CATCHMENT SCALE MODELLING OF WATER QUALITY AND QUANTITY

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This thesis is my own work. Some of the work presented in Chapter 4 has been published in Newham et al. (2000) and Croke et al. (2001b). Parts of Chapter 5 have been published in Croke et al. (2000) and Newham et al. (2001b). The research presented in Chapter 6 is based on the publication of Newham et al. (2001c). Part of the research presented in Chapter 8 has been published in Croke et al. (2002). The contributions made by the various co-authors are indicated in the text.

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Abstract

 Appropriately constructed pollutant export models can help set management priorities for catchments, identify critical pollutant source areas, and are important tools for developing and evaluating economically viable ways of minimising surface water pollution.

 This thesis presents a comparison, an evaluation and an integration of models for predicting the export of environmental pollutants, in particular sediment, through river systems. A review of the capabilities and limitations of current water quality modelling approaches is made. Several water quality and quantity modelling approaches are applied and evaluated in the catchment of the upper Murrumbidgee River.

 The IHACRES rainfall-runoff model and a simple hydrologic routing model are applied with the aim of developing a capacity to predict streamflow at various catchment scales and to enable integration with other pollutant load estimation techniques. Methods for calculating pollutant loads from observed pollutant concentration and modelled streamflow data are also investigated. Sediment export is estimated using these methods over a 10-year period for two case study subcatchments. Approaches for water quality sampling are discussed and a novel monitoring program using rising stage siphon samplers is presented.

 Results from a refinement of the Sediment River Network model in the upper Murrumbidgee catchment (SedNet-UM) are presented. The model provides a capacity to quantify sediment source, transport and to simulate the effects of management change in the catchment. The investigation of the model includes rigorous examination of the behaviour of the model through sensitivity assessment and comparison with other sediment modelling studies. The major conclusion reached through sensitivity assessment was that the outputs of the model are most sensitive to perturbation of the hydrologic parameters of the model.

 The SedNet-UM application demonstrates that it is possible to construct stream pollutant models that assist in prioritising management across catchment scales. It can be concluded that SedNet and similar variants have much potential to address common resource management issues requiring the identification of the source, propagation and fate of environmental pollutants. In addition, incorporating the strengths of a conceptual rainfall-runoff model and the semi-distributed SedNet model has been identified as very useful for the future prediction of environmental pollutant export.
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Chapter 1 Introduction

1.1 Outline of the problem

Catchments, streams and associated riparian ecosystems of Australia have been significantly altered since European settlement. These changes have resulted in the degradation of water quality and aquatic habitat. Examples of this degradation include the extensive drowning of riparian environments with sediment, an increased incidence of blue-green algal blooms and a decline in the abundance and distribution of native freshwater fish species. These changes have resulted in real economic, social and environmental costs, with short and long term consequences. Repairing the degradation is expensive, time consuming and, unfortunately, very often poorly focused.

To effectively focus remediation for repairing degradation of riparian ecosystems an improved understanding and quantification of the export of environmental pollutants from catchments is required. Effective implementation of site specific remediation will result from identifying the sources of environmental pollutants and their capacity to be transported through river systems. Clever management strategies are required to make the best use of limited funding (Brizga and Finlayson, 2000). Failure to focus remediation efforts effectively will lead to misdirected efforts, misspent funds and, most concerning, continued pollution (Hamlett et al., 1992).

This thesis is concerned with modelling stream related water quality and quantity through quantifying the sources and transport of environmental pollutants. Models can help set priorities, giving broader and longer term perspectives and are important tools for developing and evaluating economically viable ways of minimising surface and groundwater pollution (Moore and Gallant, 1991). The thesis presents a comparison, an evaluation and an integration of models for predicting the export of environmental pollutants, in particular sediment, through river systems. A range of pollutant export models is applied and evaluated.

1.2 Aim of the Research

This research has three aims:

1. Develop a capacity for catchment scale water quality and quantity modelling across the upper Murrumbidgee River catchment;
2. Develop and refine techniques for the prediction of concentrations and loads of environmental pollutants exported from upland catchments; and

3. Improve techniques of sediment generation and transport modelling at catchment scales.

1.3 Thesis Outline

This thesis has nine chapters. An outline of these follows:

Chapter 1: Introduction

Chapter 1 introduces the problem that the thesis addresses, the aims of the thesis and this outline of the subsequent chapters.

Chapter 2: Background

Chapter 2 presents a background to resource management issues and discusses the use of models that aid in improving environmental decision making. In this context, the capabilities and limitations of current water quality modelling approaches are discussed. A particular emphasis is on models associated with estimation of sediment loads. This chapter of the thesis is kept relatively brief as focused and detailed reviews of available literature (particularly modelling techniques) are made in appropriate sections throughout the thesis.

Chapter 3: Upper Murrumbidgee Catchment

A review of the physical environment of the upper Murrumbidgee River study catchment is made in Chapter 3. The chapter has a focus on the characteristics of the physical environment that influence water quality. Descriptions of various factors including climate, topography, lithology, soils, land use and vegetation are made to provide context for the subsequent chapters.

Chapter 4: Hydrologic Model Construction

Chapter 4 describes the construction of hydrologic models. The construction of the hydrologic models serves three objectives in this research:

- provision of data for hydrologic investigations across the study catchment;
- reconstruction of long-term streamflow records for estimating sediment loads; and
- provision of data for investigating hydrologic parameterisation of an associated water quality model.

The chapter describes the use of the rainfall-runoff model IHACRES for estimating flow at gauged sites. Also described is a streamflow routing technique that was developed for use in the research. The development of the Murrumbidgee Integrated Catchment Management
System (ICMS) - a network of streamflow and routing models across the upper Murrumbidgee catchment - is presented as part of the chapter.

**Chapter 5: Subcatchment Pollutant Load Estimation**

Chapter 5 presents the methods and results of estimating loads of catchment pollutants for two upper Murrumbidgee subcatchments. The chapter describes a water quality monitoring program initiated as part of this research in four other subcatchments. The program was established to provide additional water quality data suitable for calculating the export of sediment loads in several subcatchments.

**Chapter 6: Landscape Based Modelling**

The Sediment River Network (SedNet) model is described in Chapter 6. SedNet (Prosser *et al.*, 2001a) is a model designed to estimate the sources, propagation and deposition of sediment through river systems. The focus of the chapter is on sensitivity analysis and testing of the SedNet model. A review of the techniques of sensitivity analysis including investigation of parameter interactions is presented. An application of the model in the study catchment (SedNet-UM), described in the chapter, is used as a basis for this analysis. The results from the application are presented.

**Chapter 7: Comparison of Estimated Pollutant Loads**

Chapter 7 describes the comparison between the outputs of the pollutant load estimation techniques presented in this study with published sources of pollutant load information. The comparison is focused on accuracy assessment of the SedNet-UM model. The data used for comparison include the results of a detailed sediment budget, sediment tracing results, a compilation of published sediment yield data and the results from a dam sedimentation study. A comparison is also made between loads estimated at sites in Chapter 5 with the SedNet-UM model.

**Chapter 8: Elements of an Improved Pollutant Export Model**

A general discussion of elements of an improved pollutant export model is made in Chapter 8. This chapter provides a discussion of potential improvements to the SedNet model and more generally for pollutant export models. A particular focus of this chapter is on methods for improving the hydrologic components of SedNet.

**Chapter 9: Conclusion**

The conclusions reached in the thesis together with a summary of suggested further research are presented in the final chapter.
Chapter 2 Background

2.1 Introduction

The research presented in this thesis is focused on river and stream related water quality and quantity modelling. In practical terms the development of water quality and quantity models is important for focusing riparian remediation strategies and, more broadly, for influencing sustainable catchment management practices. The development of models to focus effectively riparian remediation and land management practices is a complex task that presents a fundamental scientific challenge.

This chapter describes the background of the thesis. The chapter begins by identifying the difficulties of allocating limited resources for riparian and catchment management activities to improve water quality. The particular focus of the chapter is on predictive source and transport models for sediment. A discussion is made of the roles that models can play in focusing management activities. The capabilities and limitations of present modelling approaches are identified and are used to develop a set of specific requirements for modelling water quality and quantity. These requirements are detailed as a summary of the chapter.

This chapter is not intended to provide a comprehensive review of the entire topic of water quality and quantity modelling. Rather, the chapter provides an introduction to a selection of the types of modelling techniques available. Additional background material is provided in appropriate sections throughout the thesis. For example, reviews of methods of subcatchment pollutant load estimation are provided in Section 5.1.1; sensitivity analysis techniques are reviewed in Section 6.3; and the IHACRES and SIMHYD rainfall-runoff models are described in Sections 4.3 and 4.8.1, respectively.

2.1.1 Models

In broad terms a model is a simplification of reality. Parker et al. (2001) has identified that models are constructed for one or more of the following purposes:

- an archive of contemporary knowledge for storage and retrieval;
- a collation tool for allowing different sets of data to be viewed or examined together;
- for assisting in the development of improved understanding of the system under management and of the types of interactions that exist between sub-systems, for example, the social, economic and biophysical;
• an instrument of prediction in support of decision making or policy formulation;
• a device for communicating scientific notion to and from a scientifically lay audience; and
• as an exploratory vehicle for scenario building.

2.2 Research Challenge

Sustainable land and water resource management demands the informed action of the managers of these resources (Walker and Johnson, 1996). Legislative demands and societal expectations mean that resource managers must be able to demonstrate that they have made decisions on the basis of rigorous and systematic consideration of proposed management strategies and their alternatives. Tools are needed that both integrate scientific understanding of the physical impacts of alternative decisions or actions, and provide an effective means of collating, interpreting and using that information (Walker and Johnson, 1996). The development of simulation models that characterise the behaviour of catchment systems is a common means of providing these tools. However, with respect to modelling river and stream water quality, this is a difficult proposition.

The sheer complexity of the system behaviour of catchments and riparian ecosystems and the paucity of observed data on this behaviour present considerable difficulties for modelling (Jakeman and Letcher, 2001). Consideration of numerous catchment processes including anthropogenic factors and the interactions within and between ecosystems is required. Assessment involves characterising aquatic, riparian, terrestrial features and management issues within catchments and developing linkages between catchment processes and environmental concerns (Dai et al., in press).

Focusing of efforts to repair degradation of riparian ecosystems requires quantification of the source and transport of pollutants for identification of so called critical source areas (nomenclature follows Heathwaite et al., 2000 and Hamlett et al., 1992). This is necessary as the resources allocated each year to riparian management are small relative to the scale of the problem (Prosser et al., 2001b).

It is essential that water quality models operate at spatial and temporal scales that are relevant to the context in which decisions are made (Walker and Johnson, 1996). To focus management the assessment must contend with issues at spatial scales from individual river reaches through to entire river basins. The assessment must consider a range of temporal scales - from storm events (minutes to hours) through to long term climate change (decades to centuries). Catchment assessment must also be relevant to management practices and broader natural resource management policies and the results need to be well communicated to
various stakeholders. In addition, it is important that model users are aware of the simplifications and assumptions inherent in any mathematical model and that the appropriate model is used in each individual application (Moore and Gallant, 1991). Thus, the challenge faced is the development of models that characterise complex systems but are also easily implemented, are consistent and can be easily communicated for improved management decisions (Dai et al., in press). No single model or set of models can claim to have this predictive capability for water quality or quantity estimation.

