments. The sections´ lengths were 480 m; 987 m; 1240 m and 1885 m, for sections 1; 2; 3 and 4, respectively. Before LA-PAM application the average losses in percentage per kilometer were 25.8 % Km^{-1}; 6.6 % Km^{-1}; 6.4 % Km^{-1} and 3.7 % Km^{-1} for the reaches 1; 2; 3 and 4, respectively. After LA-PAM applications weekly measurements were made to quantify treatment effect and duration. In each case, water turbidity and temperature were measured. The average water temperature were 17.4 °C; 18.6°C; 17°C and 22.5°C and average water turbidity were 39.5 FNU; 51.5 FNU; 36.4 FNU and 7 FNU, for sections 1; 2; 3 and 4, respectively. After LA-PAM application the average losses in percentage per kilometer were 7.3 % Km^{-1}; 2.4 % Km^{-1}; 1.4 % Km^{-1} and 2.9 % Km^{-1} for 1; 2; 3 and 4, respectively. In all cases the LA-PAM effect was positive, achieving loss reductions of 52% to 83% in three sections and 14% to 26% in the other. The treatment duration was 41 days on average, varying between 21 and 71 days. Granular LA-PAM allow increased irrigation security in critical periods, especially under drought conditions.

Keywords: *Canal seepage, irrigation, polyacrylamide*

Hydrological modelling for conjunctive water use in the Murrumbidgee Catchment: groundwater recharge estimation

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Abstract: Many regions of the world are under the stress of water scarcity. The stress is intensifying due to population and economic growth, and further exacerbated by global climate change. There is growing awareness of the need to manage surface water and groundwater in a more holistic way, that is conjunctively, which requires better understanding of the interactions between surface water and groundwater. Groundwater recharge is a vital interaction process and quantifying its amount in situations of interest needs considerable investigation. Recharge estimation, however, is fraught with uncertainty since the recharge process is full of complexity and plagued by heterogeneity and scale issues, and so benefits from use of multiple methods to help infer its range of possible values. Available estimation techniques include approaches that are physical, chemical and mathematical or a combination of them. Chemical and physical methods usually are expensive and their feasibility is limited to point or small scales. Numerical modelling is widely considered as an effective tool because of its potential to predict recharge rates in space and time. In this paper, we investigate a purely hydrological surface modelling approach, combined with extraction of recession-flow signals from their associated hydrographs, as one way to help appreciate the amount of recharge occurring in a catchment. Two hydrological models (SIMHYD and GR4J), one with and one without direct representation of the recharge process, are used to estimate groundwater recharge in unregulated sub-catchments in the Murrumbidgee catchment for the period 1976-2011. In addition, groundwater recharge is also estimated using the empirical and non-process-based RORA approach on the basis of daily streamflow observations and predictions. The results show that when the hydrological models are well calibrated, a notion of recharge can be estimated via the RORA approach applied to the model predictions, thereby circumventing the situation where the hydrological model itself has not included representation of the recharge process. For the hydrological model SIMHYD which has the recharge process represented, the recharge output directly from the model matches to a reasonable extent that derived from simulated streamflow using RORA. The results imply that surface hydrological modelling together with recession analysis using methods like RORA can be a useful adjunct to other methods to infer notional groundwater recharge to support decision-making on conjunctive water use.

Keywords: *Groundwater recharge, hydrological modelling, RORA approach, conjunctive water use, Murrumbidgee catchment*

Calibrating extreme precipitation forecasts from NWP models with ensemble spatial characterisation

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Abstract: Early flood warning systems provide forecasts that are useful for preparing and managing hazard events. Forecasts generated from hydrological modelling depend on the quality of inputs and models used. Studies suggest that precipitation forecast uncertainty is often of prime importance. Such uncertainty can be characterised by using ensemble precipitation forecasts as inputs to hydrological models. The post-processing of quantitative precipitation forecasts (QPFs) from NWP models can generate such ensemble precipitation forecasts. The post-processing of QPFs is usually done in two steps. Firstly a calibration is done separately for each location and lead time. Secondly, spatial and temporal structures are instilled by appropriately connecting forecast ensemble members. Spatially coherent precipitation field ensembles are essential for determining peak and timing of streamflow.

In this study, representation of precipitation forecast uncertainty is achieved by generating spatially correlated precipitation ensembles. Forecasts from NWP models are calibrated to observed data using a regression model, which corrects systematic bias and quantifies uncertainty in the forecasts. Residuals from this fitted relationship are characterised by a spatial covariance model. The fitted regression and spatial covariance models are applied to new forecast events to generate spatially coherent ensembles. This model is referred to as Model 1. The proposed method is evaluated against two calibration and ensemble generation methods based on (i) Model 2: using a bivariate distribution calibrated with selected large events and structured with Schaake shuffle, and (ii) Model 3: using a mixed-type bivariate distribution calibrated using all events and structured with Schaake shuffle.

To demonstrate the models, large precipitation forecasts based on the PME (Bureau of Meteorology's Poor Man's Ensemble) mean for three locations (Brisbane, Sydney and Melbourne) during the period of 2010-2016 are investigated. The spatial extent of 9 PME grids (0.5° x 0.5°) at each location with forecasts up to lead time of 4 days are calibrated and evaluated with observed data from AWAP dataset. A cross-validation approach is applied to evaluate the ensemble forecasts by using the Continuous Ranked Probability Score (CRPS) and corresponding skill score. The skill of generated ensembles indicates similar performance for all three models, when individual grids are considered. Taking account of spatial relationship of forecast, the evaluation is done over the entire location. The skill of forecasts from Model 1 is marginally better compared to the other two models when evaluated over the entire location. Despite similar performance at individual grids, performance over the location is better suggesting spatially coherent forecasts. Given the smaller difference in skill between the forecasts generated by three models, further evaluation with more study area is desired to draw a general conclusion regarding performance of the models.

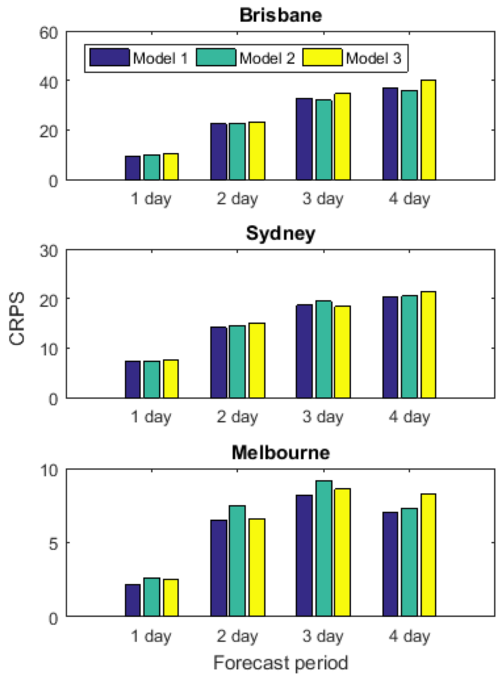

Figure 1. Comparison of CRPS for three post-processing models at three locations.

Keywords: *Post-processing, Schaake Shuffle, ensemble spatial characterization, ensemble precipitation forecasts*

Reliability game: illustrating a key principle of ensemble prediction

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Abstract: Ensemble prediction systems offer precise estimates of the uncertainty in forecasts. These estimates may not be accurate: for example, ensemble predictions may not cover the full range of possible outcomes (i.e., predictions are overconfident). When an ensemble prediction system is able to correctly estimate prediction uncertainty, it is deemed to be 'reliable'. Reliability is a key concern of ensemble forecasters (Raftery 2016), but it remains an opaque concept to many forecast users, even those with expertise in related fields such as hydrology or meteorology. Further, reliable ensemble predictions are often assumed to lead to better decisions by users of forecasts, but this is not always evident in practice.

In this presentation we will play a decision-making game (the 'reliability game') with the audience based on ensemble streamflow predictions. The game has two major aims:

1) To familiarise the audience with the concept of reliability

2) To illustrate the role ensemble reliability plays in sound decision-making

The reliability game asks members of the audience to imagine themselves in the role of a farmer and to move livestock on the basis of probabilistic predictions, to maximize their yield (and profit). The game requires audience members to make a series of decisions on the basis of reliable and unreliable ensemble streamflow predictions.

Results will be collated during the session to show whether reliable predictions do, in this case, result in more rational decisions.

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Keywords: *Ensemble forecasting, reliability, uncertainty, decision-making, probabilistic prediction, hydrological prediction, ensemble calibration*

A national short-term flow forecasting system using high resolution weather forecasts

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Abstract: In the last decades, flooding and other related natural disasters have led to an increased interest in hydrologic forecasting systems. Operational flood forecasting can mitigate the losses of human life and infrastructure by providing accurate and timely warning of major flooding events. These systems are delivered by coupling numerical weather prediction models with hydrological models, and are highly dependent on the quality of weather forecasts.

This work will present key aspects and challenges of the development of a national short-term flow forecasting system for every reach of main New Zealand rivers. The country's vast river network is forecast by coupling the hydrological model TopNet with a high resolution convective-permitting weather model, the New Zealand Convective Scale Model (NZCSM). The distributed hydrological model TopNet is based on TOPMODEL concepts of runoff generation controlled by sub-surface water storage. Within each subcatchment, a water balance model is solved with an implementation of a kinematic wave channel routing algorithm. The numerical weather prediction model is a local implementation of the UK Met Office Unified Model System (UM) for New Zealand, with a grid resolution of 1.5km.

Although high resolution weather models simulate precipitation more realistically than large scale models, they can exhibit bias with a tendency for persistent over estimation of light drizzle and under-estimation, particularly during flood events in high elevation regions. To generate accurate river flow forecasts, the bias needs to be corrected. Furthermore, it is necessary to derive ensemble precipitation forecasts from the deterministic forecasts to quantify precipitation uncertainty, usually a dominant source of uncertainty for flood forecasting at shorter lead times. We investigate a rainfall post-processing and ensemble generation method based on a Bayesian joint probability model, Schaake shuffle and lagged ensemble forecasts for application to the national flow forecasting system.

To post-process precipitation forecasts and generate ensembles available at national scales we need to rely on an observed gridded product (Virtual Climate Station Network) assumed to be the "truth". The VCSN interpolates observed meteorological values onto a grid covering New Zealand at a 5km spatial resolution and daily timescale—larger than the 1.5km and hourly weather model resolution—bringing atypical challenges that include hourly disaggregation of forecasts calibrated at daily lead times, and the choice of historical template data used for the Schaake shuffle method to reconstruct a high-resolution space-time covariability distribution in the forecast.

Keywords: *Ensemble flow forecasts, floods, rainfall, national model, post-processing*

EXTENDED ABSTRACT ONLY

Use of artificial neural networks in short-term streamflow forecasting for the Snowy Mountains Scheme

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Abstract: The Snowy Mountains Scheme is a hydroelectricity and irrigation complex situated in the Snowy Mountains in South Eastern Australia. It comprises sixteen major dams and a network of tunnels and power stations which permit Snowy Hydro (the Scheme operator) to capture and store water from runoff, to generate hydroelectricity to meet national market demands, and to divert streamflow into the Murray Darling Basin for downstream irrigation. These activities must be performed according to a complex set of physical, environmental and legislative constraints and their execution defines the operational efficiency of the Scheme.

Accurate and timely inflow forecasts with sub-daily temporal resolution are essential to optimizing the day-to-day operations of the Scheme, but the nature of alpine catchments presents challenges to simple rainfall-runoff models. The spatial variability of rainfall is typically much higher in complex terrain, which increases the variability of the runoff response. In addition, snowpack can partially or completely cover a number of the sub-catchments of greatest interest for several months over winter. This modulates the runoff response in a non-linear manner, with low-density ("fresh") snowpack capable of absorbing considerable rainfall, while melting of higher density ("ripe") snowpack can considerably amplify the runoff response or even drive runoff in the absence of precipitation.

An in-house streamflow forecasting model has been developed to aid inflow predictions for a number of critical reservoirs in the Snowy Mountains Scheme. The model is based on an artificial neural network (ANN) that is trained using historical streamflow and meteorological data (in particular rainfall, temperature, wind speed, and snowpack conditions). The ANN is capable of predicting short-term (i.e. 2-6 hour) changes to streamflow with a high degree of accuracy. Longer-term predictions may be made through recursion of the ANN by feeding the short-term streamflow prediction back as an input, while using numerical weather prediction (NWP) model data for future values of the meteorological inputs. In order to represent potential uncertainty in the streamflow forecasts, an ensemble of ANNs is typically used, with each one trained on a slightly different subset of the available historical data. Small perturbations are also applied to the input precipitation data to simulate uncertainties in the meteorological inputs.

The objective of this paper is to present a formal evaluation of the streamflow model and to determine the relative contributions of ANN internal variability and NWP prediction errors to overall prediction uncertainty. A cross-validation over five years using observed (as opposed to NWP-derived) meteorological values will be performed using a number of slightly different ANN configurations to evaluate the sensitivity to model inputs. A shorter period of re-forecasts using NWP-derived inputs will be compared to these results to evaluate the decline in forecast skill with lead time up to four days. Metrics considered for the evaluation include: mean error and bias of total and peak daily streamflow; accuracy of probabilistic streamflow forecasts (i.e. observed streamflow is within predicted range) and event-based metrics for high-inflow events.

Keywords: *Streamflow forecasting, artificial neural networks, ensemble forecasting*

A coupled hydrological-hydraulic flash flood forecasting system for Kuala Lumpur's Stormwater Management and Road Tunnel (SMART)

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Abstract: Kuala Lumpur's Storm Management and Road Tunnel (SMART) is the longest multi-purpose tunnel in the world. The tunnel serves two purposes: to relieve key locations in the city from frequent flash flooding, and to serve as a section of highway through the city to relieve traffic congestion. During flood operation, a series of gates, pumps, and storage reservoirs operate to divert river discharge into the tunnel, bypassing the city centre.

A critical component of tunnel operation is effective forecasting of flash flooding events in the city and its upstream catchment. The region is prone to flash flooding, so there is usually very little warning of events that require tunnel operation. The flood detection system is a loosely coupled hydrological/hydraulic model of the catchment, river channels, and tunnel. It acquires real-time information from a SCADA (Supervisory Control and Data Acquisition) system, which in turn retrieves data from instrumentation in the field. This includes catchment rainfall (from a dense raingauge network), streamflow (using rated stage-discharge recorders and Doppler current meters), gate position, pump operation and equipment failure.

The hydrological model is a semi-distributed conceptual rainfall-runoff model, which simulates catchment soil moisture states (storages) over time. The model is executed in two modes: (1) warmup mode: which initializes the model state variables up to the current time using the latest observed data and (2) forecast mode: which generates forecasts of streamflow at key points in the river network 2 hours into the future. The inflow hydrographs generated by the hydrological model are fed into the one-dimensional hydraulic model, which represents the river channels, storage reservoirs, gates and pumps, and tunnel decks. A series of operating rules for the tunnel infrastructure are programmed into the model, to allow it to adequately forecast flood levels when the tunnel is operated accordingly. The hydraulic model's major outputs are forecasts of river height at key locations of the catchments.

The coupled model is designed to run every 5 minutes. The forecast system assumes that there is persistence in the rainfall over a short interval of time and uses a simple algorithm to project rainfall observed in the last interval 30 minutes into the future. In the current form the forecast system does not use Numerical Weather Prediction (NWP) model rainfall forecasts since as these forecasts are not available at the fine temporal resolution or frequency required. Furthermore, at very short lead times - less than 2 hours - the skill of streamflow forecasts are predominantly influenced by the persistence (or memory) of the catchment (simulated by model state variables).

Keywords: *Flash flooding, flood-forecasting, rainfall-runoff modelling, hydraulic modelling, urban flooding*

State Updating and Calibration Period Selection to Improve Dynamic Monthly Streamflow Forecasts for a Wetland Management Application

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Abstract: Sub-seasonal streamflow forecasts provide useful information for a range of water resource management and planning applications. This work has focused on improving forecasts for one such application: the management of water available in an open channel drainage network to maximise environmental and social outcomes in a region in southern Australia. Conceptual rainfall-runoff models with a postprocessor error model for uncertainty analysis were applied to provide forecasts of monthly streamflow. Two aspects were considered to improve the accuracy of the forecasts: 1) state updating to force the models to match observations from the start of the forecast period, and 2) selection of a calibration period representative of the forecast period.

Two catchments within the study area were considered, referred to as C1 and C2 in Figure 1. Five metrics were used to assess forecast performance, representing the reliability, precision, bias and skill of the forecasts produced, using both observed and forecast climate data. The results indicate that assimilating observed streamflow data into the model, by updating the storage level at the start of a forecast period, improved the performance of the forecasts across the metrics when compared to an approach that "warmed up" the storage levels using historical climate data (representative time series seen in Figure 1). The shorter calibration period also improved the performance of the forecasts, particularly for a catchment that was expected to have experienced a change in the rainfall-runoff relationship in the past. The results highlight the importance of identifying a calibration record representative of the expected forecast conditions, and if this step is ignored degradation of predictive performance can result.

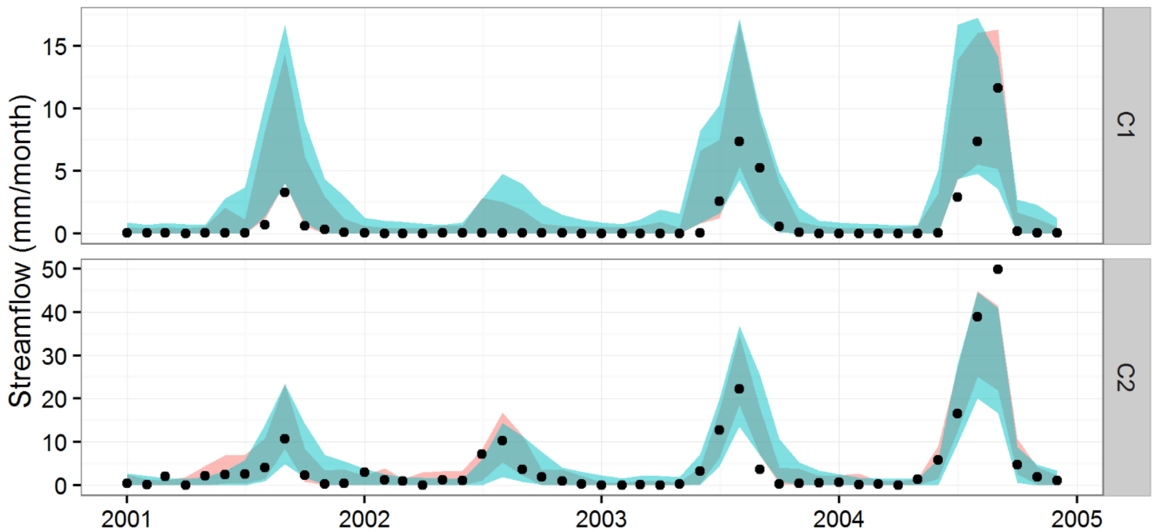

Figure 1. Time series of the 90th percentile prediction limits of monthly streamflow forecast one month in advance. Observed streamflow is presented as black dots. Using a state updating approach (red) to modify the routing state variable to force the model to simulate the observed stream at the start of the forecast can be seen to increase forecast precision compared to not using this state updating approach (green).

Keywords: *Uncertainty estimation, state updating, conceptual rainfall runoff modelling, streamflow forecasting, hydrology, South Australia*

Performance evaluation of the national 7-day water forecast service

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Abstract: The Bureau of Meteorology launched a deterministic 7-day streamflow forecast service to the public in September, 2015. These streamflow forecasts indicate likely river flow conditions in the coming week. The service has been developed mainly to assist river managers in making informed decisions about water resources management to ensure the best use is made, both from agricultural and environmental perspectives. The service currently provides daily updates of daily volume forecasts to the public for 132 locations across Australia (Figure 1). This paper investigates the performance of the operational 7-day streamflow forecasts at targeted 53 locations across Australia.

Evaluating operational forecast performance is essential to identify forecast discrepancies in order to improve the service. Performance metrics for rainfall and streamflow were investigated. Operational streamflow forecasts for more than 90% of the selected 53 locations exceed a set criterion of positive mean absolute error skill score up to 3-days lead-time. Unreliable or poor quality input data was the main cause of suboptimal performance for the remaining 10% of locations. Forecast performance for perennial streams is found to outperform those in ephemeral streams. The inability of hydrological model structure to cope with complex and highly non-linear hydrological processes in dry areas is seem to be the cause for suboptimal streamflow forecasts. Forecast performance at locations with large catchment areas show better skills than other locations having small catchment areas.

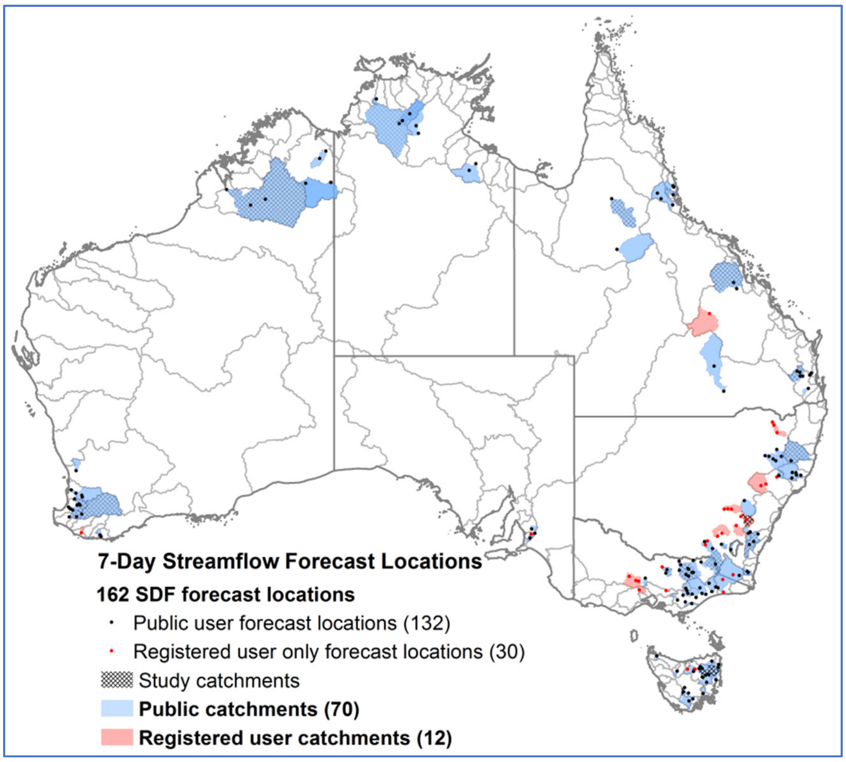

Figure 1. Study locations and catchments

Keywords: *Water, forecasting, streamflow, 7-day, modeling, hydrology, Bureau of Meteorology*

EXTENDED ABSTRACT ONLY

Forecasts and simulations of river water quantity and quality caused by Tropical Cyclone Debbie over Fitzroy River Basin

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Abstract: The Catchment Forecasting for the Great Barrier Reef project being led by the Bureau of Meteorology in partnership with Queensland Government agencies and CSIRO has developed models to forecast water quantity and water quality constituents at catchments which impact the Great Barrier Reef (GBR). Daily and hourly time-step outputs from these catchment models will support the Regional Ocean Forecasting System (ROMS) developed by the Bureau of Meteorology and the Sparse Hydrodynamic Ocean Code (SHOC) and Bio-Geochemical model (BGC) developed by the CSIRO.

