



Development of a catchment scale contaminant cycle model for stakeholder use – final project report



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Reference

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Development of a catchment scale contaminant cycle model for stakeholder use – final project report

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ABSTRACT

The project contributes to the development of a comprehensive contaminant cycle model applicable to large catchments. The project elicited stakeholder input to the identification of priority contaminants and the spatial/temporal scales important to management, which informed model design. Four issues were identified: generation of contaminants (notably sediment, phosphorus and nitrogen); effectiveness of riparian buffers in trapping particulates (sediment and nutrient); effects of nutrients, flow and riparian shade on instream algal biomass and gross primary productivity; and effects of salinity on stream benthic macroinvertebrates. Five new computer models were developed that will be delivered through the modelling framework E2 (www.toolkit.net.au) – the riparian particulate (RPM), gross primary productivity (GPP), time-varying salinity effects (TVSE), algal biomass (ABM) and stream community metabolism (SCM) models. Due to E2 and stakeholder timelines, some activities are ongoing - RPM and GPP model sensitivity testing, and implementation of the TVSE, ABM and SCM models. The RPM, GPP and salinity tolerance models are currently being applied and tested in collaboration with stakeholders in south-east Queensland and the Wimmera, and this is building stakeholder ownership and trust. In addition to the computer modules, the project submitted six milestone reports, six technical reports, four journal articles and three conference papers. The project has identified two areas for future research. First, there is a clear need to better integrate field-scale experimental and modelling work with catchment-scale models in order to accurately quantify the effects of mitigation measures (e.g. grass buffer strips for trapping particulates and riparian soils for denitrification). This may require separate modelling of soluble and particulate forms of nutrient which are transported along different flow pathways and undergo different hillslope, riparian and instream transformations – current models lump different forms of nutrients and predict only totals. It may also require separate detailed field-scale, process models to inform the design of mitigation measures; and simpler catchment-scale models that capture the emergent properties of the field-scale models. Second, current models focus on predicting flow and contaminants while managers are often concerned with ‘ecosystem health’. There is a clear need to more closely align measures of ‘ecosystem health’ with the capability of catchment-scale models.

INTRODUCTION

The project ran from 31 October 2002 – 31 December 2005 (extended from 31 August 2005). The aim was to develop a comprehensive contaminant cycle model applicable to large catchments, giving consideration to sediment, nutrients, salt and ecology, and the interlinking of land, groundwater and rivers. The objectives were

1. To develop a catchment modelling framework to integrate and link component models developed by various researchers, including those contributing to other projects under the Contaminants Program
2. To conduct initial stakeholder workshops in two regions to articulate broad focus of the project and solicit input viz-a-viz modelling needs
3. To conduct technical workshops with modelling specialists (including other National River Contaminant Program project teams) to discuss appropriate model algorithms, scale issues and model validation
4. To develop a comprehensive contaminant cycle model applicable to large catchments, giving consideration to sediment, nutrients, salt and ecology, and the interlinking of land, groundwater and rivers
5. Via stakeholder consultation, ensure that the model addresses the right questions and is presented in a form that is meaningful to both technical and lay people
6. To apply the model to two regions as case studies, engaging stakeholders throughout the process.

Acknowledgements

The project team had the support of a generous group of researchers, model developers and industry partners. While much came as in-kind support from the contributing organisations (CSIRO Land and Water, The Australian National University and the CRC for Catchment Hydrology), a smaller, though no less significant, proportion came through a network of researchers established within the River Contaminants Program itself. These contributors are named in Appendix 2 and we gratefully acknowledge their contributions to the successful completion of the project. The financial support of Land and Water Australia and the Murray Darling Basin Commission through their River Contaminants Program are also gratefully acknowledged.

Activities

With the development of the catchment modelling framework E2 being largely conducted by the CRCCH, this project focussed on clarifying the management requirements of catchment-scale models and, where required, developing new models and providing data for model users. Key project activities, mapped to project objectives and outcomes, are summarised in Table 1.