2.3 Research Scope

In this research both streamflow and water quality models are investigated. For practical reasons there are constraints on the scope of what is investigated. Effort has been concentrated on applying and evaluating predictive tools for sediment erosion and transport modelling. The development of associated decision support tools is not considered. Refer to Giupponi and Rosato (1995) for an example of the development of DSS tools and to Lam and Swayne (2001) for a discussion of issues associated with their development.

The approach of using predictive sediment models to explore modelling techniques was taken for several reasons:

- sediment is the greatest pollutant of surface waters worldwide (Robinson, 1971);
- soil loss rates for all but the most conservative of land uses exceed soil formation rates across much of Australia (Rosewell et al., 2000);
- soil loss may cause damage in three places: first to the land from which the soil is removed; second, to the water and riparian ecosystems which transport it; and third, to the sites where it is deposited (Rosewell et al., 2000);
- significant proportions of nutrients such as phosphorous (and other pollutants) are sourced from eroded soils and are often adsorbed onto clay particles to be transported together with sediment (Caitcheon et al., 1999; Rosewell et al., 2000); and
- sediment can be modelled conservatively, i.e. complex chemical transformations such as occur for nutrients, do not need to be considered.

The processes of erosion and sediment transport are not explicitly considered in this review. The processes of erosion and sediment transport, in contrast to the modelling, are relatively well described. For example see Haan et al. (1993), Thompson et al. (1986) and Merritt et al. (in press).
2.4 Current Understanding

Many models have been developed for investigating stream related water quantity and quality. Most of the models that have been developed to provide information on erosion and water quality processes are inappropriate for providing catchment scale, event based predictions of sediment loads (Merritt et al., in press). A range of problems including over-parameterisation, unrealistic input requirements and unsuitability of model assumptions or parameter values to local conditions constrain these models. Few water quality models described within the literature have been fully validated or can be routinely used by management agencies (Moore and Gallant, 1991). Many have focused on small drainage areas, are data intensive and generally require extensive parameterisation (Stein et al., 1998). In the Australian context the input data required for these models is available for only a small number of Australian catchments.

Croke and Jakeman (2001) have summarised the current state of prediction in catchment hydrology as follows:

1. Rainfall-runoff models are capable of simulating with good accuracy the effects of climatic conditions where there is a sufficient length of data for calibration and adequate climatic data inputs.

2. Predicting pollutant loads has much higher uncertainty than water yield. The level of uncertainty depends upon the catchment processes, the accuracy of the water yield predictions and the representativeness and accuracy of the water quality observations.

3. Confident prediction of streamflow and pollutant export due to changes in land cover can only be achieved where there are historic observations of the change in yield for the specified land cover change. The magnitude of change can be more confidently predicted where the land use changes are major.

4. Substantial advances in prediction and understanding are possible through integration of models with other knowledge and data.

It can be concluded that the science concerned with pollutant load modelling has not kept pace with catchment management needs (Letcher et al., 2002).

2.5 Model Categorisation and Examples

Each of the models developed for investigating river and stream related water quantity and quality have varying levels of process description, complexity and ease of application. Modelling approaches differ not only in the types of water quality parameters estimated but also by the level of physical processes simulated (Letcher et al., 1999). According to Letcher
et al. (1999), depending on the physical process simulated and the data dependence of the model, water quality models can be conveniently placed into three categories: empirical, conceptual and physics derived.

Another characteristic of model description should also be considered. Spatially distributed models attempt to represent the spatial variability of hydrologic and water quality characteristics and processes across a catchment, whereas lumped models spatially aggregate these processes (Moore and Gallant, 1991). One common method of handling spatial variability in water quality models is to divide a catchment into subcatchments, each of which is treated as internally uniform (Moore and Gallant, 1991). This approach attempts to overcome the general lack of detailed knowledge on contaminant generation at catchment scales and build on knowledge developed as part of plot scale studies or from first order catchments.

More recently, a hybrid category of conceptual semi-distributed models have emerged which retain the features of conceptual models but are applied in a semi-distributed manner. The following sections describe each of the four categories of models - empirical, conceptual physics derived and conceptual semi-distributed. An example of each type of model is also presented in the following sections unless detailed descriptions are provided elsewhere in the thesis.

2.5.1 Empirical Models

Empirical models are generally the simplest of all the model types as they are based primarily on the analysis of observations. The computational and data requirements for such models are usually less than for conceptual and physics derived models, often being capable of being supported by coarse measurements (Merritt et al., in press). A feature of this class of models is their high level of spatial and temporal aggregation and their incorporation of a small number of causal variables (Jakeman et al., 1999). Parameter values in empirical models may be obtained by calibration but are more often transferred from model application at experimental sites. They are particularly useful as a first step in identifying sediment sources and can be used as a base for additional in-depth studies (Hamlett et al., 1992). Empirical models are often criticised for employing unrealistic assumptions about the physics of the catchment system, ignoring the heterogeneity of catchment inputs and characteristics, such as rainfall and soil types, as well as ignoring the inherent non-linear behaviour in the catchment system (Merritt et al., in press). Empirical models are generally not event responsive, ignoring the processes of rainfall-runoff in the catchment being modelled.
Universal Soil Loss Equation

The best know and most widely applied empirical soil erosion model is the Universal Soil Loss Equation (USLE). The USLE is a soil erosion prediction model developed in the 1970's by the US Department of Agriculture, the model is described in Wischmeier and Smith, 1978). The USLE is a model designed to predict long term average soil losses in runoff, from specific field areas in specified cropping and management systems (Wischmeier and Smith, 1978). The model is simple to use and easy to understand (Zhang et al., 1995).

The USLE accounts for rainfall intensity, soil erodibility, topography, ground cover and land use practices in estimating soil erosion. Average soil loss is estimated using:

\[ A = R K L S C P \]

where: \( A \) is the estimated soil loss per unit area; \( R \) is the rainfall and runoff factor; \( K \) is the soil erodibility factor; \( L \) is the slope-length factor; \( S \) is the slope-steepness factor; \( C \) is the cover and management factor; and \( P \) is the support practice factor.

The USLE and associated models are essentially based on the statistical analysis of a large amount of erosion plot data. The empirical data that underpin the USLE were collected predominantly from North American plot scale experiments. Although the USLE is categorised as an empirical model it has some conceptual components. The model relates sediment delivery to slope, slope length, rainfall, soil erosivity and soil erodibility, of which the latter two are predicted both empirically and conceptually.

There are several limitations to the USLE equation, particularly in the Australian context. Gully and streambank erosion and mass movement are not considered in the erosion process, and the deposition of sediment is not modelled (Zhang et al., 1995). The model is not event based and as such does not identify individual erosion events. Unlike in the USA, the use of the USLE in Australia has also been limited by a lack of data for calculating the parameters required for running the model under Australian conditions. Nearing et al. (1994) note that the adaptation of the USLE requires a large investment of resources to collect the data base required to run the model, and to capture the effect of rainfall and other climatic variability.

The data required to adapt the model must be collected for a minimum of 10 years.

Due to the identified limitations of the USLE, several modifications to the basic format have been developed. These include the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), applied as the SOILOSS model in New South Wales (Rosewell, 1993) and other similar variants. These continue to improve components of the model, tending to make it increasingly process based however many of the basic limitations of the USLE remain.

Several models have added runoff estimation and overland flow transport processes to the
USLE to provide improved erosion prediction (Rosewell et al., 2000). Examples include the CREAMS model (Knisel, 1980) and the Agricultural Non-Point Source model (AGNPS) (Young et al., 1989).

2.5.2 Conceptual Models

Conceptual models usually incorporate the underlying transfer mechanisms of sediment and runoff generation within their structure, representing the flow paths within catchments as a series of storages, each requiring some characterisation of its dynamic behaviour (Merritt et al., in press). Conceptual models lump representative processes over the scale at which outputs are simulated. They generally include a description of catchment processes, without including the specific details of process interactions that would require detailed catchment information (Merritt et al., in press). This allows these models to provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amounts of spatially and temporally distributed input data. Parameter values for conceptual models have typically been obtained through calibration against observed data such as streamflow and pollutant concentration measurements. Simpler conceptual models have fewer problems with parameter identifiability than complex conceptual or physics derived models.

IHACRES

An example of the conceptual rainfall-runoff model IHACRES is described in Section 4.3.

2.5.3 Physics Derived Models

Physics derived models are based on the solution of fundamental physical equations describing streamflow and sediment generation within a catchment (Merritt et al., in press). In theory, parameters used in physics derived models are measurable within the catchment and so are known. In practice however, the large number of parameters involved and the heterogeneity of important characteristics within the catchment means that these parameters must often be calibrated against observed data creating additional uncertainty in parameter values (Merritt et al., in press).

Water Erosion Prediction Project Model (WEPP)

The Water Erosion Prediction Project model (WEPP) is a physics derived, distributed erosion prediction model described by Kinnell (1993) and Laflen et al. (1991). The model is applicable to hillslope erosion processes (sheet and rill erosion), as well as simulation of the hydrologic and erosion processes on small catchments. The appropriate scales for application
are tens of metres for hillslope profiles, and up to hundreds of metres for small catchments (Flanagan et al., 1995).

The WEPP model has been applied widely in the US for example Laflen et al. (1991) and elsewhere, including Australia, for example Kinnell (1993). The model simulates the erosion processes of detachment and transport by raindrop impact on interrill areas, detachment, transport and deposition by overland flow in rill channels, and detachment, transport and deposition by concentrated flow in ephemeral channels. The model also includes components which mimic climate, surface and sub-surface hydrology, irrigation, plant growth and residue decomposition to support erosion modelling (Flanagan et al., 1995; Laflen et al., 1991). The model calculates spatial and temporal distributions of soil loss, as well as sediment delivery, sediment particle characteristics and water runoff volumes and soil water balance (Flanagan et al., 1995; Merritt et al., in press).

Like many physics derived models, WEPP is based on a mass balance formulation. Being a physics derived model and containing multiple components, the computational requirements of WEPP are high, with a large number of inputs required (Letcher et al., 1999).

Erosional processes are limited to sheet and rill erosion and erosion occurring in channels where detachment is due to hydraulic shear. Through the erosion components of the model, the three stages of erosion (detachment, transport and deposition) are quantified using the rill-interill concept of describing sediment detachment i.e. the detachment and transport of sediment through raindrop impact and shallow flows. WEPP explicitly models interrill and rill detachment processes.

Letcher et al. (1999), Merritt et al. (in press) and Haan et al. (1993) have criticised the WEPP model for several reasons:

- The large computational requirements of the model limit its applicability to catchments where there is required data and resources needed to support the model;
- Many of the large number of model parameters may need to be calibrated against observed data, creating problems with model identifiability and the physical interpretability of model parameters;
- WEPP does not account for gully or streambank erosion, however in some river systems these sources are significant contributors to the total sediment load;
- The rill-interill concept of erosion used by WEPP may not be applicable in soils that have not been cultivated and do not initially exhibit rill formations;
• The model has only limited ability to be applied to large scale catchments, as simulation involves individual hillslope scale models being 'summed up' to the catchment scale, greatly increasing model complexity and raising issues of error accumulation; and

• The hydrologic and sediment algorithms of WEPP were calibrated on data collected across the United States; thus, despite the physics based nature of the model, it still contains a degree of empiricism and care should be taken when applying the model to new sites.