An hourly time-step semi-distributed rainfall-runoff model with 147 sub-areas was developed for the Fitzroy River basin. The GR4H conceptual hydrological model, Muskingum channel routing model, and an error-correction process were applied to model streamflow at 25 gauged locations within the basin. Multivariate regression models were developed for 7 water quality constituent concentrations using covariates derived from historical streamflow.

On 28th March 2017 the category 4 Severe Tropical Cyclone Debbie made landfall and caused significant damage and flooding in the populous areas of southeast Queensland. Heavy rainfall was recorded in the tributaries of the Isaac-Connors Rivers in the north-east and the Don River in the east, resulting in major flooding in the lower reaches of the Fitzroy basin. The model was applied and evaluated at gauged locations in the basin for 20 days covering the event. The intent of this study was to (i) simulate the effects of cyclone Debbie on streamflow and water quality loads to GBR lagoon, and (ii) evaluate the model's capability for near real time operational forecasting during an extreme event.

For each day of the event, the model was initialised and then forced with rainfall forecasts produced by the regional version of the Australian Community Climate and Earth-System Simulator (ACCESS-R) to predict streamflow, concentrations, and loads for next 72 hours. In addition to these forecasts, simulations were generated using rainfall recorded by 151 rainfall gauges located within the catchment.

The peak instantaneous streamflow at three specific forecast lead-times were compared against measured streamflow; these lead-times were the 24th hour, 48th hour and 72nd hour. At the model's most downstream gauged location, The Gap, these forecasts were within 10% of the observed flow for all three lead-times, the peak timing within 8 hours, and the accumulated daily forecast volumes were within 5%. Similar streamflow forecast performance was obtained for other locations in the Fitzroy river basin. Forecasts of concentration and load were generated at three locations and demonstrated good performance for most constituents in this analysis. The simulated total event loads at Rockhampton were approximately 1,500 kilotonnes of sediment, 7 kilotonnes of Nitrogen, and 2.5 kilotonnes of Phosphorus.

Results from this evaluation were favourable and suggest that the method has skill at forecasting near real-time streamflow and water quality concentration and load. As part of the eReefs project, models were developed for a set of catchments which impact the GBR and we believe that operational products derived from these models will benefit local communities, policy makers, reef managers, and the research community.

Keywords: *Water quantity forecast, water quality constituents forecast, Tropical Cyclone Debbie, Fitzroy River Basin, semi-distributed model, GR4H*

Use of seasonal streamflow forecasts to support water management in a regulated river catchment: case study of the Lachlan valley

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Abstract: This paper describes a collaborative effort to incorporate seasonal streamflow forecasts issued by the Australian Bureau of Meteorology (Bureau) in water allocation statements of the Lachlan Regulated River issued every month by the Department of Primary Industries (DPI) of the state Government of New South Wales, Australia. These statements inform stakeholders of potential changes in the allocation of water resources (water allocations) across the valley and are available online (http://www.water.nsw.gov.au/water-management/water-availability/water-allocation-statements). Forecasts of water availability during the following three months from the publication date are included on a three-month basis.

Inflow forecasts for the main dam in the Lachlan valley, Wyangala dam, are supported through the Bureau's seasonal streamflow forecasting service (http://www.bom.gov.au/water/ssf/). These streamflow forecasts are used as input into a water management model run by DPI that assesses future resource availability subject to specific inflow scenarios. Typically, this water management model is run with historical inflow scenarios (i.e. historical observed inflows), providing a wide range of the likely water resource availability during the 3-month forecast period. The Bureau's three-month inflow forecast reduces this range given the antecedent catchment conditions upstream of Wyangala Dam, climate indicators and rainfall forecasts. Consequently, the range of likely storage levels in Wyangala Dam for the forecast period is reduced. The Bureau and DPI are also looking towards incorporating three-monthly forecasts of usable tributary inflows into the Lachlan River System.

Figure 1 is an experimental graphic product indicating the range of likely storage levels of the Wyangala Dam (i.e. resource availability) from June to August 2017. The figure was included in the water allocation statement issued by DPI in June 2017. The range of storage levels from historical scenarios is shown as well as the reduced range resulting from the three-month forecast of inflows into Wyangala Dam. This graphical product provides a more targeted range of likely water availability in the forthcoming three months to assist with decision making for all water users in the valley. However, it does not affect DPI's water allocation process, which is conservatively based upon minimum historical inflows.

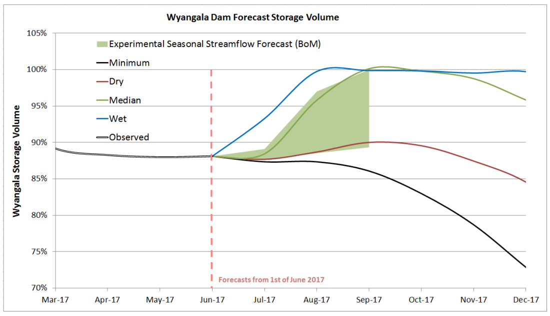

Figure 1. Observed and likely storage volumes for Wyangala Dam from March 2017 to December 2017

This work was undertaken as part of the upgrade of the Bureau's seasonal streamflow forecasting service along with other updates described in a companion paper by Shin et al, which includes new graphic products, providing individual monthly forecasts in addition to the existing seasonal forecasts, and introduction of rainfall outlooks from the Bureau's new climate outlook model (ACCESS-S).

Keywords: *Water allocation, reservoir volume, seasonal streamflow forecasts, Lachlan valley*

Subseasonal prediction of rainfall anomalies and extremes over Australia

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Abstract: The last decade has seen rapidly increasing interest in the subseasonal prediction of weather and climate anomalies and extremes over Australia. Here we describe key drivers of Australian climate on the subseasonal timescale, their role in the prediction of rainfall anomalies and extreme rainfall events, and application of this knowledge in developing real-time forecast products at the Bureau of Meteorology using the subseasonal-to-seasonal climate forecast model POAMA (Predictive Ocean Atmosphere Model for Australia) version 2. Extreme rainfall events are defined using the highest 10% (top decile) of weekly-mean rainfall anomalies for the period 1981-2010. We present our recent assessment of the Southern Annular Mode (SAM), the Madden-Julian Oscillation (MJO), and atmospheric blocking in the Australian region, with work underway to extend our analysis to the new ACCESS-S seasonal prediction system and to include key climate drivers on the seasonal timescale, namely the El Niño / Southern Oscillation and Indian Ocean Dipole.

As the leading mode of variability in the Southern Hemisphere extratropics, the SAM is characterised by north-south shifts in the strength of the zonal flow between about 55º-60ºS and 35º-40ºS, and is represented by an index that uses an empirical orthogonal function (EOF) analysis of zonal-mean mean sea level pressure between 25°S and 75°S. In its positive (high polarity index) phase, the SAM is associated with a poleward contraction of the midlatitude storm track and thus easterly wind anomalies across much of southern and central Australia which bring increased moisture from the Tasman Sea. This leads to increased rainfall and enhanced likelihood of an extreme rain event over much of the continent, particularly in spring and summer.

The MJO is the dominant mode of tropical subseasonal variability and consists of large-scale coupled patterns in atmospheric circulation and deep convection that propagate eastward over the equatorial Indian and western Pacific oceans with a period of 30-90 days. The state of the MJO is depicted using eight phases of its lifecycle as defined by the Wheeler-Hendon bivariate Real-time Multivariate MJO index, which is based on a combined EOF analysis of tropical outgoing longwave radiation and zonal wind anomalies. The influence of the MJO on Australian climate varies according to its phase and the time of year, with the greatest impact occurring in summer during MJO phases 5 and 6 when the increased likelihood of anomalous and extreme rainfall over northern Australia is explained by the direct influence of the MJO's tropical convective anomalies.

Atmospheric blocking is an important driver for Australia's agricultural districts and water catchments. During blocking episodes, large quasi-stationary high pressure systems form to the south and southeast of the continent with a splitting of the upper level westerly airstream into two distinct branches. Extended dry spells occur in the vicinity of the blocked flow, particularly in south-western Tasmania, while a relatively small cyclonic component forms on the equatorward side of the high which breaks away to create a cutoff low pressure system. This cutoff low acts to increase rainfall anomalies and extreme rainfall events over southern mainland Australia, including over the southeast during the April-October agricultural growing season.

POAMA reproduces the observed rainfall signals over Australia reasonably well in association with each climate driver, with the extreme rainfall responses to each driver broadly resembling the anomaly responses. Prediction of rainfall anomalies in weeks 2-3 of the forecast is improved over much of the tropical Indo-Pacific and eastern Australia when the MJO is strong in the initial conditions, compared to when the MJO is weak in the initial conditions, and over much of the Australian continent when there is a strong SAM or blocking event. POAMA also shows promise in its ability to predict rainfall extremes, with the positive SAM phase, the MJO and blocking all providing prediction skill for extreme rainfall depending on the region or time of year. POAMA is thus capable of providing useful forecast skill for rainfall anomalies and extremes on the subseasonal timescale for the benefit of Australian industry, such as farming communities whose management practices often rely upon decisions being made a few weeks in advance.

Keywords: *Subseasonal prediction, rainfall extremes, climate drivers, forecast skill, POAMA*

Improving probabilistic prediction of daily streamflow by identifying Pareto optimal approaches for modelling heteroscedastic residual errors

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Abstract: This research provides guidance to hydrological researchers to enable them to produce probabilistic predictions of daily streamflow with the best reliability and precision for different catchment types (e.g. high/low degree of ephemerality). Reliable and precise probabilistic prediction of daily catchment-scale streamflow requires statistical characterization of residual errors of hydrological models. It is commonly known that hydrological model residual errors are heteroscedastic, i.e. there is a pattern of larger errors in higher streamflow predictions. Although multiple approaches exist for representing this heteroscedasticity, few if any studies have undertaken a comprehensive evaluation and comparison of these approaches. This research fills this gap by evaluating 8 common residual error schemes, including standard and weighted least squares (WLS), the Box-Cox transformation (with fixed and calibrated power parameter, λ), and the log-sinh transformation. Case studies include 17 perennial and 6 ephemeral catchments in Australia and USA, and two lumped hydrological models.

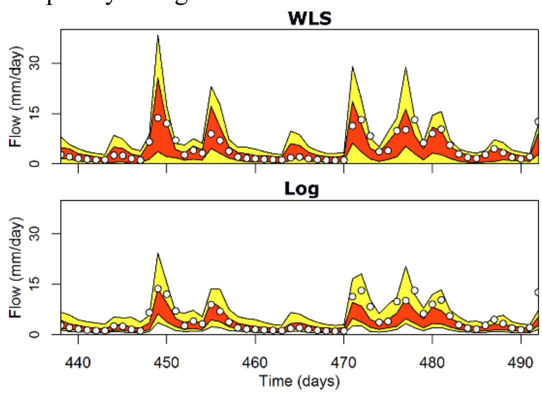

Figure 1. Probabilistic streamflow predictions in the Spring River catchment, USA, based on the GR4J model, when the WLS and Log residual error schemes are used.

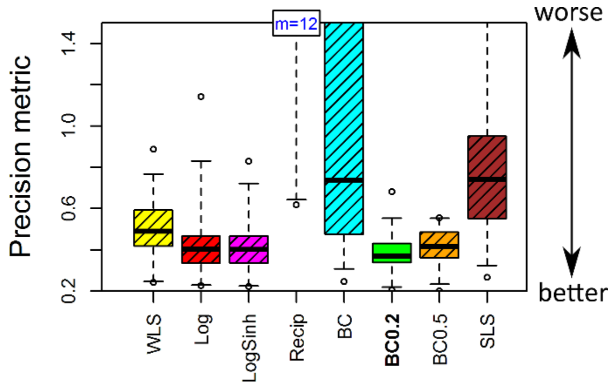

Figure 2. Distribution of precision metric for different residual error schemes in 17 perennial catchments, for both GR4J and HBV.

We find the choice of heteroscedastic error modelling approach significantly impacts on probabilistic predictions (**Figure 1**). However, no single scheme simultaneously optimizes all performance metrics. The set of Pareto optimal schemes, reflecting performance trade-offs, comprises Box-Cox schemes with λ of 0.2 (BC0.2) and 0.5 (BC0.5), and 0 (Log, perennial catchments only). These schemes significantly outperform even the average-performing remaining schemes; e.g., across perennial catchments, median precision tightens from 75% to 40% of observed streamflow (**Figure 2**). Theoretical interpretations of empirical results highlight the importance of capturing the skew/kurtosis of raw residuals and reproducing zero flows. Recommendations for researchers and practitioners seeking robust residual error schemes for practical work are provided.

Keywords: *Residual error model, predictive uncertainty, Pareto optimal, rainfall-runoff model*

EXTENDED ABSTRACT ONLY

Forecasting in changing catchments using Data Assimilation: New insights on systematic model errors

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Abstract: Hydrologic modelling methodologies capable of handling non-stationarity are becoming ever more important, particularly given the global prevalence of rapid and extensive land use change. This is particularly true in the context of Hydrologic Forecasting using Data Assimilation. Data Assimilation (DA) has been shown to dramatically improve forecast skill in hydrologic and meteorological applications, although such improvements are conditional on using bias-free observations and model simulations. A hydrologic model calibrated to a particular set of land cover conditions has the potential to produce biased simulations when the catchment is disturbed. This means that systematic error correction methods should be incorporated along with state-estimation DA in order to avoid degradation in forecast quality. We provide new insights on this issue, namely the impacts of systematic errors or biases in hydrologic data assimilation in the context of forecasting in catchments with changing land surface conditions. It is shown that when doing state-estimation DA in such cases, the impact of systematic model errors on assimilation or forecast quality is dependent on the inherent prediction uncertainty that persists even in pre-change conditions (see Figure 1). We develop a conceptual relationship between total prediction uncertainty and the nature of the impacts of land cover change on the hydrologic regime through a range of experiments. Streamflow forecasting with perfect meteorological inputs is undertaken using state estimation DA for a range of deforested catchments in Australia and Vietnam. Results demonstrate that systematic model errors as a result of changing catchment conditions do not always necessitate adjustments to the modelling or assimilation methodology, for instance through re-calibration of the hydrologic model, time varying model parameters or revised offline/online bias estimation. This occurs whenever the model biases are within the range of the pre-change prediction uncertainty, allowing the latent states to be adjusted during assimilation to reflect changed conditions.

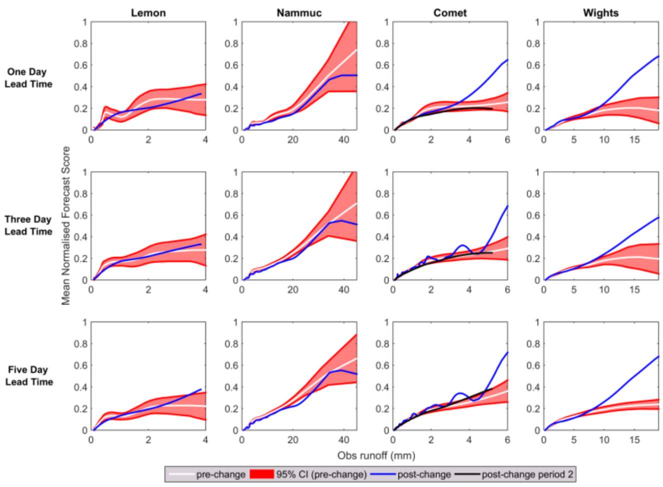

Figure 1. Variation in forecast performance between pre and post-change periods with observed runoff for the 4 study catchments. Results are shown for 1 day ahead (top row), 3 day ahead (middle row) and 5 day ahead (bottom row). The white line indicates the lowess fit to data points from the pre-change period and the shaded red area indicates the 95% Confidence intervals of the lowess fit. The blue line indicates the analogous lowess fit for the post-change conditions (note for Comet, the blue line corresponds to the first post-change period and the black line to the second post-change period). Lower values of the mean normalized score indicate better forecast performance.

Keywords: *Data assimilation, streamflow forecasting, model error, land use change*

Quantification of hydrological uncertainty in short lead time forecast of levels in frequently spilling reservoirs

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Abstract: Lake Gairdner is a frequently spilling hydropower diversion reservoir in Northern Tasmania. Comparison of forecast lake levels generated using a coupled inflow-storage model with observed lake levels suggest significant changes in the relationship between observed and forecast lake levels as the lake approaches and exceeds Full Supply Level (FSL). A wider spread (greater variance) in the relationship (between forecast and observed levels) is observed at lower lake levels and sharp converging scatter is observed above FSL. Importantly, further examination of the scatter reveals that observed and forecast levels are characterised by bimodal distributions.

A common approach to quantify uncertainty in hydrological forecasts is to model the relationship in a transformed bivariate Gaussian space. However, the peculiar shape of the scatter due the presence of FSL in Lake Gairdner rendered application of bivariate Gaussian unfeasible. This study proposed a post-processor designed to handle the change in dependence structure (relationship) and account for the 'converging scatter' at the upper tail. The post-processor served two purposes (1) quantify the hydrologic uncertainty and (2) improve the accuracy of short term lake level forecast in Lake Gairdner. It is envisaged that the method can be generalized for other frequently spilling reservoirs with similar conditions.

The post-processor was made up of 2-parameter copula functions. Marginal distributions were modelled using a number of unimodal distributions and mixtures of Gaussian distributions. The mixtures of Gaussian distributions were introduced to account for the bi-modal nature of the marginal distributions.

Separate post-processors were fitted for winter and summer to account for the seasonal operation of the reservoir levels. The best winter model consisted of BB1 copula and Gaussian Mixture marginal distributions and the summer model consisted of a T – copula and Weibull distributions. The post-processors were tested for their capacity to improve accuracy and quantify the uncertainty in the lake level forecast. The results showed that the post-processors consistently improved the accuracy of the forecast. The winter model generated reliable forecasts, and characterized the uncertainty reasonably well. However, the summer model resulted in some conditional bias and slightly over dispersive forecast distribution.

Keywords: *Post processor, hydrologic uncertainty, uncertainty quantification, short term forecast, Lake level prediction, copula, Gaussian mixture model*

Flood forecasting and optimisation for risk management of a water supply dam

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Abstract: TasWater operates numerous water storages throughout Tasmania, some of which require upgrading to bring them up to current standards in terms of acceptable flood risk. Prior to the works being undertaken, the risks associated with these storages must be managed. Optimal operation of these storages during flood events will continue to be a requirement, even after remedial works have been completed.

Floods in Northern Tasmania during winter and spring of 2016 highlighted the heightened risk that high inflows can pose to a number of TasWater's storages and structures, in particular Isandula Dam on the Gawler River. Lake Isandula is used as a water supply storage. TasWater needs to optimise operation of the dam to minimise flood risk to the dam structure, whilst maintaining water supply to residents.

To assist TasWater in managing Isandula Dam, a flood forecasting and information system has been developed using Delft-FEWS. The inputs to the system are gauged rainfall, streamflow and reservoir level (telemetered), and Bureau of Meteorology gridded ADFD rainfall forecasts. Inflows to Lake Isandula are produced from a continuous rainfall-runoff model, coded in W-FLOW. Lake Isandula is modelled using a reservoir routing model, RTC-TOOLS, which includes operation of the outlet valve. The recommended operation of the outlet valve is automatically optimised based on the forecast inflows to the storage with the aim of keeping as much water in storage as possible, whilst maintaining the lake at a safe level. Optimisation of operation is based on target lake level thresholds. The first priority is dam safety, for which a maximum water level threshold is set. The second priority is to maintain water in storage to assure water supply, for which a target minimum lake level threshold is set. The model produces an optimum valve opening over time to maintain water levels between these thresholds where possible. This is used as one of the inputs to TasWater's operational decisions when high inflows are forecast. A lake level forecast based on the valve being closed, is also produced.

The outputs from the flood forecasting system are viewed via a user interface and include forecast reservoir level up to 7 days in advance, rainfall/forecast rainfall over the catchment, and forecast releases required to maintain Lake Isandula at safe levels where possible. The water level in Lake Isandula with optimised valve operation, and with the valve remaining closed is presented. A range of forecasts are presented to give the dam manager an indication of the forecast uncertainty.

The system is currently operating as a stand-alone pilot, operating outside of TasWater's IT infrastructure. The next step in the forecasting system development is to fully integrate DELFT-FEWS with TasWater's systems. This will include direct connection to TasWater's OSIsoft PI historian application. This will allow input observational data to be passed to DELFT-FEWS via Historian, and forecasts to be passed back. This means that alerts will be able to be raised via the SCADA system, as well as directly in the forecasting system interface.

The system piloted on Isandula Dam will be expanded to cover all TasWater dams and catchments. The availability of richer, "live" information on observed and forecast rainfalls over the catchment, inflows, and observed and forecast reservoir levels, will give TasWater additional confidence in management of risks during a flood event.

Keywords: *Flood forecasting, storage optimisation*

Developing the next generation seasonal streamflow forecast products for Australia

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Abstract: Given the need to provide better information for water managers, and spurred on by major drought that affected large parts of Australia during the 2000s, the Bureau of Meteorology developed and released a probabilistic seasonal streamflow forecasting service in 2010 to provide timely, accurate and reliable predictions of water availability across the country. Since then, extensive consultation via formal meetings, surveys, case studies and informal discussions with stakeholders have led to the following key developments: (1) provide forecasts with higher temporal resolution and at more locations, (2) increase coherence between seasonal streamflow forecasts and seasonal climate outlooks, and (3) enhance forecast products to be more easily understandable. In order to achieve these, the Bureau is developing new modelling components in collaboration with CSIRO and university researchers, and is also re-designing forecast products and the service website.

The service coverage has expanded from 21 to more than 300 locations across Australia. For each location, the existing forecasts for 3-month total streamflow volume will be replaced with forecasts of monthly streamflow volumes up to 3 months ahead. This increase in temporal resolution is expected to better support river system modelling and water resource planning, which often require monthly forecasts.

The Bureau is also preparing to improve its climate outlook forecasts by using the ACCESS-S model with 60 km resolution climate forecasts. Rainfall forecasts from ACCESS-S will be ingested to drive a rainfall-runoff model and produce seasonal streamflow forecasts. Once the ingestion of the rainfall forecasts is established, the service will be able to leverage improvement of finer resolution climate modelling to enhance its streamflow forecasts.

These enhanced streamflow forecasts will be delivered using new graphic products through a more intuitive website. The service has recently introduced a new graphic product clearly highlighting difference between streamflow forecasts and historical data distributions. New criteria for forecast performance will be applied to take into account the uncertainty of estimated forecast skill scores. The new website will provide an enhanced user interface consistent with other streamflow forecasting services provided by the Bureau.

Keywords: *Water, forecast, streamflow, climate, service, Bureau of Meteorology*

Enhanced parameter inference method for post-processing rainfall forecasts

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Abstract: Unbiased, accurate and statistically reliable ensemble rainfall forecasts are critical for ensemble streamflow forecasting. The rainfall forecasts from Numerical Weather Prediction (NWP) models generally do not have those properties at the fine spatial scales for direct use for hydrological modelling. We have developed a Rainfall Forecast Post Processing (RPP) method to generate ensemble catchment rainfall forecasts with minimal bias and reliable forecast uncertainty. In previous studies, the RPP has been successfully applied to the rainfall forecasts from a range of Australian and international NWP models.

The RPP combines a simplified version of the Bayesian Joint Probability (BJP) modelling approach and the Schaake shuffle. The BJP modelling approach relates rainfall forecasts and observations by modelling their joint distribution to correct biases and to quantify uncertainty. The Schaake shuffle ensures realistic space-time patterns in the post-processed forecasts. Originally, a different BJP model was generated for each lead-time (referred to as the original parameter inference method). In this approach, the quality of the post-processed forecasts could be sensitive to the length of the NWP archive used to infer model parameters. This is a serious issue for operational post-processing methods, because NWP models are evolving rapidly and as a result the forecast archives are often short.