Table 1, Key project activities mapped to objectives and outcomes/products

Key Activity	Objective*	Outcome/Product
Framework development		
Online and email survey (March 2003) to prioritise end-user needs and preferences (notably priority contaminants, important spatial & temporal scales).	2, 5	Project attuned to stakeholder preferences Publication [1].
Review of existing catchment models in use in Australia.	2	Through analysis of strengths and limitations, inform framework and modelling needs. Publications [2], [3].
Work with existing CRCCH stakeholders (focus catchment groups, industry partners and modelling toolkit developers) via seminars, training courses, workshops and meetings.	2, 5	Direct engagement with catchment managers and water industry partners. <u>Improved understanding of stakeholder needs and model development process.</u>
Technical Workshop (March 2004) to identify key information gaps, discuss and agree upon new model algorithms, and plan delivery.	3	<u>Set priorities</u> for module development and <u>scope modules</u> . Establish Working Groups to develop modules. Publication [4].
Liaise with CRCCH modelling toolkit developers to ensure alignment between the catchment modelling framework E2 and the new modules.	1, 4	Implementation of modules within E2 as described in module reports.
Module development		
Review and update salinity tolerances for Australian macroinvertebrates. Develop a new model for the effects of time-varying salinity based on Kefford's experimental research. Field test the resulting tolerances and model using Wimmera data (with Wimmera CMA).	4, 6	<u>Updated salinity tolerances</u> . Proof of concept for a <u>new model of time-varying salinity effects</u> – further testing required. Protocol for assessing salinity effects in E2. Salinity tolerances and the model are described in [5], [6] and [7]. Field testing is described in [8].

Key Activity	Objective*	Outcome/Product
Develop a new model for algal biomass, extend an existing model of gross primary production (GPP) and scope a respiration model. Better capture the relationships between light and shade, temperature, nutrient, grazing pressure and flow variability and their effects on stream community metabolism and stream 'health'.	3, 4	<u>New algal biomass model</u> . Improved GPP model. Protocol for <u>assessing stream health</u> within E2. The models, including how to implement them in E2, are described in [9].
Develop a new, simplified model for particulate trapping in riparian buffers. Provide a capability in E2 to analyse alternate design and performance scenarios. Field test the model (Pine Rivers, south east Queensland with a CRCCH industry partner)	4, 6	<u>New model for particulate trapping in riparian buffers</u> within E2. Capability for catchment managers to assess at catchment-scale the effect of riparian buffers on particulates including nutrients. The model and its use are described in [10], [11] and [12]
Review current nutrient generation models and collate available data. Suggest new modelling approaches required to meet stakeholders' needs.	3, 4	Guidance for E2 users on selecting appropriate <u>contaminant generation</u> modules and data. Described in [13].

* Objectives are listed in the Introduction.

This report describes the delivery framework and the rationale, methods and outcomes of each module development.

DELIVERY FRAMEWORK

The modelling framework E2 is an obvious tool for the delivery of work from this project to stakeholders. E2 is a new approach to catchment modelling under development by the CRCCH (now eWater) as part of the Catchment Modelling Toolkit (www.toolkit.net.au). E2 is designed to support the construction of whole-of-catchment models, and uses a sub-catchment and node-link system to represent catchments. Within sub-catchments, modellers choose from a suite of component modules for runoff generation, constituent generation (e.g. total suspended sediment, nutrients), and constituent filtering (e.g. by riparian buffers). Sub-catchments deliver water and constituents to nodes (viz. sub-catchment outlets) that enter links (e.g. stream channels). Within links, water and constituents are routed downstream and constituents may undergo instream processing (e.g. enrichment/decay and source/sink). E2 provides a 'menu' of different algorithms (or modules) for each process. Modellers can also develop new 'plug in' modules - this project has developed and tested several such modules that are described below.

EFFECTS OF SALINITY ON INVERTEBRATES

This project was undertaken by CSIRO Land & Water (CLW) in collaboration with RMIT University with the aim of improving our capacity to predict the loss of riverine benthic macroinvertebrate species resulting from rises in salinity. Benthic macroinvertebrates are an important component of stream ecosystems and are commonly monitored to measure ecosystem health. Many freshwater macroinvertebrates are regarded as more salt sensitive than freshwater fish and many freshwater plants. Where this occurs managers can set salinity targets to protect important salt sensitive macroinvertebrates on the understanding that these will also protect other more salt tolerant organisms. Chemical and physical indicators are important surrogates for assessing and/or protecting aquatic ecosystems because they are less costly to measure and some (e.g. salinity) can be monitored continuously. Many management decisions are based upon comparing chemical and physical measurements with guideline values even when the overall objective is to protect biological integrity. Chemical and physical indicators are also attractive to managers because many can be modelled at a catchment scale to provide a quantitative basis for supporting management decisions. Within Australia there are a number of salinity models that have the potential to be used, together

with salinity guidelines, to support management decision making. This approach requires identifying important and sensitive macroinvertebrates and quantifying suitable salinity tolerances. This activity involved five phases:

- review of current salinity guidelines,
- re-estimation of species' salinity tolerances using monitoring datasets,
- development of a new model for the effects of time-varying salinity,
- developing protocols for assessing salinity effects in catchment-scale models like E2, and
- testing salinity guidelines and models in the Wimmera.