2.5.4 Lumped Semi-Distributed Models

A compromise between fully distributed methodologies and lumped models are the semi-distributed models that break a catchment down into a group of subcatchments, stream reaches or other biophysical regions over which the model is applied (Merritt et al., in press).

SedNet

The Sediment River Network Model, SedNet is an example of a lumped semi-distributed model. SedNet is used to estimate the transport and deposition of sediment sourced from riverbanks, gullies and hillslope sources through a river network. The SedNet model is fully described at the beginning of Chapter 6. Also discussed in that chapter are limitations of the model, in particular the difficulties encountered for simulating the impacts of management changes across a catchment.

2.6 Model Selection

Each model type serves a purpose and cannot be recommended as appropriate for all situations. According to Merritt et al. (in press) selection of the most appropriate model for any given application will depend on:

• the intended use and objectives of the model user(s);
• the characteristics of the catchment under consideration;
• the scales at which model outputs are required;
• the data requirements of the model including the spatial and temporal variation of model inputs and outputs;
• the capabilities of the model including its accuracy, validity and underlying assumptions;
• the ease of use of the model; and
• computing requirements of the model.
In the Australian context there are inherent problems with using many complex conceptual or physics derived models to estimate pollutant loads as intensive spatial and temporal data on concentrations or loads of environmental pollutants is relatively scarce (Letcher et al., 2002). Because of this constraint, models that can provide useful information on pollutant loads with only sparse data inputs are required. As the scale at which the catchment sub-division is carried out decreases, the data needs of models increase (Moore and Gallant, 1991). Further, the assumptions, that more detailed models are more accurate and that more accurate models are more useful for decision makers, are increasingly under question (Davis and Farley, 1997).

Advances in remote sensing, terrain analysis and GIS can potentially overcome data acquisition problems. However these have generally not been realised (Moore and Gallant, 1991). Despite widespread GIS use, limited application of these tools for modelling of pollutant loadings such as sediment, nitrogen and phosphorous are reported in the literature (Hamlett et al., 1992). Much work remains to overcome fundamental problems related to the lack of theory of sub-grid scale integration, practical constraints on solution methods and problems of dimensionality in parameter calibration (Moore and Gallant, 1991).

### 2.7 Chapter Discussion

The importance of developing appropriate water quality and quantity models has been discussed in this chapter. Models are required for resource managers to improve focusing of land management and riparian remediation activities. The development of appropriate models is a difficult task. Many of the models that have been developed to provide information on pollutant source, propagation and fate are inappropriate for various reasons for providing catchment scale event based prediction of pollutant loads.

A categorisation of models has been presented in the chapter. Included are examples of each type of model and the general strengths and weaknesses of each type. A list of considerations for model selection appropriate for water quality and quantity investigations has also been presented in the chapter.

Simple approaches to calculating the export of catchment pollutants such as using observed pollutant concentration and gauged streamflow data are limited: the effects of climate and land management change cannot be discerned, sampling programs are expensive and their estimation is fixed spatially. At the other end of the spectrum more complex models are beset with onerous data requirements and may require significant computing power. More process based approaches to estimating the source strengths show much promise. SedNet, a model discussed in detail later in the thesis, is an example of such a model.
No catchment export models were found that had all of the following characteristics:

- physically plausible;
- statistically rigorous;
- ability to simulate the effect of land and riparian management;
- ability to include climate variability;
- suitable predictive performance; and
- an ability to be applied broadly and delivered to stakeholders.

Credibility requires that model components are identifiable, plausible and explain system output behaviour satisfactorily (Jakeman and Letcher, 2001).

This research seeks to address the deficiencies identified above through analysis and testing of hydrologic and pollutant export models and improving understanding of the behaviour of these models. Rigorous model examination, testing and comparison of modelling approaches are made.
Chapter 3 Upper Murrumbidgee Catchment

This chapter presents a description of the physical environment of the upper Murrumbidgee River catchment which is used as a case study for this research. The description has a particular focus on characteristics of the physical environment that influence water quality. The chapter includes a description of the social and economic characteristics of the catchment that influence land and water resources management. The chapter also includes a description of the previous hydrologic modelling activities undertaken in the catchment.

The upper Murrumbidgee catchment comprises a complex of climate, topography, lithology, soils, land use and vegetation associations, with each set of factors exerting influence on the water quality of the catchment (Lawrence and Lansdown, 1981). The water quality of the upper Murrumbidgee determines the degree to which water can sustain a range of uses both within the catchment and downstream. In addition, water quality is an important determinant of the health of streams of the catchment which have high intrinsic environmental and ecological value.

The Murrumbidgee Catchment Action Plan (Murrumbidgee Catchment Management Committee, 1998), the catchment review of Starr et al. (1999) and the technical paper of Lawrence and Lansdown (1981) provide important reference material for this chapter.

3.1.1 Study Catchment Selection

The upper Murrumbidgee Catchment was chosen as the study site for this research for the following reasons:

- there is rising pressure on surface water quality resulting from the cumulative effects of current land use and management, the expansion of industries and a growing population within the catchment (Murrumbidgee Catchment Management Committee, 1998);
- the catchment is physically representative of other upland catchments of the Murray-Darling Basin and more broadly of temperate Australia; and
- the author was supported by an Australian Research Council Linkage Grant whose industry partners, the NSW Department of Land and Water Conservation and Environment ACT, have the Murrumbidgee catchment as a common focus.
3.2 Physical Environment

3.2.1 Location

The upper Murrumbidgee Catchment is located in the Southern Tablelands of south-eastern Australia and is part of the headwaters of the Murray-Darling Basin. The catchment lies between latitude 34°41' and 36°33'S and longitudes 148°30' and 149°34'E; see Figure 3-1. The Australian Capital Territory (ACT) is located wholly within the catchment. The remainder of the catchment is located within the state of New South Wales (NSW).

![Figure 3-1 Location of the upper Murrumbidgee Catchment.](image)

The Great Dividing Range forms the eastern and southern boundaries of the catchment, separating the upper Murrumbidgee from the Lake George internal drainage catchment and several coastal river catchments. The catchment is bounded to the north by the Lachlan River catchment and by the Fiery Range to the west. The catchment extends to the north-west as far as Burrinjuck Dam which, for the purpose of this study, defines the downstream endpoint of the catchment; see Figure 3-2. The catchment covers a total area of 13 090 km². Significant tributaries to the Murrumbidgee River within the study area include the Yass, Goodradigbee, Numeralla, Bredbo, Nass, Gudgenby, Paddys, Cotter, Queanbeyan and Molonglo Rivers.
The upper Murrumbidgee catchment is significant in social, economic and environmental terms. Australia’s largest inland city, Canberra, and diverse rural and urban populations are located within the catchment. The catchment includes large areas of national parks and other reserve areas of significant ecological and cultural value. It also forms part of the Snowy-Mountains Hydro Scheme. Approximately 4% of the total streamflow of the upper Murrumbidgee is transferred out of the catchment as part of the Snowy Scheme (Lawrence and Lansdown, 1981).

Figure 3-2 Physiographic features of the upper Murrumbidgee River catchment (source: Baker et al.)
3.2.2 Climate

The upper Murrumbidgee catchment has a temperate climate with mild summers and cool to cold winters. Table 3-1 provides summary statistics on the climate of the catchment.

Table 3-1 Average climate data from centres throughout the upper Murrumbidgee catchment. Data sourced from the Australian Bureau of Meteorology (http://www.bom.gov.au/).

<table>
<thead>
<tr>
<th>Station Number</th>
<th>Location</th>
<th>Elevation (m)</th>
<th>Annual Rain (mm)</th>
<th>Daily Evap (mm)</th>
<th>Daily Min Temp (°C)</th>
<th>Daily Max Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>073007</td>
<td>Burrinjuck</td>
<td>390.0</td>
<td>933.3</td>
<td>3.0</td>
<td>9.0</td>
<td>20.4</td>
</tr>
<tr>
<td>070072</td>
<td>Queanbeyan</td>
<td>580.0</td>
<td>595.5</td>
<td>-</td>
<td>6.4</td>
<td>20.6</td>
</tr>
<tr>
<td>070091</td>
<td>Yass</td>
<td>520.0</td>
<td>649.8</td>
<td>-</td>
<td>7.1</td>
<td>20.7</td>
</tr>
<tr>
<td>070172</td>
<td>Gudgenby</td>
<td>975.4</td>
<td>768.9</td>
<td>-</td>
<td>2.9</td>
<td>17.4</td>
</tr>
<tr>
<td>070023</td>
<td>Cooma</td>
<td>812.0</td>
<td>502.6</td>
<td>-</td>
<td>4.7</td>
<td>19.6</td>
</tr>
<tr>
<td>070014</td>
<td>Canberra</td>
<td>578.4</td>
<td>629.9</td>
<td>4.6</td>
<td>6.4</td>
<td>19.5</td>
</tr>
</tbody>
</table>

Rainfall is generally distributed uniformly throughout the year. For most of the catchment, the annual average is in the range of 500-900 mm (Murrumbidgee Catchment Management Committee, 1998). Rainfall can vary greatly from year to year and topographic characteristics produce much variation in the spatial pattern. For example the rainfall of the Cooma-Bredbo area is affected by a strong rain shadow caused by the Snowy Mountains to the west and coastal ranges to the east. Figure 3-3 shows an estimation of the annual average rainfall for the catchment. These data are sourced from Croke et al. (2001b) (this same data set is used in Chapter 4 for estimation of catchment areal rainfall). Annual average potential evaporation exceeds annual average rainfall across the whole catchment. Catchment water yield is to a large extent controlled by climatic conditions (Murrumbidgee Catchment Management Committee, 1998).

Temperature is most influenced by altitude with higher sites generally cooler (Murrumbidgee Catchment Management Committee, 1998). The phenomenon of cold air drainage (temperature inversion) also exerts an influence on the spatial patterns of temperature. Frosts can occur at any time of the year, with severe frost common in winter. Plant growth is limited in winter by temperature and frost, whereas soil moisture is the limiting factor for plant growth in the warmer months (Murrumbidgee Catchment Management Committee, 1998).
Figure 3-3 Annual average rainfall surface for upper Murrumbidgee catchment. The data used to produce this figure are sourced from Croke et al. (2001b). The unbroken black line represents the catchment boundary.
3.2.3 Geology and Topography

The upper Murrumbidgee covers much of the central and southern part of the Lachlan Fold Belt (Murrumbidgee Catchment Management Committee, 1998). The Lachlan Fold Belt has a complex geologic record. This results in a wide variety of rock types across the catchment. The rocks of the catchment are generally old (Sleeman and Walker, 1979). Various sedimentary, igneous, volcanic sedimentary and metamorphosed geological units, and also areas of colluvium, alluvium and aeolian sands, are found in the catchment. Figure 3-4 shows the geology of the catchment.

The varying rock ages and resistance to weathering, combined with folding and faulting, have contributed to the diverse landform of the upper Murrumbidgee catchment (Murrumbidgee Catchment Management Committee, 1998). The landform is dominated by the major ranges surrounding the catchment and several other significant internal ranges, many of which follow a north-south direction (Murrumbidgee Catchment Management Committee, 1998). Figure 3-5 shows the topography of the catchment.

