NEWSLETTER OF THE COOPERATIVE RESEARCH CENTRE FOR CATCHMENT HYDROLOGY

CATCHWORD

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A NOTE FROM THE DIRECTOR

Rodger Grayson

Inside...

Program Roundup

Welcome to a very special issue of *Catchword*. Back in August this year I discussed the growing need to assist industry and model users with information about models and modelling, and our intention to develop such information. This special issue is designed to help fill this need.

The need for information on modelling is driven by the increased use of models in natural resource management and the desire to maximise the benefits from the use of models. Modelling is becoming part and parcel of the way we identify and quantify issues in our catchments, determine priorities for management actions, set targets, and evaluate performance against those targets. Modelling also provides a repeatable and defensible approach that, if used correctly, enhances the confidence of all involved.

But many models, while quite possibly being easy to use, are conceptually complex and require significant knowledge to use and interpret the results intelligently. We need to be thinking about modelling in natural resource management as a "new technology" where everyone - from those who commission modelling, through the users and developers, to those who are affected by model results or outcomes - spends time coming to understand something of the "art and science of modelling". This is critical if the benefits, limitations and appropriate application of models in management are to be realised. It is often said that "what matters is not the quality of the model, but the quality of the modeller". Equally, an understanding of model limitations and being able to ask the right questions is important for the organisations that purchase modelling expertise and the communities or groups affected by modelling.

This issue of *Catchword* is one of several activities we are undertaking to assist those commissioning and involved in models to better understand how the tools we are developing will help in their business. We have also just released the first two papers in our "Series on Model Choice" on General Considerations in modelling (Paper 1) and Water Quality Models - Sediment and Nutrients (Paper 2). These are available at www.toolkit.net.au/modelchoice and provide more detailed background and guidance for selecting the right model for a particular job. In the New Year we will be conducting seminars on these topics and including components in our training programs.

There is a great breadth of modelling being undertaken across the CRC. In the articles that follow in this issue, each of the Program teams have addressed industry needs for their modelling, how their tools fit in, the capability and limitations of their tools, and commented on future developments. The article from Program 1, our integrating program, focusses more on the Catchment Modelling Toolkit concept and infrastructure designed to support delivery of our tools, including E2, our integrated whole-of-catchment modelling framework.

Clearly the focus of this *Catchword* is modelling, but models are useless without high quality data. Indeed the greatest influence on confidence in modelling is generally data availability. An important component of our research programs is the development of models based on good data and field studies. Monitoring and modelling must go hand in hand if we are to improve confidence in our predictions and make the most of the data being collected. "Smart monitoring" that combines data and models is a rapidly developing field that will improve confidence in many practical applications such as assessment of targets and predicting impacts of management actions.

Wrap up for 2004

This is the last issue of *Catchword* for the year and what a year 2004 has been! Our projects are entering the home straight and delivering outcomes at an ever-increasing rate; we have had two very successful reviews of our overall program and communications and adoption activities; collaboration with the CRC for Freshwater Ecology and several new partners resulted in the eWater CRC bid which is now at interview stage; and for me, it has meant a new role in our organisation.

I would like to take this opportunity to thank some key people who make this organisation hum and such a fabulous place to work. Firstly, thanks to the CRC Board and John Langford for such strong support and encouragement as I adjust to my new role. Similarly the Program leaders have worked tirelessly to deliver more and more within very tight budgets, ably supported by Project teams who attack their work with a passion and commitment that is infectious. A special thanks to David Perry and John Molloy for their patience and guidance for a new boy on the block, and to Rob Vertessy for making the transition as smooth as possible. Thanks also to the Toolkit Strategy Group (TSG) who have put in a huge effort this year, getting the delivery of our products to a very professional standard from 'look and feel' through documentation and resource planning, to the quality of the website. To the CRC support and office staff at our various locations, thanks for being unflappable and keeping things under control. Most importantly though, thanks to all of you who support the activities of the CRC, you are our raison d'être.

I wish you and your families a safe and happy festive season and look forward to 2005 with great anticipation and enthusiasm.

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COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

PROGRAM 1

PREDICTING CATCHMENT BEHAVIOUR

Program Leaders
GEOFF PODGER &
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Report by Robert Argent

Application of Modelling for Management

Increasingly, modelling is becoming an integral part of land and water management. It provides a method for synthesising understanding and knowledge in a way that can be applied consistently to issues such as impact assessment of management options, guiding choice on realistic catchment targets and, along with good data, assessing performance against targets. A clear focus for our CRC, in addition to contributing to a portfolio of world class research, is the integration and development of our research into tools for management of land and water resources.

Since our beginnings in 1992, the CRC research portfolio has encompassed a broad range of specific science that has advanced our knowledge and, along with advances by others, provided the core of the Catchment Modelling Toolkit products that we are now delivering. The Toolkit products directly assist the capability of our research and industry partners, and the broader catchment research and management community. The breadth of our coverage is reflected in Toolkit membership of over 2300 people, who have performed over 6000 downloads of Toolkit software, including updates, upgrades and new versions.

In addition to the Toolkit products that are available from the Toolkit website, there are additional products nearing public release, expanding the suite of tools to meet a variety of uses and user needs. This article explores these uses and users, along with some of the factors that are influencing the Toolkit products being developed across our research programs.

Diverse uses

Toolkit and model uses are often much more diverse than one might think. Typically, when a developer produces a model they have one or two specific types of use, and user, in mind. Experience with models, and the questions and feedback from users, indicates that commonly, the imagination of model users ensures much broader use than initially thought. A broad spectrum of model application exists in the modelling and management community, including:

- Systems operation, for example dam or irrigation system management.
- Data exploration and examination using visualisation tools and other easy-to-use data handling routines. This varies from loading and viewing maps of land-use or time series of flows, to analysis and stochastic generation of data for research and management purposes. Toolkit products such as RRL, SCL and trend can all be used in this way.
- Communication of issues and factors related to aspects of management. This could be, for example, providing a simple view of land use across a catchment in a way that supports thinking about future changes. This whole-of-catchment perspective can assist planners and decision makers on where to restrict or promote urban growth.
- System design, a traditional modelling role. Models such as MUSIC (Model for Urban Stormwater Improvement Conceptualisation) provide good, flexible tools that inform design and encompass the latest research.
- System understanding can be achieved through explaining and exploring some of the interconnecting components of the managed system. For example, if some urban development does go ahead, then a systems model can expose possible problems in, say, infrastructure, waterway pollution, or flooding.
- Adaptive management involving simulating and understanding the system to guide initial choice and implementation of a management action, and monitoring of the resulting effect. For example SedNet may be used to help identify hotspots of erosion in a catchment. Possible management actions are then simulated, actions are undertaken, monitoring is performed, and if the desired results are not achieved, the understanding of the system and the management approach can be revised.
- Design and operation of monitoring systems. Identification of where system indicators should be measured to inform managers and researchers of the current state of the system, and forewarn of changes that may occur due to the management decisions being implemented today. Modelling can also be an important component of interpreting data from monitoring, providing a tool for interpolation between samples that are often collected sparsely in space and/or time.

Diverse users

So there are a range of roles for modelling in land and water management - much more than the traditional planning and operational roles that have typically been associated with the use of models. People who use tools in these ways often have different purposes in mind, and these must be considered when designing Toolkit products. For example, there are direct users of model output - who make decisions and implement changes as a result of an analysis undertaken through a model. There are also those who develop policy through exploration and comparison of scenarios, weighing of competing factors and assessment of benefits and negative effects. Finally, there are community members who use these tools to inform debate and examine potential changes and future directions.

Software and product development

To support our users, the Catchment Modelling Toolkit has an expanding range of modelling products (see articles from other Programs). Some of these products provide very specific functions, such as MUSIC or the Rainfall-Runoff Library. Other products, such as E2 (see box and previous *Catchword* articles on E2) provide a more generic set of features, relevant to a variety of catchment modelling tasks.

E2 - Whole of Catchment Modelling System

E2 is an example of the "whole-of-catchment" modelling concept that reflects a broad modelling philosophy of providing a flexible modelling structure. This structure allows users to select a level of complexity appropriate to the problem at hand and the available data and knowledge (see also Paper No 1 of the "Modelling choice series"). E2 is designed to allow modellers and researchers to construct models by selecting and linking component models from a range of available choices, and will produce whole-of-catchment modelling solutions.

E2 uses a sub-catchment and node-link system representation, with generation and "filtering" of flow and material constituents (such as TSS and TN) taking place in functional units within sub-catchments (Figure 1.1A), from where they pass to a node (Figure 1.1B) before being routed and possibly processed along links. The concept of functional units is used to enable differences in things such as land use or landscape position to be represented within a sub-catchment.

The major components of the model in each sub-catchment are broken into blocks of options (Figure 1.1A. runoff generation, constituent generation, filtering) related to particular processes. This enables a "menu" of different algorithms (or modules) to be available for each process, allowing model choice to be based on available data and the problem being investigated. A similar approach is used for links Figure 1.1C, where the basic model components relate to routing (of flow and constituents), decay/enrichment and source/sink, as well as dealing with storages. Many of the algorithms and modules being developed across our research programs are designed to integrate with E2, expanding both the options available within E2 and the opportunities for our research to be directly applied to catchment management problems. Several of these are described in the articles from other Programs.

E2 is a very significant milestone in the area of modelling for catchment management, particularly in the areas of integration, flexibility and model choice. In developing E2 we are breaking new ground - developing a flexible catchment modelling system unlike anything currently available.

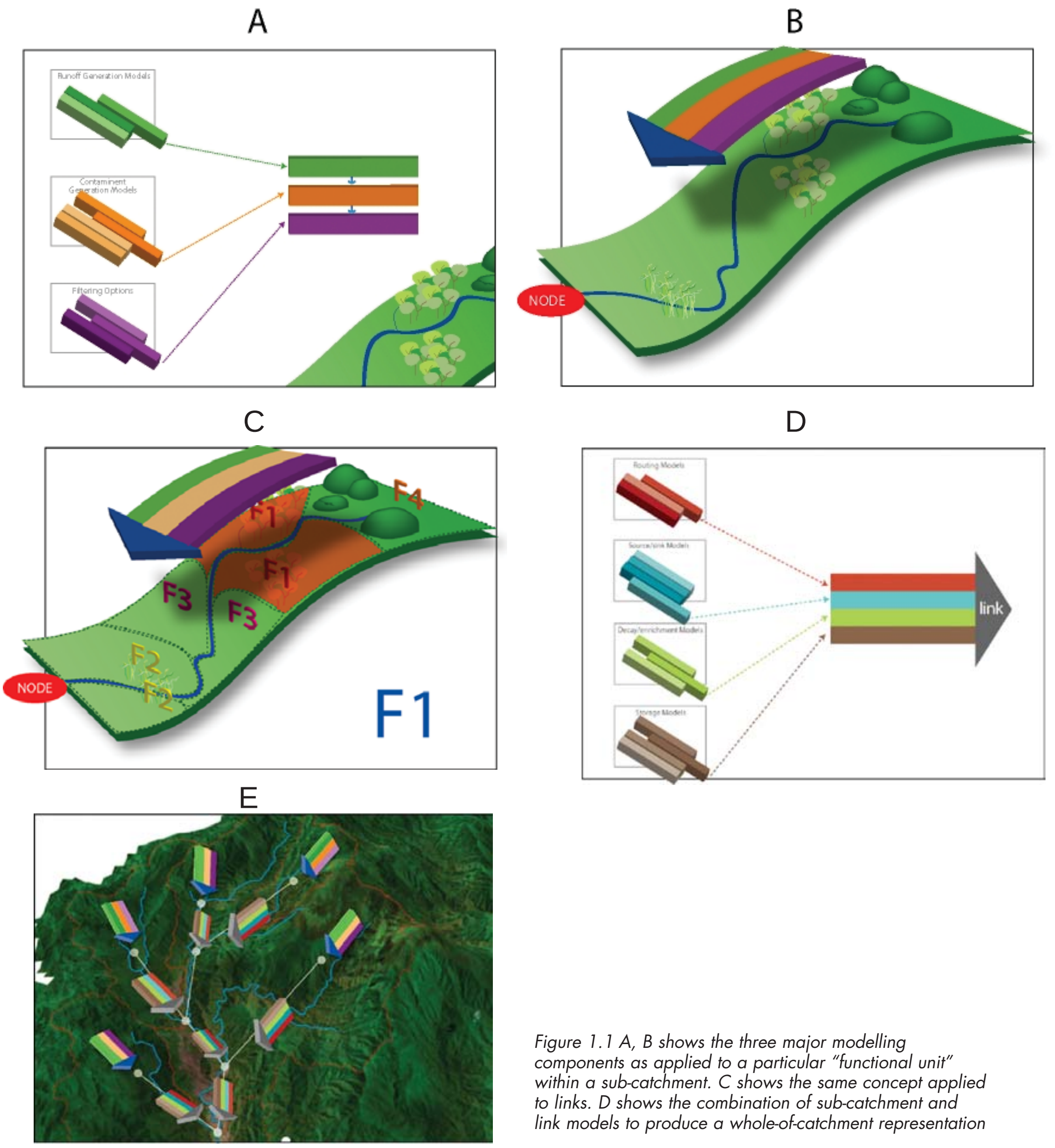

Figure 1.1 A, B shows the three major modelling components as applied to a particular "functional unit" within a sub-catchment. C shows the same concept applied to links. D shows the combination of sub-catchment and link models to produce a whole-of-catchment representation

The Toolkit products, and the product development process which underpins them, have resulted from over five years of conceptual and technical development, along with many more years of research and knowledge related to specific products. The product development process is not readily apparent when downloading and using Toolkit products, but includes:

- A software repository and integrated development process (see previous *Catchword* articles on TIME, the Invisible Modelling Environment)
- A developer network operating across a number of CRC for Catchment Hydrology Parties, where software developers share information, ideas, solutions and computer code.
- Product Managers, each of whom is responsible for overseeing some 30 steps in the product development process, including preparation of documentation and information for the product web page.
- A range of policies for operation of the Toolkit, covering development, versioning, testing, licensing, and revenue.

These processes are not static, and the nature of development of Toolkit products continues to change. For example, in the software and development arena, new technology is changing the way that we both develop models and apply them in practice.

Key aspects behind the Toolkit development

Key factors and principles that have been, and continue to be, developed as part of the Toolkit include:

- Component based software methods
- Integrated modelling
- Uncertainty - assessment and visualisation

Component based software methods

Component based software methods underpin the Catchment Modelling Toolkit. Many Toolkit models share similar visual features - such as tables and graphs - as well as similar data handling and operational components "under the hood". The way that Toolkit models are developed, and the way that the developers work together from a cooperative and shared code base, reduces the repetitious development of tools and allows more tools to be built more efficiently.

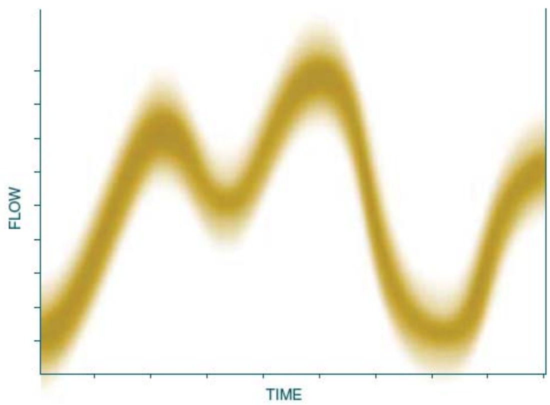

Figure1. 2 Example of visualising uncertainty in model output with depth of colour indicating level of certainty in flow.

Integrated Modelling

Integrated modelling is the process of putting bits together to answer multiple questions about some possible management options. This requires that the science be compatible or be linked across different disciplinary areas, which has been a very strong focus for those within our CRC. It also requires that tools exist to allow different combinations of knowledge to be created for different problems, supporting the 'tailoring' of models to problems (see the papers in the "modelling choice series" for discussion on this topic). E2 is designed to provide this capability (see box).