Review of Salinity Tolerances

Salinity guidelines for macroinvertebrates in Australia are predominantly based on the maximum salinity at which species are observed in the field (MFD). In this project we compared published salinity guidelines and found significant differences. We identified various reasons for these differences and have described how to improve MFD estimates, including using replication of sampling and laboratory data. Recent studies at RMIT laboratory indicate that guidelines can also be based upon laboratory mortality studies, and work is proceeding to develop this approach.

Re-estimation of Salinity Tolerances

We re-examined two large monitoring datasets (Victoria and South Australia) with the objective of obtaining robust MFD estimates and compared these with previously published data, including the Salt Sensitivity Database (Bailey et al. 2002) This Database predicts greater species loss at a given salinity than our results and than other published results. There may be sound ecological reasons (acclimation and/or differences in community composition) for these differences in which case this variability should be taken into account when making management decisions. For example the more conservative Salt Sensitivity Database may need to be used in low salinity, upland streams while the higher salinity tolerances may only be applicable in lowland, semi-arid streams. We suspect, however, that the differences may arise from weaknesses in the MFD approach. Further monitoring and analysis are required to resolve this issue.

Modelling the Effects of Time-Varying Salinity

A new process-based model was developed during this project for predicting the mortality of macroinvertebrates exposed to time-varying salinity. Salinity varies in streams as a result of natural rainfall variations and/or anthropogenic discharges but current salinity tolerances do not account for such variations. The model estimates mortality from haemolymph salinity which is predicted by quantifying salt diffusion, excretion, storage/release and uptake. The model also allows animals to acclimate to moderate salinity. The model has been calibrated for two common macroinvertebrates species *Paratya australiensis* and *Micronecta annae* using laboratory observations of mortality when exposed to sudden increases and decreases in salinity. Four variants of the model have been developed, with increasing levels of complexity. Currently none of the four models is advocated for use by managers without further testing and refinement. Nevertheless, they show considerable promise as a framework for determining guidelines to protect stream macroinvertebrates exposed to time-varying salinity. At this stage the principal value of the model is to generate hypotheses about how animals respond to time-varying salinity.

Assessing Salinity Effects in Catchment-Scale Models

Protocols have been developed for using salinity predictions made by a catchment-scale model to make predictions of macroinvertebrate response. Two approaches are suggested: average and seasonal biodiversity, and time-varying response. Average and seasonal biodiversity are assessed using previously published salinity guidelines and modifications suggested as a result of this study. This protocol is ready for implementation. The time-varying response is predicted using the recently developed model and requires further testing. Work is currently underway to demonstrate the implementation of these protocols within the new catchment model E2.

Model Testing

Work is currently underway in collaboration with the Wimmera CMA to test the revised salinity tolerances and model. The study will be completed in April 2006 and the results published. Preliminary findings support the conclusion outlined earlier that in semi-arid, lowland rivers, species often occur at higher salinities than is reported for upland and tropical rivers. It is not clear whether this is because species become acclimated after prolonged exposure to high salinity or because salinities are consistently below the species' tolerance in upland and tropical rivers.

GROSS PRIMARY PRODUCTIVITY AND ALGAL BIOMASS

Periphyton is the mixture of algae, bacteria and fungi that grows on rocks, snags and man-made structures in streams. It is an important food source at the base of the food web and in this role makes a positive contribution to ecosystem health. However, it can adversely affect aesthetics and ecosystem health if its biomass is excessive and/or its metabolism results in large diurnal fluctuations of pH and dissolved oxygen concentration. This activity investigated three key measures of ecosystem health associated with periphyton: (1) algal biomass, (2) photosynthesis (commonly termed gross primary productivity, GPP) and (3) respiration. There is sufficient (though not extensive) field and laboratory data to show that biomass, GPP and respiration have a strong relationship with catchment condition and respond in a systematic way to changes in flow, nutrients, shade and temperature. Our aim was to quantify this response using new models that can be coupled with existing catchment-scale models of flow and contaminant concentration to improve our ability to predict ecosystem response to management (e.g. land use change, riparian restoration). Stream ecosystem models have not yet reached the point where quantitative predictions can be accepted with confidence but the models developed by this project, when used in conjunction with laboratory studies and field experiments, can be used to guide both research and management.