Geology is an important determinant of soil characteristics as discussed in Section 3.2.4. Parent material is responsible for the structure and textural properties which soils inherit. The mineralogy of parent rocks is particularly important in determining the clay component of a soil (Lawrence and Lansdown, 1981).

3.2.4 Soils

Indirectly, soil is a significant determinant of water quality as the bulk of material that enters streams as a result of weathering and erosion is sourced from the soil (Lawrence and Lansdown, 1981). Water quality is particularly affected by the yields of sediment due to the erosion of soil.

According to Corbett (1969) variation in soil properties can be accounted for by five factors: climate, parent materials, organisms, relief and time. Across the study catchment there is much variability in the factors of soil development (see Sections 3.2.2, 3.2.3 and 3.2.5). Whilst there is much variability, several general trends are evident across the catchment:

- soils of upper slopes are relatively shallow, often with rock outcrop and a low moisture holding capacity (Sleeman and Walker, 1979);
- mid-slope soils are generally of a duplex (texture contrast) nature (Lawrence and Lansdown, 1981); and
- lower slope soil are generally of a duplex nature, often with sodic sub-soil.
Figure 3-4 Geology of the upper Murrumbidgee catchment. The data used to produce this figure are sourced from the Murray-Darling Basin Commission.
Figure 3-5 Digital elevation data representing the topography of the upper Murrumbidgee catchment. The unbroken black line represents the catchment boundary.
Soil erosion occurs when erosive forces, for example raindrop impact and flowing water, exceed the resistance of a soil to erosion. Detachment of soil particles is a function of the erosive forces of water, the susceptibility of the soil to detachment, the presence of material that reduces the magnitude of the eroding forces, and management of the soil (Rosewell et al., 2000). Quite severe gully erosion has occurred in the deep colluvial deposits and also on steep slopes of the catchment that have been cleared and cultivated (Starr et al., 1999). Formation of these gullies can be partially attributed to the readily dispersible subsoil clay found in some areas (Sleeman and Walker, 1979). Significant erosion also occurs on unvegetated soil by the action of rainfall and surface runoff. Surface runoff is enhanced by the generally poor surface structure and hence low subsoil infiltration rates of soil in some areas (Sleeman and Walker, 1979).

3.2.5 Land Use and Vegetation

Land use and vegetation affects the rate of runoff and erosion, and hence the amounts of pollutants - nutrients, sediments and pesticides reaching streams (Wasson et al., 1996).

Early settlers and explorers of the upper Murrumbidgee variously describe the pre-European vegetation of the catchment as treeless plains interspersed with woodland, and the occasional wooded hill (Starr et al., 1999). Prior to European settlement, dry sclerophyll forests and woodland environments dominated the vegetation. Frost hollow vegetation of grasslands and sedges were common in valley bottoms and tall open forests were found on higher and steeper areas.

The present day vegetation of the upper Murrumbidgee is a result of modification through European management. Europeans first settled the upper Murrumbidgee catchment in the early 1820's. This settlement was accompanied by a rapid increase in stock numbers and associated extensive clearing (Starr et al., 1999). Since European settlement land use in the upper Murrumbidgee has always been predominantly pastoral (Starr et al., 1999). The vegetation has been grossly modified as a result.

Presently, the predominant land use of the catchment is for wool and beef production. Forestry, viticulture, cropping and horticulture are also important industries where not restricted by soils, climate or topography (Carter et al., 1994). Important land use related factors that have influenced water quality in the catchment include the rate and extent of forest clearing, riparian management practices, fertiliser application and the occurrence and impacts of feral animals, particularly rabbits.
3.2.6 Stream Condition

Many small streams of the catchment were swampy at the time of European exploration and initial settlement (Starr et al., 1999). Various accounts of early European explorers and settlers note the existence of drainage lines containing ‘chains-of-ponds’ (Eyles, 1977) and ‘swampy meadows’ (Prosser et al., 1999). Even some large streams, such as the Yass River were chains-of-ponds, but most streams of this size had well-defined channels with shrubby steep banks, often with gravelly beds (Starr et al., 1999).

The conditions of streams and associated areas in the upper Murrumbidgee have changed significantly since European settlement. Stream channels have widened and deepened and in many cases these new channel forms have replaced the swampy meadows and chains of ponds that existed previously (Starr et al., 1999). Soil erosion particularly in the form of deeply incised hillside gullies is now evident throughout the catchment (Starr et al., 1999). Stream incision and gullies are the results of the main erosion phase of last century that followed European settlement of the catchment. The expansion of channels rapidly increased sediment yield that has since declined to current levels. But these remain higher than levels prior to European settlement (Wasson et al., 2000). In the main channel of the Murrumbidgee River the bedload fraction of this pulse of sediment remains either trapped in slow moving slugs or is episodically moving downstream (Wasson et al., 2000).

Wild Rivers

Stein et al. (1998) have investigated contemporary stream condition across the upper Murrumbidgee catchment as part of a nationwide study that had the aim of identifying near-pristine or ‘wild’ rivers. In that investigation, wild rivers were defined as streams of natural origin not significantly altered by modern or colonial society. The definition included consideration of biological, hydrologic and geomorphic processes (Stein et al., 1998). In the study indices were developed to indicate the potential of a stream to meet the definition of a wild river. The indices were based on data indicative of human disturbances to streams and their corresponding catchments. The River Disturbance Index (RDI) combines an index of both catchment disturbance and flow regime disturbance to give an overall indication of the extent to which river processes might have been degraded. The RDI has a range from 0 - 1.0, with 0 at the least disturbed end of the continuum (Stein et al., 1998). Table 3-2 shows results for the upper Murrumbidgee River catchment. Individual river reaches have been arbitrarily assigned into deciles. Pristine and near-pristine streams are defined by Stein et al. (1998) as streams with an RDI value less than 0.01.
Table 3-2 RDI results for the upper Murrumbidgee catchment.

<table>
<thead>
<tr>
<th>River Disturbance Index</th>
<th>Total Stream Length (km)</th>
<th>Proportion of Total Stream Length (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 0.7</td>
<td>2</td>
<td>0.02</td>
</tr>
<tr>
<td>0.6 - 0.7</td>
<td>11</td>
<td>0.13</td>
</tr>
<tr>
<td>0.5 - 0.6</td>
<td>166</td>
<td>1.83</td>
</tr>
<tr>
<td>0.4 - 0.5</td>
<td>97</td>
<td>1.06</td>
</tr>
<tr>
<td>0.3 - 0.4</td>
<td>362</td>
<td>3.98</td>
</tr>
<tr>
<td>0.2 - 0.3</td>
<td>741</td>
<td>8.15</td>
</tr>
<tr>
<td>0.1 - 0.2</td>
<td>3755</td>
<td>41.27</td>
</tr>
<tr>
<td>0 - 0.1</td>
<td>3963</td>
<td>43.56</td>
</tr>
</tbody>
</table>

Table 3-2 reveals that a large proportion of the upper Murrumbidgee catchment has relatively low RDI index values. This is due to the influence of large areas of National Park and other nature reserves across the catchment, particularly in the Goodradigbee River system. Summaries of the RDI index when presented in the form of Table 3-2 are sensitive to the influence of first order streams which make up the bulk of the total stream length. When perennial streams are considered in isolation the distribution of the RDI is changed, with only 33% of perennial stream length assessed as having an RDI less than 0.1.

3.2.7 Water Quality

The study of Carter et al. (1994) indicates that pollutant loads from current land use and management within the upper Murrumbidgee catchment is already close to, or in some cases exceeds, ecologically sustainable loads. The results of this have been seen in Burrinjuck Dam where blue-green algal blooms have occurred (Cuddy et al., 1997). Within the catchment, the majority of pollutants are delivered to streams from diffuse sources. For example, the majority of sediment and nutrient loads are sourced from sub-soils in active erosion areas (Starr et al., 1999). Point sources, including sewerage treatment plants are proportionally insignificant sources of stream pollutants (Starr et al., 1999). For nutrients this has been the case since the construction of the Lower Molonglo Water Quality Control Centre in late 1979 (Lawrence and Lansdown, 1981).

Over short time periods the extreme variability of streamflow is the principal determinant of water quality in terms of controlling the level of pollutants transported to streams, the levels
of pollutants in streams, and the prevailing ecological processes within streams of the upper Murrumbidgee (Lawrence and Lansdown, 1981).

Pollutants other than sediments and nutrients are also a concern in the catchment. For example in the Yass River subcatchment, there are problems associated with high salt concentrations as a result of dryland salinity (Dudgeon, 1997b). In the Molonglo River catchment, heavy metal pollution sourced from the Captains Flat mining activities was of particular concern until remediation of the mining site in 1975 (Lawrence and Lansdown, 1981).

Details of water quality monitoring activities in the upper Murrumbidgee catchment are presented in Section 5.2. Previous quantitative water quality modelling studies (i.e. those incorporating modelling components) are discussed in Section 3.3. Numerous studies without an explicit modelling component have investigated the water quality of the study catchment. Examples include:

- Pengelly (1998) has investigated potential strategies to reduce phosphorus inputs to streams of the upper Murrumbidgee catchment. The major conclusion of the study was that the single most effective strategy to minimise phosphorus inputs is to focus on the stabilisation and protection of riparian environments. Pengelly (1998) estimated that the total cost of stabilisation of riparian sediment and nutrient sources in the catchment would total approximately $11M. No rationale for the selection of riparian stabilisation sites is provided in the Pengelly (1998) study.

- Environment ACT (1999) have studied trends in water quality in the ACT. The research of Environment ACT was based on measured water quality data. Only weak conclusions regarding water quality are made in the report due to the constraints of inadequate water quality sampling. From a management perspective the study is of limited utility.

- Dudgeon (1997a) has assessed the impact of the augmentation of the Cooma Sewage Treatment Works on downstream water quality. The particular focus of the study was on nutrient (nitrogen and phosphorus) levels. Several other physical, chemical and biological indicators of water quality were also assessed before and after the augmentation work. The study concluded that the nutrient loading from sewage is small relative to streambank erosion sources.

- Dudgeon (1997b) has compiled water quality, hydrology and fisheries information for water users in the Burrinjuck Dam catchment. The objectives of the study were to report on water quality monitoring activities within the dam and to identify possible sources of pollution in the catchment.
3.2.8 Social and Economic Influences

While physical environmental factors are important influences on the quality and quantity of runoff (Lawrence and Lansdown, 1981) the scale of impacts is determined by land management factors resulting from social and economic influences. These factors largely determine the nature of the vegetative cover, the extent of soil disturbance and hence the loads of pollutants delivered to streams (Lawrence and Lansdown, 1981). Land use has the secondary influence of determining the nature of demands on local water resources.

The upper Murrumbidgee catchment has a total population of approximately 390,000 (Murrumbidgee Catchment Management Committee, 1998). Important settlements within the catchment include the major urban areas of Canberra, Queanbeyan, Cooma and Yass. Consideration of the influence of urban areas on water quality and pollutant loads in some instances, while significant, is outside the scope of this thesis.

The total value of agricultural production from the catchment in the 1994-95 financial year was estimated at $96M (Murrumbidgee Catchment Management Committee, 1998). Wool and beef production are the predominant land uses in the catchment. Viticulture and horticulture are becoming established as important industries where not restricted by climate, topography or soils. Establishment of these new industries has important implications on both water quality and quantity. See, for example, Newham et al. (2001a), Gilmour and Letcher (2002) and Vertessy and Bessard (1999).