We have developed an enhanced parameter inference method for the RPP to reduce the sensitivity of post-processed forecasts to the length of the NWP archive. The enhanced inference method uses statistical models to describe patterns in RPP model parameters in relation to the time-of-day (TOD) and to the forecast lead-time. The method infers: i) a single set of transformation parameters for all lead-times and TOD, ii) the mean and variance of observations and the mean of forecasts as a function of TOD, and iii) the variance of forecasts and the correlation of forecasts with observations as a function of TOD and forecast lead-time. These functions recognise that rainfall varies diurnally, and that NWP performance declines with lead-time.

The enhanced RPP is applied to rainfall forecasts from the ACCESS-G and ACCESS-GE NWP models for a range of Australian catchments. Forecasts from the enhanced inference method are similarly accurate and unbiased compared to the original inference method. Importantly, the enhanced inference method produces forecasts that are more stable across lead-times and less sensitive to the length of record used for parameter inference. The benefit of the enhanced method is more evident for cases with very short NWP archives and for catchments where rainfall is strongly seasonal (Figure 1). We conclude that the enhanced RPP is a significant advance for the operational post-processing of NWP forecasts.

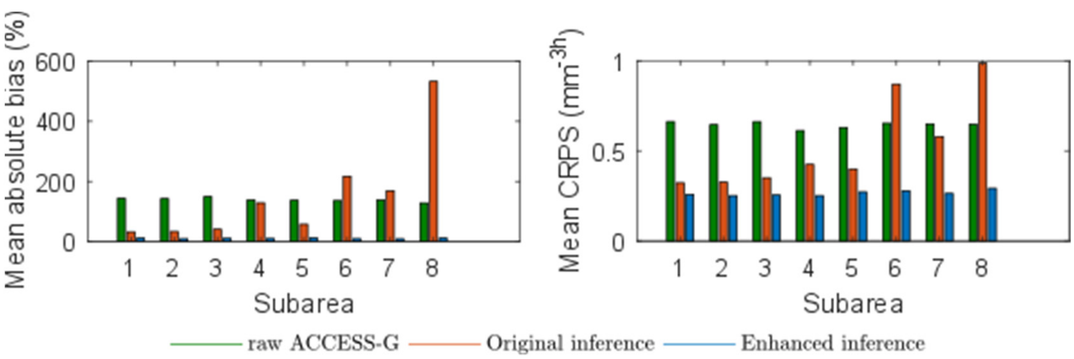

Figure 1. Forecast bias and CRPS in the raw ACCESS-G, calibrated ACCESS-G from the original and the enhanced inference method for Ord catchment.

Keywords: *Rainfall Forecast Post Processing (RPP), Bayesian Joint Probability (BJP), Numerical Weather Prediction (NWP), Schaake shuffle*

Evaluating residual error approaches for post-processing monthly and seasonal streamflow forecasts

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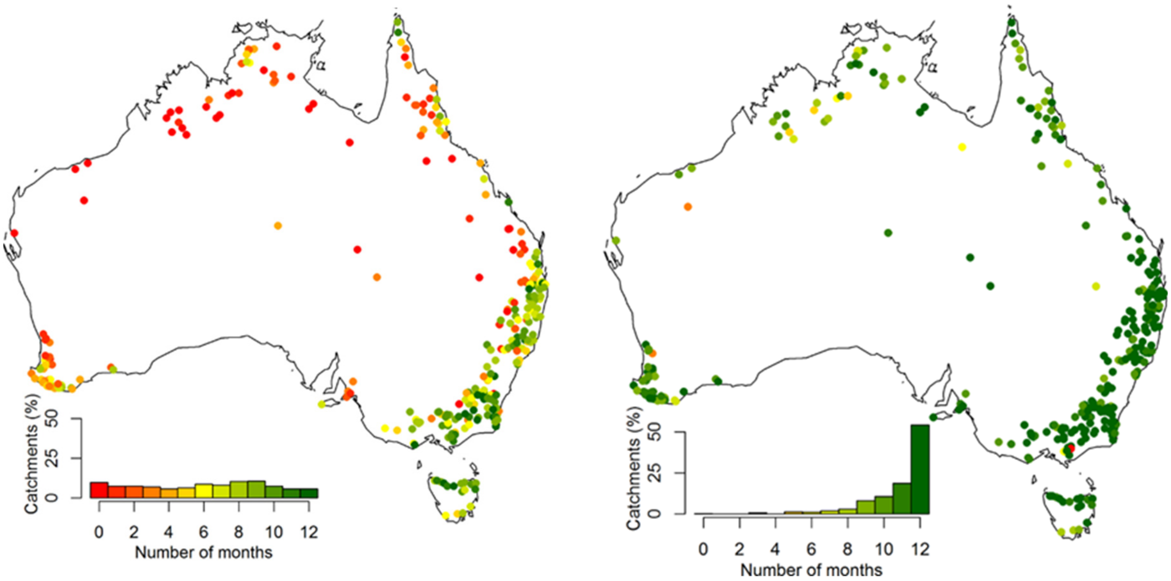
Abstract: Streamflow forecasting is prone to substantial uncertainty due to errors in meteorological forecasts, hydrological model structure and parameterization, and other components of the modelling chain. Statistical streamflow post-processing is an important technique available to improve the probabilistic properties of the forecasts. This study evaluates three residual error models based on the logarithmic (Log), log-sinh (Log-Sinh) and Box-Cox with $\lambda = 0.2$ (BC0.2) transformation schemes and identifies the best performing scheme for post-processing monthly and seasonal streamflow forecasts, such as those produced by the Australian Bureau of Meteorology. Using the Bureau's operational dynamic streamflow forecasting system, we carry out comprehensive analysis of the three post-processing schemes across 300 Australian catchments with a wide range of hydro-climatic conditions. Forecast verification is assessed using reliability and sharpness metrics, as well as the Continuous Ranked Probability Skill Score (CRPSS). Key results are as follows:

- Uncorrected forecasts (i.e. without post-processing) are unreliable at about half of the catchments (Fig 1a).
- Post-processing using the three residual error models improves reliability significantly, with more than 90% of forecasts classified as reliable.
- In terms of sharpness, the BC0.2 scheme significantly outperforms the Log and Log-Sinh schemes.
- Overall, the BC0.2 scheme achieves reliable and sharper-than-climatology forecasts at a larger number of catchments than the Log and Log-Sinh error models (Fig 1b).

This study is significant because the reliable and sharper forecasts from the BC0.2 scheme will help users of the forecasting service to make better-informed decisions in planning and management of water resources.



(a) Uncorrected forecasts (b) Post-processed forecasts using BC0.2 scheme

Figure 1. Catchment locations showing the number of months with forecasts that are reliable and with a sharpness better than climatology using (a) Uncorrected forecasts and (b) Post-processed forecasts using BC0.2 scheme. The histogram shows the percentage of catchments in each performance category.

Keywords: *Seasonal streamflow forecasts, residual error models, post-processing, Box-Cox transformation*

Seasonal soil moisture forecasting using the AWRA landscape water balance model

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Abstract: The Australian Bureau of Meteorology (BOM) publishes and presents to stakeholders seasonal outlooks of key environmental variables including precipitation, temperature and streamflow. A similar forecast system for soil moisture (SM), if skilful, could benefit many stakeholders and sectors. Potential applications include agricultural planning (e.g. irrigation and sowing scheduling, planning of tilling, sowing and harvesting), livestock management, economic forecasts (e.g. improved crop yield predictions) and emergency management (e.g. bushfire and flood risk assessment). The aim of this study was to develop a proof-of-concept for a seasonal SM forecasting system for Australia and to test its performance. Specifically, we aimed to answer the research question: Can SM over the coming three months be forecast with better skill than the climatological expectation?

This paper presents a SM forecasting methodology that combines the POAMA-2 seasonal climate prediction system with the AWRA landscape water balance model (AWRA-L). POAMA-2 is a global coupled ocean-atmosphere model that currently underpins the BOM seasonal climate outlooks. POAMA-2 hindcasts of precipitation, air temperature and solar radiation, available for 1981-2014 on a 2.5° x 2.5° grid, were converted into a suitable format to force AWRA-L. The AWRA-L gridded water balance model simulates daily land surface water fluxes and stores, including SM for three soil layers (0-10 cm, 10-100 cm, 100-600 cm), on a national 0.05° grid. Combining these two modelling systems, we produced hindcasts of monthly SM stored in the AWRA shallow soil layer (10-100 cm soil depth: corresponding to the root depth of many agricultural crops) for the period 1981-2013, with 12 hindcasts per year starting on the 1st of each month and 22 ensemble members per hindcast. Further, we calculated probabilistic hindcasts of the occurrence of a potentially harmful event (PHE). The PHE aims to capture critically dry soil conditions with potentially adverse effects on, for example, agriculture. It is defined as a month in which the 20th percentile of SM in this month is drier than a 1-in-5-year event. Each hindcast had a length of three months, and all individual forecasts at one-, two- and three-month lead time were subsequently combined into continuous monthly time series with 22 ensemble members per time series.

We assessed the skill of the hindcasts of soil moisture against i) historical SM simulations using AWRA-L forced with daily gridded climate analysis data produced by BOM and ii) ground-based *in situ* measurements of SM (0-90cm) from the OzNet network in the Murrumbidgee catchment. The predictive capacity of the hindcasts at one-month lead time appear relatively high and are mostly related to the state initialisation of AWRA-L, highlighting the importance of soil memory and SM initialisation at shorter time scales. However, at two- and three-month lead times, our results show relatively low predictive skill across Australia, with a few exceptions in wet regions in the northern, southern and south-western parts of Australia. Most of the skill stems from the ability of the forecasting system to reproduce the mean spatial and seasonal pattern of SM, however, increasing the skill to predict deviations from the mean climatology requires further work. This study presents baseline estimates of predictive skill at different time scales, which may be used as reference for future developments of SM forecasting systems, and provides recommendations for future research.

Keywords: *Soil moisture, seasonal forecasting, soil moisture hindcasts, climate services*

EXTENDED ABSTRACT ONLY

Applications of subseasonal-to-seasonal (S2S) predictions

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Abstract: While long-range seasonal outlooks have been operational for many years, until recently the extended-range timescale – referred to as 'subseasonal-to-seasonal' (S2S) and which sits between the medium- to long-range forecasting timescales – has received relatively little attention. The S2S timescale has long been seen as a 'predictability desert', yet a new generation of S2S predictions are starting to bridge the gap between weather forecasts and longer-range prediction. Decisions in a range of sectors are made in this extended-range lead time, therefore there is a strong demand for this new generation of predictions.

At least ten international weather centres now have some capability for issuing experimental or operational S2S predictions, including the European Centre for Medium-Range Weather Forecasting (ECMWF) and the National Oceanic and Atmospheric Administration (NOAA). International efforts are now underway to identify key sources of predictability, improve forecast skill and operationalise aspects of S2S forecasts, however challenges remain. If S2S predictions are to be utilised effectively, it is important that along with science advances, we learn how to develop, communicate and apply these forecasts appropriately.

In this study, we present the potential of the emerging operational S2S forecasts to the wider weather and climate applications community by undertaking the first comprehensive review of sectoral applications of S2S predictions, including public health, disaster preparedness, water management, energy and agriculture. We explore the value of applications-relevant S2S predictions, highlight the availability of data repositories of near real-time S2S forecasts and hindcasts, including the WWRP-WCRP (http://apps.ecmwf.int/datasets/data/s2s) and North American Multimodel Ensemble (NMME; http://www.cpc.ncep.noaa.gov/products/NMME/data.html) repositories, and discuss how they are promoting the use (and aiding the development) of S2S predictions.

The study shows how social sciences should be integrated with S2S development – from communication to decision-making and valuation of forecasts – to enhance the benefits of 'climate services' approaches for extended-range forecasting. To achieve this, decision-makers and forecasters need to collaborate to determine essential S2S forecast attributes, including identifying appropriate thresholds and their usefulness in decision-making, as well as their economic value. This involves the inclusion of realistic and unbiased messages on forecast skill (or lack thereof), potential usefulness and quantified uncertainties to manage expectations, as well as the integration of S2S as a key component in the concepts of seamless prediction and co-production.

The study concludes that while the uptake and integration of S2S forecasting into decision-making is neither easy nor straightforward, there now exists a growing repository of untapped predictive information that presents tangible and realistic opportunities that can be explored for application-ready capabilities that could allow many sectors to systematically plan on this new predictive time horizon.

Keywords: *Subseasonal-to-seasonal, S2S, forecasting*

Should we use quantile mapping to post-process ensemble GCM precipitation forecasts?

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Abstract: Ensemble forecasts generated by global climate models (GCMs) are an integral part of seasonal hydro-climatic forecasting systems. While raw GCM forecasts are informative, their usefulness is hampered by three well-known deficiencies: they are usually biased; the spread of ensembles is typically too narrow; and the forecasts can be less accurate than the naïve climatology forecasts. Therefore, postprocessing is a necessary step before GCM forecasts can be practically applied.

Quantile mapping (QM), also called quantile–quantile transformation or distribution mapping, is a popular method for postprocessing seasonal ensemble GCM forecasts. Its popularity is probably due to its extensive use to correct the distribution of long-range climate change projections. However, seasonal forecasts differ remarkably from long-range projections:

- As to forecasts, the focus is on individual events, instead of the whole distribution. That is, seasonal forecasts must be paired with observations, so that we can verify whether forecasts are biased, whether ensemble spread reliably captures the observations, and whether forecasts are at least as skillful as climatology forecasts;
- On the other hand, long-range GCM projections are not synchronous with observations and they almost cannot be "verified".

Here, we evaluate the effectiveness of QM in post-processing seasonal precipitation forecasts by applying it to raw forecasts from the Predictive Ocean and Atmosphere Model for Australia (POAMA). Specifically, we examine the ability of QM to

- Remove bias from raw GCM forecasts;
- Make the forecast ensemble spread reliable;
- Yield forecasts that are equivalent to climatology where there is no evident skill in raw GCM forecasts, a property termed "coherence".

The results show that while QM is highly effective in correcting bias, it cannot ensure reliability in forecast ensemble spread or guarantee coherence. This is because QM ignores the correlation between raw ensemble forecasts and observations:

- When raw forecasts are not significantly positively correlated with observations, QM tends to produce negatively skillful forecasts;
- Even when there is significant positive correlation, QM cannot ensure reliability and coherence for postprocessed forecasts.

Based on these findings, we contend that QM is not a wholly satisfactory method for postprocessing GCM precipitation forecasts where the issues of bias, reliability, and coherence pre-exist. Alternative postprocessing methods based on ensemble model output statistics (EMOS) are available that achieve not only unbiased but also reliable and coherent forecasts. This is shown with one such alternative, the Bayesian joint probability (BJP) modeling approach.

Keywords: *Precipitation, GCM forecast, seasonal forecast, forecast post-processing, forecast verification*

Operational efficiency measures of the national seasonal streamflow forecast service in Australia

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Abstract: The Bureau of Meteorology issues probabilistic forecasts of seasonal streamflows every month across Australia. Launched in 2010, the service was developed in partnership with key Australian water agencies, while the science underpinning this service is supported by CSIRO and the university sector. High quality streamflow forecasts and timely forecast releases for an increasing number of locations are critically important to water managers. Consequently, operational efficiency measures have been introduced in areas of automated data acquisition, advanced modelling, and forecast delivery to the public. Furthermore, much has been done to improve the communication and adoption of probabilistic streamflow forecasts.

Forecast generation uses a modelling framework (WAFARi) with different forecasting approaches, which has effectively combined increasingly sophisticated technology over time. To support the use of different underlying hydrological models within the same framework, WAFARi uses the Factory and Wrapper design patterns to support the creation and running of diverse models using a common interface. The wrapper Python code to individual hydrological model kernels uses the well-tested F2PY toolkit for partially automating the maintenance and calling of Fortran libraries, in a manner that is computationally efficient. This design has proved effective in allowing hydrologists to generate multiple end-points of forecast products based on the different models and compare the results.

Provision of the streamflow forecast service each month requires efficient data preparation, forecast generation, forecast review and release to the public. Within the forecasting system, statistical and dynamic forecasting approaches are used. The model inputs for statistical forecasts are observed climate indices, observed rainfall and streamflow. The model inputs for dynamic forecasts are observed rainfall, evapotranspiration, streamflow, and rainfall forecasts. Given this variety of data from different sources, monthly data preparation requires an efficient process. Automated or semi-automated data ingestion tools, together with quality-control algorithms, are applied to different types of data required to generate the forecasts.

To develop a model in WAFARi for a new forecast location, there are several tasks to complete. An automated procedure has been developed to configure a new forecasting model, calibrate the model and rigorously cross-validate the model. Statistical methods commonly used for forecasting streamflows require the selection of appropriate predictors from two sources of streamflow predictability, the initial catchment condition, and current climate influences. For operational efficiency, a hybrid forecasting approach using the output of a dynamic hydrological model as a predictor, was adopted for the forecasting service. Dynamic methods used for forecasting streamflows often require statistical post-processing to remove biases and to provide a reliable probabilistic forecast. For operational efficiency, the streamflow post-processing using the Box-Cox transformation with a fixed parameter lambda = 0.2 was adopted in the dynamic modelling approach.

With the number of streamflow forecast locations increasing (from 21 in 2010 to 181 in July 2017), greater efficiency in producing and publishing forecasts in a timely manner is of high importance. To this end, continuous development of the WAFARi system has progressively incorporated features to speed-up the rate of forecast generation per location compared to when the service began in 2010. Current features include separating the data assimilation process to enable parallel generation of production public facing forecasts and registered user experimental forecasts, and to reduce the forecast generation run time by implementing a caching mechanism.

Keywords: *Operational efficiency, seasonal streamflow forecasting, water forecasting services*

Droughts in the Central Asia: the security risks of global warming

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Abstract: Drought and water scarcity are key words for regional management in water-stressed regions. Central Asia, located in the hinterland of the Eurasian continent, is the key area of the Silk Road Economic Belt. Previous assessments of historic changes in drought index, e.g. Palmer Drought Severity Index (PDSI), over the past half century indicate that drought is expected to increase in frequency and severity as a consequence of global warming. However, different approaches for estimating PDSI lead to controversial results in assessing droughts. Meanwhile, even though using a physical-based approach for PDSI estimates has now been brought closer to key water balance components, there is still lack of comprehensive assessment for measuring long-term droughts from perspectives of meteorology (precipitation), agro-ecology (soil moisture, evaporation and transpiration) and hydrology (runoff). To this end, we conducted a comprehensive assessment for measuring long-term drought in Central Asia, the results show that:

- Based on physical approaches linked to potential evapotranspiration (PET), the PDSI in 1965-2014 showed a mixture of drying (42% of the land area) and wetting (58% of the land area) that combined to give a slightly wetting trend (0.0036 per year). Despite the smaller overall trend, there is a switch to a drying trend over the past decade (-0.023 per year), generally following the dramatic increase in air temperature. Over the past decade (2000-2014), the PDSI shows drying across 65% land area of Central Asia, especially obvious in the western and eastern Kazakhstan, Turkmenistan, Kyrghyzstan as well as the Tarim River basin in China.
- A physical-based approach was used to quantify sensitivity of PDSI droughts. Numerical experiments were designed to quantify the sensitivity of the PDSI and we found that the response level of the PDSI drought to the air temperature is higher than that with the other meteorological variables. The precipitation to the overall averaged PDSI trend is very small compared with the large variation.
- The variability of meteorological and agro-ecological droughts were broadly comparable with various PDSI drought index. Precipitation in Central Asia showed a slightly downward trend from 2000 to 2014. The annual soil moisture trends illustrate a total decrease in the soil moisture of four specific layers in Central Asia, especially of the shallow soil layers, and this is particularly obvious in the most recent (and warmest) decade. In the recent warmest decade (2001-2014), the soil moisture trend was comparable with various PDSI readings. The most prominent drying trends of agro-ecological drought occurred in northwestern Kazakhstan.
- The soil moisture drying over the past two decades intensified desertification and also led to water-based ecosystems becoming significantly more fragile in arid regions. Rising actual evapotranspiration caused by increases in transpiration from vegetation and intercepted rainfall from vegetation, and partially counteracted by evaporation from the soil decreasing will exacerbate regional ecological droughts. The detailed adverse ecological effects are reflected in the declining Normalized Difference Vegetation Index (NDVI) of natural vegetation since 1998, moreover, shrub cover and patch size exhibit a significant increase, even shrub encroachment in grasslands.
- Interestingly, the hydrological drought was not completely comparable to the PDSI, which indicates that runoff in arid and semi-arid regions was not generated primarily from precipitation. Instead, fraction of glacierized areas in catchments caused large variations in the observed runoff changes.

As the above considerations show, focusing on changes in drought indices does not indicate a regional real drought, and perhaps does not even represent the main hydrological drought in drylands basins. Under the impact of global climate change, the vulnerability of ecology system and uncertainty of water resources are increasing. Therefore, in the process of resources development, especially in the drylands of developing countries, the priority protection rules should be followed in order to adapt to the effects of global warming.

Keywords: *Climate change, Palmer Drought Severity Index (PDSI), meteorological drought, agro-ecological drought, hydrologic drought, Central Asia*

Estimating surface energy fluxes: a key component for estimating potential evaporation

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Abstract: A model has been developed that can predict the solar and infrared downwelling radiation fluxes using ground based measurements of the air temperature, relative humidity and the cloud cover. The algorithm has been validated using several years of ground-based data for 15 sites across the globe (13 sites from the Baseline Surface Radiation Network (BSRN), as well as data for two sites in Crete). These stations cover a wide range of climatic conditions, including those of arctic, desert, sub-tropical, Mediterranean, as well as elevated sites. The RMS residual for the monthly mean short wave (SW) solar flux (approximately 0.2 to 3 μm) is typically 12 Wm^{-2} (mean observed daily SW flux across all stations is 305 Wm^{-2}), while the thermal IR flux (roughly 4-50 μm) derived using the algorithms gives RMS residuals of approximately 8 Wm^{-2} (mean observed daily IR flux across all stations is 180 Wm^{-2}). Daily observed and modelled fluxes, as well as residuals are shown for 8 of the stations in Figure 1. As well as the radiation fluxes, the model also estimates the atmospheric water vapour content, which has been tested using available radiosonde data for 8 of the stations. In comparison with the observed mean water vapour content, the values derived by the algorithms have typical values for bias of 0.01 g cm^{-2} and RMS residual of 0.15 g cm^{-2} (mean across all stations is 1.65 g cm^{-2}), accounting for 80 % of the observed variation. Since the model uses readily available meteorological data, the net radiation flux at the surface can readily be calculated (given the surface albedo), providing an estimate of a dominant term in estimating potential evaporation and evapotranspiration.