Algal Biomass Model

A new, simplified model was developed for algal biomass during periods of steady, low flow. The model is founded upon the premises that: (1) maximum algal biomass can be estimated knowing only the availability of nutrient, shade and temperature; and (2) maximum algal biomass can then be modified for the effects of grazing and scour. By constraining the application of the model to low flows, the scour effect can be eliminated. Grazing effect is captured through user specification of grazer biomass. Model predictions compare favourably with a rather limited dataset from cobble-bed rivers in New Zealand but the model has not yet been tested using data from Australian rivers.

Simplified GPP Model

Gross primary productivity (GPP) is currently monitored and used as an indicator of ecosystem health. Streams with very high GPP are those that are unshaded, have high nutrients and temperature, and high algal biomass – measures that often correlate with low biodiversity and poor ecosystem health. An existing GPP model (Watson & Vertessy, 2002) was reviewed and shown to be consistent with the framework underpinning the algal biomass model described above. The Watson & Vertessy model is currently used within the EMSS model to make catchment-scale assessments of ecosystem health. However, GPP is only indirectly related to stream health – it is the fluctuations in pH and dissolved oxygen resulting from high GPP that directly affect macroinvertebrates and fish. Thus there is limited scope to generalise the simplified GPP model. Nevertheless, with some enhancements, it is recommended for on-going use at least in the short-term.

More general GPP Model

A more general GPP model is required that can be used to predict fluctuations in pH and dissolved oxygen concentration. The concepts underlying the algal biomass model can be used to predict algal photosynthesis and respiration and help build such a model. Whereas a daily time step is adequate for predicting biomass, a much finer time step of minutes-hours is required for predicting diurnal variations in dissolved oxygen and pH. A modelling framework was developed for predicting algal GPP and respiration which can readily be combined with standard models for reaeration and used to predict river dissolved oxygen concentrations. The main reason for not proceeding to implement this

more general GPP model is the difficulty in predicting respiration by bacteria and fungi associated with heterotrophic biofilms and detritus.

Attached Heterotrophs

Although a sound conceptual framework exists for modelling algal GPP and respiration which is supported by extensive laboratory and field data, the prediction of respiration by bacteria and fungi associated with heterotrophic biofilms and detritus poses a major challenge. A modelling framework for the heterotrophic component of the periphyton was proposed but further work is required to collate laboratory and field data, implement, calibrate and test the model.

Recommendations and Key Findings

The key finding is that there is common ground between the scales at which catchment modelling is undertaken and the finer scale at which instream ecological modelling is undertaken. Within the limitations imposed by gaps in the data available for their running and testing, a family of models has been developed that demonstrate sensitivity to changes in nutrient levels and riparian shade, and produce reasonable predictions of algal biomass, GPP and respiration rate. These results are sufficiently encouraging to recommend proceeding with implementation of the modules in a catchment modelling framework. The algal biomass model has been reported on in Milestone Report #5. This model is available as a stand-alone module in the CSIRO modelling environment (TIME), and is presently being ported into the E2 environment where it will be included in a library of models that can be attached to storages. The GPP and algal biomass models are currently being applied and tested in collaboration with WBM Oceanics (Tony Weber) and stakeholders in south-east Queensland. Further work is desirable to assess the robustness of the biomass and GPP models under a range of catchment conditions, to test their applicability in a range of stream types, and to assess their usefulness to managers when deliberating the merits of a range of alternate catchment action plans.

RIPARIAN PARTICULATE MODEL

Restoration of riparian buffers is widely promoted as a key management activity to improve water quality in catchments. Yet, our ability to model their performance (and thus assess their worth against other activities) is very poor. The riparian particulate model (RPM) was developed to address this deficiency. The RPM is a simple conceptual model of particulate trapping in riparian buffer zones that quantifies the particulate trapping capacity of grassed riparian buffers through settling, infiltration and adsorption. The model is sensitive to the effects of consecutive pollutant loading events and variations in buffer characteristics (e.g. vegetation type, buffer slope, size). It can be applied at both site- and catchment-scales. At catchment-scales it has been implemented within E2 to allow catchment managers to help decide where in catchments to invest in the establishment and/or protection of riparian grass buffers.