The upland catchment is a major water source for irrigated agriculture below Burrinjuck Dam - in the mid and lower Murrumbidgee - and forms an important part of the Snowy Mountains Hydroelectric Scheme.

A broad range of water-related issues influences resource management in the upper Murrumbidgee catchment. A host of policies, ranging from water trading and environmental flows to salt targets and limits on farm dams development have been constructed by various levels of government and non-government organisations for the catchment. A recent example is the development of a Murrumbidgee Catchment Blueprint by the Murrumbidgee Catchment Management Board (2001). The Murrumbidgee Catchment Blueprint is intended to guide the long term management of natural resources in the study catchment. Often incomplete or poor quality hydrologic information is used in the formulation of natural resource management policies (Newham et al., 2000). Equally concerning is that the effect of these policies on stream hydrology is rarely considered. An example of such a policy outcome is the negative hydrologic impacts of broad scale reafforestation policies in the upper Murrumbidgee investigated by Vertessy and Bessard (1999).
3.3 Previous Hydrologic Modelling Studies

A limited number of studies modelling water quantity and quality have been undertaken that focus on the upper Murrumbidgee catchment:

- **Carter et al.** (1994) have applied the AQUALM water quality model in the catchment. Description of the performance of the model is limited. This modelling incorporated a water quantity component. However, no results or assessment of this application have been reported.

- **Vertessy and Bessard** (1999) have modelled the hydrologic effects of an expansion of plantation forestry across the upper and middle Murrumbidgee River catchments. Their work was based on the Holmes-Sinclair relationship (Holmes and Sinclair, 1986) which relates mean annual evapotranspiration (and hence runoff) to mean annual rainfall. Using GIS data, the Holmes-Sinclair relationship was tested in several Murrumbidgee subcatchments. Minor modifications were made to the relationship for application and scenario testing in the catchment. Scenarios were run where the proportion of plantation forestry was varied. Results showed that major runoff reductions may be expected to result from broad scale afforestation of the catchment (Vertessy and Bessard, 1999). No temporal dynamics were included in the study. However, the authors note that runoff frequency distributions would be markedly changed due to broad scale reafforestation.

- **Newham et al.** (2001a) have modelled estimated reductions in streamflow resulting from intensification of agriculture and the conversion of present agricultural areas to forestry extending across the ACT. In a GIS-based study, the research considered the biophysical limits of the landscape to support change to higher water use activities and, using this information, constructed plausible land use change scenarios. The results of their modelling show that maximum development of available land areas would result in a 5.8% reduction in average annual runoff from the ACT given modification of only 3.9% of the total land area (Newham et al., 2001a). The medium change scenario, more realistic when economic and social factors are considered, estimated a total streamflow reduction of 3.5% and accompanying modification of only 2% of the total land area (Newham et al., 2001a). The research investigated streamflow reductions on annual average flow figures and as such did not take account of the importance of investigating impacts across a range of hydrologic conditions.

- The Catchment Management Support System (CMSS) has been applied across the whole of the Murrumbidgee catchment to analyse how land use and land management policies are likely to impact on the nutrient status of the streams of the catchment (Cuddy et al., 1997). CMSS is a simple catchment scale, empirical, nutrient export model described in
Davis and Farley (1997). The inputs to the model are land use, rainfall, slope and soils data along with estimates of nutrient generation rates (obtained from field trials or literature). CMSS calculates the likely nutrient loads (total phosphorus (TP) and total nitrogen (TN)) reaching streams given a particular land use pattern and set of generation rates. Using 1993 conditions, CMSS predicted the generation of an average nutrient delivery of 208 ± 61 ty⁻¹ TP and 2,341 ± 357 ty⁻¹ TN for the upper Murrumbidgee portion of the catchment. There are however considerable uncertainties in the generation rates and hence model estimates. Sewerage treatment plants were estimated to be the source of only 3.6% of TP and 4.4% of TN in the catchment. In the application, numerous scenarios based on proposed management practices were constructed and modelled to enable their evaluation for nutrient reduction. These are reported in Cuddy et al. (1997).

In addition to these studies, models have been developed in several other upper Murrumbidgee subcatchments:

- Schreider et al. (2002) investigated changes in streamflow response resulting from farm dam construction in the Yass River subcatchment. In their study, statistically significant reductions in streamflow and potential streamflow response were detected in the catchment thought to be due to increases in farm dam construction. The study used the rainfall-runoff model IHACRES to reproduce streamflow in the catchment. This allowed the separation of the influence of major climatic factors (precipitation and temperature) from land use.

- As part of the National Land and Water Resources Audit, Peel et al. (unpublished) have modelled streamflow for several upper Murrumbidgee subcatchments. This modelling was limited to estimation of monthly totals using a simplified version of the HYDROLOG model – SIMHYD (Peel et al., unpublished). The SIMHYD model and its performance in the upper Murrumbidgee catchment is described in Section 4.8.

- Letcher et al. (2002) modelled stream pollutant loads at two sites on the main channel of the Murrumbidgee River. This work was part of a larger study that evaluated simple conceptual and empirical pollutant export models for use in data sparse situations. Estimation of pollutant loads in the upper Murrumbidgee was hampered by limited data availability. The actual loads estimated in the study were not reported.

- Schreider et al. (1995) applied the IHACRES rainfall-runoff model in the Queanbeyan River subcatchment of the upper Murrumbidgee. The modelling was undertaken to assess the effects of climate variation on streamflow within the catchment.

- Schreider et al. (2000) modelled changes in the potential damage of flood events caused by increases of CO₂ concentration in the atmosphere. In the study the hydrology of
several catchments were modelled. These included the Queanbeyan River subcatchment of the upper Murrumbidgee.

In general terms modelling of water quality and quantity in the upper Murrumbidgee has been limited. It is on the whole difficult to access the results from previous modelling activities, few studies have focused on providing results at catchment scales, and the temporal or spatial scales of previous modelling applications limit the examination of many management issues.

### 3.4 Chapter Discussion

This chapter has described the physical environment of the catchment, the social and economic issues and previous hydrologic modelling studies to provide context to the proceeding chapters. It can be summarised that the water resources of the upper Murrumbidgee River catchment face rising pressure in terms of quality and quantity. The types of issues and the physical environment of the upper Murrumbidgee catchment are generally similar to those in many other catchments of temperate Australia. For this reason the catchment is useful for examining water quality and quantity models that are suitable for widespread application.

Whilst there are many influences on water quality across the catchment, increases in pollutant load export can generally be attributed to extensive European settlement, land clearing and agricultural land use beginning in the 1820's. Over short time periods the extreme variability of streamflow is the principal determinant of pollutant loads. However over medium to long timeframes the combination of landuse, stream condition, soils, vegetation and climate, mitigated by management, determines water quality in the catchment.

This chapter has described several water quality and quantity modelling studies undertaken within the catchment. Few of these models are currently available to aid managers in decision making.

The following chapter describes the construction of hydrologic models for the upper Murrumbidgee catchment. The models described address water quantity (streamflow) modelling requirements for the study catchment.
Chapter 4 Hydrologic Model Construction

4.1 Introduction

Water is a primary driver of many catchment processes, particularly those involving diffuse pollutant generation and transport (Smith, 1998). According to Grayson et al. (1999) accurate estimation of the catchment water balance is a vital prerequisite for water quality modelling. For these reasons hydrologic data, and particularly streamflow, is a key data set enabling the catchment scale modelling of water quality. Unfortunately the measurement of streamflow is expensive, gauges are susceptible to failure, records are often short in length and data from these gauges are spatially fixed. Observed data represent the hydrologic response of a catchment with only the fixed combination of climate and land management present at the time of measurement. As is the case over much of Australia, investment in streamflow measurement in the upper Murrumbidgee is in decline (Smith, 1998). This is occurring as resource managers within the catchment are increasingly tasked to evaluate complex hydrologic issues.

This chapter describes the construction of a modelling capacity with reasonably high spatial and temporal resolution for predicting streamflow in the upper Murrumbidgee River catchment. The modelling provides a basis to investigate water quality at various scales across the catchment.

The various models described in this chapter serve multiple purposes:

1. The collective models which are packaged within the Integrated Catchment Management System (ICMS) provide a general tool and data archive for hydrologic investigations across the upper Murrumbidgee catchment.

2. Streamflow records reconstructed using the IHACRES rainfall-runoff model provide data required for estimating pollutant loads. A full description of the methods of pollutant load estimation is provided in Chapter 5.

3. The research described in this chapter provides data to improve the hydrologic parameterisation of the SedNet model. A description of the potential incorporation of improved hydrologic components of the SedNet model is provided in Chapter 8.
4.1.1 Hydrologic Model Applications

Rainfall-runoff models are capable of interpolation and extrapolation of the streamflow record commensurate with the availability of input data. The potential capabilities and uses of hydrologic models are many and varied including:

- assessment and estimation of hydrologic impacts of land management and land cover change, for example Post and Jakeman (1998);
- assessment and estimation of hydrologic impacts of climate fluctuations, for example Jakeman et al. (1994) and Schreider et al. (2000);
- water resource allocation, for example Letcher et al. (2000);
- design of monitoring programs, for example Sanders et al. (1983);
- appropriate engineering design and flood impact analysis, for example Jackson et al. (2001) and Schreider et al. (2000);
- ecological investigation, for example Clausen and Biggs (2000); and
- water quality investigation, for example Letcher et al. (2002) and see also Chapter 5.

4.1.2 Chapter Outline

This chapter investigates four broad areas. The first area investigated is the use of rainfall-runoff models for predicting streamflow at gauged sites. The second area is the use of streamflow routing techniques for prediction of streamflow at downstream sites of a river network. The third area investigated is the incorporation of a subset of the models into a network-based streamflow modelling system - the Murrumbidgee ICMS (Integrated Catchment Management System). The final section of the chapter presents a comparison of the performance between the IHACRES and SIMHYD rainfall-runoff models in several case study subcatchments.

The chapter begins with a description of the IHACRES rainfall-runoff model and a rationale for its selection in this research (Sections 4.2 and 4.3). The data sources and pre-processing for the modelling are described in Section 4.4. Detail on the methods of calibration of the IHACRES models in the selected subcatchments is given in Section 4.5.1. The results from the model calibration and subsequent simulation on independent periods are also discussed.

Section 4.6 describes the development of a streamflow routing method and presents results from its application in the catchment. The routing technique selected is a simple hydrologic routing method. Methods for estimating the parameterisation of the routing model from stream reach characteristics are discussed.
The development of the Murrumbidgee ICMS as a general tool for water resource management applications is described in Section 4.7. The Murrumbidgee ICMS incorporates a subset of the rainfall-runoff and streamflow routing models, described earlier in the chapter, into a network system, capable of simulation of daily streamflow at a variety of scales across the upper Murrumbidgee catchment. Results of the application are presented as part of that section.

Discussion of the overall performance of the modelling presented in the chapter and suggestions for further research and improvements are outlined in Section 4.9.