Uncertainty

As modelling has become more widely used, the recognition that results can be highly uncertain due to limited data or poor models has increased. The assessment and propagation of estimates of uncertainty through the types of models that we use in catchment management is a very difficult problem and is an active area of research internationally.

While there are advances being made in uncertainty theory and model reporting of uncertainty, there is still some way to go before these methods are widely available in models. This is partly because the methods tend to be complex, but also because they commonly deal with only some of the aspects of uncertainty in modelling (such as knowledge of parameter or input values) and not other limitations such as model structure or the value judgements inherent in underlying assumptions.

The CRC for Catchment Hydrology is not actively researching the propagation of uncertainty but rather has taken a more pragmatic approach and focussed on visualisation. We are developing tools and methods for providing a visual indication of uncertainty (see previous *Catchword* article). This approach requires manual or other external assessment of uncertainty (perhaps based on some of the methods emerging from other researchers), but by incorporating this visualisation into tools that people are using will bring the questions of uncertainty assessment to the fore.

Conclusion

A clear understanding of the users and uses of the Catchment Modelling Toolkit, combined with a robust and structured approach to development and deployment of products, has placed us well on the track to achieve our mission. Beyond the current Parties of the CRC for Catchment Hydrology we are finding significant interest and adoption of not only our products, but also our whole approach to catchment modelling, encompassing code, concepts, development and deployment. This bodes well for the future of catchment modelling in Australia, and promises bigger things beyond and outside the life of the CRC for Catchment Hydrology.

In the articles that follow, each of the Programs describes the models and modules they are developing for the Toolkit in the context of the industry needs they are designed to meet.

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PROGRAM 2

LAND-USE IMPACTS ON RIVERS

Program Leader
PETER WALLBRINK

Report by Peter Wallbrink, John Hornbuckle, Scott Wilkinson, Mark Littleboy, Heather Hunter, David Rassam, Daniel Pagendam, Alice Best, Lu Zhang

Catchment Modelling in Program 2 - Land-use Impacts on Rivers

Introduction

The major brief of the Land-use Impacts on Rivers Program is to conceptualise and construct a series of models able to quantify the impacts of land-use change on a range of water quality variables in downstream river environments. The potential impacts from such changes include the release of i) soil and sediment from erosion, ii) nutrients and contaminants either attached to these soil particles or in solution; as well as iii) the movement of salts from catchments. The redistribution of these constituents is firstly of concern to both landholders (potentially representing a significant loss of productive capacity or income) and secondly to the riverine environment, which performs a host of roles in terms of the provision of viable and healthy in-stream ecosystems and delivery of flow to downstream environments.

The national response to river and land degradation has been the Natural Heritage Trust (NHT) as well as the National Action Plan (NAP) both of which have targeted catchment rehabilitation and received significant funding. Furthermore, in recent years we have also seen the rise of regional responsibility for catchment management (eg. CMA's in Victoria and their equivalents in other States) which are increasingly looking towards the setting of flow and load targets. In this environment, there is a need for sound science-based tools to both predict the fluxes of constituents as well as their impacts downstream. As the range of impacts is large, so is the suite of modelling outputs from this Program. Here we aim to outline the market needs, management requirements and capabilities of our models, and how they can be best applied by their intended industry users.

There are five main project theme areas to which this Program is contributing modelling 'outputs', (either as stand alone models, or as 'modules' within the modelling framework E2) to help us understand and quantify the movement of constituents through riverine landscapes. These areas for the CRC Projects are:

- Irrigation return flows (Project 2.19: (2A))
- SedNet: Sediment budgets for river Networks (Project 2.20: (2B))
- Salt movement from catchments (Project 2.21: (2C))
- Managing nitrogen in riparian zones (Project 2.22: (2D))
- Assessing the impacts of land-use change on daily flow duration curves (Project 2.23: 2E))

Ultimately the Program aims to develop a 'whole of catchment' modelling capability such that users are able to predict variables such as flow, sediment load and concentration, nutrient load and concentration a well as salt flows and the quality of water returning from irrigation areas at any point in the landscape. The context, knowledge gaps, priority gaps, capabilities, applications and impacts for each of the specific project areas are discussed in more detail below.

Irrigation return flows

Currently there is no tool available that specifically deals with all the complexity of irrigation areas for predicting drainage return flows (The volume and quality of water returned to the river system after irrigation).

Figure 2.2 presents a conceptual model of an irrigation area. The Project 2A team's challenge is to develop a model which adequately captures the complexity of processes inside the irrigation area and determines the drainage return flow and quality back to the river system.

There are a number of models that can determine various aspects of irrigation losses through surface runoff and drainage below the rootzone at the paddock and farm scale, such as Destiny (Xevi *et al.* 2001), MaizeMan (Humphreys *et al.* 2004), CropWat (Smith, 1992) , SWAGMAN (Khan *et al.* 2003) and BASINMAN (Wu *et al.*). However, there are currently no models at the irrigation area or regional level which have the level of detail available to adequately simulate drainage return flows from an irrigation area or district.

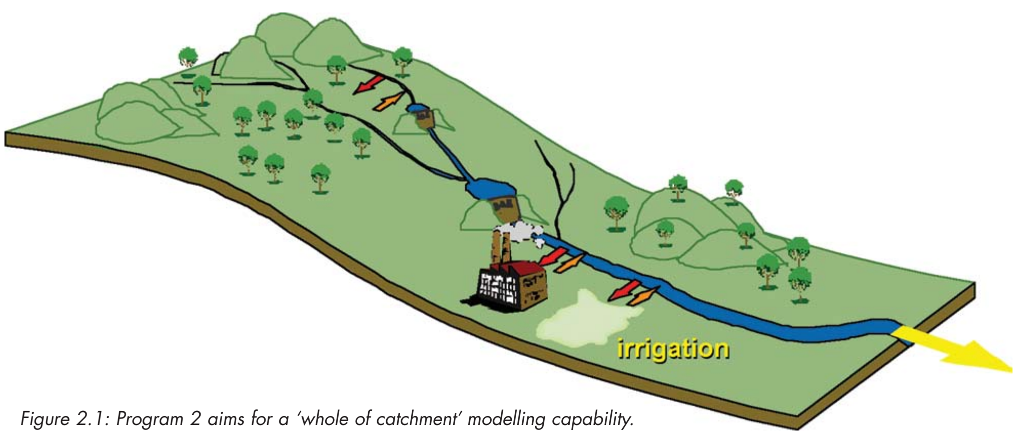

Figure 2.1: Program 2 aims for a 'whole of catchment' modelling capability.

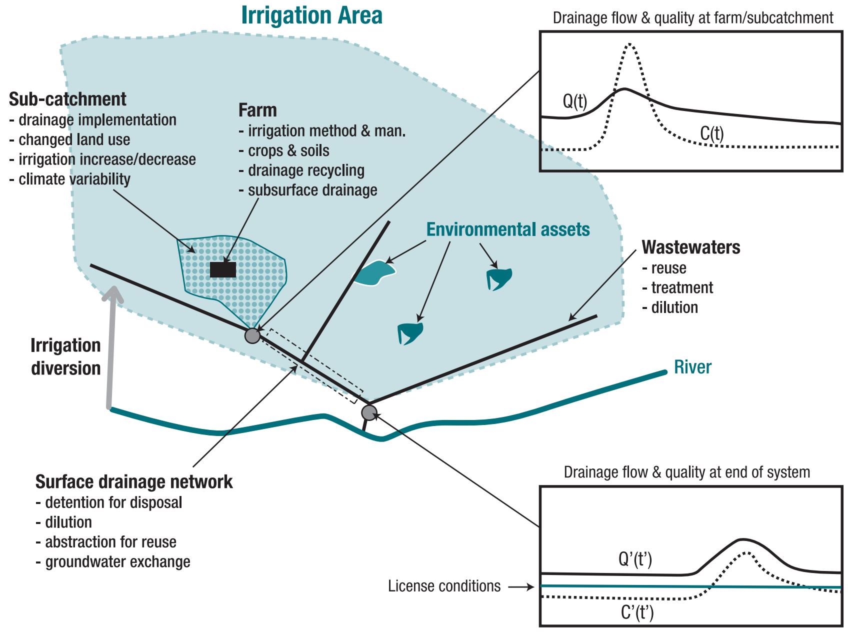

Figure 2.2. Conceptual model of irrigation area

Presently, models such as IQQM are used for predicting drainage return flows from irrigation areas, although a number of the biophysical drivers of drainage return flows and management options are not well represented. For example, some significant components, such as groundwater and subsurface drainage - which are major contributors to drainage return flows - are not yet captured by any existing software model at the irrigation district or irrigation area scale. Furthermore, the licensing conditions for irrigation discharge are becoming more stringent.

The irrigation management industry urgently requires a tool which will allow users to evaluate alternative management strategies for meeting these new licence conditions, such as the "salt credit" licensing scheme in which irrigation companies are given a licence dictating how many tonnes of salt they can export back to the river system per year, and maximum EC levels. Hence the primary challenge for the Project 2A team is to develop a tool that allows irrigation groups to investigate alternatives and consequences of different management scenarios. A further challenge is to develop this tool with the capacity to capture some of the complexity of the irrigation system while also operating in a limited data environment.

Balancing user needs and model complexity

The biggest limitation relates to the level of detail required in order to capture highly modified environments such as irrigation areas. The right balance between level of user input and model complexity is required to gain realistic model outputs. There is little point in developing sophisticated models based on complex arithmetic procedures which require parameters of which no end user will have knowledge. So our approach was to combine where appropriate well known water balance routines which adequately simulate key components or drivers of drainage (such as SWAGMAN, DESTINY, BASINMAN) with reviews of the work of others and field testing of model components where possible.

Our drainage return flow module is being delivered in two ways. Firstly, as a module in the modeling framework E2 where it will simulate both volumes and loads of salt and water in return flows; (although irrigation will only be represented as a single functional unit (FU) i.e. spatially lumped). Secondly, as a stand-alone version with the ability to model drainage districts, or even individual farm units inside an irrigation area, with multiple FU's. This will allow managers to investigate and rank farms or drainage districts based on their impacts on receiving water bodies, and to investigate options for improved usage of available salt credits. The stand-alone version of the model will also incorporate the ability to look at drainage management options for managing irrigation return flows and meeting licence conditions such as regional scale evaporation basins, as well as systems in which saline water is progressively applied through a series of irrigation bays to species of increasing salt tolerance (ie serial biological concentration systems).

Example of use

A typical example of the model's use might involve an irrigation area that has a licence condition in terms of salt load (salt credit) that it can export back to the river system. The user would be able to create a model of the current system and see what the likely return flow and salt load is. From here they would then be able to investigate the implications of such things as:

- Changing cropping systems - i.e. move from rice to grapes
- Expansion of the subsurface drainage network to control salinisation
- Expansion of the surface drainage network to control waterlogging
- Improvement in irrigation efficiency of x%

The stand-alone version will also allow irrigation managers to investigate alternative management scenarios for meeting licence conditions and constraints. Irrigation area managers will be able to investigate a range of options from changing cropping systems at the farm level, to installing regional drainage disposal facilities for dealing with drainage water. They will also be able to see what impacts these changes will have on the return flow generated from the irrigation area. For the development of new irrigation areas, the model will allow managers and policy makers to assess the likely overall impacts the irrigation development will have in terms of drainage return flow generation to the river system.

The model will still have some limitations. For example regional groundwater systems are not modelled due to their complexity, and end-users will need to be aware of the model's limitations particularly at the E2 level where many processes are 'lumped' together. However, end users will begin to see the development of an adequate tool for the determination of irrigation return flows and their impacts and how these can be managed, a tool that for many years has been lacking in the industry.

Future developments

Future developments for the stand-alone version include the use of Multi-Criteria Decision Analysis (MCDA) methods for assisting and ranking alternatives to problems (such as those listed above). We also aim in the longer term to integrate/interface our model with the SCADA (Supervisory Control And Data Acquisition) networks currently used in irrigation areas for water delivery control. This would provide real-time inputs to our model so that likely irrigation return flow estimates can be generated 'on the fly'.

SedNet: Sediment budgets for river Networks

European settlement brought widespread changes in land use across many parts of Australia that delivered massive volumes of sediment to the rivers, and changed the form of rivers dramatically. Increased sediment and nutrient supply continues to affect the health of Australian rivers. Suspended sediment and nutrients have an impact on water quality, and accumulations of bedload sediment smother bed substrate and pool habitat. The magnitude of work required to reduce sediment and nutrient loads to "natural", pre-European, rates exceeds the resources available. To produce the greatest environmental benefit, catchment works to reduce sediment and nutrient supply need to be targeted on the most important source areas and erosion processes.

SedNet is a stand-alone model currently being used by industry to identify the main sediment source areas and erosion processes in regional catchments, as well as assist in setting targets for reducing end-of-valley sediment exports. The current focus of project 2B is to:

- Implement the existing SedNet model in the TIME operating software environment
- Prepare a comprehensive set of supporting documentation
- Thoroughly road test the model.

These steps will make the existing SedNet model available to catchment managers in a form that is robust, and widely available.

Spatial prediction capability

SedNet is the Catchment Modelling Toolkit model most suited to identifying hotspots of sediment supply. It identifies the individual contributions of hillslope, gully and riverbank erosion in a catchment, so directing works to the dominant sediment source. SedNet is also ideal for simulating erosion control activities to determine realistic targets for end-of-valley loads. The software's features support simulation of management scenarios of riparian revegetation, gully erosion control, and land management change, to predict future sediment loads.

Targeted erosion control can have a much greater impact on sediment loads than random erosion control, (Fig 2.3). If reducing sediment export is the main objective, the contributor module will identify the areas of the catchment contributing most to export. Natural sediment budgets are also calculated to provide a baseline for current erosion rates. An example of the application of SedNet to a regional catchment is described in DeRose *et al*. (2003), and more information on the benefits of targeting erosion control using SedNet is available in Lu *et al*. (2004).

Without specialised input data, the uncertainties in predicted spatial patterns markedly increase over smaller catchment areas, particularly less than 2,000 km^2. SedNet predicts regional-scale patterns in sediment supply and movement, but paddock-scale targeting of erosion control still requires field investigation.

Temporal predictions

Depending on the hydrology and erosion data inputs, the results are long-term averages, over periods of 20 years or more. This coarse temporal resolution is consistent with the current (limited) understanding of erosion and transport processes. Predicting erosion and transport rates over decades, and longer, also constrains the uncertainty in predictions. Long-term averages are often suitable for planning erosion control measures, since these measures generally take many years to have full effect. For simulating the sediment loads under different management scenarios, the long-term effect taking into account hydrologic variability is usually of most interest.

Where required to address specific management questions, temporal patterns of sediment delivery can be estimated at finer timescales using rating curves built up from observed water quality measurements, and then transformed to a given location or particular management scenario. This technique captures the averaged dynamics of sediment delivery in the river system. The technique is not yet available in the SedNet software, but will be soon. (The technique will also be available in E2.)