Application

The RPM module is being trialled within an E2 model built for the North Pine catchment of south-east Queensland (WBM Oceanics, 2005). While excellent results have been obtained for observed vs predicted flows, poor water quality parameterisation and calibration highlighted a key use for the RPM module. Typical catchment models use Event Mean Concentrations (which vary with land use) to estimate pollutant loads during storm events. This approach gives the same pollutant concentration in each storm, regardless of the event size. While this is acceptable practice in many catchment models, for the North Pine application a better representation of catchment pollutant generation and filtering was needed to more accurately predict loads on a downstream dam. The RPM module is providing the ability to calibrate phosphorus loads entering the dam by allowing larger flow events to contribute higher loads to the dam and reducing the impact of smaller events through phosphorus trapping in the riparian zone.

Recommendations and Key Findings

The RPM captures some important features of experimental findings, notably vegetation damage during high flows and the recovery of trapping capacity between events. The performance of the RPM against a selection of experimental studies has been acceptable. Its first trial in south-east Queensland is encouraging, particularly its ability to discriminate between large and small events, and thus support better calibration of water quality models. Improvements in model performance should be possible through further experimental work, model development and testing, and refinement of parameters. The RPM model provides a framework for guiding ongoing experimental work.

NUTRIENT GENERATION

The generation (and consequent transport) of nutrients from the landscape (driven by climate, topography and management) is a critical component of catchment scale contaminant cycle modelling. A review of nutrient generation was undertaken [14] to summarise published data and models and assist managers predict contaminant generation rates within catchment-scale models such as E2 and guide ongoing development of nutrient generation modelling approaches.

Model and Data Review

The review focussed on generation processes in an Australian context, with a discussion and categorisation of nutrient generation modelling approaches. The review evaluates several models currently used in Australia, suggests new directions in modelling catchment-scale nutrient generation that are required to meet the needs of catchment managers, and discusses how these may be implemented in the E2 modelling framework.

Recommendations & Key Findings

The review highlights the fact that few Australian catchment contaminant cycle models and supporting datasets explicitly consider inputs from intensive agricultural areas (e.g. dairying). In such systems the fluxes of soluble nutrients can be significant. However, the majority of models in use in Australia lump soluble and particulate forms together, and model only total nutrient (e.g. total phosphorus). This presents problems where soluble and particulate nutrients follow different pathways from the land to the stream. This is the case with nitrogen – significant quantities of nitrate are delivered to streams via groundwater whereas particulate nitrogen is carried principally in surface flows. The same is also true for phosphorus in areas of intensive farming. It is, therefore, difficult using current models to accurately assess the impacts of land use on nutrient loads to stream, the resulting impacts on stream health, and the potential management options to limit pollutant inputs. The intention of the review is to address these shortcomings in currently used models.

ADOPTION AND TECHNOLOGY TRANSFER

It became clear early in the project that it was not appropriate to impose another stakeholder engagement and adoption program on the catchment modelling community (model developers and model users). The project used established programs, mainly within the CRCCH, to reach a wide audience of potential adoptees. Activities included attendance at CRCCH EMSS, E2 and Catchment Modelling School workshops and liaison with CRCCH focus catchments (Murrumbidgee and Brisbane). Relationships with catchment managers in our two case studies (North Pine, and Wimmera) are maturing and will enhance awareness in those communities. Project findings have been well publicised in the literature – through conference and journal papers, and technical reports. Embedding the project's outcomes (modules) within the highly publicised delivery framework of E2 provides a powerful adoption pathway. E2 is a product within the Catchment Modelling Toolkit which has significant penetration into the catchment modelling community (more than 2,000 members). Importantly, project activities have confirmed the need to involve the modelling community and its intended audience early in project specification, including development of the stakeholder engagement program itself.

CONCLUSIONS

This project had access to the new catchment-scale modelling framework E2 which provides a delivery mechanism for our findings and helps ensure a co-ordinated modelling approach. E2 is freely available to stakeholders through the Catchment Model Toolkit (www.toolkit.net.au) and is supported by the CRCCH (now eWater). The E2 framework is flexible and supports an expanding library of contaminant modules, so that model builders will have the components to develop comprehensive catchment contaminant cycle models. E2 was funded separately from this project and while E2 developers gave generously of their time, deliverables and timetables were separate – a problem identified early in the project. With Land & Water Australia's agreement our approach was to develop stand-alone modules capable of being implemented in E2 at some later date. In fact it was possible to implement and test the RPM and GPP modules but further work is required to implement and test the time-varying salinity, algal biomass and community metabolism models.