### 4.2 Rainfall-Runoff Model Selection

The IHACRES rainfall-runoff model, described in Section 4.3, was selected for use in this research for the following reasons:

- the model predicts streamflow well, in most instances better than more distributed models (Littlewood and Jakeman, 1994; Ye et al., 1997);
- the model is relatively easy to use, both for calibration and simulation on independent periods;
- the model is parsimoniously structured, facilitating identifiability between catchment attributes and model parameters, and allowing for potential regionalisation of the model to ungauged catchments (for examples see Post, 1996 and Croke, 2002);
- input data requirements are simple, comprising only precipitation, streamflow and temperature or pan evaporation;
- computational demands are low;
- the processes represented in the model are easily understood; and
- guidance from expert users of the model was available in-house.

### 4.3 IHACRES Model Description

The IHACRES model is a conceptual rainfall-runoff model consisting of two modules: a non-linear loss module which transforms observed rainfall to effective rainfall; and a linear module that transfers effective rainfall to streamflow. The latter routing model is defined as a recursive relation at a given time step (daily here), with modelled streamflow calculated as a linear combination of anteecedent streamflow values and effective rainfall. A diagram of the structure of the model is shown in Figure 4-1. Several versions of this model have been developed, for example Jakeman et al. (1990), Schreider et al. (1997) and Evans and Jakeman...
(1997). The model has been tested widely both within Australia and overseas (for examples see Jakeman et al., 1993, Jakeman et al., 1991, Ye et al., 1997 and Schreider et al., 2002).

Figure 4-1 Conceptual diagram of the IHACRES rainfall-runoff model showing components.

The version of the model used in this research is the IHACRES CMD version, as described in Croke and Newham (in prep). The IHACRES CMD version is based on the model described by Evans and Jakeman (1997). This model uses a Catchment Moisture Deficit (CMD) accounting scheme as the basis of the non-linear loss module. It allows calculation of evapotranspiration on the same time step at which rainfall and temperature variables are available. This non-linear loss module allows the effect of antecedent weather conditions, vegetation conditions and evapotranspiration on the current status of the catchment moisture deficit index to be taken into account.

There have been two modifications made to the parameterisation of the non-linear loss module as described by Evans and Jakeman (1997): the equation relating evapotranspiration (ET) to CMD has been altered to give a constant ET (the potential ET) for CMD less than a threshold value; and a simplified one-parameter relationship has been developed to describe drainage. This is in place of the previous two parameter version (Croke and Jakeman, in prep).

The catchment moisture deficit (CMD) at time $t$ involves three parameters $(d, e, f)$ and is calculated in two steps. In the first step the effective rainfall is calculated based on the CMD of the previous timestep. Then, the loss due to evapotranspiration is calculated using the modified catchment moisture deficit ($CMD_f$). The relationship between effective rainfall, rainfall and CMD is based on the assumption that the amount of effective rainfall produced by a small amount of rainfall depends only on the CMD value.
The relevant equations are:

\[ CMDF(t) = \begin{cases} 
CMD(t-1) \exp(- P/d) & \text{if } CMD(t-1) < d \\
 CMD(t-1) - P - d & \text{if } d \leq CMD(t-1) < d + P \\
 CMD(t-1) - P & \text{if } CMD(t-1) \geq d + P 
\end{cases} \]

where \( P \) is rainfall and \( d \) is a calibrated parameter representing the catchment moisture threshold for producing flow.

Effective rainfall \( U \) is

\[ U(t) = P - (CMD(t-1) - CMDF(t)) \]

Then evapotranspiration (\( ET \)) at time \( t \) is calculated as

\[ ET(t) = \begin{cases} 
e(T(t)) \exp \left( 2 \left( 1 - \frac{CMDF(t)}{fd} \right) \right) & \text{for } CMDF(t) > fd \\
e(T(t)) & \text{for } CMDF(t) \leq fd 
\end{cases} \]

where \( T(t) \) is maximum temperature, and \( e \) and \( f \) are calibrated parameters, \( e \) representing the evaporative effect of temperature and \( f \) the factor representing the plant stress threshold as a fraction of the flow threshold.

\[ CMD(t) = CMDF(t) + ET(t) \]

4.3.1 Unit Hydrograph

The linear module used here is based on a method of deriving the unit hydrograph directly from streamflow data (Croke and Newham in prep). This method involves combining several peaks into a mean event unit hydrograph. The parameter values for the linear module of the IHACRES model are then obtained by fitting an exponential like function to the mean event unit hydrograph (see Equation 4-5). The peak of the unit hydrograph is set to one, and then the result is scaled to give a volume of one after the profile has been fitted. Hourly data are most appropriate for determining the mean event unit hydrograph. This is because the recession limb of the hydrograph has a time constant in the order of several hours, particularly in small catchments. Hourly data is needed to capture this response sufficiently.

The mean event unit hydrograph is fitted by a function of the form:
where $a$, $b$ and $c$ are calibrated parameters and $t$ is time.

This function is generally fitted using visual inspection (rather than using a statistical measure of goodness of fit). The fit of the function is checked in various transformations of the parameter space (log-log, log-linear etc).

### 4.3.2 Linear Module

In practice the final parameter values in the IHACRES linear model are estimated by fitting the mean event unit hydrograph to a series of approximating exponential functions. The use of the exponential form is for computation efficiency.

That is,

\[
y(t) = \frac{1}{1 + \left(\frac{t}{a}\right)^b c} \approx \sum_{i=1}^{n} s_i \exp(r_i t)
\]

where

\[
\sum_{i=1}^{n} s_i = 1
\]

To apply the unit hydrograph within IHACRES, these parameters are then adjusted so that the volume of flow under this function is equal to unity. The final parameters used in the model are given by:

\[
\alpha_i = -\exp(r_i) \quad 4-8
\]

\[
\beta_i = \kappa(1 - \alpha_i) s_i / r_i \quad 4-9
\]

where

\[
\kappa = \frac{1}{\sum_{i=1}^{n} s_i / r_i} \quad 4-10
\]

The linear module then calculates modelled flow as
\[ Y(t) = \sum_{i=1}^{n} Y_i(t) \]

where \( t \) (integer) is the sample instant in sampling intervals and

\[ Y_i(t) = -\alpha Y_i(t-1) + \beta U(t) \]

where \( Y(t) \) is modelled flow and \( U(t) \) is the effective rainfall at time \( t \).

The model described above has a total of six parameters. Table 4-1 provides a summary of the parameters of the IHACRES model.

**Table 4-1 Summary of the IHACRES rainfall-runoff model parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>Unit hydrograph time to decrease to half peak flow</td>
</tr>
<tr>
<td>( b )</td>
<td>Unit hydrograph power law recession rate</td>
</tr>
<tr>
<td>( c )</td>
<td>Unit hydrograph curvature term</td>
</tr>
<tr>
<td>( d )</td>
<td>Catchment moisture threshold for producing flow (mm)</td>
</tr>
<tr>
<td>( e )</td>
<td>Temperature to potential evapotranspiration scaling factor</td>
</tr>
<tr>
<td>( f )</td>
<td>Threshold factor for stress as a percentage of ( d )</td>
</tr>
</tbody>
</table>

The calibration of the IHACRES model is discussed in detail later in Section 4.5.1.

### 4.4 Data

The modelling described in this chapter integrates both temporal and spatial data sets. As described in the previous section, the IHACRES rainfall-runoff model estimates streamflow from inputs of rainfall and temperature calibrated against observed streamflow. Streamflow data for catchments within NSW were sourced from the NSW Surface Water Data Archive - Pinneena (NSW Department of Land and Water Conservation, 1998). Environment ACT and ACT Electricity and Water (ACTEW) provided streamflow data for the catchments of the ACT. Daily rainfall and temperature records, along with rainfall station locations, were extracted from the MetAccess database (Australian Bureau of Meteorology, 1998). A description of the methods used to calculate daily areal rainfall is provided in the following section. The method used to estimate temperature inputs to IHACRES is described in Section 4.4.2. A digital elevation model (DEM), together with several spatial data layers, were used as
an input to generate summary statistics of catchment attributes. A description of methods used to calculate catchment attributes is provided in Section 4.4.3.

4.4.1 Rainfall

Rainfall data is the primary input for calibration and simulation of the IHACRES model. It has been shown that the primary factors to influence the performance of rainfall-runoff models are catchment rainfall estimates, stream gauge rating quality, catchment response dynamics and the sampling interval of streamflow (Hansen et al., 1996). Of these factors only catchment rainfall estimates and stream gauge rating quality can to any large extent be improved. Due to the difficulty in attempting to improve rating quality over the short time period of the research, effort was focused on improving subcatchment rainfall estimates.

There are numerous techniques for assessing average catchment rainfall for input to rainfall-runoff models and, according to Hall and Barclay (1975), provided there is a high density of evenly spaced rain gauges there is little to choose between them. Because of the low density of rain gauges across the upper Murrumbidgee, several methods were investigated to extrapolate daily rainfall station measurements (point) to catchment (areal) rainfall estimates.

Thiessen polygon methods make predictions at unsampled locations from the geographically closest data point. This is a commonly used and computationally efficient means of extrapolating point data. However, the assumption that data for any given site can be taken from the nearest rainfall station is not appropriate for gradually varying phenomena such as rainfall, especially where there is a low density of measurement and a topographic dependence of rainfall pattern (Burrough and McDonnell, 1998).

The second method investigated is the correction of point estimates of rainfall using rainfall-elevation regression. Croke et al. (2001b) have demonstrated that estimates of rainfall re-scaled according to rainfall-elevation regression relationships preformed equally as well as those adjusted using interpolated rainfall surfaces (described in the following paragraphs). However the major limitation of this method is that zones with different rainfall-elevation relationships exist across the upper Murrumbidgee. This can be seen in Figure 3-3 where the area in the vicinity of Cooma, with a relatively high elevation, has relatively low mean annual rainfall.

The method adopted in this research was to use a hybrid approach - Thiessen polygons weighted by a rainfall surface. Interpolated annual average rainfall surfaces constructed using thin plate smoothing splines were used to extrapolate observed measurements to a catchment average. A data surface of average annual rainfall was sourced from Croke et al. (2001b). The procedure used to extrapolate rainfall to areal estimates was as follows:
Hydrologic Model Construction

1. nearby rainfall stations are identified for each catchment area;
2. for each cell within a catchment, the closest rainfall station with observed data is identified;
3. observed data at that rainfall station are re-scaled using a rainfall surface as a reference;
4. the estimated rainfall for all cells in the catchment is then averaged; and
5. the procedure repeated for each day where data are required.

In mathematical terms:

\[
P_c = \frac{P_R \times S_C}{S_R}
\]

where \(P_c\) is the re-scaled precipitation at a cell, \(P_R\) is the observed rainfall at the closest rainfall station, \(S_C\) is the value of the interpolated rainfall surface at a cell and \(S_R\) is the value of the interpolated rainfall surface at the closest rainfall station.

Further description of the methods used for estimating catchment areal rainfall from interpolated rainfall surfaces and spatially sparse daily rainfall data can be found in Croke et al. (2001b).

4.4.2 Temperature

Daily temperature data are required as input for calibration and simulation of the IHACRES model. Chapman (2001) has demonstrated that maximum daily temperature is a better predictor of evaporation than mean daily temperature. In the upper Murrumbidgee catchment maximum daily temperature data was available at only 12 stations. A summary of sites and the period of available data is presented in Table 4-2.

