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WaterCAST – Whole of Catchment Hydrology Model An Overview

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Sharing of water resources between traditional water users and the environment is becoming increasingly complex due to competion by different sectors of the economy and environment for what is often a diminishing resource and has resulted in the need for a whole-of-catchment modeling approach that can be used to improve the strategic management of water resources. WaterCAST (**Water** and **C**ontaminant **A**nalysis and **S**imulation **T**ool) is a whole of catchment model which has been developed by the eWater CRC in response to this demand. Catchment models are by necessity a compromise between detailed description of processes local scale which are then summed up and description of emergent processes that are manifest at large scales. WaterCAST provides a flexible modelling framework in which the level of detail is dependent upon data availability and the questions that are being asked of the model. Developments to WaterCAST are aimed at improving its capabilities.

In particular major developments are occurring to improve the capability of WaterCAST so that is can reliably estimate water, solute and sediment transport in regulated and unregulated catchments. An overview of the structure of WaterCAST and future developments is presented. WaterCAST presently uses a spatial structure consisting of functional units (FUs), sub-catchments, nodes and links. FUs are the smallest spatial unit and are areas of consistent hydrologic response. The sub-catchments are defined usually from a digital elevation models but allow users to refined these subcatchments. Sub-catchments have at least one FU and a node at the bottom through which outputs of water and constituents (solute and sediments). They may also contain a link if other sub-catchments discharge into them. Both surface generated and groundwater are transported to the nodes and filter models can be used to change the delivered volume or time of delivery. The nodes are linked to form a network that ends at the final node at the end of the catchment. The spatial structure is being modified to include a gridded structure within the sub-catchment and future developments will include the concept of area bands within sub-catchments. The hydrology is generated from one of a range of water balance models available and applied at the FU scale.

Generation of constituents is modeled using either; event mean concentration and dry weather concentration concepts, corelation between water flow and constituents or observed data. The water, solutes and sediments are transported from the FU's to a node in a sub-catchment via filter functions. Current developments include a new water balance model, stochastic rainfall generation, and more process based sediment generation and nutrient transport models. The model structure is developed on a plug and play basis which allows users to implement their own component models if they wish.

The eWater CRC WaterCAST model represents state of the art, software designed for practitioners and researchers to solve real world problems..

Keywords:*Hydrology, water quality*

1. INTRODUCTION

There are many catchment models available for calculation of water quantity and water quality. Invariably, the development of a model involves tradeoffs, particularly between complex solutions, which may offer deep process insights and great predictive potential, and simpler solutions that might be more accessible to the model user and require less data. The main approaches used to calculate the water quantity are lumped parameter or top-down models (e.g SimHyd, IHACRES, AWBM), distributed models based on the physical processes at small spatial scale (e.g TOPMODEL, TOPOG, SWAT) that are then aggregated up and models which are semi-distributed (e.g SWAT, THALES, E2). Breuer et al. (2009) compares a range of popular models used from lumped to physically based. Lumped parameter models, where catchment behaviour is described by catchment scale parameters, are common in hydrology. The lumped parameters are generally attributed to a physical entity and derived by fitting (tuning) the model to input and output data sets. However, as Beven and Freer (2001) have shown the parameter set obtained is not unique and a number of equally valid parameter sets can be found. This means that the parameter set is only valid within the parameter range represented by the data set used in the calibration. These models are examples of general linear models and as such will fit best around the mean of the data sets with the results becoming less certain as the extremities of the data range are reached. The distributed models are based on describing the hydrologic processes at small scale and then adding these up and routing the flows through the landscape. Modelling of systems usually results in scaling of processes in either the time domain or spatial domain and often both. It has been thought and argued in Freeze and Harlan (1969) that bottom up approaches will result in models that will be better than lumped parameter models (top down models). There are a number of studies that now challenge this assumption (Beven and Freer, 2001). It has also been shown that at larger scales the effects of the fine scale processes cannot be distinguished as Chapman (2003) showed for evapotranspiration. The frequency of the measured data is important if fine scale information is to be resolved from the data. Kircher et al. (2000) using fractal approaches to analyse high frequency data of stream flow and stream chemistry, showed that this high frequency data was needed to resolve the solute transport processes within the catchment. They showed that although the effects of preferred pathways could not be discerned from the water flow data, it could be from stream chemistry. This necessitated using a quite different model for solute transport within the catchment than would otherwise have been chosen. The WaterCAST model at present is more of a lumped parameter model than a distributed model but has the flexibility to be used as a semi-distributed model. Breuer et al. (2009) compared and contrasted a number of models and found that all models were equally good when the parameters were fitted to gauged catchments but in ungauged catchments distributed models or semi-distributed gave better results. WaterCAST is one of a suite of models that is being developed by eWater with RiverManager being the model that is being developed for highly regulated catchments (http://www.ewatercrc.com.au/technologies/riversystems/index.html).

