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Complementary water quality modelling to support natural resource management decision making in Australia

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Identifying sources and pathways of pollutants moving through catchments is a prerequisite for effectively targeting on-ground works to improve water quality. Simulation models are an important tool in this regard to:

(i) Understand current catchment conditions including locating critical pollutant source areas, quantifying nutrient and sediment loads, determining delivery mechanism and elucidating cause-effect relationships.

(ii) Summarise current knowledge into conceptual models of catchment function and system responses.

(iii) Identify priority areas for intervention and assessing their likely impacts and cost-effectiveness.

A large number of hydrologic, nutrient and sediment models exist for research and natural resource management support. In terms of complexity, the choice of the model determines the demand for input data and calibration parameters and the spatio-temporal resolution of the simulation. All these factors influence the extent to which models provide useful information to support decision makers. Model comparisons often lead to debates about which model is better, rather than the more constructive approach of applying different models for different purposes to improve understanding or predictive capacity.

In this paper we investigate how three different water quality models, WaterCAST, CatchMODS and JAMS, could potentially complement one another to inform water quality management. The strengths, weaknesses and suitability of each model is discussed in the context of regional environmental investment planning within the Cradle Coast Natural Resource Management (NRM) region of north western Tasmania, a process typical of that being applied within Australia's 56 NRM regions. We suggest that the models potentially compliment one another in the following ways:

(i) WaterCAST and CatchMODS are appropriate for carrying out rapid estimations of sediment and nutrient loads at subcatchment and catchment scales,

(ii) JAMS is most appropriate for developing a conceptual understanding of hydrologic and solute processes and mapping critical pollutant source areas in space and time,

(iii) JAMS is the most appropriate for developing and evaluating nutrient-based management interventions

(iv) CatchMODS and JAMS together can be used to plan management interventions and evaluate the cost-effectiveness of different scenarios.

Further work will demonstrate the practicability of this approach for a selected case study in North West Tasmania.

Keywords: *Natural Resource Management, Water Quality, Complementary Nutrient Modeling Analysis*

1. INTRODUCTION

Nutrient enrichment, salinity and erosion are well documented water quality problems present across many catchments, including those in northern and eastern Tasmania, Australia (DPIWE, 2003). The approach adopted by natural resource management (NRM) regional bodies in Australia to improve water quality is based on ‘whole of catchment’ planning and commonly includes the following steps; (i) assessing current water quality conditions and levels of disturbance, (ii) setting resource condition targets for improvement in water quality parameters within specified timeframes (iii) applying a range of tools (including program logic, multiple criteria analysis and occasionally mathematical models) to plan and evaluate on-ground management actions (iv) monitoring performance against these targets and reviewing the outcomes. In this context, one of the pressing information needs is the ability to identify critical source areas of pollutants and the most appropriate and cost effective means of control, information that is generally not available to catchment managers.

Here we evaluate the potential of three water quality models to support the NRM investment cycle, with particular reference to steps (i) and (iii) above. Each model has been designed to improve nutrient management at catchment scales. Instead of a ‘one model fits all’ philosophy, we assess the capability of each model against criteria taken from the regional planning cycle to see how they could be used in a complementary way to guide the NRM decision making process. This paper is divided into two major sections:

(i) An overview of the structure and function of the three water quality models WaterCAST, JAMS and CatchMODS.

(ii) A discussion of the utility of each model for catchment management decision making and their complementary use for application in the Duck River catchment, north west Tasmania.

2. MODEL APPROACHES

This section provides an overview of the three models, including their underlying frameworks, data requirements and outputs.

2.1 WaterCAST

WaterCAST, an evolution of E2 (Argent et al. 2004), is a lumped, semi-distributed, conceptual catchment modelling framework that allows modellers to construct models by selecting and linking component models from a range of options (Argent et al. 2008). WaterCAST works on a daily time step and uses a conceptualisation of catchment processes in which a catchment is made up of sub-catchments composed of Functional Units (FUs) characterized by similar pollutant generation processes. FUs are typically based on land use. Each subcatchment or FU can use a range of component models that represent the processes of runoff generation, constituent generation and filtering. These processes are spatially lumped at the subcatchment nodes which are linked together to represent the flow network to the catchment outlet. The processes of routing, storage, decay, enrichment, as well as sources and sinks, can also be represented using combinations of the models applied to either the links or nodes (Argent et al. 2005).