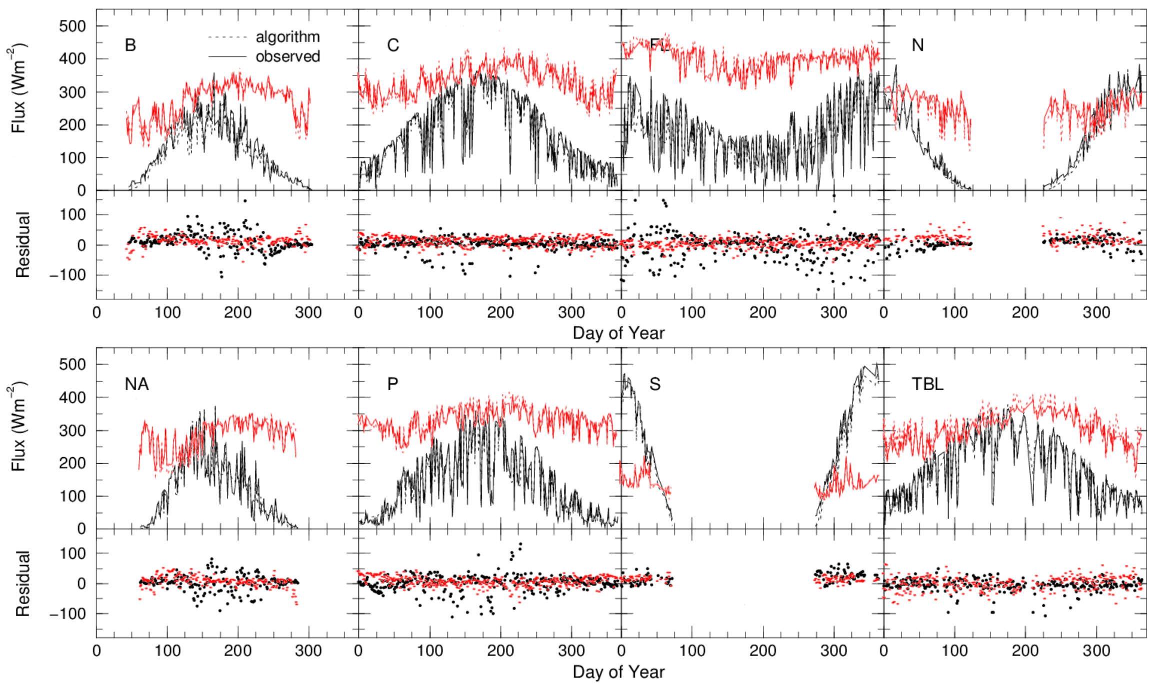

Figure 1. One year of observed and modelled daily solar (black) and infrared (red) radiation for 8 of the study sites spanning a wide range of climates from arctic to tropical.

Keywords: *Solar radiation, infra-red radiation, water vapour, potential evaporation*

Estimating water and carbon fluxes using a simple diagnostic model

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Abstract: Terrestrial evapotranspiration (ET) and gross primary production (GPP) are vital components of global water, energy and carbon cycles. Accurate estimation of these two components using practical yet mechanistic model would provide credible support for management of water and carbon budgets under climate change. Despite ET and GPP processes are closely coupled within terrestrial ecosystems, they are generally simulated separately and the uncertainty remains elusive. Here a simple mechanism-based model to integrally simulate ET and GPP is examined against field observations at globally distributed eddy covariance flux towers. The ET model is developed from Penman-Monteith equation (PM), with the surface conductance modified to take carbon fixation into account, where GPP is estimated following photosynthetic principles. The model is named as PMC and can be used to simulate the ecosystem water transfer and carbon uptake simultaneously. Only few inputs are required to simulate ET and GPP using PMC model, including routinely measured meteorological variables (radiation, temperature, air pressure, humidity and wind speed), atmospheric carbon dioxide (CO_2) concentration, and leaf area index (LAI) obtained from satellite data of the MODerate Resolution Imaging Spectrometer (MODIS). The model only has five parameters that denotes biome characters and can be easily calibrated and parameterised across ecosystems. Observations from 64 flux sites (305 site-years) that spans a wide range of global climate (temperate, tropical, boreal, sub-tropical, Mediterranean) and biomes (ENF, DBF, EBF, MF, SH, WSA, SA, CRO, GRA, WET) were used to test the model. The parameters were optimised using the least square method for both ET and GPP at each site. Results indicate that this coupled algorithm can well reproduce ET and GPP time series when compared to observations. This is indicated by the overall high values of coefficient of determination (R^2) and low values of root mean square error (RMSE), with the median R^2 of 0.8 and 0.73, and RMSE of 0.5 (mm d^{-1}) and 1.3 (g C m^{-2} d^{-1}) for ET and GPP respectively across sites. The inter-annual variations of both ET and GPP are also well reproduced by the model, with a slightly better performance found during wet season than that of dry season. The optimised parameter sets represent the biophysical characters of different ecosystems. Higher light extinction coefficient and lower quantum and carboxylation efficiency were found at forest biomes, which are symptoms of energy-limited ecosystems in contrast with the non-forests. The plant functional type based parameter sets were used to validate the model and the estimated ET and GPP were satisfactory, with slight degradation found for both R^2 and RMSE. As the model is inherently simple and efficient, it has a promising capability of being applied to upscale water and carbon fluxes from stand to regional or global scale with readily available data.

Keywords: *Evapotranspiration, gross primary production, model, eddy covariance*

Multi-objective calibration of Xinanjiang model by using streamflow and evapotranspiration data

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Abstract: Hydrological model calibration is normally carried out against a single set of observations, particularly streamflow, which often limit overall model performance. Compared to that, multi-objective model calibration can overcome these problems and result in better model performance. In this study, daily streamflow data and catchment evapotranspiration (ET) estimates in 210 catchments in southeastern Australia, were used for multi-objective calibration of Xinanjiang model. The daily ET was estimated from the state-of-the-art Penman-Monteith-Leuning (PML) model together with remotely sensed time-series vegetation data due to unavailability of actual ET data in most catchments. The results show that the PML ET estimates compare well with the flux measurements, and it is regarded as 'ground truth' and used for model calibration.

Two calibration schemes are used to evaluate hydrological modelling performance, including single-objective calibration against streamflow data alone (Scheme 1) and multi-objective calibration against streamflow and evapotranspiration (Scheme 2). For model calibration, the median of NSE of daily streamflow for the 210 catchments are 0.78and 0.76 for Scheme 1and Scheme 2, respectively, while the median of R^2between observed and simulated daily ET are 0.79and 0.88. Model regionalization results are overall consistent with the calibration results, with Scheme 2 showing a less degradation for streamflow and ET predictions compared to Scheme 1. The medians of NSE for Scheme 1 and Scheme 2 are 0.51and 0.52, respectively, while the median of R^2 are 0.68and 0.79. The results show that the multi-objective calibration reduced the uncertainty of parameters and can improve runoff predictions in ungauged catchments. More researches should be carried out for further reducing the parameter uncertainty.

Keywords: *Penman-Monteith, evapotranspiration, multi-objective calibration, runoff prediction*

Modelling the impact of deforestation on dry season flows across the tropics

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Abstract: Forests act as pumps through evapotranspiration (ET) and as sponges by enhancing soil infiltration capacity and moisture retention. Ongoing tropical deforestation and post-forest land use will likely result in a reduction in ET (the pump effect), but potentially also in a reduction in surface infiltration (the sponge effect). The latter may translate into overland flow enhancement and possibly a concurrent reduction in groundwater recharge and baseflow despite lower post-forest ET. This would thus have a net negative impact on water availability in the dry season, particularly in catchments dominated by a marked seasonal precipitation regime (wet-dry cycles).

A grid-based land surface hydrological model (W3RA-LUM) was tailored to incorporate the pump and sponge trade-offs in order to examine impacts of vegetation changes on hydrology, particularly on dry season flows. Sensitivity analyses for scenarios with or without full forest cover and/or good or poor surface infiltration conditions were performed for: (i) selected tropical catchments with documented changes in dry season flows as a result of deforestation, and (ii) across the tropics.

The catchment sensitivity analyses showed that several relevant hydrological processes (particularly for the seasonal tropics) as well as the response to imposed deforestation and changes in soil conditions were reasonably captured by the model. Across the tropics, results showed an increase in mean annual streamflow of 18% if only vegetation changes (from forest to grassland) were taken into account. The predicted increase in mean annual streamflow was 26% if there were also reductions in soil surface infiltration. Much of the increase occurred in water-limited regions. When poor soil conditions were imposed as well, some areas showed a reduction in streamflow for some of the driest months despite the decreases in ET associated with the conversion from forest to grassland (Figure 1).

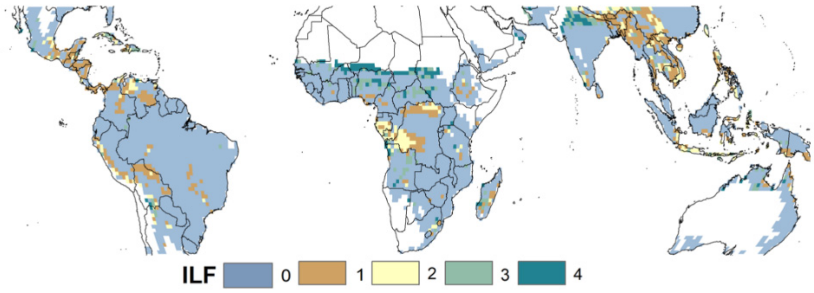

Figure 1. Number of months with modelled decreases in dry season flows (ILF) out of four months with low flows following deforestation and changes in infiltration capacity (100FC–0FCSC).

The affected areas had key climatic and biophysical characteristics (as represented in the model) that made them susceptible to reductions in dry season flows after deforestation and severe reductions in infiltration capacity. These characteristics were: (i) strong precipitation and streamflow seasonality; (ii) sufficient precipitation in excess of potential ET during the wet months to recharge deeper soil profiles and/or groundwater; (iii) a sufficiently high soil infiltration capacity under forested conditions to accommodate prevailing wet season rainfall intensities; (iv) sufficient soil water storage under forested conditions to 'carry over' rainfall infiltrated during the wet season; and (v) a sufficiently long 'buffer time' (in terms of groundwater recession) that modulates the release of water stored in the deep soil profile or saturated zone as baseflow.

Keywords: *W3RA, Soil Conservation Service Curve Number, infiltration, hydrological modelling*

Energy, water and carbon flux responses to meteorological and edaphic drivers in agricultural ecosystems of Australia and New Zealand

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Abstract: Despite occupying one-third of the terrestrial surface and being highly sensitive to changes in hydrology, agricultural ecosystems are under-represented in flux studies of water and carbon cycles across the globe. Australia and New Zealand are no different, where only 16% of OzFlux sites are located in predominately agricultural landscapes. Consequently, the primary objective of this study was to investigate and compare the responses of agricultural fluxes of surface energy (sensible heat flux), water (evapotranspiration, ET) and carbon (net ecosystem exchange, NEE) to eight meteorological and edaphic drivers (net radiation, atmospheric specific humidity, vapour pressure deficit, net radiation, air temperature, ground heat flux, soil temperature and soil water content). Three levels of management intensity were considered, including minimal management (e.g. grazed rangelands); moderate management (e.g. dryland agriculture and pasturelands); and irrigated or other intensively managed agricultural systems (e.g. dense grazing in fertilised and irrigated paddocks). The responses of sensible heat flux, ET and NEE to meteorological and edaphic drivers were investigated on a daily timescale using a novel statistical approach based upon wavelet theory (wavelet-based canonical correlation analysis, wCCA). The approach consisted of (i) wavelet-based principal components analysis (wPCA) to reduce the number of driving variables and to separately identify dependencies amongst fluxes or drivers, followed by (ii) wavelet-based multiple linear regression (wMLR) to infer relationships between drivers and fluxes. We found that irrigation of crops released NEE and ET from dependence upon all meteorological and edaphic drivers, except in extreme conditions such as inundation (rice) or high heat (almonds). By contrast, moderate intensity agriculture and pasture (along with high intensity grazing in the energy-limited environments of NZ) were most closely coupled to these drivers, especially vapour pressure deficit, available energy and air temperature. Low intensity grazed rangelands were most strongly coupled to the large fluctuations in available energy and atmospheric humidity which characterise the summer wet season across northern and much of central Australia. Results from this study provide a consistent, detailed understanding of factors related to optimisation of water use and crop and forage production across a variety of conditions.

Keywords: *Agriculture, water, carbon, eddy covariance, wavelet statistics*

EXTENDED ABSTRACT ONLY

A general framework developed for predicting hydrological signatures

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Abstract: Predicting hydrological behavior is an important but challenging task from catchment to regional scale. One fundamental question that hydrologists face is to understand and predict hydrological behavior under different climate or catchment conditions. When various hydrological signatures are identified, it can relatively easy to conduct water resource management, catchment classification and even predicting runoff time series. A hydrological signature refers to a distinctive set of hydrological indices for a catchment at different temporal steps. Hydrological signatures can include runoff coefficient, zero flow ratio, a measure of runoff seasonality, flow duration curves, etc. Several existed studies show that it is very hard to accurately estimate hydrological signatures that reflect low flow regimes, such as low flow days, zero flow days and low percentiles in flow duration curve. In this study a general framework was developed to predict various hydrological signatures: low flow signatures, high flow signatures, and signatures reflecting slope and concavity of the flow duration curve. This framework uses ensemble regressions to establish relationships between catchment attributes and each hydrological signature. It has been successfully applied to predict twelve hydrological signatures (zero flow ratio, mean annual runoff (Q), Q10, Q50, Q99, Inter-quantile runoff, high flow days, low flow days, concavity index, seasonality, standard deviation of log Q, mean of logQ) for 600 catchments widely spread across Australia. This framework is noticeably better for predicting low flow hydrological signatures than traditional methods, such as Budyko-framework, rainfall-runoff modelling and linear regression. It has great potential to use this framework for large-scale hydrological signature predictions across global land surface.

Keywords: *Hydrological signatures, ensemble regression, hydrological modelling, prediction*

Modelling Impacts of on-farm Mitigation Features at Increasing Scales

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Abstract: Mitigation interventions are being used increasingly to tackle diffuse pollution issues by encouraging the retention of sediments, nitrate (NO_3) and phosphorus (P) in features such as riparian buffer strips, sedimentation ponds, wetlands and ditches. This poster will address the modelling of these features where they have been installed and monitored at the farm scale (i.e. in headwater catchments of less than 1 km^2). High frequency monitoring data have been obtained to evaluate the performance of these features in terms of trapping sediment, and attached NO_3 and P loads, from a major and unique monitoring project undertaken since 2011 in the River Eden catchment in North West England (the Eden Demonstration Test Catchments Project, EdenDTC). These catchments are dominated by pastoral farming (sheep and cattle) with a small amount of arable farming (mostly rotational fodder and cereal crops). Since 2014 Runoff Attenuation Features (RAFs) have been constructed in order to demonstrate the ability of these features to trap sediment and particulate P during events.

The model used, the Catchment Runoff Attenuation Flux Tool (CRAFT), was first applied to the entire Newby Beck sub-catchment (catchment area of 12.5 km^2) in one "before" and two "after" mitigation scenarios, the larger modelling scale being primarily chosen because time series of hourly flows and concentration have been obtained at this location. The "before" scenario modelled the time series of historical runoff, total reactive P (TRP), total P and suspended sediments (SS), over the period WY (Water Year) 2011-2. A Water Year starts on 1st September in this region. The "after" scenarios ran with the same forcing data but changes were made to model parameters in a 1.6 km^2 nested mitigation sub-catchment only. Note that the period WY 2011-2 was chosen for modelling because there were (i) high-quality nutrient and sediment data available with only a few gaps due to problems with the bankside monitoring equipment (fewer than other years) (ii) there were a series of more than 10 large runoff events during 2012 that were representative of typical runoff events observed between WYs 2011-6. Validation of the CRAFT model was also carried out using the monitoring data collected during WY 2012-3.

Subsequently, two variants of the "after mitigation" scenario were evaluated: Scenario 1 The mitigation sub-catchment had 10% of its area treated by riparian buffer strips with a removal efficiency (trapping efficiency) of 40% adding a maximum of 2000 m^3 storage during runoff events; and Scenario 2 the mitigation sub-catchment had 5% of its area treated by engineered features (a mixture of ponds and ditches) with double the removal efficiency (80%) and adding a maximum of 8000 m^3 storage during runoff events. In these scenarios we added this additional attenuation storage volume in the model to simulate the effect of mitigating the (1.6 km^2) sub-catchment only. The remaining 10.9 km^2 catchment was modelled as unaltered, i.e. its parameters were identical to the "baseline" scenario.

The "after mitigation" scenarios were evaluated to see firstly if the modelled improvement at the local (mitigation sub-catchment) scale in terms of nutrient (P) and sediment (SS) flux reductions could be observed at the NBC sub-catchment outlet in terms of reducing loads and peak runoff and secondly in terms of reducing nutrient (P) and SS concentrations. Water Framework Directive (WFD) targets are set in terms of not exceeding set thresholds of TRP concentrations for extended period of time, however no standards are currently in place for sediments. The model results from Scenarios 1 and 2 indicated that has been a considerable reduction in SS and TP yields from the mitigation sub-catchment with smaller reductions at the larger catchment. This reduction was achieved in the model by trapping SS and particulate P in the attenuation store which thus replicates the behaviour of the runoff attenuation features during WY 2014-5. Lastly, the long term goal of the modelling component of the EdenDTC is to upscale the model to the larger River Eden sub-catchment gauged at Temple Sowerby (over 600 km^2), which will require in-stream routing effects and nutrient transformations to be considered. Model results can be used to evaluate the number and area of the mitigation features that will need to be constructed in the larger catchment in order to improve water quality and meet the WFD targets for phosphorus in the Eden.

Keywords: *Phosphorus export, suspended sediment export, lumped hydrological modelling*

Concepts, Philosophy and Methods for Development of a General Linear Statistical model for River Water Quality

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Abstract: The modelling of water quality is of considerable importance understanding how to intervene or manage the water quality output from catchments. Modelling methodologies exist from bottom up mechanistic models, through hybrid models to statistical models. Here we will describe a statistical modelling methodology which was developed for forecasting water quality in the Great Barrier Reef catchments using a general linear model in terms of the concepts, philosophy and methods.

The conceptual model considers the pathways that exist for constituents (solutes and particulates) in the streamflow to be transported from the soil in the catchment to the stream (Fig. 1). These can be grouped into those flowing over the surface of the soil where there is an interchange between the soil and the surface soil, including exfiltration and flow coming into the stream via groundwater flow mainly as baseflow.

The philosophy of this model is to create the most efficacious model using the least complex modelling framework with easily available data. Streamflow components of: the hourly streamflow (Q (m^3 s^{-1})); hourly baseflow (q (m^3 s^{-1})); the sum of Q minus the long-term mean flow (Q_m (m^3 s^{-1})) were chosen to represent the flow components. Q_m represents a measure of the catchment condition prior to the flow, with negative values representing dry and positive values wet catchment conditions. The differentials of these flow components with time (t (s)) were calculated. The sign of the differentials represents the rising or falling limb of the hydrograph and the magnitude the rate of change. Integrals of Q, q and Q_m were calculated for different lengths of times prior to the measurement time. Transforms of all these components with a power of 0.2 and 2 were calculated. Finally, two orthogonal periodic time-based components $\sin(2\pi t/86400P)$ and $\cos(2\pi t/86400P)$ with P = 365 day were calculated. These covariates are first filtered in a univariate way with the seven constituents: Total Suspended Solids (TSS), Particulate Nitrogen (PN), Dissolved Inorganic Nitrogen (DIN), Dissolved Organic Nitrogen (DON), Particulate Phosphorus (PP), Dissolved Inorganic Phosphorus (DIP) and Dissolved Organic Phosphorus (DOP). With the transforms, this results in 77 possible univariate relationships. These are filtered so only those with an $r^2 \geq 0.1$ are selected subsequent analysis using a multivariate additive general linear model. The fitting process also allows the constituent to be transformed and the best model selected with a maximum of five covariates. This process is semi-automated and can result in millions of possible models which reduced in a selection processes to give the model that best fits measured constituent data. The data was split so that validation could be attempted. This model can then be used along with the streamflow data to estimate the constituents in hindcast and forecast mode and uncertainty estimated.

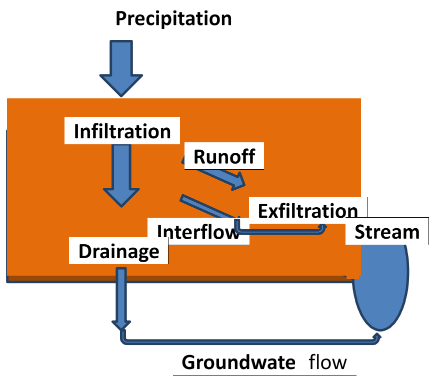

Figure 1. Schematic diagram of components of flow from a catchment to stream

Keywords: *Water quality, statistical model*

Dispersion in Solute Transport Models: Concepts and Limitations in Simple Models

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Abstract: Dispersion occurs when solutes are transported in the atmosphere, porous media or waterways due to several processes. Dispersion smears out the concentration if a pulse input occurs on the inlet face of a domain as the solute is transported in the domain. This is due to a combination of molecular diffusion, due to the concentration gradient and fluid velocity differences occurring within the fluid. The effect of dispersion is critical when computing solute transport as the solute will arrive sooner than under purely advective (piston front) and although at a lower concentration may still be critical if a contaminant is above a threshold level.

Many models that describe solute transport use a simple box structure, with the spatial domain split into discrete volumes. The solute is then transported between the boxes using a transfer coefficient to account for both advection of the carrier fluid and dispersion. When both the time step and spatial discretization are small these models can approximate the differential equations of flow. However, when the time step and or spatial discretization is large they become models where dispersion is either added explicitly or implicitly as a consequence of the method of computation. In both cases it is worthwhile being able to determine how the method of computation affects dispersion in these models.

One method that is used with box models is to assume that all of the solute entering the box in the time step is fully mixed by the end of the time. This method is called a fully mixed tank reactor (FMTR). This method introduces dispersion purely by the method of computation, but this may be too little or too much dispersion. We consider a box model for a river or stream and use both the travel time of the water through the box and the Peclet number to consider their effect on the solute concentration at the outlet compared to an analytical solution of the transport.

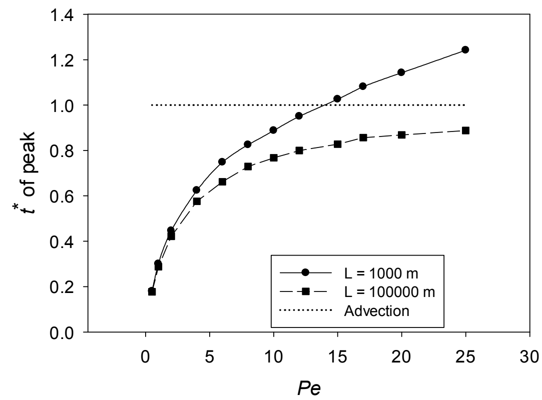

Figure 1. Dimensionless time (t^*) at which the peak concentration is reached at $x = L$ for a pulse input at $x = 0$ at $t = 0$. Also shown is the time that a 'piston' or advective peck would arrive at L.

Box models can trace a pulse of solute using advection and a fully mixed tank reactor (FMTR) model or by determining the centre of mass of the pulse. Here we compare how these different approaches will introduce errors in the concentration, related to the Peclet number of the flow, and show that if the true behaviour is to be approximated using a FMTR, the reach length or time step would have to vary with the flow velocity.

A purely advective approximation for determining the concentration center of mass can also fail as dispersion will move the centre of mass as well as advection. This can result in underestimation of concentration and arrival times of the peak concentration. Figure 1 shows the time of arrival at the outlet for a FMTR and piston flow methods.