The EMSS and E2 (Argent et al. 2005, Perraud et al. 2005) models where semi-distributed models but at the lumped parameter end of the scale between lumped parameter and distributed models. These models were a departure from such models being more user friendly, well supported, coded and documented models. They used simple models for water quantity and constituent (particulate and solute) generation. The WaterCAST model builds on this legacy (Argent 2007) and has and will have increasing capacity to for semi-distributed functionality into the future. Here we will present some of the features added to a beta version and planned in the near future.

Here we will present state of the WaterCAST model as well as changes planned in the future. Other papers within this and other sessions will elaborate further on the development of WaterCAST.

2. EXISTING MODEL FRAMEWORK

2.1. Spatial structure

The WaterCAST model, based on the E2 framework (Argent et al., 2005; Perraud et al., 2005), consists of a node link network for transport of water and constituents within the major channels in a catchment. Sub-catchments are defined based on the area draining directly to each link. The delineation of nodes, links and subcatchments it typically done topographically using a DEM, although work elsewhere in the CRC (Hardy et al. 2006a,b) is allowing engineered structures such as pipes and diversions to be represented in the same framework. The sub-catchments are made up of functional units (FUs) which are considered to have homogeneous hydrologic properties within the model. Importantly, the model user has control over how many distinct FUs to use and how they are defined. So, although the model does not explicitly consider the spatial position of FUs in a sub-catchment, the user could make use of positional information when defining FUs, such as defining 'upland agricultural' and 'floodplain agriculture' as different FUs. This decision is based on whether there is sufficient information to distinguish between the alternate FUs, which may be the case when considering constituents (Lyon et al., 2006; Niedzialek and Ogden, 2004). Filter models, which modify either the volume or transit time for water or constiuents, can be applied to each FU. This nested spatial structure allows the model to have only the necessary spatial discretisation for the problem at hand.

Routing of the flows through the network occurs using one of a number of routing algorithms attached to links; simple lags, Laurenson non-linear models, or Muskingham-Cunge routing. Storages such as dams are considered to be special types of link models. The storage models have the capability to represent storage losses, demands and extractions. However complex storage demand rules are not usually a major feature of WaterCAST models as WaterCAST is intended to be used in mainly catchments without major water diversions and extensive floodplains. This functionality is being built into the E2 framework within the River Manager product (http://www.ewatercrc.com.au/technologies/riversystems/index.html).

2.2. Rainfall Runoff

A number of rainfall/runoff models are available to the user within WaterCAST including AWBM, SimHyd, Sacramento, SMAR Tank or observed data (http://www.toolkit.net.au/Tools/RRL). The climate data required as input to the rainfall/runoff models can be generated by a number of methods and are often based on SILO data (SILO, 2004). A number of optimisers are available to provide parameter estimation. The Rainfall/runoff processe is the first step in generation of flows within WaterCAST. Two examples of the use of the rainfall/runoff models are Feikema et al. (2007) and Waters and Webb (2007).

2.3. Farm dams module

The WaterCAST farm dam model has been developed by integrating the TEDI model (Jordan et al., 2004; Nathan et al., 2005) into the WaterCAST modelling framework. Further details on the farm dam model and a comparison of the performance of the model with TEDI are provided in Cetin et al. (2009). The farm dam model is an example of a Filter function where some of the runoff generated by the rainfall/runoff model is filtered out at the FU level. The farm dams model is in the beta version of WaterCAST which has recently been released.