The rainfall/runoff component of WaterCAST consists of a choice of lumped conceptual models including AWBM, SimHYD, Sacramento and SMAR. Rainfall and evaporation data can be imported as a daily time series from SILO (www.longpaddock.qld.gov.au/silo/) using methods developed by Jeffrey et al (2001). Constituent generation in each FU is typically determined using the event mean concentration (EMC), and/or dry weather concentration (DWC) approaches (Chiew et al. 2002). EMCs represent storm flows and DWCs represent baseflow pollutant concentrations. Each FU is considered to be independent and therefore runoff and constituents are generated without considering connectivity and flowpath variation. Runoff and constituents are then transferred from each unit directly to the node and summed with the outputs from the other FUs (Neumann et al. 2007). Soil water processes are not considered explicitly.

2.2 Spatial distributed model JAMS

JAMS (Jena Adaptable Modelling System) is a modular oriented framework system (Kralisch and Krause 2006) developed by the Department of Geoinformatics, Hydrology and Modelling (DGHM) at the University of Jena, Germany. JAMS is a freely available tool (http://jams.uni-jena.de) for hydrologic and solute landscape analysis. It consists of process-oriented hydrological components, a groundwater module, modules for nitrogen transformation and transport as well as land use management components, a database system and a 2D/3D visualisation tool. Details are described in Krause 2001, Krause et al. 2006, Bende-Michl et al., 2006 and Fink et al., 2007. JAMS can be used in a custom-tailored fashion with the user defining the modules to be used for a particular application.

All modules operate on a daily time step. However, hydrologic and solute models are flexible if input data are available on a finer scale. To conduct landscape assessments, the model uses a fully distributed approach despite the fact that the hydrologic and solute components of JAMS can be modelled on flexible spatial scales. Modelling entities are mostly derived according the ‘Hydrological Response Units’ (HRU) concept (Flügel 1995). HRUs are defined as distributed, heterogeneously structured model entities representing specific landscape units of similar response in terms of their hydrological process dynamics. Criteria used for defining homogeneity are based on the hydrological system in the basin of interest. HRUs are delineated by overlaying GIS data layers, such as land use, soils, geology and topography, that have been identified as important for hydrological process dynamics. Water and solute transport routing between HRUs is based on digital relief analyses (Staudenrausch 2001).

Simulation outputs are derived for each of the HRUs, or aggregated for chosen parts of a catchment, subcatchments and/or different timescales (e.g. daily, monthly, and annual). These outputs include all components of the water and solute balances as well as simulated time series data (discharge, nutrient concentration or loads).

2.3 Catchment-Scale Management of Distributed Sources Model (CatchMODS)

The CatchMODS model is designed to simulate current conditions and the effects of management activities on the quality of receiving waters at catchment scales (Newham et al. 2004). The model integrates hydrologic, sediment and nutrient export models with a simple economics submodel. This enables development and evaluation of the impacts of management strategies for reducing nutrient and sediment yields to waterways.

CatchMODS is based on a series of linked river reaches and associated subcatchment areas. The modelling is lumped at these stream reach and subcatchment units (Newham et al. 2004). The topology of the stream network enables the downstream routing of pollutants with the individual submodels each simulating processes of pollutant attenuation and/or deposition. Reaches and subcatchments are disaggregated using an area threshold to define reaches. The topology of the stream network defines the associated subcatchment areas. The size of a subcatchment in a typical application of CatchMODS averages 30 km^2.

The IHACRES rainfall-runoff model (Jakeman et al. 1990) is used to estimate both surface and subsurface discharge in CatchMODS. It is applied at a daily timestep with its temperature and rainfall inputs scaled linear according to subcatchment mean rainfall and mean elevation, respectively. The sediment submodel of CatchMODS is modified from the SedNet model (Prosser et al. 2001) but retains several of its underlying algorithms. The focus of CatchMODS is on the simulation of the suspended sediment (SS) fraction only. This reflects the importance of SS as a source and transport medium for many common stream pollutants e.g. phosphorus. It also enables investigation of contemporaneous SS fluxes and management effects over the more historic perspective of SedNet. Sediment inputs are estimated from hillslope, gully and streambank erosion sources. Dissolved and particulate nutrient fractions are simulated separately in CatchMODS. The P and N submodels of CatchMODS are identical in structure. A generation-rate-based or flow-based approach (or a combination of the two) may be used for to simulate dissolved nutrients. The attenuation of dissolved nutrients through the system is simulated using a simple exponential decay function.