The procedure used for estimating catchment maximum daily temperature was as follows:

1. daily maximum temperature records from individual temperature stations were scaled to sea level using an arbitrary temperature-elevation lapse rate of 6.0°C per 1000m change in elevation as suggested by Chow (1964);
2. individually scaled temperature records were then averaged to create a catchment wide estimate of maximum temperature (at sea level) for the whole upper Murrumbidgee catchment;
3. using the catchment wide sea level estimate, daily maximum temperatures were determined for individual catchments by re-scaling (by the lapse rate) to the catchment mean elevation.
The re-scaled estimate was used as input for calibration and simulation of the IHACRES model.

Table 4-2 Sources of temperature data in the upper Murrumbidgee catchment.

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Station Name</th>
<th>Data Period</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>070014</td>
<td>Canberra AMO</td>
<td>1939 -</td>
<td>571</td>
</tr>
<tr>
<td>070015</td>
<td>Canberra Forestry</td>
<td>1957 - 1980</td>
<td>581</td>
</tr>
<tr>
<td>070206</td>
<td>Orroral Valley</td>
<td>1968 - 1985</td>
<td>925</td>
</tr>
<tr>
<td>070241</td>
<td>Honeysuckle Creek</td>
<td>1967 - 1981</td>
<td>1116</td>
</tr>
<tr>
<td>070258</td>
<td>Cooma North</td>
<td>1959 - 1973</td>
<td>860</td>
</tr>
<tr>
<td>070260</td>
<td>Uriarra Forest</td>
<td>1971 - 1973</td>
<td>625</td>
</tr>
<tr>
<td>070282</td>
<td>Canberra City</td>
<td>1974 - 1988</td>
<td>564</td>
</tr>
<tr>
<td>070310</td>
<td>Tidbinhilla Nature Reserve</td>
<td>1982 -</td>
<td>743</td>
</tr>
<tr>
<td>070312</td>
<td>Namadgi National Park</td>
<td>1983 - 1992</td>
<td>950</td>
</tr>
<tr>
<td>070316</td>
<td>Bendora Dam</td>
<td>1984 - 1988</td>
<td>815</td>
</tr>
<tr>
<td>070317</td>
<td>Corin Dam</td>
<td>1986 -</td>
<td>962</td>
</tr>
<tr>
<td>073007</td>
<td>Burrinjuck Dam</td>
<td>1965 -</td>
<td>390</td>
</tr>
</tbody>
</table>

4.4.3 Catchment Attributes

Catchment attributes used for hydrologic modelling purposes should characterise the factors that drive the hydrologic response of a catchment and should be easily extracted from widely available data sources (Kokkonen et al., in press). Many different catchment attributes are described in the literature. Post (1996) makes a comprehensive listing (developed from Post and Jakeman, 1996, 1999) which is used as a basis for selection in this research. Kokkonen et al. (in press) has classified the catchment attributes described by Post (1996) into the following groups:

1. dimensions (e.g. area and perimeter);
2. shape (e.g. elongation);
3. topography (e.g. slope, aspect);
4. stream network structure (e.g. drainage density and stream gradient);
5. geology and soils;
6. vegetation;
7. climate; and
8. land use.

There is redundancy in the Kokkonen et al. classification in the sense that many attributes may be allocated to more than one category. Nonetheless the classification is convenient and informative for this investigation. Catchment attributes from each of the eight categories were considered in this study.

An extensive GIS database was developed for the upper Murrumbidgee catchment to support the modelling undertaken in this research. A set of programs was developed to generate summary statistics describing catchment attributes for each subcatchment of interest. Figure 4-2 shows a simplified diagram of the data inputs and processing of the series of programs. Two main data inputs are required: a DEM and a list of drainage points that define subcatchments of interest. Slope is calculated in-the-flow-direction. This improves the representation of hydrologic processes, particularly for surface water flow, over the default methods (steepest decent) of calculation incorporated within many GIS packages.

Figure 4-2 Simplified data transfer and process framework of the program used to generate catchment attributes.
Table 4-3 lists the attributes calculated for subcatchments of the upper Murrumbidgee and also the Kokkonen et al. (in press) category number.

**Table 4-3 Catchment attributes calculated using the catchment attribute program. The Kokkonen et al. (in press) category is also listed.**

<table>
<thead>
<tr>
<th>Catchment Attribute</th>
<th>Kokkonen et al. (in press) Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>1</td>
</tr>
<tr>
<td>Perimeter of the catchment boundary</td>
<td>1</td>
</tr>
<tr>
<td>Mean, minimum and maximum elevation</td>
<td>3</td>
</tr>
<tr>
<td>Relief - difference between maximum and minimum catchment elevation</td>
<td>3</td>
</tr>
<tr>
<td>Mean, minimum and maximum slope</td>
<td>3</td>
</tr>
<tr>
<td>Channel length (an area threshold is used to identify a stream)</td>
<td>4</td>
</tr>
<tr>
<td>Drainage density - ratio of the channel length to catchment area</td>
<td>1, 4</td>
</tr>
<tr>
<td>Circularity - ratio of total area of the catchment to the area of a circle having the same perimeter as the catchment</td>
<td>2</td>
</tr>
<tr>
<td>Mean soil depth</td>
<td>5</td>
</tr>
<tr>
<td>Mean annual maximum daily surface temperatures</td>
<td>7</td>
</tr>
<tr>
<td>Mean annual potential evapotranspiration</td>
<td>7</td>
</tr>
<tr>
<td>Percentage woody vegetation cover</td>
<td>6, 8</td>
</tr>
<tr>
<td>Mean saturated hydrologic conductivity of the top-soil</td>
<td>5</td>
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</tbody>
</table>

Table 4-4 summarises catchment attributes of Table 4-3 for each of the subcatchments where hydrologic models are constructed and also for subcatchments investigated in subsequent chapters.
<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Name</th>
<th>Area (km²)</th>
<th>Perimeter (km)</th>
<th>Mean Elev (m)</th>
<th>Min Elev (m)</th>
<th>Max Elev (m)</th>
<th>Relief (m)</th>
<th>Mean Slope (°)</th>
<th>Min Slope (°)</th>
<th>Max Slope (°)</th>
<th>Channel Length (km)</th>
<th>Drainage Density (km/km²)</th>
<th>Circularity</th>
<th>Mean Forest Cover (%)</th>
<th>Saturated Hydraulic Conductivity (mm/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>410024</td>
<td>Goodradigbee River at Wee Jasper</td>
<td>992.9</td>
<td>230.5</td>
<td>1016</td>
<td>388</td>
<td>1873</td>
<td>1485</td>
<td>8.83</td>
<td>0.01</td>
<td>45.76</td>
<td>186.7</td>
<td>0.188</td>
<td>0.235</td>
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<td>253</td>
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<tr>
<td>410026</td>
<td>Yass River at Yass</td>
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<td>646</td>
<td>468</td>
<td>919</td>
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<td>22.97</td>
<td>231.5</td>
<td>0.191</td>
<td>0.237</td>
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<tr>
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<td>Murrumbidgee River at Mittagang Crossing</td>
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<td>740</td>
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<td>0.00</td>
<td>55.09</td>
<td>717.1</td>
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<td>0.147</td>
<td>58</td>
<td>164</td>
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<td>410062</td>
<td>Numeralla River at Numeralla School</td>
<td>677.8</td>
<td>149.1</td>
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<td>510</td>
<td>3.77</td>
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<td>0.383</td>
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<td>Rock Flat Creek at Bunyan</td>
<td>237.3</td>
<td>102.1</td>
<td>911</td>
<td>730</td>
<td>1194</td>
<td>464</td>
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<td>Big Badja at Numeralla</td>
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<td>Max Elev (m)</td>
<td>Relief (m)</td>
<td>Mean Slope (°)</td>
<td>Min Slope (°)</td>
<td>Max Slope (°)</td>
<td>Channel Length (km)</td>
<td>Drainage Density (km/km²)</td>
<td>Circularity</td>
<td>Mean Forest Cover (%)</td>
<td>Saturated Hydraulic Conductivity (mm/hour)</td>
</tr>
<tr>
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<td>Strike-a-light Creek at Jerangle Road</td>
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<td>127.3</td>
<td>993</td>
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<td>1869</td>
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<td>0.00</td>
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<td>189.9</td>
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<td>Relief (m)</td>
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<td>Min Slope (°)</td>
<td>Max Slope (°)</td>
<td>Channel Length (km)</td>
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<td>Circularity</td>
<td>Mean Forest Cover (%)</td>
<td>Saturated Hydraulic Conductivity (mm/hour)</td>
</tr>
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<td>410700</td>
<td>Cotter River at Kiosk</td>
<td>472.5</td>
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<td>1910</td>
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<td>410705</td>
<td>Molonglo River at Burbong</td>
<td>505.1</td>
<td>145.8</td>
<td>858</td>
<td>675</td>
<td>1302</td>
<td>627</td>
<td>4.00</td>
<td>0.00</td>
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<td>0.299</td>
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<td>1145</td>
<td>642</td>
<td>1777</td>
<td>1134</td>
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<td>Molonglo River at Coppins Crossing</td>
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<td>317.7</td>
<td>867</td>
<td>503</td>
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<td>0.244</td>
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<td>410759</td>
<td>Molonglo River below Carwoola</td>
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<td>126.4</td>
<td>873</td>
<td>720</td>
<td>1302</td>
<td>582</td>
<td>4.17</td>
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<td>29.36</td>
<td>78.2</td>
<td>0.188</td>
<td>0.327</td>
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<td>1548</td>
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<td>0.14</td>
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<td>0.238</td>
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<td>58</td>
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4.5 Rainfall-Runoff Modelling

This section describes the application of the IHACRES rainfall-runoff model in several subcatchments of the upper Murrumbidgee. A description of the calibration of the individual IHACRES models and subsequent simulation on independent data periods is provided. Results are discussed and a summary of the modelling is presented in the final part of this section.

4.5.1 IHACRES Calibration

The IHACRES model has been calibrated in 17 subcatchments within the study catchment. Sites for streamflow modelling were selected based primarily on the suitability of streamflow data. Several subcatchments were also modelled to provide data for the Murrumbidgee ICMS and the load estimation modelling described in Chapter 5. Summary statistics describing each modelled subcatchment are presented in Table 4.4.

Calibration of the model using observed streamflow data was undertaken over a 1200-day calibration period in the majority of catchments. A longer period (2000 days) was used for calibration of the IHACRES model in a small number of ephemeral subcatchments. In these catchments the longer period was needed to allow the model to be calibrated with a sufficient number of runoff events. Calibration periods were selected to have a continuous observed streamflow record, to incorporate several streamflow events and, for consistency, to be located where possible in the mid-1970's. Where streamflow data was not available in the mid-1970's the beginning of the streamflow record was selected.

Six statistics of model fit were considered in the calibration and evaluation of the individual IHACRES models ($R^2$, bias, $R^2_{\text{hyp}}$, $R^2_{\text{inv}}$, X1 and U1):

\[ R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_O - Q_M)^2}{\sum_{i=1}^{n}(Q_O - \overline{Q}_O)^2} \]

where $n$ is the number of samples, $Q_O$ is observed streamflow, $\overline{Q}_O$ its mean and $Q_M$ is modelled streamflow.
The coefficient of efficiency describes the degree of agreement between observed and modelled values of a data series. The closer the $R^2$ value is to 1 the better the model reproduces the variance characteristics of the observed data.