2.4. Constituent generation

The constituents (sediment and solutes) in WaterCAST are generated using the concept of event mean concentration (EMC) and dry weather concentration (DWC). Although not stated explicitly the EMC and DWC represent different pathways for constituents to move from the sub-catchment to the node. The weakness of the EMC/DWC approach in not considering the mechanism of where the constituents are generated has been recently highlighted by Lyon et al. (2006). For sediments, the gully erosion mechanism is not at present included in WaterCAST. Future developments are aimed at improving the constituent generation and transport. However, Feikema et al. (2005), Jordan et al. (2006) and Waters and Webb (2007) have used the EMC/DWC approach to model constituents. The values for EMC/DWC are either derived from measured data, literature or from the study of Chiew and Scanlon (2002) for South East Queensland.

2.5. WaterCAST model integration and "plug-ins"

The WaterCAST software is modularised such that each predictive element (eg a rainfall runoff model) is written as a component model class, which models for a single model unit (eg a single functional unit in a sub-catchment, or a single link). To produce a linked model of a catchment, the system creates an instance object of each model class for each unit that is applied to. For example, if a system has 100 sub-catchments, each with 5 functional units, there will be 500 instances of rainfall runoff models. Depending on the user's selections, some of these could be SimHyd while others could be AWBM or an alternative. With the inclusion of constituent generation, constituent filter and river routing processes, there can be thousands of model instance objects. The integrated execution of these is orchestrated by the simulation engine, which orders the models from the top (head waters) of the system to the outlet, one time step at a time.

New component model classes can be incorporated as plug-ins, where compatible component models are loaded into WaterCAST and run alongside or as a substitute to current WaterCAST models. For example the Sacramento rainfall/runoff model is developed as a plugin and now available for use as an additional plug-in. Outputs from other models such as PERFECT, GRASP or APSIM have been coupled to WATERCAST (Searle and Ellis, 2009).

2.6. User interface

The WaterCAST user interface has been under continual development and improvement over the past three years based on end user feedback. The user interface improvements include enhanced presentation of model output in both graphical and map format, easy access to model outputs at the FU, node and link scales (Figure 1). These improvements include:

- The project explorer, which allows the user to select the particular outputs that they want from each model run, using a tree structure. The project explorer also links with the main map view window of the catchment, to highlight the subcatchment, link or node where output has been produced from the model;
- The map view window now allows additional spatial layers to be shown. This allows the user to display landuse maps, aerial photos, satellite images or road maps as a background layer to the WaterCAST model.
- WaterCAST now automatically calculates time series of constituent concentrations (as well as constituent loads and streamflow) for each subcatchment, node and link selected for output by the user.

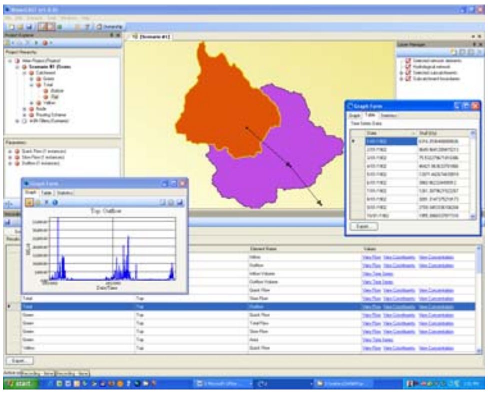

Figure 1. Sample of user interface and results displayed in both tabular and graphical formats.

The time series output window includes the key daily statistics of each model run, including mean, median, maximum, minimum and standard deviation of the time-series, displayed for the whole time-series, each calendar year, each calendar month or as a monthly average.

2.7. Calibration

Calibration of hydrology parameters can be performed within or externally to the model. There is an inbuilt rainfall/runoff calibration tool within WaterCAST which enables the user to calibrate the selected rainfall/runoff model to a set of observed gauging station data for a headwater catchment at a single location in a catchment. The most common approaches to generating model parameters is to derive them externally in the Rainfall Runoff Library (RRL) (www.toolkit.net.au/rrl).