SedNet is not designed to predict immediate responses to specific extreme events, such as large wild-fires. Sediment mobilisation and movement in the short term must account for antecedent conditions, rainfall distribution, system response, and transient

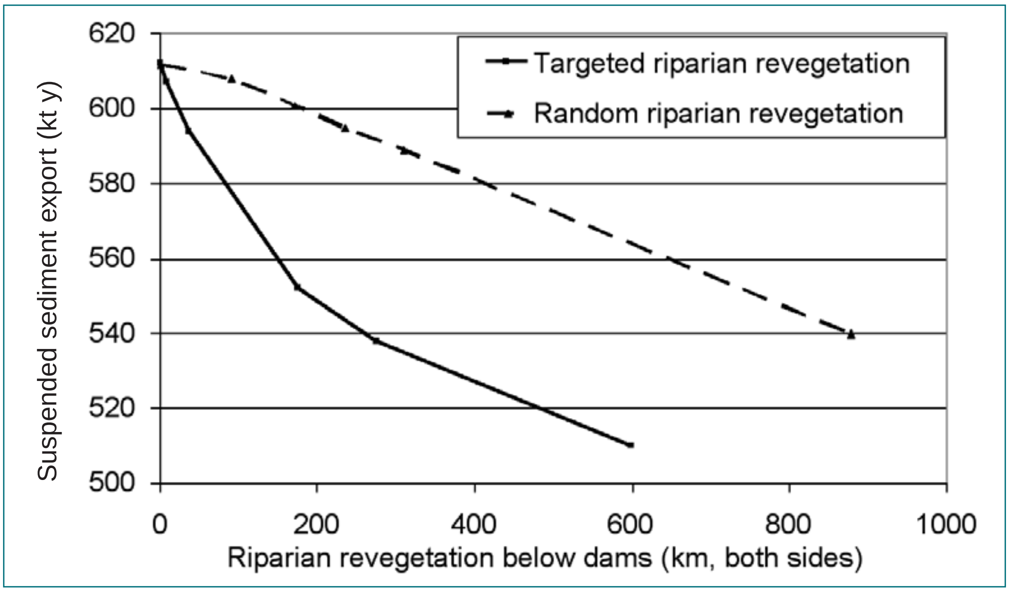

Figure 2.3: Comparison in the predicted sediment export from SedNet scenarios of targeted and random riparian revegetation in the Murrumbidgee catchment.

storage of fine sediment, and these are difficult to predict with any certainty. The longer-term impacts over 10-20 years can be investigated, provided these events are represented in the input datasets.

SedNet does model the progression of bedload sediment through river networks following the extensive channel erosion in historical times. This behaviour is important to accurately predict sand slug distribution, and is being represented in a dynamic bedload budget, available in early 2005.

Testing Predictions

As with all modelling, testing of results is critical. SedNet predictions have been tested in a number of catchments, using radionuclide tracers and observed sediment loads. The predicted spatial patterns of erosion and sediment loads are consistent with observations. We have also assessed the process representations of individual components of the sediment budget, to reduce uncertainties and ensure that we are not getting the "right result for the wrong reasons." This effort involves collaboration with many other projects, both within and outside the CRC.

Future development

Now that SedNet is available to assist in setting targets for reducing catchment sediment export, and for setting priorities for erosion control measures, upcoming refinements include:

- Incorporation of the 'contributor' module to determine and quantify those areas exporting the highest amounts of suspended sediment
- The addition of nutrient (nitrogen and phosphorus) budgets
- The incorporation of a dynamic bedload budget to provide improved prediction of sand slug distribution
- Methods for quantifying and communicating uncertainty in model outputs.

Salt movement from catchments: Project 2.21 (2C)

Introduction

Salinity models are critical to guide investment decisions, catchment planning activities and future salt loads trends analyses under State, Murray-Darling Basin and National Strategies. In eastern Australia, salinity management planning is underpinned by the concept of a future salt target. Intervention strategies (e.g., land-use changes) are designed and implemented so that a catchment may achieve its target. To support these strategies, hydrological and salt balance models must reflect the impacts of land-use changes within a catchment on salt export from a catchment. A current focus for salinity investment is to target areas in the landscape where tree planting and other land-use change will reduce salt export from a catchment. To enable this output, salinity modelling incorporates information on where salt is stored in the landscape and how much there is, and identifies how much salt is mobilised by surface runoff, subsurface flow or groundwater discharge. Salinity modelling also aims to give the impacts of land-use change on hydrology and salt export at property, catchment, and river basin scales

A variety of modelling tools are being used across national, State, regional, catchment, subcatchment and property scales. These models are generally complementary rather than competing in that they address different aspects of salinity processes across different scales. Models can be used to quantify assessments where salinity is an issue, when it is likely to become an issue, how bad it is likely to get, and what are the likely impacts of intervention strategies. Generally, biophysical salinity modelling in Australia can be classified into four broad categories:

- Salinity hazard maps that identify areas where landscape salinity might be an issue. These are a static representation of a dynamic process, and only consider factors that predispose a landscape to salinity

- Trend modelling predicts how bad will salinity get in the future. With this type of model, trends through time are statistically derived from historical data and extrapolated into the future. Trend models are typically applied at broader scales, for example, catchment to national scales.
- Scenario modelling predicts the impacts of salinity management actions on hydrology and salinity.
- River basin modelling predicts how much salt moves through the river system.

The 2C project is delivering a stand-alone scenario model that estimates flow, salinity and salt loads for catchments of between 100 - 2,000 km^2. It also estimates the impacts of land-use changes within a catchment on flow, salinity and salt loads. This type of model can be used to aid setting priorities for on-ground works to combat salinity. It can also be used to assess the impacts of land-use changes on future stream salinity trends.

Need for consistency across States

There is a variety of salt balance models currently being developed and applied in eastern Australia. However, these often operate at a range of different spatial and temporal scales and there is a general lack of integration in these modelling efforts across different agencies and organisations. This lack of consistency has led to anomalies in model outputs along State borders, and results that cannot be readily compared across States. In this respect, the 2C model was designed to be a consistent model across eastern Australia for State reporting to the Murray-Darling Basin Commission (MDBC) to support salinity management planning at catchment and regional scales. As a consequence, it attempts to splice together the best components of available salinity modelling used by industry and State Parties of the CRC for Catchment Hydrology into a single model. A concurrent objective is to ensure that model complexity is consistent with available data, which in many cases lags behind the conceptualisation of the model itself. The new 2C model is currently being evaluated by State Agencies in Queensland, New South Wales and Victoria as well as CSIRO Land and Water. A significant challenge at the moment concerns the compilation of the spatial datasets (such as improved groundwater flow systems, recharge modelling etc.) required to underpin the spatial processing of the model.

2C Model capability

The 2C model will be able to achieve a number of separate but important salt modelling tasks for water and salt pollutant targeting and management. In particular, the tasks include:

- Prediction of streamflow, stream EC and saltloads at the catchment outlet,
- Prediction of the impact of land-use changes on water flow, EC and saltload at the catchment outlet and
- Spatial apportionment of surface and baseflow within a catchment.

The 2C model focusses on dryland salinity processes rather than irrigation salinity and has been designed to be applicable for upland catchments in eastern Australia. The model is capable of predicting the impacts of land-use changes on surface and groundwater pathways of water and salt at the catchment outlet. There are a number of additional design considerations that have been included to ensure adoption as a salinity management tool. The 2C model has been designed to:

- integrate with the node-link hydrological models to link catchment scale predictions to end-of-valley targets.,
- to predict transitional phases of land-use change
- align with currently available data, for example, Groundwater Flow Systems mapping;
- provide output at a daily timestep for compatibility with salinity targets
- to link "scenario" modelling and "trend" modelling so that the impacts of a land-use change on future salt load trends can be predicted.

Model evaluation and roll out

The model is currently being evaluated in ten subcatchments in three of the CRC for Catchment Hydrology Focus Catchments. After the Project finishes, State Agencies will ensure a full roll out across upland areas of the Murray-Darling Basin (MDB). The main advantages of the overall 2C modelling approach is that the model is constant across States and there is a consistent platform for each State agency to report on targets to the MDBC.

Future development

The immediate future for the 2C model includes the initial spatial rollout in the 10 upland areas of the MDB, as well as the testing, calibration and validation of the rollout process. Parts of the 2C model will also be incorporated as modules into E2. which are envisaged as 'generators' of salt. Conceptual developments for the future include gaining a better understanding of:

- Interactions between the unsaturated/saturated zone
- Evapotranspiration estimation from hillslope aquifers
- The feedback between hillslope aquifer and hillslope unsaturated store as the latter fills
- Soil salinity and plantgrowth interactions
- The influence of regional groundwater systems.

Managing nitrogen in riparian zones: Project 2.22 (2D)

Role of riparian buffers

Nitrogen has been identified as a major problem nutrient in the coastal environments of eastern Australia, including Moreton Bay. Further, recent research suggests that algal growth in some Australian river systems may be limited by nitrogen supply. Thus, while small amounts of nitrogen are essential for aquatic ecosystems, input of extra nitrogen to these systems is likely to boost algal growth, to the detriment of ecosystem health. This is particularly the case for readily bio-available forms of nitrogen such as nitrate, which can constitute a significant proportion of the total nitrogen loading in some streams.

The positive role of riparian buffers in removing nitrate from shallow groundwater has been widely recognised in the related literature. The most common questions being asked are: How can nitrate loads in catchment waterways be reduced? To what extent does riparian restoration reduce nitrate loads? How do we optimise riparian restoration and how do we identify target areas?

The knowledge gaps in relation to riparian nitrogen modelling generally relate to identifying the basic processes through which nitrate is removed, as well as the relative importance of each process. In the broader context there is also a requirement to understand the critical role of hydrology in the behaviour of riparian buffers and the impact of this on the efficiency of nitrate removal. Ideally this requires a sound understanding of groundwater flow systems, supported by real groundwater and soil data.

Denitrification processes

In order to fill these gaps we have identified denitrification as one of the most important processes that removes nitrate in groundwater. We have also conducted laboratory and field studies to measure denitrification rates and conducted a comprehensive field experiment to study the hydrology of riparian buffers in an ephemeral and a perennial stream. The latter studies helped us to construct conceptual models, which now form the basis of the riparian nitrogen model. For further details see Rassam *et al.* (2002, 2003) and Pyper and Hunter (2003).

Project outputs

The output of this project will be a module for E2 which will have the capability to evaluate the amounts of nitrate removed, as a result of denitrification, when shallow groundwater interacts with the carbon-rich root zone under anoxic conditions. The main factors that influence denitrification processes are: riparian vegetation (provides the carbon source), the proximity of the water table to the root zone (ensures anoxic conditions), and slow flow rates (thus allowing time for the microbial processes of denitrification to occur). The geometry of the riparian buffer and how it links to the stream also play a crucial role in determining the extent of denitrification.

The riparian nitrogen module operates at three conceptual levels:

- Surface water interacting with riparian buffers in low-order streams that have floodplains with the capacity to perch shallow groundwater
- Base flow passing through the root zone
- Surface water temporarily stored in stream banks (bank storage).

Denitrification in riparian zones of ephemeral streams takes place during flow events, after surface water flows laterally from the stream and into the riparian zone to form a shallow perched water table (Figure 2.4). Where conditions are appropriate, this results in the denitrification of water derived from runoff, which later drain from the riparian zone and return to streams at lower areas in the catchment.

Denitrification in riparian zones of perennial streams primarily occurs when base flow passes though the riparian zone; and secondly, as stream water gets stored in banks when a flood wave passes. The first mechanism (shown in Figure 2.5) involves the entire base flow component of flow, obtained from the hydrologic engine of the catchment model, e.g. SIMHYD. The extent of interaction between base flow and the saturated part of the root zone is crucial in determining the amount of denitrification that takes place. This interaction is a function of floodplain slope, water table slope, and depth of the root zone. Soils of medium hydraulic conductivity promote optimum hydrological conditions for denitrification processes as they can maintain a shallow water table.

Bank storage is similar in concept to the axial flow processes described in Figure 2.4 for ephemeral streams, i.e., surface water temporarily becomes groundwater, loses nitrate through denitrification, then drains back to the surface water system. The volume of water stored depends on the width of the floodplain and its slope, the soil's specific yield, and the volume of the flood event.

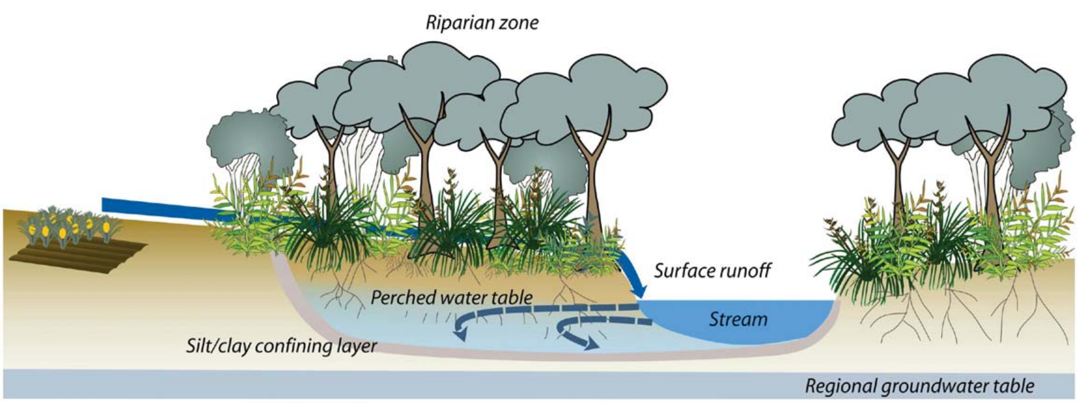

Figure 2.4: Surface water interaction with riparian buffers in ephemeral streams

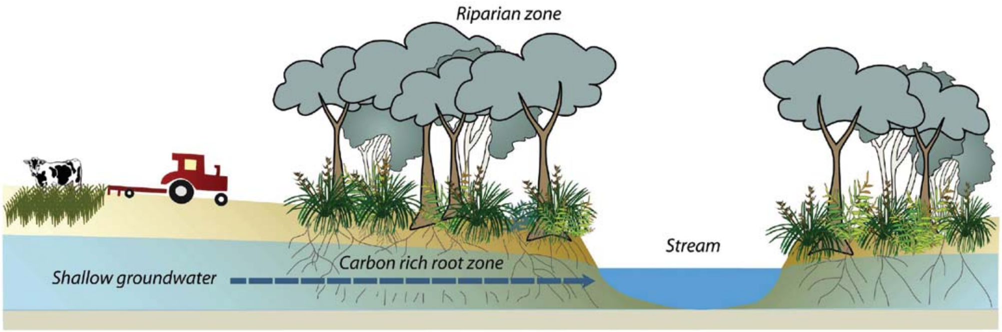

Figure 2.5: Ground water interaction with riparian buffers in perennial streams; base flow component

The riparian nitrogen module will operate within E2 and require input from a hydrology engine (such as SimHyd) to provide flow data. Nitrate removal is then estimated on a sub-catchment scale and at this stage is not spatially explicit (i.e., we will not report loads along reaches of a stream). As such, the riparian nitrogen module is a tool that estimates potential nitrate removal in riparian buffers. Given the complexity of the processes involved, the model will probably be more useful for scenario modelling rather than providing absolute values of nitrate masses being removed.

The riparian nitrogen module can also make use of the spatial layers that are used as model input and transform them into maps to assist managers in identifying target areas for riparian restoration in large catchments. Although the maps provide indicative rather than precise information, they can be useful for informing managers about the areas where riparian restoration is likely to provide greatest effect in reducing stream nitrogen loads.

Future developments

In the near future we aim to test the model outputs and compare predictions with real data. It would also be beneficial to ground-truth the predictions made by the model as to where restoration should occur. We are currently extending the field studies to other locations (in south east Queensland, Victoria and Western Australia), with funding from Land and Water Australia and the Murray-Darling Basin Commission. Information from these sites (and ideally, further new sites) will assist with testing and refinement of the current model. Mid-term developments may include the incorporation of the denitrification module into other tools such as SedNet and MUSIC from where its utility in new environments such as wetlands and streams can be explored.