Keywords: *Dispersion, box models, solute transport*

Modelling the impact of climate change on water quality

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Abstract: In order to capture the impact of climate change on water quality, it is necessary to capture the impact of rainfall intensity on streamflow generation and mobilization of constituents transported in surface flows. This can be achieved by either using a daily model that has an additional input information about the rainfall intensity probability distribution within each timestep, or running the model at a high temporal resolution.

As part of a study of water quality in six catchments in the ACT, a model has been conceptualised using the second approach (running the model at a high temporal resolution). The model consists of 2 components. The first component is a rainfall-streamflow module which uses 6 minute resolution rainfall data to model the impact of rainfall intensity on generation of streamflow. The second component uses the effective rainfall generated by the rainfall-streamflow module to estimate the mobilisation of each constituent, and from there, an estimate of the load. The concentration is then obtained by dividing the load by the streamflow.

The first component uses the catchment moisture deficit (CMD) version of the IHACRES rainfall-streamflow model to generate the effective rainfall, and state dependent non-linear unit hydrograph to convert effective rainfall into streamflow. The discrete-time state dependent model has the form

$$q_k = a(S_k)S_k,$$

where q_k is the average flow over timestep k, S_k is the storage at time t_k (start of timestep k) and a is the state dependent storage coefficient. By definition, a must lie between 0 and 1, and be a monotonically increasing function of S_k. In addition, conservation of the magnitude of flows (if $q_{1,k} > q_{2,k}$, then q_1 must be greater than q_2 for all future timesteps) requires that $\frac{dq_k}{dS_k} < 1$. An example of a functional form that satisfies these conditions is

$$a(S_k) = \frac{S_k^\beta}{\alpha + S_k^\beta},$$

providing that $\alpha \geq 0$, and $\beta \leq 1$.

While the first module has been developed, the available data does not permit testing of the second module (primarily due to the lack of information about the time of observation). Work is underway to test the second module. In this paper, the performance of the first module will be presented for a number of catchments. The form of the second module will also be discussed, as well as an analysis of the behaviour of the model in terms of predicting probability distributions and long-term loads.

Keywords: *Water quality, rainfall-streamflow modelling, temporal resolution, non-linear unit hydrograph*

Exploration of implications of water quality constraints for land use intensification using a national model

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Abstract: The National Policy Statement for Freshwater Management in New Zealand (NPS-FM) has introduced a system of national water quality objectives. We developed a national modelling approach to identify the implications of this policy for the capacity for new agricultural development. The analysis addresses questions of whether contaminant loads need to be reduced to meet the desired water quality state, or whether there is capacity to increase loading while remaining within water quality objectives, including consideration of whether new mitigation measures can create capacity for further development.

The water quality objectives include ‘bottom-lines’ for stream nitrate toxicity, periphyton biomass, *E. coli* concentrations, and lake TN and TP. For this study, periphyton biomass was linked to mean annual TN and reactive phosphorus via regression models. The current water quality state was assessed for each reach in a digital representation of New Zealand’s river network (about 560,000 reaches) using either monitoring data or spatial regression models. Changes in water quality state resulting from land use change or introduction of mitigation measures were assessed by changes in mean annual loading of contaminants, which in turn were determined from a national water quality model CLUES. Water quality was assessed against bottom lines at monitoring locations and confluences of large streams or rivers. In addition to bottom lines, the NPS-FM also requires water quality to be maintained or improved, and this condition was applied in our modelling either at assessment nodes or only catchment outlets to the coast.

Heuristic methods were used to determine the implications of water quality constraints spatially. As a first step, mitigation was applied. Then, loading in the catchment was increased to either bring the concentrations back to the original level or to the bottom line, except that if bottom lines are still breached after mitigation, then no increase in loading was permitted. A key concept is that the loading could not increase for any subcatchment if any downstream location breaches the bottom line or exceeds the original concentration. To deal with such spatially-cumulative effects, an iterative stream tracing procedure was used. In this procedure, the most constraining node in a catchment was identified (the location where the required fraction of load reduction was largest, or allowable increase was smallest), then the load in all upstream locations was reduced accordingly, and then the process of finding the constraining location and adjusting loads was repeated until all locations met the bottom-line and maintenance constraints.

The study found that current *E. coli* guidelines for primary contact severely constrains capacity for development; current loads need to be reduced to meet the primary contact objectives, even after applying mitigation. We note that, water quality bottom lines for primary contact recreation have been altered subsequent to this study. At the other extreme, nitrate toxicity bottom lines provided were limiting in only small areas; consequently, the capacity for development was limited by the requirements for maintaining or improving water quality, and capacity essentially matched the amount of mitigation. Applying constraints to maintain water quality only at the stream outlets rather than at all nodes did not appreciably change the estimated capacity for further development. If water quality was allowed to deteriorate to the bottom of the current water quality grading band, then significant capacity could be introduced.

Overall, the results were consistent with our intuition. However, we found that often people did not appreciate how failing to meet a bottom line at a location constrains development in the entire upstream catchment. The analysis entailed multiple assumptions and calculations and aspects of the methodology were difficult to communicate. Generally, it was understood that the analysis was approximate in nature only, so many of the uncertainties and inaccuracies were accepted. More fundamentally, the model did not address how contaminant loads could be redistributed while maintaining current loads and increasing land intensification by, for example locating intensive land use on areas that are less prone to contaminant losses through cap and trade approaches. Alternative methods such as land use optimisation at national scale could be used in the future, to explore the implications of more subtle load allocation approaches.

Keywords: *Water quality, planning, model*

Conceptual modelling for water quality management

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Abstract: Water quality models are replete with implicit assumptions. Some of the assumptions may be legacy in nature, having originated from early development of a model and subsequently taken for granted within the scientific community. For instance, Easton et al. (2008) reported that the SWAT model implicitly assumes an infiltration-excess response to rainfall when predicting storm runoff, which is not applicable to humid, well vegetated regions and where saturation-excess is the dominant process. The re-conceptualisation of the SWAT model then led to the development of a new modelling approach SWAT-VSA.

Development of an appropriate suite of conceptual models should be one of the first steps in water quality modelling – appropriate in the sense that they capture key operating processes (runoff generation, transport and delivery) and landscape connectivities within catchments. The history of water quality modelling is one of evolution with most of the popular models built on, or adapted from, existing models or experimental studies. As a consequence, the conceptualisations underpinning these models are rarely scrutinised sufficiently.

In this paper, we use the eWater Source modelling framework as a case study for critically analysing conceptualisations of constituent generation and transport fluxes. We have selected this product as its water quality modelling component is currently being enhanced and our analysis can usefully inform its future. Our observations, which are pertinent to many water quality models, include:

- The current filtration and transport processes are basic representations. Depending on the water quality parameters being modelled, these may not be sufficient to capture the range of processes needing to be quantified in catchment modelling projects.
- The base spatial unit for generation is an unlinked functional unit (FU), which is a property-based semi-distributed approach to spatial discretisation. This limits the ability to capture important factors such as the distance of FU to streams, drainage/channelisation on FUs and relationships between FUs in the same subcatchment.
- The temporal scale for constituent generation is generally daily. Moving to sub-daily scales may be needed to better capture the influence of rainfall intensity, especially in urbanised catchments.
- Some aspects of management impacts are not adequately considered, such as lag-time between catchment management actions and system response.

It could be argued that many of these conceptualisations are simplifications designed to balance complexity with usability and computational efficiency. Nevertheless, they need to be challenged and alternatives explored if we are to advance the science and practical effectiveness of water quality modelling. In this paper we report our initial investigations and propose some potential improvements in conceptualisation to allow for better representation of the system for water quality management.

Keywords: *Conceptual modelling, water quality, eWater Source, water quality modelling, generation, delivery and transport processes*

Water quality modelling needs survey: are we doing the right sums?

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Abstract: Water resources management often involves the monitoring and management of water quality and quantity. Many water quality models have been developed to determine the source, transformation and transport of constituents in catchments and through a water body. In practice, they can be used to predict water quality in areas where monitoring is not feasible, or to predict water quality conditions resulting from different management strategies and under specified climate regimes. Research into the development of water quality models has mostly focussed on better representation of the biophysical processes (e.g. formulae to represent the generation, filtration, transformation and transport processes of different constituents, spatial and temporal dynamics of the constituents), better software platforms, or on tools for measuring the predictive skill of the models (e.g. calibration tools, sensitivity and uncertainty assessments). There has been limited research into the relationships between management practices and water quality (e.g. instream and riparian buffers, land cover practices and land use change effects). Most of the development and investigations into water quality modelling has focused on making better predictions, but few studies have reported on model user needs and how to design and select models that are fit-for-purpose. That is, a lot of focus has been on doing the sums right, but not a lot on doing the right sums.

One example of the above is the development of the eWater Source software framework. In the last few years, Source has increasingly been adopted in Australia as a national level approach to catchment modelling, and large investments are being made by State government agencies to make the transition to the Source framework. The water quality modelling within Source was informed by a survey of user needs undertaken in late 2003 (Newham et al, 2004), adapted to suit the underlying catchment conceptualisation. Sufficient time has passed to revisit that implementation as experience has shown that the existing default constituent models in Source do not have sufficient capacity to support investigation of the land use and land management changes happening, or proposed to happen, in Australian catchments. This points to our assertion that the questions being asked now are different to those asked in 2003 and that water quality modelling may require a 'better' conceptualisation. Is this true?

In this presentation, we review some of the commonly used water quality models, focusing on the type of questions they endeavour to answer. We then present findings of our pilot survey with selected water managers that was aimed to elicit their water quality model needs. Finally we propose a survey design to elicit user needs of water quality modelling. The audience will be invited to participate in the survey onsite.

Keywords: *Modelling, water quality, catchment management, water quality conceptualisation, user survey*

Understanding the spatial variability in catchment dynamics: a case study of 107 stream catchments in Victoria, Australia

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Abstract: Rivers and streams around the world are being affected by declining water quality. When designing remediation strategies, we must first understand the key factors affecting spatial and temporal variability in stream water quality. As such, the objective of this investigation was to investigate the relationships between in-stream constituent concentrations and streamflow and to understand how these relationships vary across space. We intend to use these findings to add a temporal component into existing statistical models of spatial variability in water quality.

Monthly water quality data for total suspended solids (TSS), total phosphorus (TP), filterable reactive phosphorus (FRP), total Kjedahl nitrogen (TKN), nitrate-nitrite (NO_x) and electrical conductivity (EC), in addition to streamflow collected between 1994 and 2014 from 107 water quality monitoring sites in Victoria were used for this study. Using these data, we characterized the interaction between constituent concentrations and streamflow in terms of (i) the ratio of the coefficient of variation (CV) of constituent concentrations to the CV of streamflow (CV_C/CV_Q) , and (ii) the slope of the linear regression between the log-transformed constituent concentrations and log-transformed streamflow (the C-Q slope). We then linked the spatial variations in CV_C/CV_Q and the C-Q slope to catchment characteristics (e.g., land use and climate).

We found that the interaction between constituents and streamflow depends significantly on the reactivity of the constituent, and whether the constituent is in the dissolved or particulate state. TSS, TP, TKN, FRP and NO_x demonstrated chemodynamic behavior, with the concentrations varying with streamflow (i.e., high CV_C/CV_Q and large absolute value in C-Q slope). On the other hand, EC demonstrated chemostatic behavior for the selected sites, with low CV_C/CV_Q values and C-Q slopes.

The interaction between streamflow and constituents varied significantly across space. The variability in CV_C/CV_Q for TSS, nutrients and salts correlated positively with catchment characteristics such as mean catchment slope, average annual rainfall and woodland cover. This could be due to the weaker sources of TSS due to reduced erosion, nutrients due to zero or low application and salts due to high leaching in steeply sloping, vegetated and high rainfall catchments (as they tend to be less disturbed). Lower magnitude and less temporal consistency of constituent sources can lead to greater variability in constituent concentrations relative to streamflow. The spatial variability in C-Q slopes generally did not correlate strongly to catchment characteristics, likely due to the presence of major dams in approximately half of the water quality monitoring sites. However, once these sites were removed, we found that the TSS C-Q slope correlated strongly to average annual rainfall and the mean 7-day low flow. This suggests that there is a stronger positive linear relationship between TSS concentrations and streamflow in catchments with temporally consistent rainfall and streamflow. There were weak correlations between catchment characteristics and the C-Q slopes for nutrients regardless of the exclusion of the water quality monitoring sites with dams. This could be due to the reactive nature of these compounds, leading to less predictable interactions between streamflow and in-stream concentrations.

The results of the analysis will be used to develop statistically-based predictive models of spatio-temporal variability in stream water quality.

Keywords: *Stream water quality, spatial variability, temporal changes, catchment dynamics*

Modelling Pittwater Lagoon for risk assessment of an effluent spill

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Abstract: We present a model system that quantifies the spatial and temporal footprint of passive tracer release to inform the assessment of risk of microbial contamination associated with a waste water effluent spill. Whilst biological contaminants are dynamic in nature a passive tracer can be used as a proxy over short timescales to quantify the spatial and temporal footprint of risk. The model system is demonstrated in Pittwater Lagoon, southeast Tasmania and operates in near-real-time with a 1-2 day forecast capability for live prediction of waste water spill dispersal.

The CSIRO SHOC hydrodynamic model was implemented on a very fine resolution curvilinear 3D grid (40 m horizontal; 0.5m vertical) and assessed against in situ observations collected by near real time sensors reporting pressure, temperature and salinity. The timing and magnitude of observed fluctuations in temperature, salinity and sea level were well reproduced by the model indicating that the main drivers of the thermal, salinity and flushing dynamics were well captured by the model, and confirming that the model is suitable for the investigation of potential spill dispersal scenarios. Near real time simulation of potential effluent spills was achieved by the periodic release of passive tracer particles from known vulnerable locations in the inner- and outer-Lagoon. Movie loops of particle dispersal from each location are displayed on the web and results are updated every few days to provide a synopsis of recent conditions and a short term forecast. In addition eleven specific hind-cast spill scenario simulations were implemented to explore the impact of variations in river in-flow, Spring-Neaps tidal cycles and wind direction on spill dispersal proximal to oyster leases. Model results were analysed to calculate the time taken for 1% of the spill source to arrive at each of 31 separate oyster lease locations. In general spills in the inner Lagoon rapidly arrived at oyster leases in the inner Lagoon (in less than 1 day), whilst spills in the outer Lagoon rapidly arrived at leases in the outer Lagoon. During spring tides spills were more rapidly distributed throughout the region and arrived at oyster leases faster than under comparable conditions at neap tides. Wind impacted the trajectory of spills with northwest winds slowing the dispersal of distant sources into the inner Lagoon by several days (compared to northeast winds). Under high river in-flow oyster leases in the inner Lagoon were quickly impacted by potential river effluent, but under low river in-flow this source did not spread to any lease within a week.

These scenario simulations have provided valuable insight into the dynamics of potential effluent spills in Pittwater Lagoon and their impact on local oyster leases. In addition, the ongoing near real time and forecast model provides continuous and timely insight of the potential risk of effluent spills for science based resource management. This study can be generalized and applied to other shellfish farming areas and species.

Keywords: *Spill dispersal, risk forecast, hydrodynamic model, coastal lagoon*

Assessment of the GBR Source Catchments model to estimate fine-sediment streambank erosion and export

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Abstract: Streambank erosion presents a serious threat to a range of aquatic ecosystems, from freshwater to marine, including the Great Barrier Reef (GBR), Australia. Therefore, it is imperative to continue to assess and improve techniques to estimate the magnitude and spatial distribution of streambank erosion across the GBR catchments to assist with prioritising where remediation should be undertaken and to evaluate the efficacy of strategies proposed to prevent bank erosion.

The GBR Source Catchments modelling framework via the Dynamic SedNet (DS) plugin, provides a means of predicting fine-sediment streambank erosion at a user specified stream reach scale. DS calculates a mean annual rate of streambank erosion as a function of various hydro–geomorphic characteristics of streams. The mean annual streambank erosion is then disaggregated as a function of the daily flow and distributed over the model run period. The daily streambank erosion load is then apportioned to fine and coarse sediment according to the clay and silt proportion. Where appropriate data is available to parameterise the model, DS can also be used to assess the efficacy of strategies proposed to prevent streambank erosion. Moreover, in addition to streambank erosion, DS estimates total fine-sediment export to the GBR by simulating fine-sediment supplies from other major sources (e.g. hillslope and gully erosion) and losses at various sinks (e.g. floodplains and dams).

In this study, DS modelled fine-sediment streambank erosion along the O'Connell River (~ 45 km), lower Burnett River main-stem (~ 300 km), East and West Normanby Rivers (~ 42 km and 39 km) and Laura River (~ 29 km) were compared against published estimates. DS modelled total fine-sediment exports to the GBR from the O'Connell and Burnett basins, and Normanby River were also compared against estimates from the Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP) to ensure modelled total fine-sediment exports were sensible.

The comparison between DS modelled fine-sediment streambank erosion along the O'Connell River between 2010 and 2014 against that estimated by the O'Connell River stability assessment (ORSA) was encouraging. The DS estimate was only 8% greater than the ORSA estimate. Moreover, DS modelled total fine-sediment export from the O'Connell basin to the GBR was only 2% lower than the GBRCLMP estimate.

The Burnett River channel and bank stability assessment (BRCBSA) estimate of fine-sediment streambank erosion along the lower Burnett River main-stem was approximately six times greater than that modelled by the DS between 2009 and 2013. The Normanby basin sediment budget assessment (NBSBA) estimates of average annual fine-sediment streambank erosion along the East and West Normanby, and Laura Rivers were approximately 75, 50, and 55 times greater than that estimated by DS. Despite these discrepancies, it is encouraging to note that DS modelled total fine-sediment loads exported from the Burnett basin and the Normanby River showed good agreement with the GBRCLMP estimates. Modelled total fine-sediment exports from the Burnett basin and Normanby River were only 3% greater and 6% lower than the GBRCLMP estimates respectively.

This work demonstrates that the GBR Source Catchments modelling framework via the DS plugin can be used for approximating total fine-sediment loads being exported to the GBR. Despite the ability of DS to estimate fine-sediment streambank erosion along the O'Connell River, further investigations are required into the discrepancies between DS modelled and published estimates of fine-sediment streambank erosion by the BRCBSA in the Burnett, and by the NBSBA in the Normanby, and Laura Rivers.

Keywords: *Streambank erosion, GBR Source Catchments Modelling, Dynamic SedNet*

Spatial Variation in Dissolved Inorganic Nitrogen Export from Sugarcane Areas in Mackay-Whitsunday

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Abstract: Anthropogenic dissolved inorganic nitrogen (DIN) loads exported from sugarcane areas in the Great Barrier Reef (GBR) catchments have the potential to impact the health and resilience of the GBR. Therefore, water quality targets have been set as part of the Reef Water Quality Protection Plan to reduce anthropogenic DIN loads. While it is recognised that achieving those targets will require changes to landuse and nutrient management practices, uncertainties around the underlying processes that contribute to DIN loads limit the ability to prioritise management practices needed to maximise water quality benefits. Thus, as part of the Paddock to Reef program, significant efforts have been made to better understand the pathways and quantities of DIN export from sugarcane areas. This includes an integrated paddock-to-catchment scale water quality modelling approach informed by an extensive monitoring program.

Paddock scale models developed on the Agricultural Production Systems sIMulator (APSIM) framework estimate DIN export in sugarcane areas via surface runoff and through 'leaching' beyond the root zone. APSIM estimated DIN export via surface runoff is delivered entirely to the streams in the catchment scale models developed on the GBR Source Catchments modelling framework. The GBR Source Catchments models also have the ability to deliver a proportion of the APSIM derived leached DIN below the root zone to the stream via lateral flow. DIN load delivered to the streams via lateral flow is controlled by a user-specified delivery ratio.

A Mackay-Whitsunday catchment model was developed to estimate the regional DIN export to the GBR between 1986 and 2014. The model was calibrated by minimising the bias of the modelled average annual DIN loads against that measured as part of the Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP) at seven monitoring sites located in the Pioneer, O'Connell, and Plane basins. The delivery ratio for the DIN load delivered to the streams via lateral flow was modified spatially to minimise the bias.

The best match between modelled and measured average annual DIN loads was achieved with a higher delivery of leached DIN to the streams via interflow (~ 4.7 kg/ha/yr) across sugarcane areas in the Pioneer basin, while that was lower (~ 0.8 kg/ha/yr) across sugarcane areas located upstream of the Sandy Creek at Homebush and O'Connell River at Caravan Park GBRCLMP sites. These results suggest an increased proportion of DIN loads percolated below the root zone may be exported from sugarcane areas in the Pioneer basin. This may be due to a combination of reasons, including:

- preferential lateral flow across sugarcane areas located along steeper foothills of the upper Pioneer basin due to downslope hydraulic gradient; and
- seepage of perched water tables (or ephemeral aquifers) as a consequence of shallow bedrock and (or) subsoil layers of the texture-contrast (duplex) soils that impede drainage.

Spatially varying the delivery of leached DIN export via interflow in the model to match the average annual DIN loads at monitoring sites is a good first approximation in the absence of detailed experimental data and requires additional monitoring and modelling to further validate this approach.

Keywords: *Dissolved inorganic nitrogen, APSIM, GBR Source Catchments model, leaching, seepage*

River plumes of the Great Barrier Reef: freshwater, sediment and optical footprints quantified by the eReefs modelling system

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Abstract: The rivers of the northeast coast of Australia flow into the coastal and shelf regions of the Great Barrier Reef (GBR), delivering high loads of nutrients, sediments and freshwater during the wet season period. A significant component of the loads come from anthropogenic activities. These river plumes impact on marine environments through exposure to low salinity and high pesticide concentration seawater, and increased attenuation of light as a result of terrestrially-derived colour dissolved organic matter (CDOM), suspended sediments and phytoplankton. A coupled hydrodynamic, sediment, optical and biogeochemical model of the GBR (eReefs) provides a new means to quantify the multiple impacts of river plumes. In this paper, the spatial and temporal extent of freshwater plumes are calculated using the release of river tracers from 21 rivers along the Queensland coast in the first six months of 2016. To quantify the sediment plume extent, we use a threshold of 1 mg L^{-1} surface suspended sediment concentrations. Past observational studies have quantified optical plumes along the GBR using changing ocean colour. We use the eReefs optical model capability of simulating remote-sensing reflectance from simulated optically-active in-water properties (e.g. sediment concentration) to provide a quantification of the footprint of optical plumes. Simulated optical plumes are classified using the same scheme developed for remotely-sensed optical plumes, providing the opportunity to assess simulated plume classification against the observed plume classifications. Snapshots on a relatively cloud-free day of the observed plume classes and observed true colour, and of the simulated plume classes and simulated true colour, show that the model captures the broad regions of colour, and therefore plume classification.

A comparison of different methods of plume identification in the Burdekin plume during a high discharge event illustrates complexities of quantifying plume extent. The river tracer shows the distribution of Burdekin River water, with a plume extending to $\sim$ 7 km offshore, in a roughly 5 m deep surface flow. The shape of the freshwater plume is similar, although during periods of evaporation / rainfall it becomes difficult to distinguish individual plumes from salinity alone. The optical plume classifications correspond well to the river tracer and freshwater plumes within the actual plume, but result in plume identifications outside the actual plume due to tidal and wind-driven resuspension and bottom reflectance.

The river discharge, as well as the river tracer, freshwater, sediment and optical plume extents were quantified for the wet season of 2016. The strongest mean river discharge came, in decreasing order, from the Fitzroy, Normanby, Burdekin and Tully rivers. The freshwater footprints were slightly re-ordered, with the largest spatial extents of the Normanby, Fitzroy, Burdekin and Tully. The Fitzroy had easily the largest sediment plume, followed by the Pioneer. In summary, through considering freshwater, sediment and optical plumes of the major rivers, we provide a comprehensive view of the footprint of terrestrially-derived loads on the marine waters of the GBR.