An example of where external parameter estimation software has been coupled to WaterCAST for parameter optimisation and uncertainty estimation are outlined in Ellis et al. (2009).

3. FUTURE DEVELOPMENTS TO MODEL FRAMEWORK

The first version of WaterCAST was released in beta version recently and is currently being tested by regular and trusted users of eWater products. New modules are being developed for WaterCAST that will add to its functionality and usability. Below we briefly describe some of the new features that are currently under development or will be developed.

3.1. Ground water model

A model to improve the characterization of groundwater flow is being developed by a team of researchers lead by Ian Jolly and part of their work will be incorporated into WaterCAST and other parts in to the related RiverManager product of eWater's. When completed it is proposed to offer this groundwater module as an option to replace the groundwater storage/flow pathways in rainfall/runoff models. This module is described in more detail by Gilfedder et al. (2008).

3.2. Spatial structure or Ill Slope Delivery Ratio (HSDR)

The lack of spatial information at the FU level will be addressed by using a gridded approach at the sub-catchment scale. A hill slope delivery ratio (HSDR) will be developed. This will be based on the travel time for flow, with direction taken from the work of Wooding (1965) and McGuire and McDonnell (2006). The desire is to provide better scaling for the constituent concentrations particularly sediments where a constant value of HSDR is often used.

3.3. Climate data – Stochastic generation and downscaling

A prototype module has been developed for generating stochastic rainfall data for the catchment and allowing multiple simulations to be run. The stochastic data generator implements the multi-site daily rainfall generator included within the Stochastic Climate Library (SCL) (Srikanthan et al., 2004). The stochastic data generator obtains the rainfall data to be simulated from the climate data in the base simulation, which is usually the historically recorded rainfall data for each sub-catchment of the model. The user selects the number of replicates to be simulated and the length of the simulation period to be represented, with the default value being the number of whole years in the historical simulation. The model produces the replicates and runs the model multiple times, extracting statistics on the outputs of the model run that have been specified by the user. Efficiency in storage of output results is achieved by the model retaining only key output statistics from each run, rather than the full time series of results from every run at every selected location.

3.4. Flow weighted Constiuent Concentration

Modellers with the Queensland Department of Natural Resources and Water have written plug-ins that allow sediment contributions from FUs to be calculated using process based models and time series inputs. For example, the Revised Universal Soil Loss Equation (Renard et al., 1997) is applied by combining time series inputs of soil and landscape characteristics with temporally and spatially variable cover estimates. By applying a daily rainfall erosivity model (Yu, 1998, Yu et al., 2008), the eroded soil contribution from each FU can be calculated on a daily time step. Alternatively, the runoff and erosion contribution may be calculated externally to WaterCAST, with relevant time series supplied to WaterCAST containing relevant data. These alternative methods of constituent generation become available to the user once the plug-in is loaded, and are accessed and applied in the same way as the 'traditional' EMC/DWC model. This plug-in will be coded into the WaterCAST framework in the near future.

Further improvements using a spatial weighting will be developed for sub-catchments where a gridded spatial approach is used. This is will allow the filter function to be based on travel times for water parcels and have some physical meaning. These components will be incorporated into WaterCAST if testing proves that they are useful.

3.5. Porting of SEDNET/ANNEX

In order to improve the constituent modeling in WaterCAST the SEDNET and ANNEX programs for annual average sediment and solute loads from catchments (Prosser 2001; Sherman et al., 2006) will be developed into daily time-stepping modules. These will then be provided as additional approaches for constituent generation options in WaterCAST. In developing these modules improvements are planned for the gully erosion and HSDR (see above) modelling as well as for some of the solute calculations.

3.6. User interface and Output

The key developments in the user interface will be to make the model more user friendly for novice users and non-modellers. This will involve a redesign of the "wizard" used to set up new models that is better suited to new users and provides better guidance on the set up process. In addition, improvements to model output analysis are underway. These include the ability to compare observed and modelled data sets by a range of methods, and improvements to the generation of modelled output data in map format eg runoff and constituents.