Assessing the impacts of land-use change on daily flow duration curves: Project 2.23 (2E)

Need to predict impacts

The impacts of land-use change on stream flow have been recognised and it is important to consider these impacts in natural resources management. For example, managers concerned with water allocation, water quality and environmental flows need science-based tools to predict changes in stream flows resulting from afforestation or the effects of wildfire. A commonly used approach for making such predictions is to rely on detailed physically-based models or statistical models derived from paired catchment studies. Both methods require either detailed data or are limited to local conditions. While methods exist that do not rely on detailed data at annual time scales, there is a need to make predictions at a finer timescale so they are compatible with catchment scale and industry models (such as E2).

Flow Duration Curves

Project 2E is providing a model that determines the impacts of forest cover change on finer time scales than the previous annual and annual average estimates. Its approach involves the construction of Flow Duration Curves (FDCs). In effect, these are a cumulative frequency curve showing the percentage of time that specified flows are equalled or exceeded, as shown in Figure 2.6. FDCs provide an easy way of displaying the complete range of flows for a particular catchment under existing land-use conditions. The benefit of the FDC approach is that it effectively provides a summary of streamflow which can then be used to make predictions at scales finer than mean annual and annual without having to look at flows during individual days or months.

Project 2E has now developed a methodology which allows a flow duration curve to be modified to reflect a change in forest cover based on the current stream flow data. This method links changes in mean annual water yield to changes in forest cover. The estimates of changes in mean annual water yield are based on a data set of world-wide catchments (Zhang *et al.* 2001). These estimates of mean annual water yield are linked to a flow duration curve model to reflect changes in flow regime under altered land-use conditions. However, the estimates of changes in mean annual water yield do not consider forest age or forest type.

2E model applications

The output from Project 2E is a stand-alone tool, however it will also be a module within E2 and easily linked to catchment scale models such as IQQM and REALM. Upon completion, the model will allow the impacts of change in forest cover on FDC's to be predicted. At this point the model can then be applied to scenarios where broad scale changes in forest cover are likely. On the positive side, it is a simple model requiring minimal inputs and providing a quick and easy way of assessing potential impacts of forest cover changes without having to build and calibrate complex process based models. However, a limitation is that it will not be suitable for looking at the differences between different forest or crop types.

Future developments

This work will allow the impacts of forest cover changes to be incorporated into catchment scale models (E2) and water allocation models such as IQQM and REALM, via adjustment to inflow time series. This adjustment can be made using a connecting tool such as a rainfall runoff model from RRL (the Rainfall Runoff Library), calibrated to the modified FDC which will represent the distribution of flows under the new percentage forest cover. The method developed in this project provides a simple tool for assessing the impacts of broad scale changes in forest cover on stream flow regime. The outputs of the model can be readily linked to existing water allocation models. This will allow industry to estimate the impacts of likely forest cover change on other water users. Future developments may include the capacity to differentiate between different forest types, ie. such as native forest and Pinus plantations.

Land-use Impacts on River Program conclusion

In totality, the suite of products emerging from Program 2 will make excellent progress towards our intended aim of constructing a 'whole of catchment' modelling capability. From Project 2B we can quantify the loads of sediments passing through various points from the headwater to catchment outlet. Project 2A will provide a tool for analysing management options for drainage from irrigation areas and the effects on the broader catchment, while Project 2D will enable the influence of riparian areas on nitrogen loads to be represented. With the products from Projects 2C and 2E, we will be able to predict the movement from salt under various land-use scenarios and estimate changes on river flows due to change of landcover from pasture to forests. These outputs substantially assist the task of catchment managers to assess the current conditions of their catchments and the impacts of any future land-use changes to the redistribution of constituents within them. The challenge of setting priorities for rehabilitation works to achieve maximum return to end of valley targets will become far more tractable with the utilisation of these tools.

Finally, it is important to remember that the development of natural resource management computer models, such as those conceived and produced in Program 2, is a science in its own right, and is still in relative infancy. Users can expect to see much development and improvement in these models in the upcoming years, and the process will most probably be characterised by continual evolution and refinement. Updates will be common - as bugs are fixed and new features are added as a result of user feedback and improved process understanding. Much improvement can also be expected as our new and existing industry users begin the process of further adopting and applying these tools. Lessons learnt from different 'real world' applications will continue to be integrated into our tool development program.

As noted in the introduction to this issue of *Catchword*, the biggest limitation in predictive capacity (or accuracy) into the near future will also remain the quality (or lack) of data for development and testing of these models. Every effort must be made to continue the maintenance and operation of monitoring networks and to design 'smart' monitoring and modelling to maximise the information we get from the data collected.

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PROGRAM 3

SUSTAINABLE WATER ALLOCATION

Program Leader
JOHN TISDELL

Report by John Tisdell and Bofu Yu

WRAM (Project Leader Bofu Yu.)

MWATER (Project Leader John Tisdell.)

Introduction

The water reform initiatives of the past decade are beginning to result in a major shift in the way water is viewed and managed in Australia. As water users accept water entitlements as chattels and actively engage in water markets, water authorities and those entrusted with water management need integrated hydrologic, economic and socio-economic models to effectively estimate and evaluate these changes.

Water authorities have developed sophisticated hydrologic and river system models, such as IQQM and REALM. These models, however, were not developed for modelling the post-water-reform environment in which we now live. Similarly, economic modelling at best inputs hydrologic characteristics in a static form. There is a pressing need for integrated hydrologic-economic models in Australia. The CRC is meeting that need with WRAM.

Along with hydrologic-economic models to manage the bio-economic aspect of water reform, there is a need for methods to effectively observe, understand and interpret the cultural and socio-economic factors that are playing a major role in the effectiveness of water reform. Water markets, unlike most markets, are highly dependent on the interactions and reactions of farmers, stakeholders and others in rural communities. Economic models do not take account of behaviour and shed little light on the relative merits of alternative market structures, rules and incentives driving water trading in such environments. The input of individual choice and human behaviour into modelling is essential if we are to properly plan water reform (and understand the implications of policy decisions). Experimental economics is proving to be state-of-the-art in such socio-economic simulations and teases out the consequences of policy options. Some industry standard experimental software has been developed to explore economic theory, but it is extremely limited in capturing the salient issues unique to water markets. The CRC for Catchment Hydrology has developed experimental software MWATER that can incorporate the important and unique salient features of water markets in Australia.

WRAM (Water Reallocation Model)

REALM and IQQM

Over the past decade or so, our industry Parties have spent considerable resources to develop, maintain, and upgrade hydrologic network models for water resources planning and assessment. Given the variations in the climate, water entitlements and policies across the States, as well as different software development history, disparate modelling frameworks have been adopted by government agencies at the State level. In Victoria, the model to simulate water resources allocation is REALM (Resources Allocation Model), while IQQM (Integrated Quantity and Quality Model) has been exclusively implemented for all the significant catchments - in water allocation volume terms - in NSW and Queensland. These hydrologic network models have been extensively used for developing water management plans and assessing water allocation scenarios. In addition, there are legislative requirements to use and maintain these models for planning purposes. With the Murray-Darling Basin Commission (MDBC) committed to setting up IQQM for the Murray, support for these hydrologic network models will continue for many years to come.

Over recent years, water markets are developing as part of a Council of Australian Governments initiative to promote the efficient use of Australia's water resources. For the period from 1995-2000, for example, the intra-valley water trade component accounts for about 5% of the total entitlement in the regulated Murrumbidgee River. On top of the intra-valley trade, there is also a net inter-valley trade of 1.5% of the total entitlement. With better informed markets, water trading is likely to increase over time. REALM and IQQM, as purely hydrologic and river system models, are unable to simulate water trading because they do not describe the factors and processes that drive water trading. WRAM (Water ReAllocation Model) was developed to simulate trading of water entitlements among 'nodes' or 'centres' used by hydrologic network models to represent irrigation or other significant water demands, and to interface with IQQM and REALM to greatly enhance the capability of these models.

WRAM assumptions

The WRAM software is based on the assumption that water entitlement is traded for economic gains. The buyer gains because the return per volume of water purchased is greater than the water price, and the seller also gains as the lost production is well compensated with proceeds from the trade. The engine that drives WRAM is an economic optimisation model that maximises the net benefit for all potential traders subject to a series of constraints, for instance, on land areas, crop growth patterns and delivery capacities.

WRAM versions

Three separate versions of WRAM have been developed:

- A stand-alone version available through the Catchment Modelling Toolkit website (www.toolkit.net.au/wram)
- A version that dynamically links with IQQM (being trialled in the Murrumbidgee Catchment)
- A version that dynamically links with REALM (being trialled in the Goulburn-Broken catchment)

Common to all versions of WRAM is a linear programming (LP) solver that optimally allocates and reallocates water resources to maximise the net benefit for all irrigation demand centres among which water can be traded.

WRAM capability

WRAM is able to simulate the volume of water traded, shadow water price[1], and balance of water account for irrigation demand centres. To illustrate the capability of WRAM, Figure 3.1 shows the simulated volume of trade among 12 irrigation nodes in the regulated region of the Murrumbidgee. Figure 3.2 shows the magnitude of trading volume in relation to the level of water allocation. At sufficiently high levels of water allocation, there is no need for water trading as the water demand can be met for all irrigation centres. As the level of allocation decreases, the trading volume increases in response to differing production patterns, and water entitlements. Simulated trading volume from this particular implementation of WRAM for the Murrumbidgee River is higher than historical values because the water trading market for the Murrumbidgee is not yet fully developed.

Interaction with existing water allocation models

Unlike most other Toolkit products, which are either stand-alone or designed to interact with each other, a key requirements for WRAM is the ability to interact with the existing water allocation models, and more specifically, IQQM and REALM. Implementation and maintenance of IQQM and REALM for large catchments, i.e. Murrumbidgee and Goulburn-Broken, are quite complicated. Full-time dedicated staff are required to maintain the code and data sets to simulate a range of planning scenarios for these catchments. Coupling WRAM with IQQM or REALM for large catchments will similarly require considerable resources for implementation and maintenance. Developed capabilities alone will not be sufficient to provide all the answers to some of water resources management issues our industry partners will have to face.

Challenges for WRAM

Two challenges lie ahead for the WRAM development team. The first is the issue of model validation; the second is integrating water trading simulation among different valleys. The notion of

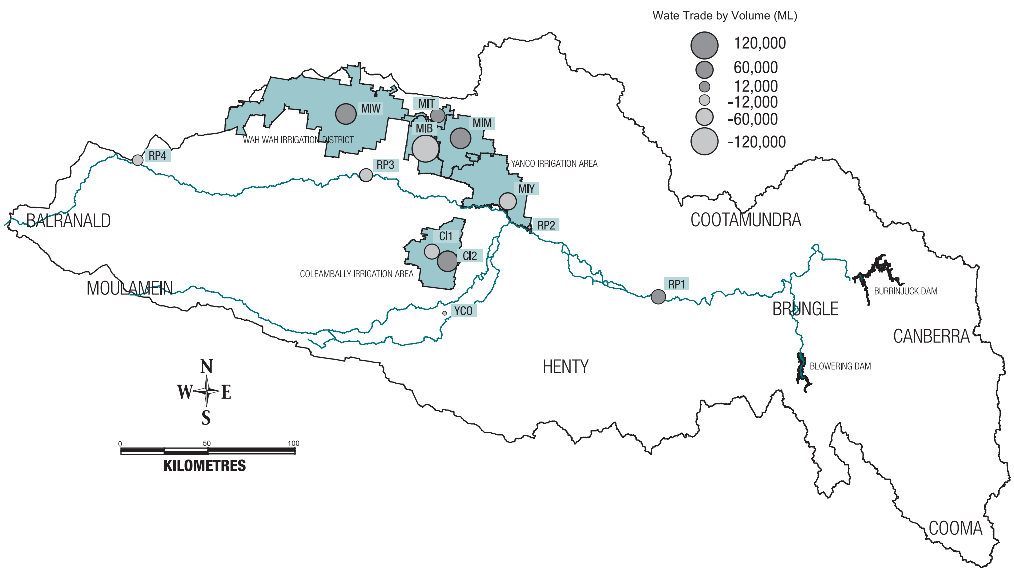

Figure 3.1 Magnitude and spatial distribution of simulated water trading using a 12-node representation of the regulated Murrumbidgee (+ water traded out of the node, - water traded into the node[B5])

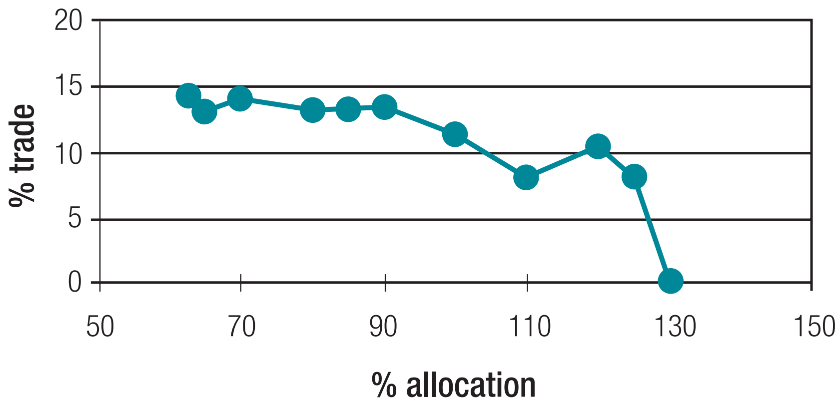

Figure 3.2 The extent of water trading as a function of the level of water allocation for a 12-node representation of the regulated Murrumbidgee catchment.

[1] Defined as the increase in the net benefit ($) when extra 1 ML of water is available for allocation. Shadow water price essentially measures the sensitivity of the net benefit with respect to water availability.

model testing and validation is so innate to hydrologic modellers that existing IQQM/REALM users require, and in fact demand, that simulated water trading volumes be validated against the historical trading figures at the node level. This is an entirely fair requirement, as WRAM would be of no value to hydrologists if the software model is unable to reproduce water trading volumes among irrigation nodes. On the other hand, economists baulk at the idea of validating economic optimisation models. To an economist, the focus is squarely on comparative evaluation of alternative policy instruments and structure of water markets in terms of efficiency and equity. Whether or not water trading matches the reality is at most, of secondary consideration. There is a need to articulate the objective of water trading simulation to both hydrologists and economists, and to enhance our understanding of professional requirements.

It has become apparent in recent years that irrigation areas for which the current generation of hydrologic models are implemented are no longer closed systems as far as water trading is concerned. There is significant inter-valley water trading. Notable examples include water trading between the Murray and the Murrumbidgee Rivers, and the Goulburn-Broken and Murray Rivers. Consequently, water-trading simulations for the Murrumbidgee through IQQM and the Goulburn-Broken through REALM are no longer able to capture this water movement through trade in the valley. Further integration for the entire lower Murray-Darling is called for to represent the water allocation and trade both within the valley and among different valleys.

MWATER

Optimising water trading

To gain a full understanding of the drivers and outcome of water allocation and water trading policies, policy makers need mathematically estimated optimal outcomes combined with an understanding of the consequences of the myriad of influences on human behaviour surrounding the use and trade of water.

It is well recognised that often water users (and the general community for that matter) do not always act according to optimisation algorithms. Attitudes to risk and uncertainties of weather, crop prices and water market activity, for example, are important determinants of what to plant, when to irrigate, and most importantly whether to trade water allocations. MWATER provides a controlled environment in which farmers, given a model farm and financial incentives, manage a farm and have the opportunity to trade water under alternative water allocation or trading regimes. The results of such simulations shed light on how farmers may react to alternative policy options, which until recently has not been observable until well after a policy has been implemented. This methodology allows policy makers to observe possible operational problems under controlled conditions prior to implementation.

Evaluating water policy options

Australia's water policies have resulted in over-allocated water resources and significant water quality and river health deterioration in many catchments. This has come about in part as a result of a lack of tools to rigorously test and fully evaluate the implications of water policy options. When we introduce new varieties of crops, pest controls or drugs, they go through extensive testing in laboratories under controlled conditions. Those that show promise in the laboratory then are taken to controlled field trials before final release.