This project elicited stakeholder input to the identification of priority contaminants and the spatial/temporal scales important to management, which informed model design. Project findings are currently being applied and tested in collaboration with stakeholders in south-east Queensland and the Wimmera and this is building stakeholder ownership and trust. Although these applications are still ongoing, it is clear that catchment-scale models (e.g. E2) may be too complicated for stakeholders to operate themselves. Modelling is best undertaken by experienced consultants who need to maintain close contact with stakeholders to ensure that the latter assimilate results, debate issues and take ownership of findings. There is evidence that in the past over-complicated models developed by 'experts' in isolation have done little to inform catchment management – the remedy is to involve stakeholders throughout the model scoping, development and scenario running stages. The implication for stakeholders is that they will need to fund a modelling consultant and a stakeholder participation process to obtain maximum benefit from catchment-scale models.

The project has identified two areas for future research. First, current models lump soluble and particulate forms of nutrient together even though they are transported along different flow pathways and undergo different hillslope, riparian and instream transformations. This limits the ability of current models to accurately quantify the effects of mitigation measures such as grass buffer strips for trapping particulates and riparian soils for removing nitrate. There is a clear need to better integrate field-scale experimental and modelling work with catchment-scale models. The best approach is probably to develop separate models. Detailed, process-based, field-scale models are needed to help design mitigation measures (e.g. riparian buffer strips). Although too detailed for direct inclusion, the emergent properties of field-scale models can inform catchment-scale models. The project adopted this approach for riparian particulate trapping but further work needs to be done on topics including hillslope particulate delivery ratios, and groundwater delivery of salt and nitrate. Second, current models focus on predicting flow and contaminants while managers are often concerned with 'ecosystem health'. Measures of 'ecosystem health' that combine macroinvertebrate and fish species composition cannot be predicted by current catchment-scale models. There is a clear need to more closely align measures of 'ecosystem health' with the capability of catchment-scale models. The project developed a framework for relating nutrient, flow and shade to algal biomass and GPP although further development of this approach is required. It also developed a salinity effects model although further work is needed to consider multiple stressors.

APPENDIX 1 – PUBLICATIONS AND REFERENCES

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APPENDIX 2 – CONTRIBUTORS

Framework development

Joel Rahman, Jean-Michel Perraud, Robert Bridgart, Nick Murray and John Coleman (CLW) and Robert Argent and Rodger Grayson (CRCCH) – members of the E2 development team.

Stakeholder engagement

The project team worked mainly through CRCCH stakeholder programmes, in particular those run by Carolyn Young (Murrumbidgee River) and Tony Weber (Brisbane River). Paul Fennell (Wimmera CMA) and Leon Metzeling (VicEPA) also supported our engagement in the Wimmera.

Salinity module development

Ben Kefford (RMIT) was a key science collaborator. Research assistance was provided by Kristen Feher (CLW) and Sue Powell (ANU). Datasets were provided by EPA Victoria (Leon Metzeling), South Australia (Peter Goonan) and Wimmera CMA (Rhonda Butcher, Paul Fennell).

Instream periphyton biomass module development

Myriam Bormans, Barbara Robson and Ian Webster (CLW) assisted in refinement and review of conceptualisation of modules.

Riparian buffer module development

Peter Hairsine (CLW) reviewed the technical specifications of the module. Robert Bridgart and John Coleman (CLW) designed, coded and tested the module. Tony Weber and Tony McAlister of WBM Oceanics, a CRCCH partner, implemented and field-tested the module.

Nutrient generation module development

Much of the nutrient generation review was drawn from background PhD thesis work of John Drewry (ANU), project work of Peter Cornish, Murray Hart and Les McNamara (University of Western Sydney) and experience of Barry Croke and Tony Jakeman (ANU).

Companion activities

This report has focussed on key activities. Many other activities were conducted to inform the contaminant cycle model development and to ensure its alignment with complementary research being conducted within the River Contaminants Program and the CRCCH.

Working with other contaminant cycle models

In the first two years of the project, the project team worked on, and with, developers and implementers of the EMSS and CatchMODS catchment-scale contaminant cycle models. This involved running and attending modeller workshops. We thank the CRCCH and iCAM, ANU, for their involvement and support in these interactions.

Riparian Zone Denitrification

We worked closely with another project team in the River Contaminants Program, namely the team of Heather Hunter, Christy Fellows and David Rassam, who were developing a riparian denitrification module. That module has also been delivered through the E2 framework.