3.7. Calibration and uncertainty

Optimisation tools for both calibrating and providing estimates of uncertainty in model outputs are being developed. These will firstly be incorporated in the Urban Water Management models being developed by eWater and then will become part of WaterCAST after they have been tested and trialed. These will provide users with better calibration, and uncertainty information to assist when using WaterCAST for catchment load setting targets.

4. DISCUSSION AND CONCLUSIONS

WaterCAST is a catchment model which is building on E2 as described in Argent (2007). Here we have given an overview of some WaterCAST's current capability and future developments that are close to being incorporated or still in the research phase of development. Other papers within this session and conference will provide more detailed information on WaterCAST and how it is being used or some of the new modules within WaterCAST.

A controlled release of WaterCAST versions will occur as improvements outlined here are added. Beta versions will be firstly released to eWater partners and competent users for trialing and 'bug' identification. Following bug fixing and comprehensive testing, new versions will be released for general use. It is envisaged that WaterCAST will become the major model used in Australia for catchment modelling of mainly unregulated, upland catchments.

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REFERENCES

Argent R.M., (2007), E2 – Past, present and future. In Oxley, L. and Kulasiri, D. (eds) *MODSIM 2007 International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand, December 2007, pp. 860-866.

Argent, R.M., R.B. Grayson, G.D. Podger, J.M. Rahman, S. Seaton, and J-M. Perraud, (2005), E2 – A flexible framework for catchment modeling, In Zerger, A. and R.M. Argent, (eds) *MODSIM 2005 International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand, December 2005, pp. 594-600.

Beven, K.J., and J. Freer (2001), Equilfinality, data assimilation and uncertainty estimation in mechanistic modeling of complex environmental systems using the GLUE methodology. *Journal of Hydrology*, 249, 11–29.

Breuer, L. et al. (2009), Assessing the impact of land use change on hydrology bt ensemble modeling (LUCHEM). I. Model intercomparison with current land use. *Advances in Water Resources*, 32, 129-146.

Cetin, L.T., A.C. Freebairn, P.W. Jordan, and B. Huider, (2009), A model for assessing the impacts of farm dams on surface waters in the WaterCAST catchment modelling framework. In *MODSIM 2009 International Congress on Modelling and Simulation*, Cairns, July 2009.

Chapman, T.G., (2003), Estimation of evaporation in rainfall-runoff models. In *International Congress on Modelling and Simulation*, D.A. Post (ed), Townsville, July 2003, 148-153.

Chiew, F.H.S., and P.J. Scanlon, (2002), Estimation of pollution concentrations for EMSS modeling of the south-east Queensland region. Technical report 02/2, February, 2002.

Ellis, R., J. Doherty and R. Searle, (2009). Applying parameter estimation and prediction uncertainty analysis to WaterCAST water quality models. *MODSIM 2009 International Congress on Modeling and Simulation*. Modeling and Simulation Society of Australia and New Zealand, Cairns, July 2009, (in press).

Freeze, R.A., and R.L. Harlan, (1969) Blueprint for a physically-based, digitally-simulated hydrologic response model. *Journal of Hydrology*, 9, 237-258.

Feikema, P.M., G.J. Sheridan, R.M. Argent, P.N.J. Lane, and R.B. Grayson, (2007), Using E2 to model the impacts of bushfires on water quality in South-Eastern Australia. In Oxley, L. and Kulasiri, D. (eds) *MODSIM 2007 International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand, December 2007, pp. 1126-1132.

Hardy M.J., G. Kuczera, and P.J. Coombes, (2006), Integrated urban water cycle management: the UrbanCycle model. *Water Science and Technology,* 52(9), 1–9.

Hardy M.J., G. Kuczera, and P.J. Coombes, (2006), Embedded hierarchical network modelling: a means to integrate across scales and systems. Proceedings of the 7th International Conference on Urban Drainage Modelling and the 4th International Conference on Water Sensitive Urban Design, Melbourne, Australia, 3–7 April 2006 (eds A. Deletic and T.D. Fletcher).