There is no reason why water policy should not be subject to the same level of screening because the consequences of releasing untested water policy options could be just as devastating as the release of untested pest controls or new varieties of crops. Why haven't such policies been through similar rigorous testing in the past? One reason is that the tools to support this testing have simply not been available until recently. Now there exist well developed experimental economic methods and procedures to evaluate the impacts of different policy options. These methods and procedures, such as those used in any laboratory, produce results that can be replicated and statistically validated.

Using experimental economics

Experimental economics - the basis of MWATER - is a formalised, replicable approach to rapidly assess alternate policy directives, typically expressed as market outcomes, prior to implementation of the policy. The methodology provides a relatively inexpensive means of institutional analysis coupled with substantially reduced time horizons. Well-designed experiments allow for the evaluation of participant willingness to exchange, the stability of diverse institutional structures across an array of market conditions, and the efficacy of policy directives. Experiments can also highlight potential detrimental outcomes, which may compromise a water reform process. The application of experimental results can provide water authorities and decision-makers with sufficiently robust information to circumvent or mitigate the consequences of inappropriate policy commitments, minimising the time for trial and error and associated social expense. It captures those all-important human factors that come into play when a policy option is implemented.

Water use and water trading by farmers - simulated decisions

The performance of water markets, especially temporary water markets, has a number of important features, such as crop water demand schedules, risks of crop loss, uncertain rainfall and interdependent environmental outcomes. At best, currently available experimental software allows the experimenter to change the name of the good traded from "units" to "water". The CRC has developed experimental software that can take on board these features unique to water and the fleeting and interdependent nature of supply and environmental consequences. Participants in the experiments may face alternative water policy options, multiple timed cropping decisions, dynamic rainfall conditions, potential crop losses and unique farm models. Each participant sits at a computer screen and makes irrigation and water trading decisions based on information they are provided on their model farm, for example, alternative cropping options, irrigation schedules, historical (and eventually actual) rainfall, and the expected financial returns to the crops grown. The MWATER computer package can be used to simulate a full season of monthly water use and water trading decisions. With the simulation, users can explore the consequences of temporary water market policy options and or years with forecasts of long-term climate changes and crop prices for permanent markets, each under a alternative water allocation or trading rules and procedures.

The true test and external validity of any such system is with those in the field. Over 70 farmers across the Goulburn-Broken and Murrumbidgee catchments and 50 industry staff have reviewed, participated in and contributed to MWATER's development. The system also needs the endorsement of the experimental economics community. The software was demonstrated at the International Conference on Experimental Economics earlier in the year where it was seen as state of the art in the field.

Testing policy options

MWATER has been developed so it can be tailored to the detail of specific water trading systems and locations, yet flexible enough for application to other issues, such as non-point and point pollution trading. Now, as a result of work by the CRC, industry can and does test significant water and other catchment management policy changes using MWATER. MWATER operates on a server at Griffith University and is specifically designed for resource market experiments. The software links to an Oracle database and can be used either in the laboratories, through the internet to remote sites (Yanco, Shepparton, Gatton or Emerald) or with the pocket palm computers where no computer access is readily available (a farm shed with electricity). In testing and developing policy options, industry staff associated with the CRC work with CRC researchers to develop scenarios and conduct experiments prior to implementation.

The future

It was a strategic decision within the CRC to develop dual modelling approaches to water allocation and trading developed in Program 3, as together they capture the range of possible outcomes and limitations of alternative water policy options. Each approach has benefits and limitations that need to be taken into account, but is essence provide high quality modelling capabilities that have not previously been available and will assist in developing more robust water policy options in the future.

The CRC for Catchment Hydrology over the coming months will continue to work with our industry participants to answer important hydrologic economic and socio-economic questions and issues that arise as the impacts of water reforms take effect and new water policies options emerge.

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PROGRAM 4

URBAN STORMWATER QUALITY

Program Leader
TIM FLETCHER

Report by Tim Fletcher

Super-Modelling

The Need for an Urban Stormwater Model

Managing urban stormwater involves the multiple objectives of drainage, water quality and environmental protection (Burkhard *et al.*, 2000). Legislative provisions at national, State and local levels now require the pursuit of "best-practice stormwater management" across this range of objectives. Consequently, stormwater managers need to be able to predict and evaluate:

(a) the quality of urban stormwater from catchments of varying land use and characteristics,

(b) the performance of alternative stormwater management scenarios, in terms of water quality improvement, flow attenuation, and lifecycle costs, and

(c) ecosystem responses to alternative stormwater management scenarios.

Professionals across the stormwater industry - development consultants, agency regulators, municipal planners - need to be able to undertake these assessments for both structural treatment measures (e.g. wetlands, biofilters, swales, porous pavements, etc) and non-structural measures (e.g. community education, planning policies).

MUSIC

Existing tools did not encapsulate current research knowledge, and had not fully exploited advances in continuous modelling approaches (see McAlister *et al.*, 2003). The CRC saw the need to develop a user-friendly tool which captured the latest scientific understanding of stormwater pollutant generation and treatment. In response to this need, we developed MUSIC, the Model for Urban Stormwater Improvement Conceptualisation (Wong *et al.*, 2002).

MUSIC is a standard node and link model (Figure 4.1), which incorporates:

- Source nodes (where rainfall-runoff and pollutant generation is simulated)
- Drainage links (where flows and pollutants are conveyed and routed)
- Treatment nodes (where flow and water quality treatment are simulated).

Underpinning Philosophy for MUSIC

The overall approach adopted in developing MUSIC has been to balance the need for accurate process descriptions with the need to provide a user-friendly tool.

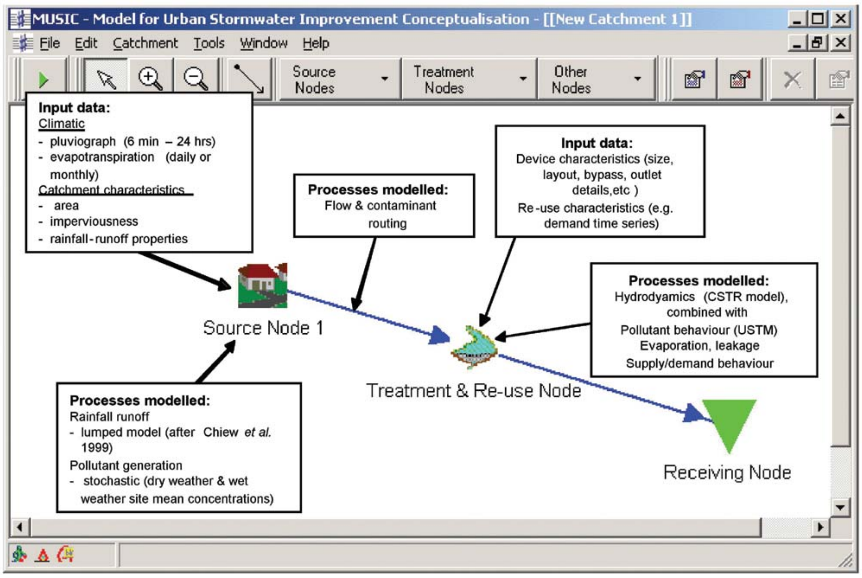

Figure 4.1. MUSIC interface layout, data input requirements, and processes modelled.

The objectives in developing MUSIC were that it must:

1. Be relatively intuitive to use (since it would be used by a wide range of professionals, including urban planners, civil engineers, and environmental scientists),
2. Be modular, so that improvements in its scientific basis could be easily incorporated (a new version of the model is generally released on an annual basis),
3. Be able to undertake modelling at a range of time steps to accommodate the requirements of various spatial scales for projects. (Small projects will often require modelling to be undertaken at small time steps to better capture the influence of storm temporal patterns on the operation of WSUD elements. For larger scale projects, coarser time steps (hours) may be adequate to capture storm temporal patterns and WSUD operation, while allowing more efficient data handling, storage and reporting).
4. Focus on continuous simulations, to allow a risk-based approach to assessment (Whilst the model can be used on a single event - e.g. a design event - basis, its focus is more on continuous simulation over a relatively long time series of rainfall-runoff conditions to capture the dynamic behaviour of hydrology, water quality and ultimately eco-system responses),
5. Integrate urban water cycle objectives where possible (primarily enabling water resource allocation to be modelled without being too complex).

It is important to note that MUSIC is not a detailed design tool, and other methods are required to translate the conceptual design delivered by MUSIC into engineering specifications necessary for construction.

Modelling rainfall-runoff processes and pollutant generation

- Rainfall-runoff

  Rainfall-runoff processes are modelled using a sub-daily model, based on the lumped conceptual model of Chiew and McMahon (1999). The model runs at timesteps from 24 hours down to 6 minutes, matched to: (a) the time of concentration of the smallest subcatchment, and (b) the detention times in the specified treatment measures.

- Pollutant generation

  There have been numerous attempts to model the generation of pollutants from urban catchments (e.g. Ahlman and Svensson, 2002; Bertrand-Krajewski *et al.*, 1998; Chiew and McMahon, 1999; Deletic *et al.*, 1997; Sartor *et al.*, 1974). These have varied in approach and complexity, accounting for one or more of deposition, buildup, washoff and transport processes (see also Paper No. 2 in the Model Choice series). None so far have provided a definitive prediction of intra-event stormwater quality. The approach taken in MUSIC is quite different, aimed at describing the observed variation in pollutant concentrations, during dry weather and storm event conditions.

To that end, Duncan (1999) undertook a review of water quality from different land uses, from more than 600 studies worldwide. The results have been adapted to specify default event mean (and standard deviation) and dry weather concentrations of TSS, TP and TN (Fletcher *et al.*, 2002b). Analysis of local data can be used to replace the default values. MUSIC generates a stochastic time series of pollutant concentrations based on the means and standard deviations, with a degree of correlation between TSS and TP. Serial autocorrelation can also be specified. This approach makes MUSIC easy to apply across catchments of different land use, with local calibration data relatively simple to obtain (subject to appropriate sampling and analysis standards). However, there are a number of significant drawbacks in such an approach. The most obvious is that this model cannot accurately predict pollutant concentration at any given point in time, because it is a purely stochastic approach (ie.randomly generates concentrations based on user-specified statistical distributions - see also Paper No. 1 in the Modelling Choice Series).

Flows and pollutants are conveyed via a drainage link, with routing simulated using a Muskingum-Cunge routing algorithm (see Bedient and Huber, 1992).

Modelling stormwater treatment processes

Wong *et al.* (2001) described the unified stormwater treatment model (USTM) that forms the basis of MUSIC's prediction of stormwater quality improvement (or deterioration) through treatment measures. MUSIC models stormwater treatment using two principal algorithms; hydraulic behaviour is described as a series of continuously stirred tank reactors (CSTRs) (Persson *et al.*, 1999), whilst water quality changes are described as a first-order kinetic decay model (Kadlec and Knight, 1996). In addition, seepage and evaporation losses are modelled within the treatment devices.

Hydraulic behaviour

Hydraulic behaviour within a treatment device - such as a wetland or vegetated swale - is very much dependent on the shape and arrangement of that device. The best water quality treatment will occur where the entire surface area of the treatment is engaged, without the presence of flow short-circuiting or stagnant zones. Kadlec and Knight (1996) describe this in terms of a retention time distribution (RTD), with ideal (plug flow) behaviour occurring when every 'parcel' of water in the treatment device receives an identical time of treatment. Hydraulic behaviour can be described using a series of continuously stirred tank reactors (CSTRs) (see Persson *et al.*, 1999), where water entering each tank is assumed to be instantaneously completely mixed. A high number of CSTRs (e.g. 10) can be used to simulate near-plug flow, whilst devices with distinct short-circuiting and turbulence (poor hydraulic performance) can be simulated by a low number of CSTRs (e.g. 1-2). This approach is used in MUSIC, with users examining a chart of treatment device layouts to select the appropriate number of CSTRs.

Pollutant behaviour - the k-C model*

MUSIC uses a simple first-order kinetic decay algorithm (Eqn. 4.1), known as the "k-C* model", to describe the rate (k) at which pollutant concentration moves towards an equilibrium or background concentration (C*).

$$q \frac{dC}{dx} = -k(C - C^*) \qquad \text{(Eqn.4. 1)}$$

where q = hydraulic loading rate (m/y)
x = fraction of distance from inlet to outlet
C = concentration of the water quality parameter
C^* = background concentration of the water quality parameter
k = areal decay rate constant (m/y)

Testing of model performance

Wong *et al.* (2001) tested the suitability of the k-C* model on a range of stormwater treatment devices, including ponds, wetlands (Figure 4.2), vegetated swales and infiltration trenches, and found it capable of describing the overall water quality behaviour. However, there are a number of assumptions inherent in the model (such as the constancy of k and C*), which are unlikely to hold in all circumstances, and further research is being undertaken to investigate these (read on...).

Model Output Diagnostics

MUSIC's outputs reflect its focus on continuous simulation and a probabilistic approach to assessing the performance of individual or a combination of stormwater management measures. The output diagnostics are designed to allow a risk-based analysis of compliance of a stormwater management strategy or individual stormwater treatment measure, to relevant flow and water quality objectives. The range of output diagnostic options available is based on analysis of the simulated time-series of flows and pollutants at any node. Analyses include:

Figure 4.2. Testing the applicability of the k-C algorithm using field dosing tests in Hallam Valley Wetland, Victoria.*

- Mean annual flow volume and pollutant loads and percentage reduction (these are also computed for the treatment train upstream of the node in question),
- Statistics of the stormwater discharge and pollutant concentrations (mean, median, 1st decile and 9th decile),
- cumulative frequency plots of discharges and pollutant concentrations and comparison against user-defined water quality objectives.

In computing the statistics of the model outputs (ie. time series of flows and pollutant concentrations), the user is not restricted to using all data (ie. predictions for every time step being a discrete data point) and has the option of undertaking these statistical analyses using an aggregated daily mean sample, a flow-weighted daily mean pollutant concentration, the daily maximum, or a "daily sample" taken at a pre-determined time every day. Furthermore, the diagnostic tools provided by the model allows the user to undertake a statistical analysis from a sub-sample defined by a low flow or high flow value, which can be useful in separating dry-weather and wet-weather conditions.

Current Research to Improve MUSIC

MUSIC provides the focal point for research being undertaken with the CRC for Catchment Hydrology, with the aim of improving the accuracy and capability of MUSIC, whilst attempting to maintain the user-friendly approach, so that the model can be readily applied by industry. Our ongoing research is aimed at:

(i) improving the accuracy and reliability of processes currently simulated within MUSIC, and

(ii) expanding the capability of MUSIC to answer other key questions which urban waterways must consider in formulating and assessing stormwater management strategies.

Improving simulation of pollutant generation

A new project in Melbourne aims to improve prediction of urban stormwater quality emanating from catchments of given land use (as an alternative to MUSIC's current stochastic method). The aim of this project is to produce a simple (efficient) physically-based model of pollutant generation, based on catchment and pollutant characteristics, and short-duration climate data. Early indications are that a model that predicts pollutant loads as a function of rainfall intensity, measured at short timesteps throughout a storm, may be effective.

Improving simulation of treatment processes

One assumption underlying the first-order decay (k-C*) model that underpins MUSIC's treatment simulation, is that of constancy of the model parameters - decay rate (k) and background concentration (C*) (Kadlec, 2000). Our own research (e.g. Deletic and Fletcher, 2004; Fletcher *et al.*, 2002a; Wong *et al.*, 2000; Wong *et al.*, 1999) and that of others (Kadlec, 2000) suggests that this is not really the case. There appears to be a relationship between the model parameters and hydraulic loading, and possibly inflow concentration. It is evident that further research is needed to examine how k and C* vary with these factors. Given the importance of physical processes in removing many stormwater pollutants, the influence of particle size and settling velocity distributions also require investigation.