Keywords: *Ocean colour, catchment loads, suspended sediment, chlorophyll*

Sensitivity analysis of constituent generation parameters of an integrated hydrological and water quality model using a GMDH polynomial neural network

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Abstract: Catchment water quality models are notoriously over-parametrised. Given this condition, it is useful to be able to identify which parameters have the greatest influence on the model results. In theory, this could be accomplished through a detailed first principles interrogation of the mathematical structure of the model in an abstract manner. This however, is impractical in most instances owing to the complexity of the models and *posteriori* methods of parameter sensitivity analysis are more conventional.

As with most aspects of large-scale modelling endeavours, a major consideration in choosing a technique for sensitivity analysis is efficiency and a compromise between computational effort and numerical accuracy is usually negotiated. ANOVA based sensitivity analysis methods are very popular as they offer a holistic survey of the parameter sensitivity by not only accounting for the response of the model output surface due to the activity of single parameters acting independently, but also due to the interaction between parameters. These global sensitivity indices are usually calculated by Monte Carlo simulation and may be too computationally demanding to be routinely applied in water quality modelling scenarios.

We demonstrate the application of the group method of data handling (GMDH) inductive, self-organising modelling method to the sensitivity analysis of constituent generation parameters of an integrated hydrological and water quality model. By using a modestly sized sample input-output dataset, a GMDH neural network is used to synthesise a sparse, random-sampling high dimensional model representation (RS-HDMR) that can be used to calculate first and second order Sobol sensitivity indices. This algorithm potentially leads to reductions in computational cost of 2-3 orders of magnitude over Monto Carlo simulation.

Although several other adaptive methods for efficiently constructing a sparse RS-HDMR have been reported in the literature, such as polynomial chaos expansions, the parameter selection and noise filtering characteristics of the GMDH network may result in more optimal HDMR expansion.

Keywords: *Sensitivity analysis, neural networks, water quality model*

Use of remote imagery to verify modelled streambank retreat rates

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Abstract: The Source Catchments model attributes fractions of the sediment load carried by the rivers discharging into the Great Barrier Reef (GBR) lagoon, to specific sources – namely, hillslope, gully and streambank erosion. This study was conceived to determine whether it was possible to derive estimates of streambank retreat rates in a river discharging into the GBR lagoon, by using remote imagery. This remote imagery was to be in the form of readily available historical aerial photographs and more recent satellite imagery. Any usable estimates of streambank retreat rates that were obtained, were to be evaluated in regard to their suitability for the verification of the algorithms in the streambank erosion module in the Source Catchments model.

The streambank mapping exercise was undertaken using sets of historical aerial photographs and more recent satellite imagery covering some 150-kilometres in the middle reaches of the Mary River. This river carries a disproportionately large sediment load relative to its volumetric discharge. The Source Catchments model attributes this differentiating characteristic to above-average rates of streambank erosion in the Mary River.

The likely inundation extents associated with bankfull discharge were delineated in the various sets of historical imagery. This process yielded a time series of bankfull discharge polygons covering the subject reaches. Estimates of bankfull width were then obtained by laying transects at 500-metre intervals along and at right angles to the river centerline, in each set of images. This provided measurements of bankfull width at each transect location in each polygon in the time series. Digital elevation data obtained from airborne LiDAR surveys was used to aid verification of the bankfull width estimates derived from contemporaneous remote imagery. Streambank retreat rates were then determined on the basis of the change in bankfull width in the intervals between the sets of images in the time series. The statistical significance of the long-term rate of streambank retreat at each transect location was assessed by fitting the non-parametric Theil-Kendall Robust Line to the data.

Changes in bankfull width varied substantially along the studied reaches, but did show a somewhat remarkable lack of temporal variability at the various transect locations. Spatial variability appeared more closely related to stream sinuosity than it did to presence of upper storey riparian vegetation. Notwithstanding the observed uniformity of the long-term trends, temporarily accelerated streambank retreat rates were associated with major floods.

This study confirmed that the streambank retreat rates in the Mary River are relatively high when compared to other rivers discharging into the GBR lagoon. Furthermore, the broadscale retreat rate values presently adopted in Source Catchments model were found to be reasonably accurate. However, at a finer scale the modelled and measured estimates of retreat rates were somewhat disparate. The nature of this study precluded definitive identification of causative factors, but indicated that some refinement of the streambank erosion algorithms, or the applied data values, might be required if this disparity was to be addressed.

Keywords: *Source Catchments model, Mary River, remote imagery, model verification, streambank retreat*

Pollutant target setting for the Great Barrier Reef: Using the eReefs framework

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Abstract: Loads of fine sediment, nitrogen and phosphorus from the 35 major basins of the Great Barrier Reef (GBR) catchment have increased greatly over the last 150 years associated with catchment development for agriculture and urban uses. These increased loads have caused a range of effects in the GBR resulting in loss of coral and seagrass. Major effects include the promotion of increased populations of the coral predator – the crown of thorns starfish via increased nutrient availability, now a major cause of coral mortality on the GBR. A second major effect associated with increased fine sediment and nutrient loads is an increase in GBR inner-shelf turbidity and a subsequent reduction of light for coral and seagrass photosynthesis. Currently coral cover on the GBR is in a state of severe decline associated with these water quality effects and the increasing effects of climate change.

The water quality management plan for the GBR – Reef Plan, requires targets to be set to reduce basin pollutant loads so that marine and coastal ecosystems can be maintained in a satisfactory state. In the past targets were set for the whole of the GBR but it is now recognized that targets at the individual basin scale are required to guide management and account for the differing river plume footprints and spatial distributions of marine ecosystems along the GBR. Now as part of the Reef 2050 Water Quality Improvement Plan 2017-2022, targets for fine suspended sediment (FSS), dissolved inorganic nitrogen (DIN), particulate nitrogen (PN) and particulate phosphorus (PP) are to be set for the 35 basins to be achieved by 2025. The targets are designed such that an ecological endpoint is reached in the GBR, which represents a satisfactory ecological condition.

Over the last 4 years CSIRO and partners have developed the eReefs marine modelling framework. The eReefs regional and relocatable models include hydrodynamic, sediment, wave and biogeochemistry models for the GBR ecosystem. The numerical models are capable of simulating and predicting the hydrodynamic state, sediment transport, water quality and basal ecology of the Great Barrier Reef lagoon and reef matrix and hence model the transport and fate of waterborne material, whether of oceanic or terrestrial origin, and its impact on GBR water quality. eReefs is now being used to help set the basin scale targets.

eReefs has included 17 of the GBR basins in the modelling carried out in 2016. Targets for the other 18 basins were estimated using other models and techniques. The eReefs modelling used the 4 km resolution version, four years of simulation (2011 – 2014) with loads from the Source Catchments model. The final endpoint criteria chosen for the estimation of targets such that specific ecological outcomes were included in the modelling were:

1. Improved coral diversity versus macroalgae. Reducing DIN loads leads to an increase in coral diversity and a reduction in macroalgae abundance. Meeting a threshold Chlorophyll a (Chl-a) concentration is used as a proxy for nutrient status. The criteria is: Chl-a $< 0.45\ \mu g\ L^{-1}$, all years, all waters within river footprints.

2. Improved seagrass "health". Reducing FSS loads leads to reduced turbidity throughout the year and improved light availability in shallow areas (< 10 m) which is a key driver of seagrass abundance. The underwater light field is a reasonably intrinsically-predictable phenomena. As the major human impact on seagrass health in GBR coastal regions is reduced light, it was considered better to directly consider bottom light than other possible criteria such as seagrass biomass. The criteria is: PAR-integrated light > 6 mol/m^2/day for seagrass, all years, < 10 m, all waters within river footprints – the "chronic" case.

Using scenarios that reduced fine sediment and DIN (and PN and PP in proportion with the FSS), in steps from each of the modelled basins, estimates of the loads required to meet the ecological endpoints were derived. Examples of the results include for the Tully Basin a reduction of 20 % of the current anthropogenic fine sediment load and a reduction of 50 % of the current anthropogenic DIN load are required by 2025.

Keywords: *Great Barrier Reef, pollutant load reduction targets, ecosystem health*

Improving gully density maps for modelling water quality within Great Barrier Reef Catchments

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Abstract: Fine-sediment has been shown to have a detrimental impact on water quality across the Great Barrier Reef (GBR). Gully erosion is one of the dominant sources of fine-sediment loads to the GBR, in particular from the Burdekin and Fitzroy basins. Significant funding has been allocated across the GBR catchments to reduce sediment erosion from gullies. Modelling the relative fine-sediment contribution from gully erosion, and assessing the potential water quality improvement due to investment in gully remediation projects within GBR catchments, is reliant on accurate maps of gully density. Hence, techniques that improve mapping of gully density are essential for improving the quality of inputs into catchment models, and will ultimately lead to improved modelled load estimates and better representation of the impact of remediation programs on sediment loads that are delivered to the GBR.

Previous attempts to map gully density within the GBR catchments have been conducted by either intensively mapping gully erosion for relatively small isolated areas where gullies are prominent, or by defining the extent of gully erosion at a number of sample sites and then using predictive models to estimate gully density across much larger areas. Due to scale limitations, low accuracy or limited geographic extent, both these approaches have produced maps with limited usefulness for modelling water quality improvements. Consequently there is a need for a methodology that can improve the confidence in gully density maps over broad areas, in a timely fashion, and at a spatial scale that enables the modelling of water quality improvements due to on-ground investments, and allows prioritising of remediation strategies in the GBR.

This paper outlines a repeatable process that allows an operator to map the presence or absence of gully erosion within a grid cell, using custom-built geographic information system (GIS) tools, aerial photography and uniform grids. Initially, a number of catchments in the Fitzroy and Burdekin basins were mapped using this approach to improve baseline model inputs for gully erosion. Over the past three years 125 000 km^2 have been mapped using this grid-based presence mapping (GBPM) approach.

Stage two of the work combined the grid-based mapping with a range of landscape attributes such as slope, distance-to-stream and soil erodibility to produce a predictive model that has the ability to generate gully density maps for all GBR catchments.

Finally, the maps from both processes were compared against ground-based observations and previously published estimates of gully density, to determine if these approaches delivered improved inputs for catchment models. Comparison of grid-based gully erosion mapping against ground-based observations show that the grid-based mapping improves the accuracy of the maps compared with previous mapping approaches. The grid-based mapping method developed in this project provides an effective way of capturing gully density data across broad areas. Combining grid-based mapping with predictive modelling enables the acceleration of gully-density mapping.

Keywords: *Source catchments, water quality, Great Barrier Reef, gully erosion*

Great Barrier Reef Source modelling: Assessing hillslope erosion modelling performance at paddock scale experimental sites

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Abstract: Catchment modelling is used as one of multiple lines of evidence to report on progress towards Great Barrier Reef (GBR) Water Quality Protection Plan (Reef Plan) water quality targets. Progress is monitored via the Paddock to Reef (P2R) Integrated Monitoring, Modelling and Reporting Program. Within the P2R program, the Source modelling framework is used to construct GBR specific models (McCloskey 2017) and the overarching purpose of the modelling is to assess the impact of land management changes across the GBR against Reef Plan targets.

To optimise predictive capability and thereby help facilitate better targeting, the modeller is faced with two common problems. Firstly, assessing the quality of model inputs and outputs and secondly, where possible, improving modelling performance. While observation datasets such as flow are often adequate, water quality data are scarcer, sporadically sampled, and frequently well downstream of their source. To further improve the water quality model validation data pool, the modelling team have attempted to tabulate all relevant datasets that can be used in model evaluation. However, utilising all available datasets to assess and improve performance can be an arduous task. As such, small catchment studies can initially be overlooked as a validation source in large "lumped" catchment scale modelling studies due to scale and the inherent spatial and temporal mismatch issues.

As a small illustrative case study, we firstly designed a simple methodology to disaggregate the lumped modelled hillslope loads for a grazing landuse in a subcatchment. We then discuss the benefit of paddock scale research sites for informing the GBR Source modelling.

In the GBR Source framework, spatially variable Revised Universal Soil Loss Equation (RUSLE) was used to generate the hillslope sediment loads for rangelands. Sediment loads are lumped and reported for a single landuse (typically1 km^2 – $30km^2$) for a given sub-catchment at a daily timestep. However the modelled daily loads are initially generated at a finer scale, typically, 30m by 30m - 900 m^2. As the individual grid calculations are not recorded at model runtime, they needed to be recorded prior to aggregation in the model. This enabled evaluations between GBR Source modelled loads and the much smaller catchment study data to be made at appropriate scales.

The disaggregation and assessment of modelled loads outlined in this paper facilitated small to large scale hillslope erosion comparisons. For the two case study sites, erosion and cover are shown to be well predicted at the average annual scale and areas for further improvement and investigation have been highlighted. We recommend further sites across the GBR be assessed.

Validating disaggregated modelled data against plot scale experimental data, provides an alternative data set for validation previously not utilised. The approach shows a lot of potential to improve confidence in modelled sediment generation predictions.

Keywords: *GBR Source model, GBR water quality, fine sediment*

Simple sensitivity analysis of a catchment scale water quality model at a range of spatio-temporal scales

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Abstract: Fine sediment generated from catchments of the Great Barrier Reef (GBR) is considered to be one of the main pollutants of serious concern affecting the quality of water entering the reef. Estimation of the amount of sediment that is generated from these catchments and the proportion that enters the reef lagoon for a given combination of land use and land management is being carried out under the Paddock to Reef (P2R) Program using the eWater Source modelling platform and the Dynamic SedNet plugin. Currently, water quality monitoring data from selected sites, including end of system sites, are being used to manually calibrate and validate the water quality model. However, the manual calibration attempted so far has mainly been based on trial-and-error. The main objectives of the simple one-at-a-time (OAT) local sensitivity analysis reported here are to: (1) identify parameters that the model reacts most sensitively to in order to simplify and accelerate the calibration of the model; (2) examine if the results of the sensitivity analysis depend on the spatial and temporal scales of investigation; and (3) compare the results to a more computationally intensive global sensitivity analysis reported in an associated global sensitivity analysis paper to be presented in this conference (Bennett and Fentie, 2017).

The choice of parameters included in the sensitivity analysis was determined based on a preliminary investigation on a relatively small test sub-catchment in the Burnett catchment by the first author. The preliminary investigation showed that fine sediment load is most sensitive to changes in three parameters (i.e., streambank sediment bulk density (ρ_s), hillslope sediment delivery ratio (HSDR) and gully sediment delivery ratio (GSDR)), which represent the three sources of sediment (streambank, hillslope and gully erosion, respectively) in the Source/Dynamic SedNet water quality model. The other three parameters included in the analysis – floodplain deposition settling velocity (V_p), channel average terminal fall velocity for fine sediment remobilization (ω_{dep}), and channel average terminal fall velocity for fine sediment deposition (ω_{mob}) – represent the effect of settling velocity of particles on sediment deposition on the floodplain and in the stream, and channel remobilization, respectively.

In order to explore the effect of catchment size and other characteristics on the sensitivity analysis, three locations with differing catchment area were chosen in this study. The location with the smallest catchment area drains the upper parts of the Burnett catchment while the location with the largest catchment area represents the Burnett catchment end of system (EoS). The third location is at the outlet of the Mary catchment.

Temporal variability in results of the sensitivity analysis was investigated by conducting the analysis at an annual time step summarised from the daily time-step model outputs of the 28 years modelling period of the Great Barrier Reef catchment modelling for Report Card 2016.

Results show that: (1) the modelled fine sediment loads were relatively highly sensitive to changes in streambank sediment bulk density (ρ_s), hillslope sediment delivery ratio (HSDR) and gully sediment delivery ratio (GSDR), but were only marginally sensitive to changes in the other three parameters; (2) the sensitivity of fine sediment load to changes in parameters varied across the three locations; and (3) the sensitivity of fine sediment load to changes in parameters varied annually. Sensitivities from this study have similar rankings of parameters to those from Bennet and Fentie (2017). Both approaches determined that modelled fine sediment load is relatively insensitive to changes in particle settling velocity parameters for both stream deposition and channel remobilization. Based on these findings it is concluded that (1) the simple one-at-a-time sensitivity analysis conducted in this study is adequate in determining the sensitivity of modelled sediment to changes in model parameters; and (2) since results of the local sensitivity analysis vary spatially from catchment to catchment and temporally from year to year, the analysis needs to be carried out for each specific catchment and period of interest.

Keywords: *Sensitivity analysis, water quality model, Source model, Dynamic SedNet, Great Barrier Reef*

Development of a dissolved inorganic nitrogen runoff concentration model for non-cultivated land in Great Barrier Reef catchments

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Abstract: Dissolved inorganic nitrogen (DIN) in runoff from agricultural systems has been identified as being the cause of more frequent outbreaks of the crown-of-thorns starfish (*Acanthaster planci*) which are a major factor leading to reduced coral cover of the Great Barrier Reef (GBR). To address this problem the Australian and Queensland governments Paddock to Reef Integrated Monitoring, Modelling and Reporting Program aims to document reductions in dissolved inorganic nitrogen (DIN) export to the GBR due to improved management in agricultural systems. DIN losses from sugarcane farming systems has been of particular interest due to sugarcane farms being in close proximity to the GBR, and a number of research studies indicating that stream water quality from catchments with a high proportion of sugarcane land use have elevated DIN concentrations. An analysis of sugarcane field trial data collected over the last 10 years indicates that surface runoff DIN losses at the paddock scale is not the major contributor to reef DIN loads. These results suggest reason to refocus on ascertaining DIN contributions from sources such as leachate from sugarcane farming and surface runoff from non-cultivated land. Here we focus on DIN contributions from non-cultivated lands.

DIN contributions to the reef from non-cultivated land are currently modelled using static event mean concentrations (EMC). However, a review of EMC's from non-cultivated lands indicated that there is up to a 10-fold range in DIN concentration (predominantly nitrate) between the 10th to 90th percentiles, indicating that the use of a static EMC within a model may be improved upon. EMCs are often used to represent a range of water quality constituents (e.g. sediment and nutrient concentrations). However, DIN unlike sediment is potentially a more variable constituent in the environment due to the various transformations and movements of nitrate in the soil e.g. - plant uptake, mineralisation, immobilisation, and denitrification. On this basis, and using the precept that the concentration of a constituent in runoff is related to the concentration of the constituent in the surface soil at the time of runoff, we used two Queensland government data resources to develop an approach of representing a spatial and temporally variable DIN EMC for non-cultivated lands.

The two resources used were: 1) measurements of surface soil (0-10cm) nitrate from the Queensland Government's Soil and Land Information database (SALI) and; 2) nitrogen cycle components derived from the Australian wide (resolution 5km x 5km) applied AussieGRASS pasture productivity model. The AussieGRASS model represents daily plant growth and water balance for 47 pasture communities in Queensland. Importantly these two resources are independent of each other and hence this provides the opportunity to identify whether there is alignment between the factors that drive soil DIN concentrations.

Two important factors were identified to be driving temporal variability in soil nitrate concentrations. Firstly, we identified surface soil nitrate was higher during October to February based on data from SALI. This annual pattern was closely aligned to the annual patterns of soil nitrogen derived from the AussieGRASS model. Secondly from using the SALI database we found important inter-annual variability in soil nitrate between wet and dry years. Median soil nitrate concentrations in dry years were up to five-fold greater than those in wet years. On a spatial basis, mean soil nitrate from the SALI database was found to be broadly correlated to the AussieGRASS parameter that represents soil fertility for the 47 pasture communities. The general agreement between SALI soil nitrate measurements and AussieGRASS nitrogen dynamics indicate that there is a sound basis for developing a spatial-temporal DIN EMC model for non-cultivated land. These preliminary results suggest that a spatial-temporal variable DIN EMC model could be developed using AussieGRASS outputs averaged at catchment scale. Advancements in representing the dynamic nature of soil nitrate in GBR catchments may allow for improved attribution of land use DIN losses to the GBR.

Keywords: *Nitrate, water quality, great barrier reef, land use*

Sensitivity analysis of the GBR Source catchment models

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Abstract: The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (P2R program) measures progress towards Reef Plan's goals and targets. Water quality modelling in the Great Barrier Reef (GBR) P2R program is implemented through the Dynamic SedNet Plugin (Ellis and Searle, 2014) developed within the eWater Source modelling framework, and has been used as a tool to report on progress towards Reef Plan water quality targets. Due to the complexity of the GBR Source catchment models, extensive assessment of parameter sensitivity and uncertainty is challenging. To address this gap, a project was commenced in mid-2017 to develop a method and tool for systematic sensitivity analysis of the GBR Source catchment models to assist model development.

Effective use of water quality models for decision making requires examination of sensitivity of model outputs to variation or uncertainty in parameters, inputs and assumptions (thereafter input factors). Sensitivity analysis for complex models can be expensive, due to influences such as large number of input factors, their nonlinearity and interactions. Considering the spatial and temporal dynamics of these input factors are also challenging. This is particularly the case for integrated models such as the GBR Source catchment models that contain a hydrology model and a number of constituent generation, filtration and transport models. In the context of integrated models, understanding of submodels is not sufficient to generate insight into the overall system behaviour. For example, local responses may have little overall significance to the outputs at the end of the system; feedbacks and interactions may strongly modify model behaviour. Therefore, it is critical to design a sensitivity analysis that is fit-for-purpose, i.e. to provide useful information required by modellers and/or model users.

In this presentation we report some of the key challenges of a systematic sensitivity analysis for the GBR Source models. These include:

- multidimensionality of the model inputs and outputs;
- dependency of parameters;
- spatial dynamics and uncertainty cascading;
- difficulty interfacing with the Source platform;
- long run time.

We then present a proposed sensitivity analysis approach for the GBR Source Catchment models. A range of sensitivity analyses methods are considered for screening, ranking and mapping the sensitivity of the input factors. Experimental setup (i.e. selection of input factors and outputs) are carefully designed to ensure the analyses are fit-for-purpose. Traditional and advanced sampling strategies are considered for scientific robustness and computational efficiency. Veneer (a system for linking eWater Source to other applications such as scripting tools) and veneer-py (a Python module to support scripting eWater Source models through the Veneer plugin) are used to allow powerful interfacing with the Source platform, and Jupyter notebook is used to ensure reproducibility and transparency of the analyses. Some preliminary results for the O'Connell case study, a subcatchment in the GBR, are discussed.

Keywords: *Catchment models, water quality, sensitivity analysis, Source*

Advancing Water Modelling through Networks and Engagement

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Abstract: The Queensland Water Modelling Network (QWMN) is an innovative approach to improve model capability, the integration of water resource, groundwater and water quality domains, the transferability and access to modelling tools, and to build modelling capacity and skills within Queensland. Following several independent reviews that highlighted gaps in modelling performance and planning, the Queensland Government embarked on a 4-year program to improve the strategic positioning of, and integration between, the discipline-based groups developing and applying modelling tools supporting policy and planning. These groups included water resource planning and flood management studies, groundwater resource assessments, and water quality modelling at paddock and catchment scales in the Great Barrier Reef, Murray-Darling Basin and Southeast Queensland. With an initial focus on models used within government, there was a strong desire to improve computational efficiencies, the R&D of models to more accurately reflect land and water transport processes, and embrace the use of visualisation to enhance model calibration, data interpretation and communication of modelling products. Access to calibrated models and their datasets, as well as best practice guidelines on modelling principles, and strengthening the governance arrangements of current modelling tools, were also identified as desirable outcomes through consultation across government agencies. While there is recognition of the role of models to inform policy, target-setting and planning initiatives within the Queensland Government, there is also the opportunity to capitalise on the strengths and capability in water modelling external to government within the research organisations, universities and the private sector. For this reason, the QWMN is a network in name and in nature, driving towards a 'community of practice' in modelling principles, the coordination of model R&D efforts, synergies in model applications, and the establishment of access hubs through collaborative partnerships and engagements. For example, joint arrangements with universities are designed to embed students with government modelling practitioners working on real-world applications to support the water sector, while a catalogue of water models used within government is intended to enhance awareness of these tools and attract participation towards improving these models. This paper describes the thematic and governance arrangements underpinning the QWMN, the approaches to grow a network focusing on the water modelling and uptake, and capacity building through progressive collaborations, fellowships and co-investments. Achievements within its first year of operation and current investment portfolio are summarised. With the transition to Stage 2 in 2018, the QWMN also provides a catalyst for broader cross-institutional participatory processes, with the potential to be positioned as a national training and education collective in modelling research, development and applications.