The costs of management change scenarios are also estimated in CatchMODS. Three types of costs are estimated: fixed, ongoing and landuse-related. Fixed costs are those one-off costs which are incurred during the implementation of riparian and gully zone remediation works. Ongoing costs are the maintenance costs required to maintain the effectiveness of riparian and gully zone remediation works for pollutant control. The landuse-related costs represent the change in gross margins associated with the conversion between landuses.

3. MODEL ELEMENTS

This section examines how model characteristics relate to the NRM decision making process (Table 1). This is similar to other comparative studies such as Letcher et al. (2002) and Schoumans et al. (2009) but focuses on the regional NRM needs for Tasmania (see steps i-iii in Table 1). Three main criteria were considered: model complexity, capability for prognostic and scenario modelling and operational considerations (see step iv in Table 1).

Table 1. Assessment of selected attributes of the WaterCAST, JAMS and CatchMODS models against key NRM planning steps used in Tasmania.

NRM planning steps	***Key elements***	**WaterCAST**	**JAMS**	**CatchMODS**
(i) Analyze current water quality status	*Pollutants considered*	Any defined constituent	Nitrogen, salt (sediments and phosphorus under development)	Suspended sediment, nitrogen and phosphorus
	Pathways considered	Surface runoff, baseflow, drainage routing (links and nodes)	Surface runoff, baseflow, matrix flow, preferential flow, groundwater interactions, drainage, in-stream and land based water and nutrient routing (links and nodes)	Surface runoff, baseflow, channel-derived, in-stream routing of nutrients and sediment
	Solute processes captured	Simple in-stream processes, filtering, riparian buffering, storage nutrient and sediment deposition (via plug-ins)	Nitrification, denitrification, volatilisation, plant N uptake, in-stream retention (under development	Quick flow, baseflow and point sources
	Spatial discretisation	Lumped, semi distributed	Fully distributed, with a flexible vertical soil profile	Lumped, semi distributed
	Temporal resolution	Daily	Daily, Sub-daily	Daily for discharge, annual for nutrients and sediment
	Generated outputs	Discharge and concentration at catchment outlet, subcatchment nodes and links	Water and nutrient budget, discharge, concentration and pollutant load at catchment outlet, at subcatchments, at variable locations, separated according to flow processes at various temporal resolutions	Discharge and concentration of pollutants at all subcatchment outlets.
	Uncertainty analysis	External application of PEST	Monte Carlo, Shuffle Complex Evolution	External sensitivity analysis
(ii) Set Resource Condition Targets	*How much catchment improvement is necessary and realistic?*	Comparison of different model scenarios (model specifications)	Regional scenario development and outcome assessment for feasibility of chosen RCT	Comparison of different model scenarios (model specifications)
(iii) Tools for on-ground interventions	*Scenario assessment and cost-functions*	External plug-in for scenario development	Comparison of different land use management and climate scenarios and cost functions	Cost functions
(iv) Operability	*Spatial data required*	Land use data or similar, DEM or subcatchment map	DEM, soil, geology, land use, land use management GIS preprocessor is included to determine modelling units	Land use data, DEM and/or subcatchment maps, surface soil nutrient concentration, gully, channel erosion
	Hydro climatic data required	Daily rainfall, daily evaporation, observed flow	Daily (or less) rainfall, temperature, radiation, wind and humidity	Daily rainfall, temperature and observed flow
	Other data required	Event mean concentrations, dry weather concentrations, sub model parameters (as required)	Crop growth data: Leaf Area Index, Biomass development	Streambank and gully erosion rates
	Operational experience and skills required for users	Medium, training recommended	High, training recommended	Medium, training required
(v) Main evaluated applicability	*Assisting NRM planning steps i-iii*	Rapid analysis of current nutrient loads at subcatchment scale (i) Scenario modelling	Detailed process understanding of nutrient nitrogen delivery via different pathways to stream (i-ii) and comparing different management scenarios and cost functions (iii)	Planning for best regional interventions (iii)

Table 1 illustrates that the three models use different concepts and approaches to simulate the movement of water, nutrients and sediment. The differences occur at the level of detail used to summarise catchment function; the level of spatio-temporal complexity; the detail of the processes, transformations and pathways represented; and the outputs generated to simulate system responses. While the data driven models WaterCAST and CatchMODS are less complex than JAMS, their strength lies in the ability to rapidly construct a functional representation of a catchment for descriptive purposes, and in the case of WaterCAST, to do this for any defined constituent. The strength of the JAMS model is the ability to create spatially explicit simulations of water and solute fluxes and develop some understanding of the processes that determine the occurrence of ‘hot spots’ of nutrient loss. The JAMS model therefore requires more detailed input. All models include some form of sensitivity analysis aimed at understanding model behaviour, although WaterCAST and CatchMODS rely on this being externally driven.