MUSIC's treatment model has been developed primarily using data from storm events. However, current research suggests that the inter-event processes may be very important in determining the overall treatment effectiveness (Fletcher *et al.*, 2004). We are also examining the influence of particle size on pollutant behaviour in both open water and vegetated systems. Intensive monitoring, both during storm events, and during the inter-event dry period, is also being conducted at two stormwater treatment wetlands (one in a temperate climate in Melbourne, and another in sub-tropical Brisbane), to validate the appropriateness of MUSIC's k-C* algorithm for these systems, and refine the model as required. .

Incorporating additional capability into MUSIC

Predicting the performance of non-structural techniques

Relative to the performance of structural treatment devices, very little is known about the performance of non-structural measures for improving stormwater quality (Taylor and Wong, 2002). A thorough review of a range of these measures (e.g. municipal planning, education, and enforcement) has been undertaken, and resulting performance estimates can be incorporated into MUSIC (via a user-specified Generic Treatment Node) as part of the treatment train.

Predicting ecosystem response

The general relationship between catchment urbanisation and degradation of receiving water ecosystems is well known (Booth and Jackson, 1997; Walsh *et al.*, 2000). However, there has been little success in developing predictions of ecosystem response to stormwater management scenarios. A large multi-disciplinary project is underway to develop such models, with promising results (Walsh, in review; Walsh and Fletcher, submitted). Whilst several studies have demonstrated the impact of impervious area on aquatic ecosystems, the research undertaken in this project has highlighted the importance of the connection between the impervious area and receiving waters. The models show that an impervious area which is not connected to receiving waters has little or no impact (up to a threshold total impervious level) on, for example, macroinvertebrate community composition (Walsh and Fletcher, submitted). It is therefore effective impervious area which provides a good prediction of aquatic ecosystem health. These integrative catchment-scale models are now being refined in an attempt to be able to describe the influence of stormwater best-management practices (which reduce the connection - both hydraulically and in pollutant transport efficiency - of impervious areas to streams) on aquatic ecosystem health. The resulting predictive algorithms will be incorporated into MUSIC.

Lifecycle cost analysis

Data on the design, construction, operation and maintenance costs of a wide range of stormwater treatment measures have been collected. Regression analyses are being used to build relationships between these costs and variables such as catchment area and treatment area (or volume). The resulting equations are being incorporated (with their associated uncertainties) into MUSIC Version 3, so that users are presented not only with predictions of the performance of a given treatment strategy in terms of flow and water quality (and later ecology), but also in terms of lifecycle costs. Whilst this module will be useful to stormwater managers, the relative scarcity and poor quality of lifecycle cost data on which the model was built means that uncertainties in its predictions are relatively large. There is an urgent need to undertake a disciplined program of collecting lifecycle cost data for best-practice stormwater management measures.

The big picture - linking to whole-of-catchment models

MUSIC provides urban stormwater managers with a user-friendly tool to help them formulate, assess and set priorities for strategies relating to stormwater management and water sensitive urban design. However, often the management of urban issues is just one part of a broader catchment management strategy. Therefore, users need to be able to incorporate MUSIC simulation results into whole-of-catchment models, such as the CRC's E2 model. To facilitate this, MUSIC v3 (due for release during February 2005) is being written with the capability to export simulation results directly to the modelling framework E2 (and E2 will have an "Export MUSIC simulation results" function). In addition, key components of MUSIC such as the k-C* model and a stochastic approach to pollutant generation will be available in E2.

Impact on industry

MUSIC has become the standard tool for stormwater management planning in most of Australia (and is also being used now in New Zealand, Europe and the USA). For example, Melbourne Water requires development proposals to be assessed using MUSIC, and they use it for their drainage scheme planning processes. It is being widely used by engineering consultants, for a wide range of applications, from single-treatment stormwater improvement strategies, to more complex integrated urban water management plans. Applications also involve stormwater and wastewater treatment, water harvesting and re-use, and management of groundwater-surfacewater interactions.

It is intended that ongoing research knowledge will continue to be delivered through MUSIC, beyond the lifespan of this current CRC.

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PROGRAM 5

CLIMATE VARIABILITY

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Report by Francis Chiew

Climate Variability Modelling

Hydroclimate Variability

Hydroclimate variability occurs over various time scales (seasonal, inter-annual, 3-7 year El Niño/Southern Oscillation (ENSO) cycle, inter-decadal and "climate change"). The management of land and water resources involves designing and operating systems to cope with this variability. For example, all water resources projects take into account seasonal and inter-annual variability, some farmers and irrigation authorities use ENSO-based forecasts for operational water management, and most are now concerned with the potential impacts of climate change on hydrology and water resources (see Figure 5.1).

Hydroclimate variability presents various challenges and opportunities to the management of land and water resources in Australia. The management challenges in Australia are compounded by Australian streamflow (and to a lesser extent climate) being more variable than elsewhere in the world. On the other hand, the hydroclimate-ENSO relationship in Australia is amongst the strongest in the world and can be exploited to forecast hydroclimate variables several months in advance.

This article describes two modelling tools relating to climate variability that can be used with hydrological, environmental and system operational models - stochastic climate models and seasonal hydroclimate forecasting models.

Stochastic Climate Models

What is stochastic climate data?

In short, stochastic climate data are random numbers that are modified so that they have the same characteristics (in terms of mean, variance, skew, short-term and long-term persistencies, etc...) as the historical data from which they are based. Each stochastic replicate (sequence) is different and has different characteristics compared to the historical data, but the average of each characteristic from all the stochastic replicates is the same as the historical data. The boxed section gives a simple example of an algorithm for generating stochastic data.

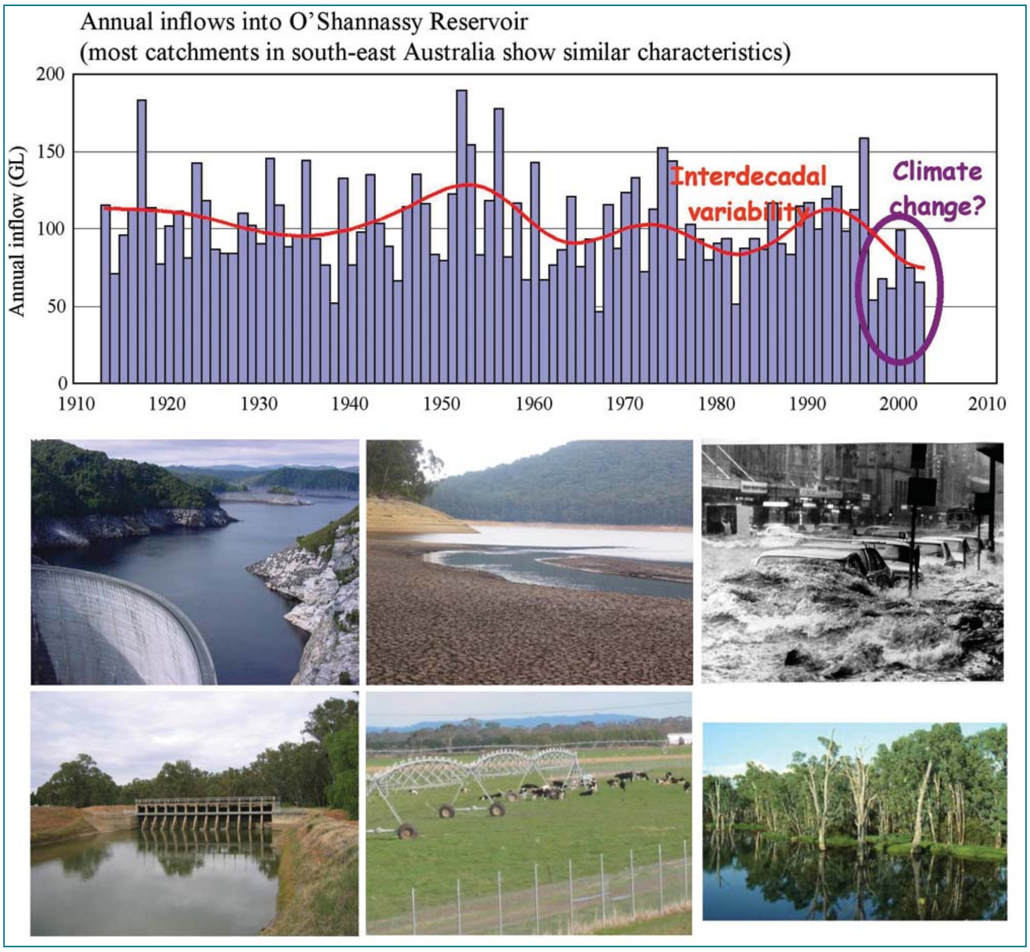

Figure 5.1: Hydroclimate variability and land and water resources management

A simple example of a stochastic annual rainfall model (not necessarily a good model) is,

$X_t = r X_{t-1} + (1 - r^2)^{0.5} \varepsilon_t$ (5.1)

$x_t = \bar{x} + s X_t$ (5.2)

The three parameters in this model are the mean annual rainfall ($\bar{x}$), the standard deviation of annual rainfall (s) and the lag-one serial correlation of annual rainfall (r). The standardised rainfall for the current year (X_t) is estimated from Equation 5.1, where X_{t-1} is standardised rainfall in the previous year and ε_t is a random number (generated from a normal distribution with zero mean and unit variance). The rainfall (x_t) is then calculated from Equation 5.2. These steps are then repeated to obtain a stochastic time series of annual rainfall.

What is the use of stochastic climate data?

Climate is the key driver of hydrological and environmental models. The use of historical climate data as inputs into these models provides results that are based on only one realisation of the past climate. Stochastic climate data provide alternative realisations that are equally likely to occur, and can therefore be used with hydrological and ecological models to quantify uncertainty in environmental systems associated with climate variability. As an example, many replicates (say 1,000) of stochastic climate data can be used as inputs to drive water resources models (such as REALM and IQQM) to estimate system reliability for alternative allocation rules and management practices (here, the tenth worse results in the 1,000 simulations have a 1% chance of occurring) (see Figure 5.2).

Use of stochastic climate models in Australia

A survey by McMahon *et al.* (1996) indicated that 85% of the 73 respondents benefited from the use of stochastic climate data in their modelling applications. The key perceived advantages for stochastic climate data are that it:

- allows assessment of uncertainty and risk (52% of respondents);
- facilitates investigation of response of complex systems (52%); and
- allows simulation of long sequences (19%).

The key perceived limitations are:

- reliability/quality of stochastic climate data (>50%)
- difficulty in setting up model (30%)
- lack of input data (26%)
- poor understanding of limitations (18%).

Types of stochastic climate models

The types of stochastic climate data required for different applications are:

- stochastic data for single-site or multi-site (or gridded data)
- stochastic data for single climate variable or many climate variables

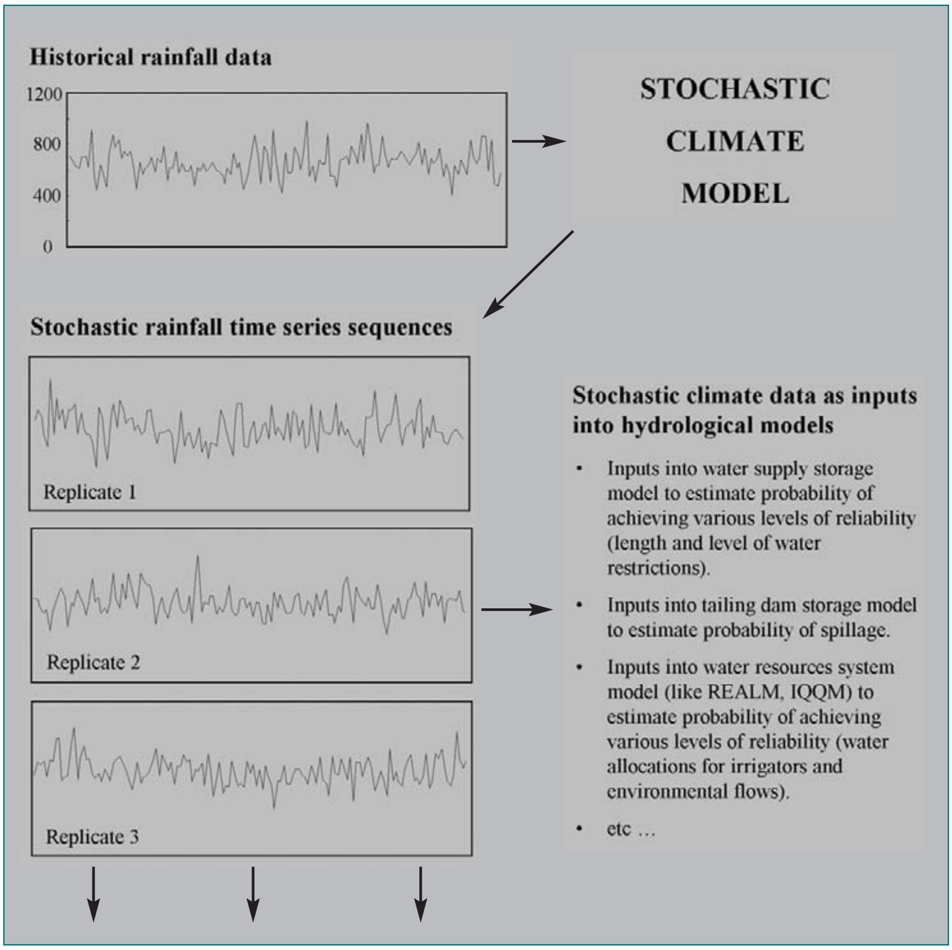

Figure 5.2: Using stochastic climate data as inputs into hydrological and ecological models to quantify uncertainty in environmental systems associated with climate variability

- the time step of the stochastic data (annual, monthly, daily or sub-daily).

There are many stochastic climate models in the scientific literature. They attempt to do the same thing, but some model structures simulate certain data characteristics better than others. Some of the more recent models also take into account parameter uncertainty. Srikanthan and McMahon (2000), and the references therein, provide a review of stochastic climate models.

What is a good stochastic climate model?

A good stochastic climate model must be able to reproduce the particular characteristics of the historical climate data in which you are most interested for your particular application, that is, the average of each key characteristic from all the stochastic replicates should be the same as that of the historical data.

In general, there is a tendency for stochastic models to reproduce satisfactorily the data characteristics at the time steps that they are developed for, but less satisfactorily the characteristics at other time steps. The key characteristics that a stochastic climate model should reproduce are dependent on the modelling application. In general, models should at least reproduce the key moments/parameters, like the mean, standard deviation, skew and serial correlation. For water system reliability studies, stochastic climate models should also simulate long-term persistencies satisfactorily (e.g., 2-year and 5-year low rainfall sums). For flood-related studies, stochastic models should simulate the extremes satisfactorily (e.g., intensity-frequency-duration characteristic).

Stochastic Climate Library (SCL)

The Stochastic Climate Library (SCL) is a library of stochastic models for generating climate data. SCL is a model product in the CRC for Catchment Hydrology Modelling Toolkit (www.toolkit.net.au/scl). SCL is designed for hydrologists, environmental scientists, modellers, consultants and researchers to facilitate the generation of stochastic climate data. There are other stochastic climate data software/programs, but they are either not freely available, written for specific applications or research purposes, tested with limited Australian data, or do not contain the range of stochastic climate models in SCL.

SCL is easy to use and is based on relatively robust stochastic climate data generation models. Although stochastic hydrology is a matured science, new models are continually being developed, usually with marginal improvements on previous models. The models in SCL are selected because of available expertise, their robustness, and extensive and successful model testing using data from across Australia (see Srikanthan and Chiew (2003) and references therein).