Keywords: *Model research and development, model arrangements, Source model, reef modelling, Queensland government*

Modelling the impact of land use and catchment characteristics on stream water quality using a Bayesian hierarchical modelling approach in the Great Barrier Reef catchments

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Abstract: The near-shore ocean ecosystem is influenced by catchment runoff. The Great Barrier Reef has been experiencing significant water quality deterioration over the past 150 years, due in part to agricultural intensification and urban settlement in adjacent catchments (Thorburn et al., 2013). There is a need for us to understand the influences of catchment characteristics on stream water quality, with an aim to mitigate and manage the water quality issue in the terrestrial stream runoff derived from the adjacent Great Barrier Reef catchments. The event-based water quality monitoring data set from the Paddock to Reef Integrated Monitoring Program across six Natural Management Regions provides a potential opportunity to develop a data-driven understanding of catchment characteristics affecting water quality at the catchment scale. This requires a robust and reliable modelling tool to relate the monitoring data to anthropogenic and natural processes.

In this study, monitoring data of Total Suspended Solids (TSS) and dissolved Oxidised Nitrogen (NO_X) from 32 sites across the Great Barrier Reef catchments are selected as case study constituents due to the high risk they pose to reef health when exported from catchments to the receiving marine environment. Also, these two constituents have distinct biogeochemical processes in catchments. Specifically, TSS is typically conserved (although mobilized and deposited) while travelling through river systems; while NO_X can be potentially processed and removed from the system altogether. A Bayesian hierarchical linear modelling framework is adopted, due to its ability to borrow strength among sites, allowing information to be transferred across space, and due to its ability to provide uncertainty of the predictions. The Bayesian hierarchical linear regression model in this study is developed to evaluate the significance of various catchment characteristics (e.g., land uses, catchment topography and geology) on spatial variation in water quality.

The main findings of this study are listed as follows,

- Sites located in the Burdekin and Fitzroy Natural Management Regions tend to have greater TSS concentrations, illustrated by the modelled site-specific spatial random effects (deviation from the overall average concentration). Additionally, grazing and dry land agriculture land uses are positively correlated with the spatial random effect on TSS. The complexity of interaction between different catchment characteristics (e.g., land use and topography) can potentially result in a negative spatial random effect on TSS, which is reduced in the relatively steeper Great Barrier Reef catchments with a denser stream network.
- Sugar cane is one of the most significant NO_X contributors according to the modelling results, likely partially due to the excessive application of fertilizers; however, conservation land use has limited effect on NO_X removal, indicating denitrification process alone may not be sufficient to remove NO_X.

The modelling results demonstrate different land management strategies are required for the purpose of reducing different constituents. This work will provide scientific insights for water quality management at the catchment scale.

Keywords: *Water quality, land use, Suspended Solids, Oxidised Nitrogen, Bayesian hierarchical modelling*

Simulated sediment transport in the GBR region

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Abstract: This paper summarises the development and subsequent application of a 3D fine resolution model of sediment transport in the Great Barrier Reef (GBR) region. The model is driven by a 3D hydrodynamic model and provides input to a complex biogeochemical and optical model established through the eReefs project. The sediment transport model is calibrated against 6 months of remote sensing data via decomposition of the model solution into a truncated set of basic functions and subsequent assimilation of data into the reduced model (emulator). The quality of the calibrated model (validated against ground measurements) varies in space and time. Numerical experiments highlight discrepancies between relatively short-term processes targeted by the data assimilation and long-term evolution of the sedimentary dynamics of the region. Simulations over the four-year period show good agreement between the model and observations for the first two years and a decline in simulation quality for the next two years. This behavior is attributed to the erosion and advection of the top layers of sediments, translated into exposure of deep benthic layers that are characterized by a higher resistance to resuspension. The long-term drift of the model was eliminated through adjustment of vertical profiles of the critical shear stress in sediments, resulting in improved simulation results over the whole four-year simulation period.

A number of scenarios with varying loads from catchments have been simulated in order to assess the fate of catchment sediment in the GBR region. Numerical experiments suggest an impact of catchment sediment on the GBR shelf (in terms of the probability of suspended sediment exceeding the trigger value of 2 mg/L) is confined to inshore regions adjacent to river mouth locations. These regions may extend many kilometers from the river mouth along the coastline, covering areas roughly corresponding to the extent of the turbidity plumes developed during the flood events. Suspended sediment mass on the GBR shelf as a whole (including shallow inshore regions) is dominated by resuspension of historical deposits of sediment. The model predicts limited transport of catchment sediments north-west along the coastline over the simulated four-year period. The quality of the model can be improved further through the assimilation of real-time data.

Keywords: *Coastal, sediment, model, data-assimilation, emulator, Great Barrier Reef*

Visualising spatio-temporal modelling results: Getting modelling results into the hands of decision makers

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Abstract: Water quality models are routinely developed to support the natural resource management planning process. Each scenario of a water quality model generates a large volume of data. However the collective spatial and temporal elegance of the model output is usually summarised into simple coarse measures to allow straightforward document-based reports to communicate the key points to decision makers. This need to grossly simplify model results removes opportunities for decision makers and others involved in natural resource management to gain a greater appreciation of the underlying processes and interactions represented by the model.

By adopting a web based presentation of modelling results (compared to current document-based reporting), a 'progressive disclosure' approach can be adopted whereby high-level summaries can be linked to underlying results. This progressive disclosure approach allows decision makers and others to initially see the highest level summaries but then to also explore the underlying temporal and spatial richness of modelling results. This approach also allows a single reporting approach to suit an audience from a wide range of backgrounds. For example, senior managers may only wish to see a single summary table, but modellers and operational staff may need to access animated spatial representations of sediment and nutrient generation by sub catchment for particular climatic periods.

In this paper we describe a workflow for integrating models in the natural resource management process. We step through four case studies (one from the Great Barrier Reef catchments, two from South East Queensland and one from Victoria) where web based data visualisations have been used to deliver complex modelling results. These examples demonstrate the progressive disclosure approach for delivering sophisticated scientific understanding to different audiences. The case studies use data from a range of sources (observational data, SOURCE model output, TUFLOW model output, a spatially applied simulated annealing optimisation model and expert panel derived conceptual models).

The vast majority of the results generated through the modelling process never see the light of day, never get to a decision maker and ultimately never get to influence the process for which they were commissioned. Getting model results into the hands of decision makers adds value to the models and supports the education of the end users of model results

Keywords: *Catchment modelling, data visualisation, web delivery, natural resource management*

Validation and calibration of Source water quality models in the Great Barrier Reef catchments

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Abstract: The Paddock to Reef (P2R) Integrated Monitoring, Modelling and Reporting Program uses modelled catchment loads to estimate annual load reductions as a result of improved management practices in the Great Barrier Reef (GBR) catchments. Calibrating and validating catchment models across a large spatial scale is challenging, and requires a range of approaches to continue to refine and improve modelled load estimates. Catchment models have been built for the six Natural Resource Management (NRM) regions draining to the GBR in the Source framework. The NRM regions range in area from 9,000 km^2 to 155,000 km^2, with the total modelled area 423,000 km^2. Load estimates are modelled for 10 water quality constituents.

Many improvements have been made over the past seven years to improve confidence in modelled loads. An example includes hydrology recalibration and baseflow optimisation to align with estimates derived from gauged flow. Typically, the larger, drier regions required more gauges to be recalibrated than for the wetter regions. In Cape York (CY) following recalibration of the model, the baseflow proportion was improved from an average of 43% to 33%, which better aligns with the baseflow estimate from gauged flow of 31%.

A second notable model update is the improved representation of Dissolved Inorganic Nitrogen (DIN) in sugarcane areas. The DIN runoff model was updated to incorporate a new algorithm which correlates fertiliser input to nitrogen in runoff, derived from the pool of P2R field monitoring data. This daily model of DIN concentration in runoff was based on >200 sugarcane field monitored DIN runoff events. These changes have resulted in modelled DIN loads now being within ± 30% of measured loads in the Wet Tropics (WT), compared to ± 50% in previous model iterations.

The improved representation of fine sediment sources as a result of new datasets (for example, gully mapping in CY, Burdekin and Fitzroy) is another example of model calibration using the most up-to-date data. CY is typically a data poor region and early model estimates of the hillslope/gully/streambank contribution to fine sediment loads suggested that up to 90% of the fine sediment load was derived from hillslope sources. Recent field surveys combined with LIDAR data and a desktop gully mapping exercise in the Normanby basin conclude that gullies are the major source of sediment in CY. The updated gully map was incorporated into the Source model, and gullies now account for >70% of the fine sediment load in the Normanby basin.

A major component of the P2R program is the catchment loads monitoring program critical for model validation. The number of monitoring sites has expanded from 26 in 2006 to 43 in 2017. This means that 85% of the sediment and nutrient loads exported are now monitored across the GBR. As the pool of water quality data increases both spatially and temporally, there has been a shift to manual model calibration to align with monitoring data as opposed to using the data for validation as was the case in the early years of the program.

Whilst the average annual load estimates for the models have not changed significantly there is much greater confidence in the relative contribution of constituents, for example sediment sources and sinks, or DIN loss path ways (surface versus subsurface drainage) from different land uses. This leads to greater confidence in the model outputs, particularly from external stakeholders.

At the outset of the P2R modelling program there was limited observed data available to calibrate and/or validate modelled loads. Over the course of the program, knowledge gaps were identified and prioritised, resulting in targeted research being undertaken. This has enabled the refinement of different aspects of the models in each region. When considering a long-term modelling exercise, that is data poor, the model improvement cycle should be flexible enough to for regular updates to algorithms in the models, input data sets, and modelled constituent loads. Model validation must draw on a range of data sources to constrain the models. The P2R modelling has been highly beneficial for identification of dominant sources of constituents, guided water quality monitoring and research, and just as importantly, generated debate about load predictions across the GBR.

Keywords: *GBR modelling, water quality, model validation and calibration, DIN, fine sediment*

Measuring progress toward Reef Water Quality Protection Plan Targets

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Abstract: The Reef Water Quality Protection Plan 2013 (the Plan) is a joint commitment by the Australian and Queensland Governments to improve water quality entering the Great Barrier Reef (Reef). The Plan describes targets for reducing pollutant loads, improving agricultural management practices and catchment indicators including groundcover, riparian vegetation and wetlands. Progress towards the Plan's targets is assessed through the Paddock to Reef Integrated Monitoring, Modelling and Reporting program (Paddock to Reef program) and presented in an annual report card.

The Great Barrier Reef Report Card 2015 showed that progress was more than halfway to the targets outlined in the Plan to be achieved by 2018, with an estimated reduction in sediment of 12.3% and 33.7% for pesticides to date. Progress in reducing other key pollutants has slowed with a modelled dissolved inorganic nitrogen reduction of 18.1% falling short of the 50% reduction target for 2018. Land management practice adoption in 2015 showed some positives with almost half the horticulture and grains land across the Reef catchments using best management practice systems for water quality outcomes. More work is needed in the sugarcane and grazing industries which fell below 90% best practice adoption target for priority areas scoring a 'D' reef-wide. The ground cover target was met, scoring an 'A' overall. Wetland and riparian management targets are assessed every four years and were not included in the 2015 report card.

There have been a number of challenges for the Paddock to Reef program in nine years of evaluating and reporting. Adoption of land management practices has slowed after a period of early uptake. The size of the Reef catchments (430,000 km^2) makes reporting against Reef-wide targets challenging. Reef wide targets overlook the degree to which each region contributes to a target. Through the update of the Reef Water Quality Protection Plan in 2017, targets are being developed for each of the 35 Reef catchments; this will address the issues associated with reporting across a large area. The Queensland Great Barrier Reef Water Science Taskforce concluded that although the basis of the Paddock to Reef program was sound, the level of monitoring and modelling investment was inadequate. An additional $9 million has been invested to improve the monitoring and evaluation of the Reef Water Quality investment. This includes an expansion of the catchment monitoring network with 16 new sites; improvements to modelling capacity to better understand the outcomes of investment and undertake scenario modelling; as well as improvements to tracking land management practices and wetland condition.

The Paddock to Reef program is recognised as a world class innovative program, integrating monitoring and modelling across a range of scales to evaluate the effectiveness of on-ground actions and assess progress to targets. Information from the program is summarised in annual report cards for government and high level stakeholder use, supported by summary results and methods for further information. Detailed technical reports and independent reviews provide additional scientific rigour. Program outputs are used to produce case studies, underpin on-ground education efforts, guide the development of actions to reduce pollutant loads and inform priorities for investment.

Keywords: *Policy, adaptive management, monitoring and evaluation, Great Barrier Reef*

Measuring management practice adoption to model pollutant load reductions in the Great Barrier Reef

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Abstract: The Great Barrier Reef Water Quality Protection Plan (Reef Plan) is a collaborative program of coordinated projects and partnerships designed to improve the quality of water in the Great Barrier Reef (GBR) through improved land management in reef catchments. Reef Plan sets targets for improved reef water quality through adoption of improved land management practices which reduce pollutant loads from agricultural production systems.

To monitor and report the progress toward these targets the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program) was developed. A key understanding of the program is that it will take time for the adoption of improved land management practices to translate into reduced pollutant loads on the GBR. The Paddock to Reef program incorporates a number of modelling components in order to estimate the possible future benefits of monitored farm management changes.

The Management Practice Adoption component of the Paddock to Reef program monitors and reports on the adoption of best practice land management in the agricultural lands of the Great Barrier Reef. The program has developed Water Quality Risk Frameworks for each major agricultural sector. These frameworks define the practices with greatest influence on off-farm water quality, and articulate management descriptions for each practice according to likely risk. They provide a clear and consistent method for describing land management status and for quantifying the type and degree of management practice change.

Land management status across the GBR catchments is assessed according to the water quality risk frameworks. Various lines of evidence are drawn together to establish a realistic management 'Baseline' for each sector, in each of the 47 river basins of the GBR catchment. These lines of evidence include previous project and program reporting, surveying of representative farmers within each population, records of actual farm inputs, and aggregated data from industry 'Best Management Practice' programs. Baselines inform the catchment scale modelling of pollutant loads in the 'current' situation.

Improvements from the 'current' situation (baseline) are modelled on annual basis. All organisations delivering programs or projects under Reef Plan are required to report the impact of their work (land management change) as per the Water Quality Risk Frameworks. Data is received in spatial format as site characteristics are critical in estimating the site contribution to catchment pollutant loads. Spatial data for every site is accompanied by a suite of management practice attributes which describe exactly how the site is managed in the terms articulated in the Water Quality Risk Framework.

This management description captures both a 'before' and 'after' state – how the land was managed before an intervention, and how the land will be managed in the future as a result of the intervention. In this way the impacts (the difference between the before and after assessments) of many site-specific interventions are reviewed and passed on for incorporation into one of several sector-specific agricultural production system models (grains, sugarcane, grazing, and bananas).

Using the frameworks the Paddock to Reef program attempts to quantitatively describe the management of agricultural landscapes, and how that management is changing over time due to a range of government and industry investments. Alignment between the monitoring of management practice adoption and the modelling of the possible outcomes of that adoption enable the estimation of future benefits for the water quality of the Great Barrier Reef.

***Keywords**:* *Great Barrier Reef, adoption, practice change, water quality*

Modelling reductions of soil erosion and pesticide loads from grain cropping due to improved management practices in the Great Barrier Reef catchments

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Abstract: The greatest water quality risks to the Great Barrier Reef are excess nutrients, fine sediments and pesticides contained in terrestrial runoff as these are a major issue affecting the health and resilience of the Great Barrier Reef. In response to a decline in water quality entering the Great Barrier Reef lagoon, the Reef Water Quality Protection Plan (Reef Plan) was developed as a joint Queensland and Australian Government initiative. Reef Plan set water quality improvement targets. Progress towards these targets are assessed through the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program. To help achieve the targets, improvements in land management are being driven by a combination of the Australian Government's reef investments, along with Queensland Government and industry-led initiatives in partnership with regional Natural Resource Management groups.

Identifying farm management practices that reduce sediment, nutrient and pesticide runoff loads at a paddock scale is the first step towards improving water quality at the larger catchment scale and subsequently in the Great Barrier Reef lagoon. To model the grains industry, farm management practices for dryland cropping were defined under a water quality risk framework. Practices in the framework primarily affect soil/sediment transport, nutrient and pesticide application practices; and were grouped as Low, Moderate-Low, Moderate and High risk practices. This paper summarises the paddock scale modelling of the effectiveness of improved management practices for reducing off farm losses of sediment, nutrients and pesticides in dryland grain cropping.

Paddock scale agricultural models allow explicit representation of management options available to producers. These include changes in crop rotations, tillage intensity and pesticide and nutrient application timing and rate. Importantly, the ability to simulate management practices on a daily time step means that interactions between the timing of management events and rainfall can be calculated. The results of paddock scale modelling are used in the catchment models to assess the effects of farm scale management decisions on water quality for the whole of the Great Barrier Reef catchment. Key messages from the development and application of the paddock scale modelling for dryland grain cropping in the Great Barrier Reef catchments are:

- Greatest overall reductions in soil erosion can be made by coupling reduced or zero-tillage practices with well-designed controlled traffic farming (CTF) systems.
- Greater than 90% reduction in soil erosion results from changing management practice from "D" management scenarios (High risk; full cultivation) to "A" management scenarios (Low risk; zero-till farming with CTF and contour banks).
- Soil erosion is greater in fallows after chickpea, mungbean and sunflower crops than after sorghum and wheat crops. This is due to the small amounts and more rapid decomposition of stubble after chickpea, mungbean and sunflower crops than after sorghum and wheat crops, leaving less cover to protect the soil surface.
- Atrazine runoff loads from cropping land respond directly to both application rate and to time of application relative to runoff. Tillage and traffic systems had a secondary level of effect.
- There was a clear trend of decreasing atrazine runoff load as a percentage of atrazine applied, with the change from D (High risk) to A (Low risk) management scenarios. However, total atrazine loads do not follow this trend because atrazine use increases with A and B management practices. This could be viewed as an outcome of practices that achieve Low risk sediment outcomes (reduced tillage) or the Water Quality Risk Framework could be improved to reduce atrazine use for low risk scenarios.

Keywords: *Paddock to Reef, grain, cropping, water balance modelling, HowLeaky*

Development of a simple nitrogen loss model for HowLeaky

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Abstract: Contaminants contained in terrestrial runoff are one of the main issues affecting the health and resilience of the Great Barrier Reef (GBR) (Scientific Consensus Statement, Brodie *et al*., 2013). In response to a decline in water quality entering the GBR lagoon, the Reef Water Quality Protection Plan (Reef Plan) was developed as a joint Queensland and Australian Government initiative. The plan outlines a set of water quality and management practice targets, with the long-term goal to ensure that by 2020, the quality of water entering the reef lagoon from broad scale land use has no detrimental impact on the health and resilience of the GBR. Progress towards achieving these targets is assessed through the Paddock to Reef (P2R) Integrated Monitoring, Modelling and Reporting Program. The program uses a combination of monitoring and modelling at paddock through to basin and reef scale.

Identifying farm management practices that reduce sediment, nutrient and herbicide loads at a paddock scale is a step towards improving water quality at the larger catchment scale and subsequently in the GBR marine lagoon. Agricultural systems models which consider paddock scale processes allow explicit representation of a range of management options available to land managers, such as crop rotation, time of planting, irrigation and fertiliser practices. Importantly, the ability to simulate management practices at a daily time step allows interactions between timing of management practices and weather to be investigated.

Van der Laana *et al.* (2014) caution that our current ability to simulate nitrogen (N) leaching at the paddock scale is not sufficiently developed for reliable and accurate predictions. Existing models are often too complex in their representation of N processes and require parameters that are difficult to estimate. This complexity introduces the risk of having compensating errors during model testing and calibration (the right answer for the wrong reason). This has resulted in low confidence in simulated N leaching.

We have approached the problem by aiming to reduce model complexity and have added a quantitative model of N losses to the HowLeaky model, an existing model used for water balance and sediment export in P2R. One of the main requirements is to have a model that responds to changes in N management and environmental factors in a predicable way. In reviewing model approaches, we took our lead from the SafeGauge for Nutrients risk assessment tool (Moody, 2016). The resultant model accounts for excess N on a daily basis by considering N contributions from fallow management, mineralisation and fertiliser applications, and N losses by crops (based on yield targets) and denitrification. Loss of N as dissolved inorganic N (DIN) in runoff and drainage are based on the pool of excess N.

We have used off-site nutrient loss monitoring data from a range of sources, including the P2R program, to benchmark model performance. While the model is at an early stage of development and testing, the simulated concentrations and loads show a capacity to reproduce expected relationships from measured sources. Importantly, the simplicity of the model has improved our confidence in partitioning excess N and DIN losses. The simpler approach is more predictable in its response to management, and hence provides greater confidence in model behaviour, is transparent and reduces the risk of unknowingly implementing compensating errors in the drivers of N loss.

Keywords: *Dissolved inorganic nitrogen, deep drainage, HowLeaky, water quality*

Evaluating the eReefs Great Barrier Reef marine model against observed emergent properties

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Abstract: The eReefs marine models simulate hydrodynamics, sediment dynamics, biogeochemistry and optical conditions in three dimensions on 1 km and 4 km grid scales across the whole Great Barrier Reef (GBR) Lagoon. The models are designed to support management of the Great Barrier Reef through operational provision of near real-time hydrodynamic, water quality and optical conditions over the reef, as well as supporting prognostic scenarios to facilitate catchment management policy. During development, the hydrodynamic and biogeochemical models were calibrated and validated against remotely sensed temperature, *in situ* measured physical properties, and *in situ* sampled dissolved and particulate nutrient species at sparsely distributed monitoring sites, most of which are located in near-shore waters along the length of the GBR Lagoon. A range of evaluation metrics provided a baseline degree of confidence in the model results. An additional level of confidence can be achieved by evaluating the model's performance in reproducing a range of system-scale *emergent properties*. These are large-scale patterns and relationships that are neither directly coded into the model nor used in model calibration – ideally, relationships that are not obvious from an inspection of the model algorithms, but arise from the complex system that these algorithms combine to create. This paper describes the evaluation of the 4 km grid-scale eReefs marine models against a range of emergent properties. Properties used in this evaluation included (a) the relationship between chlorophyll *a* concentrations and phytoplankton community size-structure; (b) the relationship between river discharge and annual mean photic depth on the mid- and outer-shelf; and (c) the relationship between flood-plume optical class and water quality. The results show good agreement across all three sets of emergent properties, enhancing confidence that the eReefs suite of process-based models is producing "the right results for the right reasons," correctly simulating a complex range of physical and biogeochemical processes across the Great Barrier Reef.