All models can assist in planning step ii, setting regionally-specific Resource Condition Targets (RCTs). All models also have the capacity to develop intervention scenarios to some degree, which provides a test of the feasibility of these targets. Scenario building, which provides additional functionality and explanatory power, can also assist with NRM planning step iii, assessing the likely effectiveness of interventions and management options. The emphasis of the JAMS model is on investigating the effects of small scale management change. JAMS can be also used to run future climate change scenarios to assess the likely outcomes of climate change adaptation measures. To handle different intervention strategies, the WaterCAST model requires the user to input alternative source data such as land use maps or alternatively use a plug-in such as the Riparian Particulate Model (Newham et al. 2007). CatchMODS has built in options for interventions including gully and riparian zone remediation and land use and land management changes. JAMS and CatchMODS have the extra functionality of assessing the cost functions of interventions, enabling the assessment of costs and benefits for different scenarios.

Due to the different levels of model complexity and outcomes, the operational requirements and skills needed to run the three models differ accordingly. Initial training is recommended for each of the three models. However for the JAMS model, more input data are required and the setup of the model will be more time consuming. To achieve the level of spatial and temporal specificity of which JAMS is capable, it is highly recommended that multiple sources of data are used for model validation and calibration including targeted high frequency nutrient monitoring data.

4. COMPLEMENTARY MODEL APPLICATION IN THE DUCK RIVER CATCHMENT

The theoretical complementarity of the three models is currently being tested in the Duck River catchment in northwest Tasmania with the aim of assessing the spatial and temporal distribution of nutrients and sediments and developing a range of cost effective interventions. To achieve these goals, the application of the three models is being staged so that the ability of each approach to inform management is maximised and the development of each model is informed by the learning developed from the others. The remainder of this section describes progress towards this goal.

The benefits of using the models WaterCAST and CatchMODS are that they can easily identify high risk areas of subcatchments with a high potential of sediment and/or nutrient losses by taking both point and non-point sources into account. The WaterCAST modelling has been completed for total phosphorus (TP) (Broad and Cotching 2009) and this identified a single subcatchment in which modelled TP concentrations were disproportionately elevated. However, the WaterCAST model does not allow direct interpretation of the causes of this result (Broad and Cotching 2009). As JAMS incorporates interactions between hydrologic and solute processes and the physiogeographic, hydrologic, climatic and land use characteristics of a catchment, development of a JAMS model for the identified subcatchment was then initiated. With JAMS it is possible to develop understanding of some of the underlying mechanisms of pollutant generation which can be used to inform intervention decisions. This is currently being undertaken together with increased monitoring efforts and high temporal resolution nutrient modelling to infer dominant nutrient generation processes and likely sources. The outputs of the monitoring will be used to directly inform the development and application of the JAMS model. This targeted monitoring also provides direct input to the conceptualisation and calibration of the CatchMODS model and calibration of EMC and DWC for WaterCAST.

CatchMODS will be used in a similar manner as WaterCAST to examine sediment losses in the catchment, with the outputs of the JAMS model being used to test the likely effectiveness of different management strategies for pollutant control. CatchMODS will be the primary tool used to analyse the cost effectiveness of interventions, and its user friendly interface will allow catchment managers to directly construct and explore their preferred management scenarios.

5. SUMMARY

We have explored an approach for complementary application of three different complex models to the management of nutrient and sediment pollution at catchment and regional scales, highlighting the strengths of the different models. The value of WaterCAST is in regional scale assessment to identify those catchments and subcatchments with the potential to generate high pollutant loads under a range of land use scenarios. The advantage of CatchMODS is its ability to carry out more detailed assessment of the most cost effective mix of interventions to manage pollutant loads at sub catchment and catchment scale. The JAMS model, used in conjunction with targeted high frequency water quality monitoring, provides a test of the assumptions in both WaterCAST and CatchMODS about the processes that drive nutrient generation and delivery.

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