Gilfedder, M., D.W. Rassam, M.P Stenson, and M. Littleboy, (2008), Groundwater component of the WaterCAST catchment modeling framework. In *MODSIM 2009 International Congress on Modelling and Simulation*, Cairns, July 2009.

Jordan, P., R. Morden, and H. Sommerville, (2004), CHEAT: Complete Hydrological Evaluation of the Assumptions of TEDI User Manual, version 3.02 for software version 4.01. Sinclair Knight Merz Pty Ltd.

Jordan, P.W., R.M. Argent, and R.J. Nathan, (2006), Past, present and future of catchment modeling in E2 and the eWater CRC modeling toolkit. Proceddings: 30th Hydrology and Water Resources Symposium [CD-ROM]: Launceston, Tasmania, 6pp.

Kirchner, J.W., X. Feng, and C. Neal, (2000), Fractal stream chemistry and its implications for contaminant transport in catchments. *Nature*, 403, 524–527.

Lyon, S.W., M.R. McHale, M.T. Walter, and T.S. Steenhuis, (2006), The impact of runoff generation mechanisms on the location of critical source areas. *Journal of The American Water Resources Association*, 42(3), 793-804.

McGuire, K.J., and J.J. McDonnell, (2006), A review and evaluation of catchment transit time modeling. *Journal of Hydrology*, 330, 543-563.

Nathan, R., P. Jordan, and R. Morden, (2005), Assessing the impact of farm dams on streamflows, Part I: Development of simulation tools. *Australian Journal of Water Resources, 9, 1-11.*

Niedzialek, J.M., and F.L. Ogden, (2004), Numerical investigation of saturated source area behaviour at small catchment scale. *Advances in Water Resources*, 27, 925-936.

Perraud, J-M., S.P. Seaton, J.M. Rahman, G.P. Davis, R.M. Argent and G.D. Podger, (2005), The architecture of the E2 catchment modeling framework. In Zerger, A. and R.M. Argent, (eds) *MODSIM 2005 International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand, December 2005, pp. 690-696.

Prosser I.P., P. Rustomji, B. Young, C. Moran, and A. Hughes, (2001), Constructing river basin sediment budgets for the National Land and Water Resources Audit. Technical Report 15/01, CSIRO Land and Water, Canberra.

Renard, K.G., G.A. Foster, G.A. Weesies, and D.K. McCool, (1997), `Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE).' Agriculture Handbook No. 703. (USDA: Washington, DC.)

Searle, R. and R. Ellis, (2009), Incorporating variable cover in erosion algorithms for grazing lands within catchment scale water quality models. *MODSIM 2009 International Congress on Modeling and Simulation*. Modeling and Simulation Society of Australia and New Zealand, Cairns, July 2009, (in press).

Sherman, B., A. Read, Y. Chen, and J. Brodie, (2006), Nutrient modelling. Carroll, C., A. Cogle, and B. Sherman, (eds.), The use of SedNet and ANNEX models to guide GBR catchment sediment and nutrient target setting 1, Brisbane :Department of Natural Resources, Mines and Water: 22-33.

SILO - Queensland Department of Natural Resources. (2004), The SILO Data Drill. Department of NRM. Available from http://www.nrm.qld.gov.au/silo/datadrill/datadrill_frameset.html

Srikanthan, S., F. Chiew and A. Frost (2007), *Stochastic Climate Library User Guide version 2.1b*, Cooperative Research Centre for Catchment Hydrology, February 2007.

Waters, D.K. and P. Webb, (2007), The application of the E2 water quality model for regional NRM planning. In Oxley, L. and Kulasiri, D. (eds) *MODSIM 2007 International Congress on Modelling and*

Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2007, pp. 888-894.

Wooding, R.A. (1965), A hydraulic model for the catchment-stream problem I. Kinematic-wave theory. Journal of Hydrology, 3, 254-267.

Yu, B. (1998), Rainfall erosivity and its estimation for Australia's tropics. *Australian Journal of Soil Research*, 36(1), 143 – 166.

Yu, B., R.J.Ellis, and Z. Zhu, (2008), A report on estimating rainfall erosivity and peak rainfall intensity for the greater Fitzroy region.