Keywords: *Model evaluation, emergent properties, Great Barrier Reef, phytoplankton community structure, photic depth*

Effect of application timing on herbicide runoff losses

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Abstract: To improve water quality entering the World Heritage listed Great Barrier Reef (GBR) lagoon, Reef Plan 2013 has set a target to reduce pesticide runoff loads by 60 per cent by the year 2018. This target may be achieved through changes in land management practices in agricultural industries in the GBR catchment. Runoff monitoring at demonstration sugarcane farms in Queensland has shown that the timing of a pesticide application relative to the next runoff event has a significant impact on offsite pesticide losses. Pesticide runoff concentrations decay exponentially with time. These field studies suggest that the 20 days following application is the period of greatest risk for pesticides to be transported in runoff.

Effective weed management is important in the early stages of crop development. In this study we have evaluated the effect of timing of pesticide applications on runoff losses for products applied for residual weed control during early emergence in plant cane; atrazine, ametryn, imazapic, isoxaflutole, metribuzin, pendimethalin and s-metolachlor. Planting of cane typically occurs May to September in the Wet Tropics region. Using the pesticide model from HowLeaky and the sugarcane cropping model from APSIM, runoff losses were compared for applications occurring 10 days following planting in Tully for five planting dates between mid-May and mid-September. Simulations covered a 28 year period and included four ratoon crops and a cowpea fallow crop.

Applications that occurred in months with higher average rainfall resulted in higher herbicide runoff losses. For the same herbicide application scenario (product, rate, timing of application) the offsite loss of herbicides may be reduced by more than 60 per cent by applying in a month with low average rainfall (e.g. August in Tully) rather than closer to the previous (e.g. May) or coming wet season. Application in the month with the lowest rainfall (September) did not correspond to the lowest runoff losses for herbicides with the longest half-lives. September was followed by months with high rainfall. Herbicides applied in September remained present in the soil and available for loss in runoff in the wetter months following.

The half-life of the applied herbicides influenced whether the 20 days following application could be considered the period of greatest risk for runoff losses. The proportion of total herbicide runoff loss occurring in the 20 days immediately following application ranged from 75 per cent to zero in instances where no runoff occurred. For the same application date, 68 per cent of the total atrazine loss occurred in the first 20 days compared to 18 per cent for pendimethalin, due to the slower degradation rate of pendimethalin (40 days in soil) compared to atrazine (17 days).

In the Queensland Government's Water Quality Risk framework for land management practices, controlling weeds early in the sugarcane crop cycle with reduced or no use of residual herbicides through the ratoon crops is considered good practice. Timing herbicide applications early in the crop cycle to drier months may also be an effective way to reduce annual loads of herbicides lost in runoff.

Keywords: *Herbicides, HowLeaky, APSIM, Great Barrier Reef, runoff*

Assessing the cost for pollutant load reductions in the Great Barrier Reef: a case study

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Abstract: The slow progress of pollutant reduction towards the Great Barrier Reef water quality improvement plan targets has increased the pressure to achieve more cost effective outcomes. Consistency in how costs are captured for different policy mechanisms from the paddock scale to the catchment scale would allow more robust evaluation of achieving overall pollutant reduction targets. Progress in the Paddock to Reef monitoring and modelling program (P2R) in the areas of landholder adoption, ground cover and monitoring the program have improved decision making. However, the costs involved in current optimization approaches have data paucity, and could be improved with more consistent, and comprehensive data to evaluate investments. This paper provides a framework on how economic data could be collected to integrate into Paddock to Reef program to optimise investments.

Keywords: *Grazing management. Great Barrier Reef, cost-effective, optimisation*

Paddock to Reef water quality monitoring program expansion - calibration and validation of catchment models

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Abstract: Terrestrial runoff from intensive agricultural land-use in Queensland is resulting in poor water quality in fresh and estuarine systems and is potentially impacting the ecological health and resilience of the Great Barrier Reef (GBR).The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program) includes catchment scale water quality monitoring of pollutant loads (total suspended solids, nutrients and pesticides) entering the Great Barrier Reef lagoon that is implemented through the Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP). Water quality sampling is based on a citizen science model, where, community members and groups, local councils and government agencies, natural resource management bodies, collect water quality samples and whom are all annually trained to the event monitoring standard of the *Monitoring and Sampling Manual* under the Queensland *Environmental Protection (Water) Policy 2009*. The monitoring data generated by GBRCLMP provides the point of truth to calibrate and validate loads predicted by source catchment models.

Following recommendations of the Great Barrier Reef Water Science Taskforce (2016 Final Report), the number of water quality sampling sites encompassed by the GBRCLMP has expanded from 26 sites in 14 of the 35 priority basins, established in 2006, to 43 sites in 24 basins in 2017. The expanded program means that approximately 80% of the total surface water discharge and over 85% of the sediment, nutrients and photosystem II inhibiting pesticides discharging to the GBR lagoon are now monitored annually. The addition and reprioritisation of sampling sites was guided by a prioritisation process which included feedback from the modelling team as to where the greatest deficiencies were in model validation data and broader consultation. Monitoring is conducted from the Mary River in the South of the GBR to Cape York in the North.

The loads monitoring program is essential to ensure that robust and reproducible data are available for model calibration and validation. Further to this, extensive monitoring for pesticides is occurring to build a foundational data set and understanding prior to the pesticide model rebuild.

This presentation will summarise our monitoring data to date, explain how the data is used in the calibration and validation of source catchment model, demonstrate how the program has helped to improve modelled load estimates and highlight limitations and challenges faced by the program.

Keywords: *Great Barrier Reef, loads, monitoring, validation, water quality*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Assessing the risk from anthropogenic pollutants to Great Barrier Reef marine ecosystems

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Abstract: The Great Barrier Reef (GBR), Australia, is an iconic natural and cultural system that is under threat from a range of pressures including climate change, land based pollutant runoff, fishing and coastal development. This paper presents an ecological risk assessment approach to assess the likelihood of exposure and potential risks from land-based pollutants to marine ecosystems (coral reefs and seagrass meadows).

The main water quality pollutants of concern to GBR coastal aquatic and marine ecosystems are enhanced levels of suspended sediments, excess nutrients and pesticides (predominantly photosystem II inhibiting herbicides) discharged to the GBR lagoon from the adjacent catchments. The assessment was conducted using different methods for nutrients and fine sediments, and pesticides.

The likelihood of exposure of coral reefs and seagrass to (a) dissolved inorganic nitrogen (DIN) and (b) fine sediment was conducted by combining several classified spatial layers to represent wet season and annual average marine water quality conditions. These included: the distribution and frequency of anthropogenic DIN (a1) and fine sediment loading (b1) in the wet season, and assessment of the degree of difference between current (baseline) average annual concentration of Chlorophyll *a* (a2) and light attenuation (b2) compared to pre-development load scenarios (derived from the eReefs coupled hydrodynamic – biogeochemical model). The assessment included all 35 basins that discharge into the GBR and defined Marine Zones using remote sensing imagery and the eReefs model to capture the predicted areas of marine influence from the GBR basins.

Relative exposure was assessed by calculating the area of coral reefs and seagrass in the highest 'likelihood of exposure' classes. The consequence, and therefore the risk, assessments were limited to two examples: (a) the risk of DIN and the area of influence from Crown-of-Thorns starfish on coral reefs, and (b) the risk of the benthic light thresholds for seagrass being exceeded due to excessive concentrations of fine sediment. In both cases, the results were then linked to the 35 GBR basins by applying a weighting factor to represent the proportional contribution of anthropogenic fine sediment or DIN load from each basin. All results were normalised to generate a score between 0 and 1, thereby presenting a relative assessment.

The pesticide risk assessment was performed using two methods which assess consequence and likelihood. Consequence was first determined using the multisubstance-Potentially Affected Fraction (ms-PAF) method. The analysis assessed whether concentrations of pesticides (as a mixture of five PSII herbicides) entering the GBR World Heritage Area (GBRWHA) would be protective of 99% of species. This approach assessed the compliance of monitoring data with the Australian and New Zealand Guidelines for Fresh and Marine Water Quality and the GBR Water Quality Guidelines. Likelihood could then be determined using methods of a probabilistic ecological risk assessment (PERA); the area under the curve of the ms-PAF cumulative frequency distribution. An ecotoxicity threshold assessment was completed for 28 individual pesticides (for which a threshold values are available) collected over a three year period (2013 to 2016), as many of these pesticides were not analysed prior to 2013.

The assessment highlighted ecosystem specific and geographical 'hot spots' for coral reef and seagrass exposure to land based pollutant runoff in the GBR. Several basins are identified as high exposure for two or more pollutants. These are all located south of Cairns and as far south as Bundaberg and include the Russell-Mulgrave, Johnstone, Tully, Haughton, Burdekin, O'Connell, Pioneer, Plane, Fitzroy, Burnett and Mary Basins. The results of this assessment are being used to inform management priorities for improving water quality discharge from the GBR catchments into the GBRWHA.

Keywords: *Great Barrier Reef, pollutant risk, pollutant exposure, ecosystem health, management prioritisation*

Calculating sediment trapping efficiency for Reservoirs in series

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Abstract: Trapping Efficiency (TE) is defined as the proportion of inflowing sediment that is accumulated in a reservoir. Accurately predicting the trapping efficiency (TE) of sediment in reservoirs is critical to estimate their useful life and inform catchment models for sediment budget estimation. A daily formulation of the Churchill sediment trapping efficiency equation previously implemented in the eWater Source modelling framework, enables the user to account for the accumulation of sediment and hence the subsequent sediment yield exiting a reservoir. Where reservoirs are in series, the particle size of sediment passing through an upstream storage is generally finer than the 'local' sediment. Therefore, the application of the Churchill equation to each reservoir in isolation, not taking into account the different sources of sediment, may result in an under prediction of the sediment yield for a basin. Churchill (1948) proposed a method to account for sediment that had already passed through an upstream reservoir.

The original daily Churchill equation was applied to all storages and compared to a modified Churchill equation, applied to upstream reservoirs for three scenarios across the Great Barrier Reef (GBR), Namely: 1. The Pioneer River in the Mackay Whitsunday region which contains three small weirs (<10,000 ML); 2. The Burnett River in the Southern GBR which contains three large upstream storages that flow into a reservoir in the lower reaches of the catchment and; 3. The proposed Hell's Gate Dam to be constructed on the Burdekin River upstream of the Burdekin Falls Dam.

The results showed negligible differences for the small storages and indicated that the application of TE models for such storages is probably redundant. Larger differences in sediment loads were calculated with the application of both TE models for the larger storages which demonstrate its usefulness to incorporate into future modelling. The scenarios also demonstrate the usefulness of models to quickly forecast the influence of proposed new reservoirs (or the modification of existing reservoirs) on sediment loads.

This paper will describe the modified Churchill approach and provide estimates of sediment yield with and without the modification and recommend where the curves are appropriate to be used in the GBR. The approach will also provide a method to improve estimates of sediment yield from basins where reservoirs are in series.

Keywords: *eWater Source, Churchill, trapping efficiency, sediment yield*

A Sediment Budget for the Queensland Murray Darling Basin

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Abstract: Source Catchments Water Quality models were developed for the Queensland section of the Murray Darling Basin. The Queensland Murray Darling Basin (QMDB) Water Quality Models were built to assist in the development of water quality guidelines for Murray Darling Basin planning requirements. Total Suspended Sediment (TSS), Total Nitrogen (TN) and Total Phosphorus (TP) were the constituents of interest.

This work built on the experience of the Great Barrier Reef (GBR) Paddock to Reef modelling program and applied a similar modelling approach. Three separate models were created for the QMDB: South West catchments Bulloo, Paroo, Warrego and Nebine catchments (SWNRM), Condamine, Balonne and Maranoa catchments (CBM) and Border Rivers and Moonie catchments (BRM). Models were calibrated using the Sacramento rainfall runoff model coupled to the parameter estimation software (PEST). Due to the limited water quality monitoring data available across the region for calibration, historical water quality (WQ) data was correlated against log transformed flow to build a relationship between TSS, TP and TN and gauge discharge by catchment. The resulting concentration values were used to calculate daily through to average annual loads. These loads were then used to assist with model calibration.

The hydrological calibration achieved a percent bias (PBIAS) of less than 5% for 36 of the 37 gauges used for calibration. Modelled average annual TSS loads were estimated to be 1,906 kt/yr for the SWNRM catchments, 198 kt/yr for CBM and 53 kt/yr for the BRM catchments for the 35 year climate period (1980-2015). In terms of the overall QMDB sediment budget, gully erosion contributed 43%, streambank 37% and hillslope erosion 20% of the total sediment load exported. Limited measured data was available across the full range of flow heights for water quality calibration which meant that there is a degree of uncertainty about the measured estimates used to validate the model, a common problem worldwide.

This model has been used in the development of high and low flow water quality guidelines for Water Quality Objectives for the Qld Environmental Protection Policy. The model has the potential to be used and refined by regional NRM bodies in future years to prioritise natural resource investment in improved land management practices. Using a model in a data poor area has highlighted the value of event monitoring data collection to calibrate and validate water quality models. Development of such a model incorporating a range of erosion processes provided a basis for prioritising future research in catchments, in particular improve our understanding of sediment transport where limited measured data is available.

Keywords: *Water quality, Source Catchments, Queensland Murray Darling Basin*

Spatio-temporal modeling of salinity as a function of climate variability, flooding dynamics and GRACE total water storage across Australia's Murray-Darling Basin

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Abstract: Australia's Murray-Darling Basin (MDB) supplies water to over two million people but over the course of the last century, land clearing, agricultural intensification and water resources development have led to alarming declines in water quality and problematic increases in naturally high freshwater salinity throughout the basin. The infiltration of salty groundwater into rivers as a result of rising groundwater tables was the key source of increasing salinity levels and, since 1989, the construction of 15 salt interception schemes has reduced river salinity to levels that are acceptable for drinking water. Nevertheless, other factors such as irrigation runoff, salt mobilization from floodplains and changes in climatic conditions and corresponding river flow and flooding regimes are also affecting salinity levels and need to be accounted for in the basin-wide salinity management strategy. Considering the high socio-economic value of water-dependent ecosystems, irrigated agriculture and industry in the MDB, it is therefore critical to better understand the links between surface water quality and and these additional drivers. The majority of existing studies that analysed this complex relationship have focused on individual river and wetland systems, and did not account for the up- and downstream dynamics that occur across large river systems. To address this limitation, the goal of this study was to holistically quantify the role of changing flooding regimes, climate variability and water resources development on commonly available water quality parameters (i.e. salinity and water temperature), using a whole-of-basin approach. We integrated in-situ time-series of salinity from more than 30 gauges across the MDB with a novel 26-year record of surface water inundation maps (1986-2011) and time series datasets of evapotranspiration, water temperature, rainfall, river flow and total water storage anomaly (TWSA) provided by the GRACE satellite. We used a fully-connected and directed river network to define the hydrologic connectivity and hierarchy of sub-catchments within the modelling framework. Based on this framework, we generated de-seasonalised trend time series of all variables with monthly time step for each model catchment and used generalised additive models (GAM) to investigate the role of driver variables across space and time. Time series decomposition revealed significant and alternating positive and negative multi-year trends in salinity and water temperature (2000 – 2012) that differed greatly across model catchments. Our model results indicate that very dry conditions during the millennium drought (2000 - 2009) followed by the big wet (2010 - 2011) partially explain these trends and the role of individual driver variables differed greatly between catchments. Flood inundation dynamics and GRACE TWSA were the most influential driver variables and explained more than 40% (r^2=0.47) and 60% (r^2=0.64) of the variability in salinity in some catchments respectively. Our study provides new insights into the role of drought and flooding cycles in river salinity and temperature across a large and highly-regulated river basin which are of great value for the ongoing multi-million dollar effort of improving and maintaining water quality across the MDB.

Keywords: *Water quality, salinity, spatio-temporal modeling, GRACE, remote sensing, time series analysis*

The Loads Regression Estimator (LRE) App

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Abstract: The quantification of uncertainty is an important step in the calculation of river loads as it provides a precision around the loads estimated and an indication of the adequacy of the sampling regime implemented for the site over the time period investigated. The Loads Regression Estimator (LRE) Application or App has been developed to assist water quality specialists with the estimation of sediment, nutrient and pesticide loads at a site. The App, which is developed within the R programming language using the LRE and Shiny packages, adopts a statistical approach to loads estimation that quantifies uncertainty and provides a user friendly platform to explore and model the underlying processes of water quality and flow data for a site of interest. The LRE methodology comprises four steps: (1) estimation steps for flow that ensures flow values occur at regular intervals (e.g. hourly, daily or monthly); (2) estimation steps for concentration, where a generalised additive model (GAM) is proposed for estimating concentration using covariates that account for seasonality and important hydrological processes of complex river systems; (3) the estimation of the load that includes a bias correction, and (4) the quantification of the standard error, which accounts for transect (spatial) error in addition to measurement error.

The main features of this app may be summarized as follows:

1) A “point and click” implementation of the LRE package that allows a water quality specialist to analyse their water quality data without needing R programming experience or requiring the R software installed on their computer.
2) The App will be freely accessible and housed on a CSIRO server which will perform the necessary computations to run the model and obtain the predictions and uncertainties.
3) A robust statistical methodology for quantifying loads with uncertainties that can take into account correlated data.
4) A module for robustly interpolating flow records using rainfall data when gaps in flow exist.
5) Visualisations of the outputs from the exploratory analyses and GAM to assist with interpretation and decision-making.

We present a tutorial showcasing the LRE App for the Burdekin and Tully end of catchment sites in the Great Barrier Reef. In this tutorial and live presentation, we will outline the data and requirements for running the App to quantify loads at a site. In this example, event based water quality samples (daily or every few hours) will be used. After reading in the flow and concentration data, we will show through exploratory plots how a water quality specialist can investigate any anomalies and highlight events that may contribute to larger than expected loads. We will demonstrate how the GAM is fit to the concentration data to estimate water quality concentrations given flow and other hydrological terms and we will demonstrate a selection of diagnostic plots to determine the fit of the model. We present daily and annual predictions of the load from the App along with a selection of graphics to showcase the results. Finally, we show how the App could be used to assist with regular reporting requirements.

Keywords: *Concentration, flow interpolation, Generalized Additive Model (GAM), Pollutant loads estimation, prediction, uncertainty*

Modelling the runoff, nutrient and sediment loadings in the Torrens river catchment, South Australia using SWAT

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Abstract: Torrens River is situated in the most populated catchment of Adelaide, South Australia. Over the past several decades the lower part of the catchment has been heavily altered by urbanization that has impacted the water quality of Torrens streams. Recurrent algal blooms along the river are driven both by stormwater runoff and in-stream pollutants. This study aims to estimate the loadings of nutrients and sediments of the urban section of Torrens river catchment (also known as Karrawirra Parri Prescribed Watercourse) between 2007 and 2016. This part of the river initially receives water from the Gorge weir and its flow is swelling by urban tributaries downstream. The Soil and Water Assessment Tool (SWAT) has been applied to develop a comprehensive model by integrating all available data on weather, soil, land use, hydrology and water quality in the catchment. The data from 2007 to 2009 were used as a "warm-up" period. The model has been calibrated from 2010 to 2013 for the main stream and one creek site. The calibrated model has been validated for the main stream from 2014 to 2015 as well as for tributaries that have been spatially-explicit monitored from 2015 to 2016. The results indicate that the model simulates reasonably well the runoff and nutrient loadings whilst results for sediment loadings are less satisfactory. The reasons behind these shortcomings are analyzed, taking into account the length and quality of available data records. The results obtained from this case study suggest that SWAT is an effective tool for simulating the long-term characteristics of surface runoff of urbanized semi-arid catchments, and can assist in estimating nutrient loadings of the main stream and tributaries. The validated model is currently tested as a tool for simulating prospective effects of future land use and climate changes.

Keywords: *Catchment modelling, River Torrens, runoff, nutrients, sediment, SWAT*

Investigating residual error models in the simulation of Total Suspended Solids (TSS)

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Abstract: In many water resource studies, the concentration or load of total suspended solids (TSS) in a water body is considered an effective assessment proxy for water quality deterioration. TSS transport can be efficiently simulated by conceptual water quality models, such as the Build-up/wash-off model (BwMod) which is frequently coupled to a hydrologic model for improved model simulations. However, these models have considerable uncertainty associated with the specified model parameters, observation data, and simple model structure. With the aim to improve the accuracy and reliability of TSS predictions, this research investigates a Bayesian approach to acknowledge the uncertainty associated with a TSS model. The study has two main objectives: (1) to explore the ability of data transformations for improving the goodness-of-fit of BwMod simulations and provide an appropriate estimate of the uncertainty of a Total Maximum Daily Load (TMDL) criterion; (2) to investigate the influence of streamflow as additional information in model calibration. This study applied two traditional transformations (log transformation and Box–Cox transformation) and introduced a new transformation based on Flow-Corrected Time (FCT), meaning the time is expanded during high values of data and compacted during low values; In a case study involving daily simulation of TSS concentrations in a catchment in southeast Wisconsin, USA, four data transformations (no, log, Box-Cox and FCT transformation) , three calibration scenarios (calibrating TSS concentration and streamflow with precipitation as input; calibrating only TSS concentration with precipitation as input; calibration with streamflow as input) are compared.

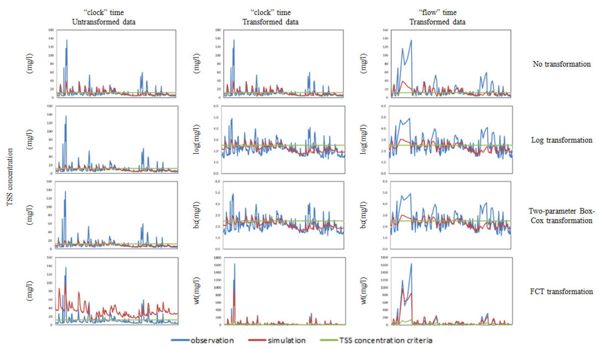

Figure 1. Comparison of TSS concentration after different data transformations in 2013

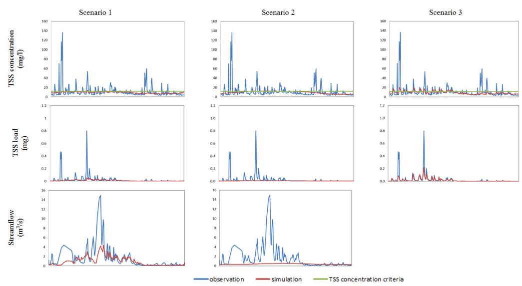

Figure 2. Comparison of simulations of different calibration scenarios in 2013

Figure 1 demonstrates that data transformations have a positive influence on the simulation's fit. The FCT transformation performs best in the flow time transformed space but has a bigger bias for TSS concentration observation in the untransformed space. Log transformation and Box-Cox transformation can improve the accuracy of water quality assessment.

Figure 2 shows Scenario 3, applying the observed streamflow as the input, has the best overall performance. This suggests that the availability of gives rise to improved TSS simulations. The comparison of Scenario 1 and Scenario 2 demonstrates that including streamflow as calibration data can improve the simulations fit, and also get a more accurate assessment.

Keywords: *TSS, uncertainty analysis, Bayesian inference, residual error, data transformation*

Author index

A

B

C

D

E

F

G

H

I

J

M

Q

R

S

T

U

V

W

X

Y

Z

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