SCL requires a historical climate time series as input data, and calibrates and generates the stochastic data automatically. [Therefore, because stochastic models are driven by historical data, they do not improve poor records, but can improve the design made with whatever historical records are available].

SCL also displays the comparison between the characteristics of the stochastically generated data and the historical data. This allows the user to make an assessment of the quality of the stochastically generated data for their modelling application.

Figure 5.3 shows the types of stochastic climate data that can be generated using existing models in SCL, and other types of stochastic models that will be added to future versions of SCL. Figure 5.3 also reflects the state-of-the-art in stochastic hydrology and the capability of generating the different types of stochastic climate data.

Two types of models that will be added to SCL are of particular relevance to the industry. The multi-site (or spatial) daily rainfall model can be used to generate correlated daily rainfall series

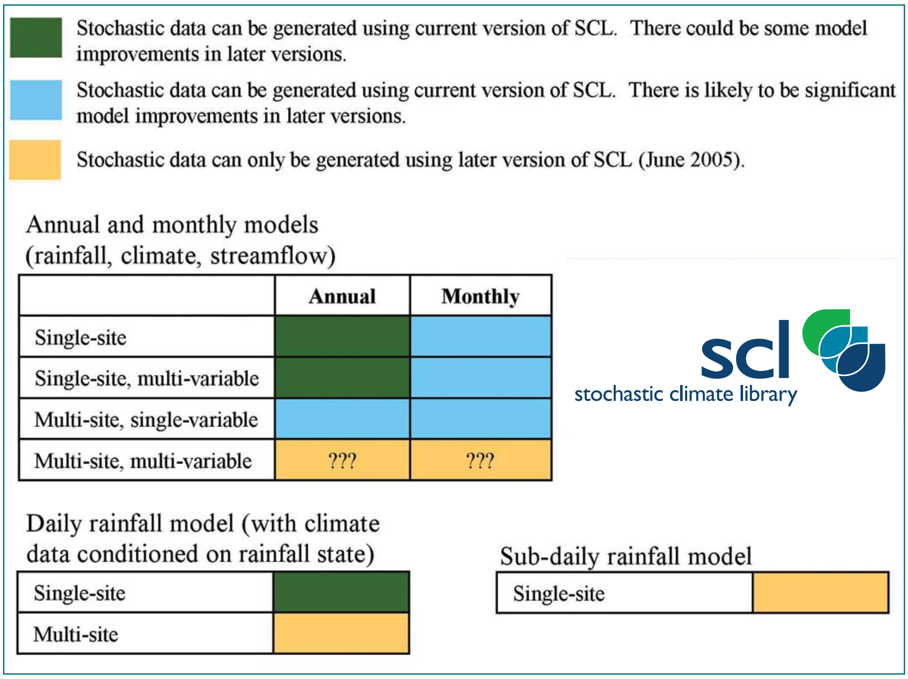

Figure 5.3: Stochastic climate models in SCL (Stochastic Climate Library)

from different catchments/stations that can be used as inputs to drive water resources models like REALM and IQQM. The single-site sub-daily rainfall model can be used to generate sub-daily rainfall series for inputs into urban stormwater quality models like MUSIC and sub-daily erosion and sediment generation models.

What about climate change?
The stochastic climate models discussed here attempt to reproduce the characteristics of the historical data from which they are based, and therefore do not take into account the potential impacts of climate change. It is likely that the climate characteristics in a greenhouse-enhanced environment will be different to the characteristics in the historical data.

The simplest approach to represent climate change is to generate climate data using existing stochastic models and scale the entire stochastic time series by the projected change in the mean of the climate variable in a greenhouse-enhanced climate. Climate change projections for 2030 and 2070 relative to 1990 (changes in mean rainfall, mean temperature and other variables) for Australia are available from CSIRO Atmospheric Research (www.dar.csiro.au/publications/projections2001.pdf).

The main limitation of this approach is that it takes into account only the potential change in the mean, and does not consider potential changes in the distribution of the data (e.g., changes in the inter-annual variability, different changes to rainfall extremes, changes to number of wet days, etc...). In any case, it is difficult to consider these changes realistically as there are large uncertainties in the climate change projections (even in the mean).

There are other approaches for generating stochastic climate data that also reflect changes to the distribution in the data. However, they are considerably more difficult to apply compared to the "constant scaling" approach above. They also tend to consider only a limited number of scenarios and therefore do not take into account the range of uncertainties in climate change projections, which can be larger than the stochasticity in the climate data. Nevertheless, these approaches should be considered in more detailed climate change impact studies.

Seasonal Hydroclimate Forecasting Models

What is seasonal hydroclimate forecast?
The relationship between El Niño/Southern Oscillation (ENSO) and Australian rainfall and streamflow is amongst the strongest in the world, particularly in eastern Australia in spring and summer (Chiew and McMahon, 2002). Australia is typically dry under El Niño conditions (warm sea surface temperatures in equatorial Pacific Ocean, and high negative value of Southern Oscillation Index (SOI)) and wet under La Niña conditions.

There is also a strong serial correlation (persistency) in streamflow, particularly in southern parts of Australia where it is stronger than the streamflow-ENSO relationship. In addition, unlike the streamflow-ENSO relationship, the persistency in streamflow exists throughout the year (Chiew and McMahon, 2003).

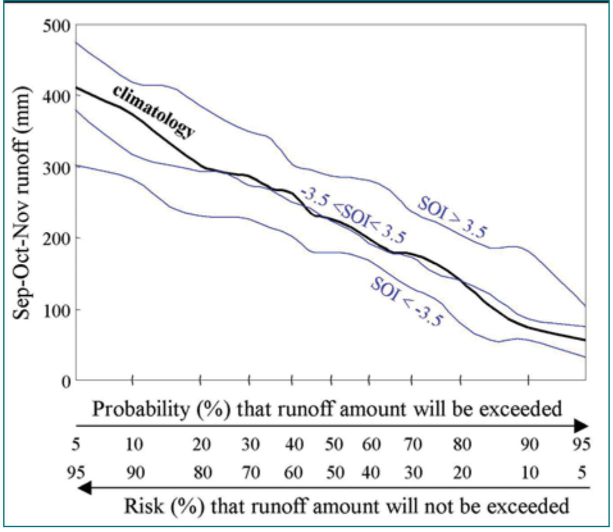

Figure 5.4: Distribution of Sep-Oct-Nov runoff in Nariel Creek (south-east Australia) for three catagories of Jun-Jul-Aug SOI values

The lag relationship between streamflow (or rainfall) and ENSO and the serial correlation in streamflow can be exploited to forecast streamflow (or rainfall) several months in advance.

Seasonal streamflow forecast and water resources management
Many studies have shown that the use of seasonal streamflow forecasts can benefit the management of land and water resources in Australia (e.g., Hammer *et al.*, 2000; Abawi *et al.*, 2001; Chiew *et al.*, 2003; and Letcher *et al.*, 2004). For example, seasonal streamflow forecasts can be used to:

- provide probabilistic indications of future water allocation in an irrigation system (currently provided by Goulburn-Murray Water) or water availability in a dryland system
- make better informed risk-based decisions for farm and crop management (adopted by many farmers)
- establish water restriction rules for rural towns
- make better decisions on water allocation for competing users.

Statistical seasonal hydroclimate forecast models
Probabilistic forecasts (or exceedance probability forecasts) are required to manage systems and applications with different levels of risk. Figure 5.4 presents an example of probabilistic seasonal streamflow forecasts (all the examples here are based on 98 years of unimpaired streamflow data from Nariel Creek in south-east Australia). Figure 5.4 also shows that spring (Sep-Oct-Nov) flows are generally higher when the winter (Jun-Jul-Aug) SOI is positive.

Statistical models estimate probabilistic streamflow forecast by relating streamflow to explanatory variables from previous months. Explanatory variables that are commonly used include streamflow, Southern Oscillation Index (SOI), Sea Surface Temperature (SST) anomaly, Multivariate ENSO Index (MEI) and upper atmospheric pressure.

The boxed section gives examples of statistical seasonal hydroclimate forecasting models.

Figure 5.5 illustrates the data fitting by three statistical models. In the Tercile model, the exceedance probability forecasts of Sep-Oct-Nov runoff are determined using the Sep-Oct-Nov runoff distribution in three discrete categories of antecedent (Jun-Jul-Aug) SOI values (as shown in Figure 5.4). The exceedance probability forecasts can be easily determined using simple operations in Excel, and only need to be done once, as there are only three possible forecasts. The main limitation of the Tercile model is the use of discrete categories resulting in the same exceedance probability forecast over a large range of antecedent SOI values (e.g., Sep-Oct-Nov runoff forecast for Jun-Jul-Aug SOI of -20 and -5 are the same, see Figures 5.4 and 5.5).

The Nearest Neighbour model overcomes the discrete categories problem in the Tercile model by using the Sep-Oct-Nov runoff data close to the present antecedent Jun-Jul-Aug SOI to determine the exceedance probability forecast. In the example in Figure 5.5, the exceedance probability forecast of Sep-Oct-Nov runoff is determined using the Sep-Oct-Nov runoff distribution resulting from the ten closest antecedent SOI (e.g., forecast for Jun-Jul-Aug SOI of +10 is based on the ten Sep-Oct-Nov runoff values when SOI is between +8.6 and +15.6). The exceedance probability forecasts in the Nearest Neighbour model can also be easily established using Excel, but the forecast has to be determined separately for different values of the explanatory variable.

More sophisticated models, such as the non-parametric models of Sharma (2000) and Piechota *et al.* (2001), consider all the data, with higher weighting given to the present antecedent condition (e.g., NSFM in Figure 5.5). This results in a smoother relationship between the forecast variable and the explanatory variable. Nevertheless, Chiew and Siriwardena (2005) show that there is little difference in the "best-estimate" forecast skill (e.g., 50% exceedance probability forecast) between the more complex non-parametric models and the Nearest Neighbour model. However, the non-parametric models are likely to perform better in estimating the very high exceedance probability forecast, and can better exploit the use of two or more explanatory variables compared to the Tercile and Nearest Neighbour models.

State-of-art of seasonal hydroclimate forecasting

The most direct source of seasonal forecast information for Australia is the Bureau of Meteorology's seasonal climate outlook (e.g., the probability that the total rainfall over the next three months would exceed the median) (see www.bom.gov.au/climate/ahead). There is also commercial software for performing simple analyses of hydroclimate data and plotting the data distribution (i.e., exceedance probability forecast) in different categories of antecedent values of various explanatory variables (like the Tercile model), the most widely used of which is Australian Rainman (Clewett *et al.*, 2003). The CRC for Catchment Hydrology has developed a non-parametric seasonal forecasting model (NSFM) for forecasting exceedance probabilities of hydroclimate variables, which will available in the Catchment Modelling Toolkit (www.toolkit.net.au) in early 2005.

Statistical forecasting models are already well developed, and at present, offer the best approach for forecasting hydroclimate variables. Research in this area is concentrating on fine-tuning existing models and searching for better explanatory variables for different locations and time of the year.

It is possible that global climate models (GCMs) - which model the large-scale interactions between the atmosphere-ocean-land

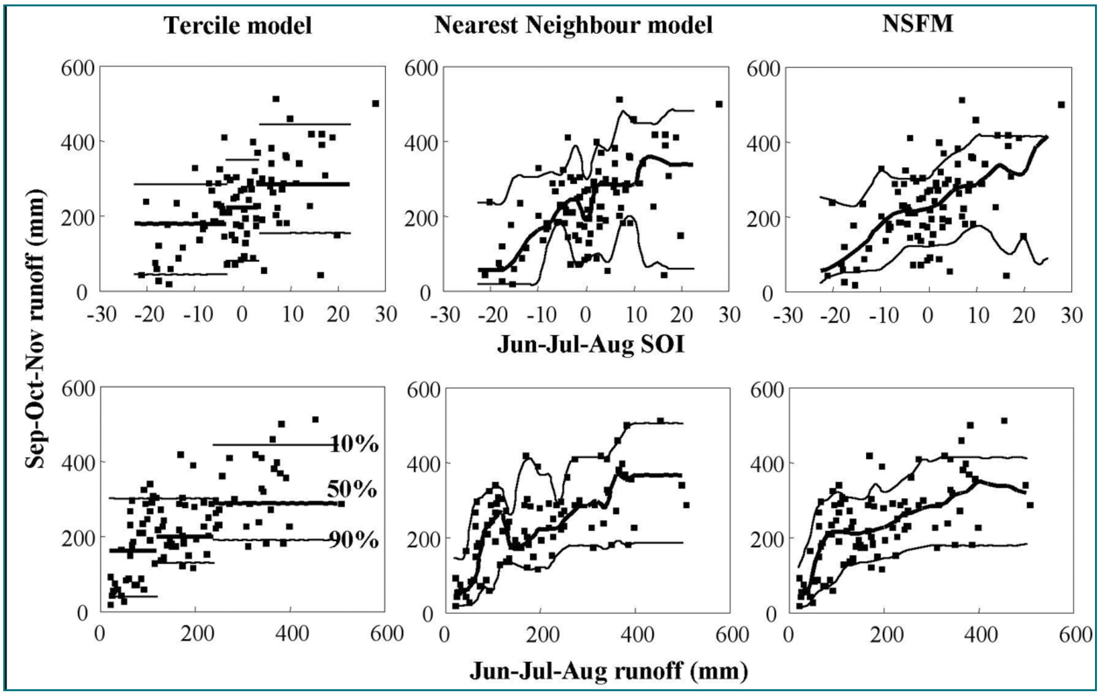

Figure 5.5: Data points for Sep-Oct-Nov runoff versus Jun-Jul-Aug SOI and versus Jul-Jul-Aug runoff and illustration of the fitting of three statistical models to provide probabilistic Sep-Oct-Nov forecasts (lines show 10%, 50% and 90% exceedance probability forecasts)

processes - as they improve, can provide better seasonal climate forecasts than statistical models, particularly for large regions and for longer lead times. Unlike the statistical models, GCMs also automatically take into account the changing rainfall-ENSO relationship over time. However, at present, GCM results are not reliable over small scales, but are better at large scales. Therefore statistical downscaling approaches are needed to relate large-scale atmospheric variables to catchment rainfall. The parameterisation of downscaling methods for specific regions is time consuming and adds additional errors to the modelling. Currently, the most reliable forecasts are coming from methods based on analysis of historic data described above, such as the NSFM which will be released in the Toolkit in early 2005.

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PROGRAM 6

RIVER RESTORATION

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MIKE STEWARDSON

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River Restoration Modelling

Modelling context in river restoration

The River Restoration Program is providing models to predict the impact of flow modifications and river management on physical habitat conditions and biological communities throughout river networks. The two core projects are focussed on modelling river response to environmental flows which have become the key element of river restoration plans throughout Australia. Two Associated/Additional projects (funded by Murray-Darling Basing Commission and Land and Water Australia) focus on river responses to riparian restoration, the other major restoration activity in Australia.

Environmental flow studies normally use hydrological models such as IQQM or REALM to predict discharge regimes for alternate water-use scenarios and then assess the likely biological impacts of these alternate scenarios. Although a number of different methodologies are in use across Australia, they all rely on defining characteristics of the flow regime which are important for river ecosystems. The current methods (including MFAT, FLOWS, Scientific Panels, Building Block Methodology and Flow Events Method) all rely on building models which (a) identify a specific ecological response to flow modification, and (b) link this response to changes in a specific characteristic of the flow regime.

Although States each have a different "environmental flow method", there are common elements, in particular the quantitative modelling used to support these methods. In partnership with the CRC for Freshwater Ecology, the River Restoration Program is providing a product called the River Analysis Package (RAP) to undertake the quantitative modelling necessary in environmental flow studies across Australia. This common product will benefit the water industry by:

(i) facilitating exchange of modelling methods used in different projects

(ii) providing a system for archiving models for future reference

(iii) providing an efficient pathway for adoption of new research outcomes by the industry.

The RAP package is used to analyse habitats at the reach-scale. However, RAP will also interface directly with the Catchment Modelling Toolkit E2 model. For each river link in the E2 model, time series of the modelled parameter (e.g. discharge) can be produced and used in RAP to model biological consequences of alternate natural resource management scenarios modelled in E2 for that particular river reach. Elements of RAP will also be incorporated within E2 to allow calculation for habitat parameters throughout river networks.

Gaps that the River Restoration Program is filling

Compared to the relatively mature modelling approaches for predicting the response of physical parameters (water, sediment and nutrients), the modelling approaches for relating these to a biotic response are varied. This variability in the precision, accuracy and specificity of models often means that a common modelling framework would have to be reduced to the lowest common denominator (i.e. the model parameter that we know the least about). In addition, there is no single (agreed) way to summarise the 'biotic response', instead, the level of response is defined for each project. In some instances, we may be interested in broad ecosystem processes like nutrient cycling, and in other projects we are interested in the impact on a particular life history stage of a particular organism (e.g. how does this altered flow regime affect the spawning habits of a particular fish species).

To develop a single biotic response model would mean imposing our own values on what type of biotic responses are important. Hard-coding numerical models of these biotic responses also limits the modelling approach to what we know here and now. It would require recoding each time new information becomes available. The approach that we have taken to modelling biological response is to focus less on the individual biotic response models that are region-specific and project-specific, but rather to provide a flexible framework to capture existing and new models of biological response. Our intention for the framework is to provide a method to capture a range of models (from simple conceptual models to complicated numerical models) and also to allow for any level of ecosystem component to be considered (from nutrient cycling to the life history stage of a single organism). The framework is essentially a database for storing models relating ecosystem components to habitat drivers at a range of scales.

Environmental flow response models can be developed in RAP based on well-tested statistical models documented in the literature or someone's conceptual model of system response. RAP provides a method of rating the confidence in each model through a quantitative ranking process using a series of categories based on the publication source, type of study to produce the model, and specificity of the model.

The Ecological Response Models (ERM) module within RAP provides a database structure for storing generic or project-specific response models. The user can select the appropriate model for a particular project (or develop their own). The database then provides the information to implement the chosen model. As new information comes to hand, the confidence of the modelled result can be increased, or the numerical computation of the model can be changed. The database is essentially a library of all the models that have gone before. Each study using ERM builds the database. The database does not replace the need for ecological expertise in environmental flow teams, but it does simplify their job and promotes consistency across studies.

Capability of models/modules

The River Restoration Program is developing the River Analysis Package (RAP) which includes a series of modules:

(i) Hydraulic Analysis

(ii) Time Series Analysis

(iii) Time Series Manager.

In addition, we are currently developing the core Ecological Response Models Module (concept described above) which uses the functionality in the three numerical modules to predict habitat change for alternate management scenarios (Figure 6.1).

Hydraulic Analysis module (HA)

Status: Version 1.1.0 available in RAP

The Hydraulic Analysis (HA) module can be applied to environmental flow studies and is specifically designed to use a one-dimensional hydraulic model output to produce time series of available hydraulic habitat. For example, to investigate how habitat availability differs under alternate flow regimes, consider the case of shallow flow (say less than 1m) and low velocity (say less than 0.1m/s). Here, HA creates a rating curve relating the availability of the shallow, low velocity habitat to the discharge, and in combination with a time series of discharge, HA creates a time series of habitat availability (Figure 6.2). To more intensively investigate the alternate time series of habitat availability one would use the Time Series Analysis module.

The current version of RAP relies on a one-dimensional hydraulic model to relate discharge to hydraulic habitat conditions. For this approach, one must have a survey of a representative portion of the river channel. We are also developing an empirical model which predicts habitat-discharge relations from various catchment and stream attributes. This will allow modelling of habitat conditions throughout a river network and overcomes the restrictions of costly hydraulic surveys and modelling, although the empirical models will not be as accurate as the more detailed hydraulic modelling.

Time Series Analysis Module (TSA)

Status: Version 1.1.0 available

The Time Series Analysis (TSA) module provides a series of ecologically relevant functions commonly used for investigating daily time series data. Some functions include high and low flow spell analysis, flood frequency, frequency-magnitude plots, seasonality index, baseflow analysis and some common summary statistics (Figure 6.3). The TSA module allows users to analyse single or multiple time series (say for comparing between alternate flow scenarios), and can include the analysis of ecologically sensible time periods such as the spawning period of a particular fish rather than monthly summaries. The TSA module can use any daily time series that is gap free. The Time series Manager module includes some gap filling tools.

Time Series Manager Module (TSM)

Status: In preparation, internal beta version operational (beta version scheduled for March 05)

The Time Series Manager (TSM) module provides a series of tools for modifying and combining time series. Multiple time series can be combined using the time series rule engine. These functions are specifically used in the Ecological Response Models module where we manipulate and combine time series to allow consideration of multiple biologically important environmental (e.g. physical/

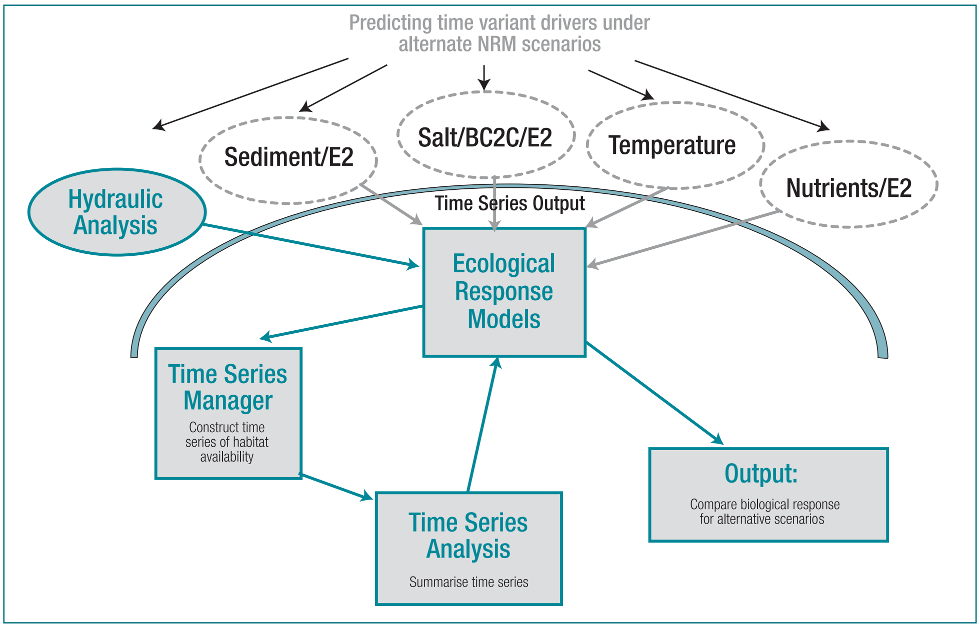

Figure 6.1: River Analysis Package modules are dark circles, Interaction with other Catchment Modelling Toolkit elements also shown.

chemical) drivers. For example, a fish species may have particular hydraulic habitat requirements for spawning, (say shallow depths and low velocities), and using the HA module we can provide a time series of habitat availability, but there may also be salt tolerance limits. Hence, by considering a time series of salt concentration from the Catchment Modelling Toolkit 2C model, we can combine the two time series (hydraulic habitat and salt concentration); there may also be a temperature tolerance limit, hence with a modelled time series of temperature we can also include that time series. For example, for every day of the time series, if the salt concentration is less than 10000ppm and the temperature is between 13-25 degrees Celsius then the available habitat equals the hydraulic habitat; otherwise there is zero suitable habitat available. In this way we can create complicated time series that provide the opportunity to consider multiple time variant environmental drivers.

Ecological Response Module (ERM)

Status: Specifications complete, code development commenced (beta version scheduled for March 05)

The Ecological Response Models (ERM) module provides a structure for capturing models of biological response to any time variant environmental driver (or combination of drivers). The key element of ERM is flexibility, both in terms of the ecosystem component under consideration and the ways that drivers are considered. The key principle of ERM is not to model absolute biological response based on a time series input, but to compare the suitability of time variant drivers for a given scenario against the natural distribution of the time variant driver.

The ERM can consider any time variant driver. In environmental flow studies, this driver is usually 'flow'. However, other drivers such as temperature can also be important for river habitat analysis. If you can quantify the biological response to such drivers, then ERM can be used to model it. The types of models that ERM will initially handle are simple numerical combinations of time variant drivers (like a multiple regression), preference curves (like PHABSIM), and we are currently reviewing the value of providing the capacity to include some limited Bayesian modelling.

Context for model application

The biological response modelling tools are designed to provide more rigor and defensibility to the expert panel process and assist in natural resource management planning by providing a tool to evaluate potential ecological responses to alternative scenarios in a rapid, repeatable and defensible manner. The Ecological Response Models module does not directly predict biological response, but rather changes in habitat availability. Hence interpretation is still required to predict the likely role of habitat availability in determining the response a particular species.

Impacts of models on gaps

One of the main features of the ERM module is to not only provide a mechanism for modelling ecological response, but to capture the confidence of that model. ERM effectively highlights the deficiencies in our knowledge by highlighting where the uncertainties exist. We may predict a dramatic change in environmental conditions required by a particular species under a given scenario. However, there may be a high level of uncertainty about that prediction because little is known about the ecological requirements of that species. Hence ERM identifies both the

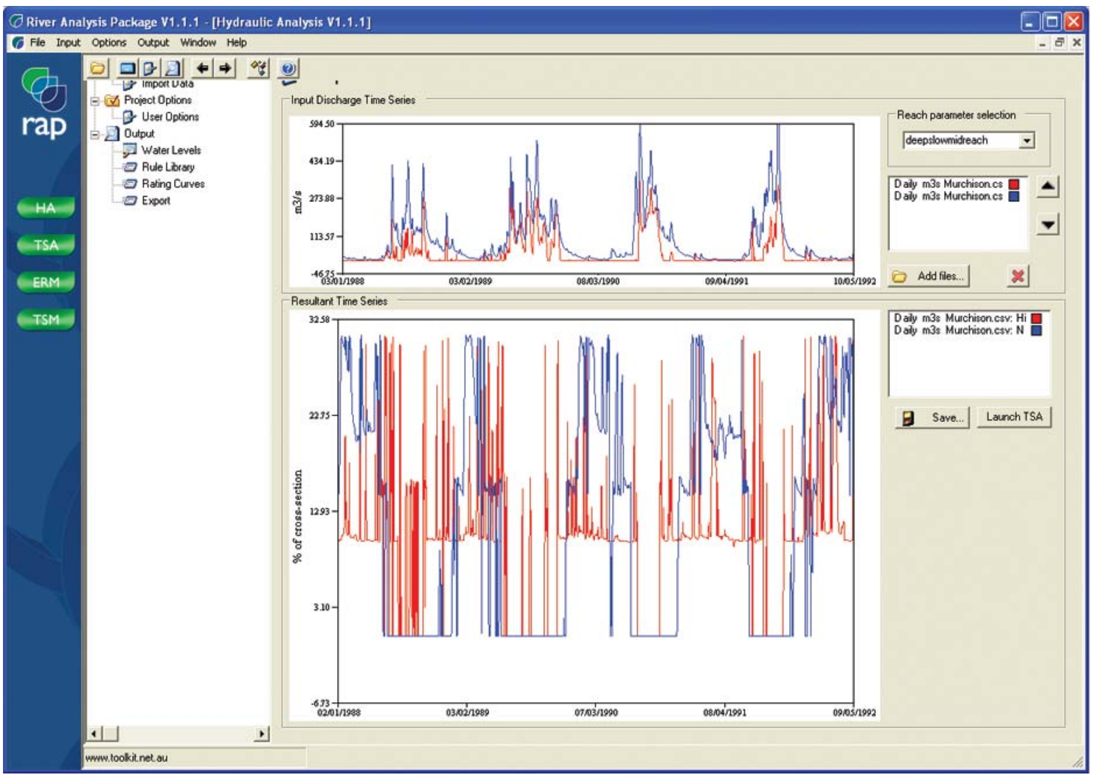

Figure 6.2: Hydraulic Analysis Module: example of time series of habitat availability

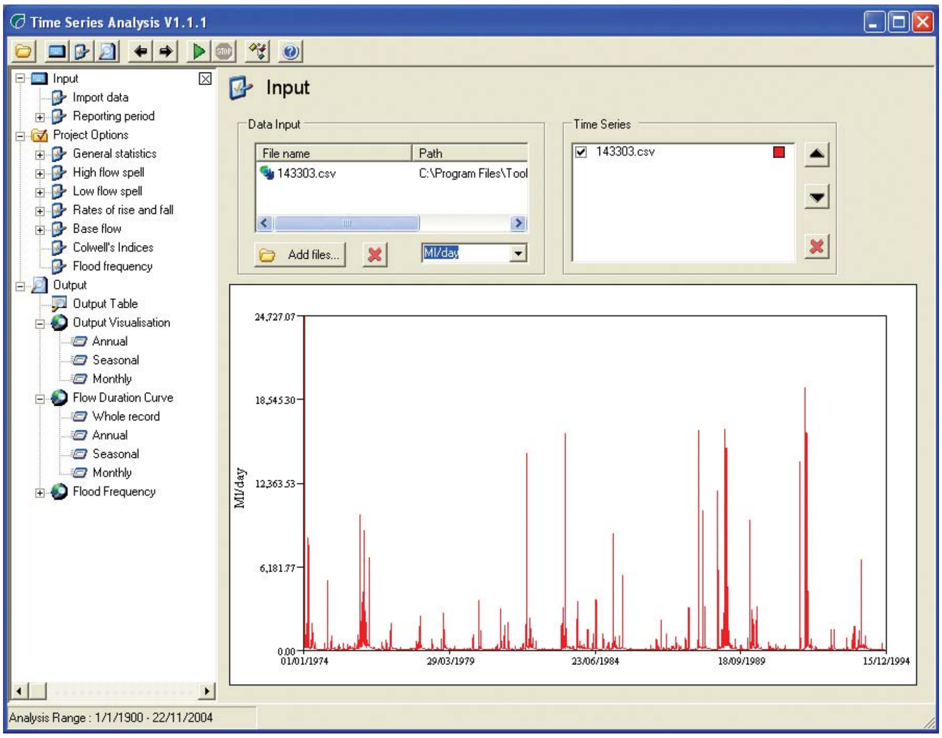

Figure 6.3: Time Series Analysis

threatened organisms and the processes that we don't fully understand. The combination of these two elements should provide the basis for organism-specific research. In this way, ERM provides a tool for natural resource management planning, which requires a decision here and now, but also highlights the deficiencies in our knowledge to focus future research efforts.

The Future

The Ecological Response Models module is designed for comparing the habitat suitability of one scenario against the natural condition. ERM is essentially a comparison of the distribution of long-term measurements of ecologically important habitat parameters. The next major advance would be to directly model biological response by considering both the changes in habitat availability through time (e.g. on an annual time-step) and the interactions between ecosystem components to also be modelled.

We have developed some ideas based on other Catchment Modelling Toolkit products as to how the user could create complicated ecosystem interaction models "on the fly" by using a node-link style framework, and then model biotic response based on the combination of habitat availability and interactions with other ecosystem components on an annual basis. However, this direct prediction of biological response will not be included in the first releases of ERM.

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To deliver to resource managers the capability to assess the hydrologic impact of land-use and water-management decisions at whole-of-catchment scale.

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To achieve our mission the CRC has six multi-disciplinary research programs:

- Predicting catchment behaviour
- Land-use impacts on rivers
- Sustainable water allocation
- Urban stormwater quality
- Climate variability
- River restoration

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