Bias is a measure of the average difference between observed and modelled values of a data series. In the following series of results, bias is expressed in mmy$^{-1}$. Bias ($b$) is given by:

$$b = \frac{1}{n} \sum_{i=1}^{n} (Q_O - Q_M)$$  \hspace{1cm} 4-15

Other statistics considered are $R^2_{\text{sqrt}}$ and $R^2_{\text{inv}}$, these are given by:

$$R^2_{f(s)} = 1 - \frac{\sum_{i=1}^{n} (f(Q_o) - f(Q_M))^2}{\sum_{i=1}^{n} (f(Q_o) - f(Q_o))^2}$$  \hspace{1cm} 4-16

where for $R^2_{\text{sqrt}}$:

$$f(Q) = \sqrt{Q}$$  \hspace{1cm} 4-17

and for $R^2_{\text{inv}}$:

$$f(Q) = \frac{1}{Q_{10} + Q}$$  \hspace{1cm} 4-18

where $Q_{10}$ is the value which 90% of flows exceed (considering only days with flow > 0).

Like $R^2$, both $R^2_{\text{sqrt}}$ and $R^2_{\text{inv}}$ measure the degree of association between individual observed and modelled values. $R^2_{\text{inv}}$ is more highly weighted towards low streamflow conditions. More often than not negative values are obtained for the $R^2_{\text{inv}}$ statistic due to the difficulties in reproducing low flows which may contain large relative measurement errors. By equilibrating the differences between high and low flow values with a square root transformation, $R^2_{\text{sqrt}}$ considers the association weighted more highly towards high flow but not as highly as for $R^2$.

All models were constrained to have a bias equal to zero. $R^2$ and $R^2_{\text{sqrt}}$ were the primary statistics considered in selection of the model parameters. Where all else was equal the $R^2_{\text{inv}}$
statistics are compared. For general applications, the $R_{inv}^2$ measure of model performance (weighted toward low flows) is generally of less importance than $R_{sqr}^2$ and $R^2$. Two other statistics considered in the calibration of IHACRES are X1 and U1. X1 is the cross correlation coefficient of modelled flow and error with a one-day lag. U1 is the cross correlation coefficient of effective rainfall and error, also with a one-day lag. Values of these statistics take the range from -1 (perfect anticorrelation), through 0 (no correlation) to 1 (perfect correlation). High absolute values indicated a problem with data inputs to the model. Good model fits have correlations close to 0. The XI and U1 statistics are used to eliminate model fits with systematic bias in the residuals. In practice, large values of these statistics are used to eliminate model parameter estimates. The statistics are considered when all other measures of model performance - $R^2$, $R_{sqr}^2$ and $R_{inv}^2$ are very similar.

All statistics were calculated daily for calibration of the models.

### 4.5.2 Calibration Results

Section 4.3.2 described that the non-linear module parameters are selected by fitting a power function to a mean event unit hydrograph as per Croke and Newham (in prep). For the modelling described here the fitted unit hydrograph was derived from a composite of hydrograph peaks constructed from observed hourly streamflow data. Table 4-5 shows the fitted parameters of the mean event unit hydrograph for all catchments with sufficient hourly data.

Figures 4-3 and 4-4 show the fitted event unit hydrographs for the subcatchments of the Yass and Gudgenby Rivers respectively. It can be seen in each of the figures that the hydrograph shape is well fitted by a function of the form of Equation 4–5. Some deviation is seen between the observed and fitted recession curves towards the tail of each of the fits (particularly evident in Figure 4-4). This is due to the influence of other hydrograph peaks in the construction of the mean event hydrograph. This deviation is ignored in fitting each of the curves.

The IHACRES rainfall-runoff model was successfully calibrated (e.g. $R^2 > 0.6$) in 14 of 17 modelled subcatchments. Table 4-6 provides a summary of the calibration results. In Table 4-6 the calibration start date, calibration period, IHACRES modelled parameters, timestep delay and the four statistics of model fit ($R^2$, bias, $R_{sqr}^2$ and $R_{inv}^2$) are tabulated.
Table 4-5 Parameters of the fitted mean event unit hydrograph for gauges of the upper Murrumbidgee.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>410024</td>
<td>0.24</td>
<td>0.76</td>
<td>0.4</td>
</tr>
<tr>
<td>410062</td>
<td>0.56</td>
<td>1.725</td>
<td>0.85</td>
</tr>
<tr>
<td>410063</td>
<td>0.18</td>
<td>1.85</td>
<td>1.05</td>
</tr>
<tr>
<td>410067</td>
<td>1.125</td>
<td>1.175</td>
<td>0.48</td>
</tr>
<tr>
<td>410075</td>
<td>0.10</td>
<td>1.35</td>
<td>0.5</td>
</tr>
<tr>
<td>410076</td>
<td>0.13</td>
<td>1.205</td>
<td>0.75</td>
</tr>
<tr>
<td>410088</td>
<td>0.23</td>
<td>0.715</td>
<td>0.5</td>
</tr>
<tr>
<td>410090</td>
<td>0.13</td>
<td>1.9</td>
<td>1.0</td>
</tr>
<tr>
<td>410105</td>
<td>0.3</td>
<td>1.30</td>
<td>1.0</td>
</tr>
<tr>
<td>410107</td>
<td>0.20</td>
<td>1.35</td>
<td>0.75</td>
</tr>
<tr>
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<td>0.21</td>
<td>1.45</td>
<td>0.75</td>
</tr>
<tr>
<td>410711</td>
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<td>0.55</td>
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<tr>
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<td>0.94</td>
<td>0.65</td>
</tr>
<tr>
<td>410731</td>
<td>0.27</td>
<td>1.05</td>
<td>0.67</td>
</tr>
<tr>
<td>410759</td>
<td>0.2</td>
<td>1.62</td>
<td>0.67</td>
</tr>
<tr>
<td>410774</td>
<td>0.08</td>
<td>1.25</td>
<td>0.65</td>
</tr>
<tr>
<td>410790</td>
<td>0.11</td>
<td>1.25</td>
<td>0.685</td>
</tr>
</tbody>
</table>

Figures 4-5 and 4-6 show observed and modelled streamflow duration curves over the calibration period for subcatchments of the Kybeyan River and Paddy's River respectively. These two figures show that the IHACRES models adequately reproduce the distribution of flow through the calibration period. There are some deviations, particularly at lower flows, which partly reflects the higher weighting given to peak flows in the selection of the model parameters (i.e. selection of model parameters primarily based on $R^2$ and $R^2_{adj}$) and the effect of optimising the model to constrain bias. In Figure 4-6 the effect of optimising the model to constrain bias can be seen where the lower flow conditions are systematically overestimated to compensate for underestimation of some peak flows.
Figure 4-3 Observed and fitted mean event unit hydrograph for Yass River at Yass subcatchment (gauge number 410090).

Figure 4-4 Observed and fitted mean event unit hydrograph for Gudgenby River at Tennent subcatchment (gauge number 410731).
Table 4-6 IHACRES model parameters and calibration performance measures.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Calibration Start Date</th>
<th>Calibration Period</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>Time Delay</th>
<th>$R^2$</th>
<th>Bias</th>
<th>$R^2_{adj}$</th>
<th>$R^2_{inv}$</th>
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<tr>
<td>410063</td>
<td>11-Sep-76</td>
<td>1200</td>
<td>0.18</td>
<td>1.85</td>
<td>1.05</td>
<td>220</td>
<td>180</td>
<td>79</td>
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<td>0.682</td>
<td>1.4</td>
<td>0.564</td>
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<td>0.05</td>
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<td>0.48</td>
<td>25</td>
<td>180</td>
<td>41</td>
<td>1</td>
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<td>0.549</td>
<td>0.130</td>
</tr>
<tr>
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<td>24-Feb-76</td>
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<td>0.10</td>
<td>1.35</td>
<td>0.50</td>
<td>128</td>
<td>180</td>
<td>64</td>
<td>1</td>
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<td>1.2</td>
<td>0.718</td>
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</tr>
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<td>1.21</td>
<td>0.75</td>
<td>64</td>
<td>180</td>
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<td>0.2</td>
<td>0.583</td>
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</tr>
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<td>1.00</td>
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<td>0.462</td>
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<tr>
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<td>0.72</td>
<td>0.50</td>
<td>18</td>
<td>180</td>
<td>318</td>
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<td>1.00</td>
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<td>180</td>
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<td>1.00</td>
<td>10</td>
<td>180</td>
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<td>180</td>
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<td>1.00</td>
<td>300</td>
<td>180</td>
<td>89</td>
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<td>0.524</td>
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<td>180</td>
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<td>180</td>
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<td>410</td>
<td>180</td>
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<td>80</td>
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<td>0.723</td>
<td>1.2</td>
<td>0.595</td>
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<td>1.25</td>
<td>0.65</td>
<td>100</td>
<td>180</td>
<td>99</td>
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<td>0.7</td>
<td>0.645</td>
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<td>1.25</td>
<td>0.69</td>
<td>206</td>
<td>180</td>
<td>80</td>
<td>0</td>
<td>0.607</td>
<td>1.1</td>
<td>0.559</td>
<td>-0.372</td>
</tr>
</tbody>
</table>
Figure 4-5 Observed and modelled flow duration curves for model calibration period at gauge number 410075. Calibration $R^2 = 0.635$.

Figure 4-6 Observed and modelled flow duration curves for model calibration period at gauge number 410713. Calibration $R^2 = 0.684$. 
Figures 4-7 to 4-10 show example plots comparing observed and modelled streamflow at a variety of sites (410063, 410077, 410088 and 410790) across the study catchment for the calibration period. It can be seen in each of the plots that streamflow is generally reproduced well. Some peak flows are underestimated. However the shape of the recession limb of the hydrograph is generally well reproduced. The IHACRES models have been calibrated to have close to zero bias. Thus errors shown in each of the figures have the same sum above and below the zero error line. Error over the calibration period can principally be attributed to error in catchment areal rainfall. This is discussed further in later sections.

Figure 4-7 IHACRES calibration result for site 410063. Modelled, observed and residual streamflow is plotted. Calibration $R^2 = 0.682$. 
Figure 4-8 IHACRES calibration result for site 410077. Modelled, observed and residual streamflow is plotted. Calibration $R^2 = 0.863$.

Figure 4-9 IHACRES calibration results for site 410088. Modelled, observed and residual streamflow is plotted. Calibration $R^2 = 0.614$.
4.5.3 IHACRES Simulation

Each of the calibrated IHACRES models has been used to simulate streamflow for a period independent of the calibration period. The simulated streamflow has been compared against the corresponding observed data in the same period. The simulation periods were selected to follow immediately after the calibration period and continue to near the end of the period of observed data. Periods of missing observed streamflow data were avoided for the comparison, resulting in some short simulation periods. Simulation results (model performance measures) for each site are shown in Table 4-7.

Figure 4-10 IHACRES calibration results for site 410790. Modelled, observed and residual streamflow is plotted. Calibration $R^2 = 0.607$. 

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Some decrease in the performance of the model is expected when simulating on periods independent of the calibration data. The IHACRES models performed adequately in simulating streamflow in the majority of catchments. Streamflow was successfully simulated \(( R^2 > 0.5 \) ) in 11 of 17 catchments. Two other catchments, 410090 and 410711, with \( R^2 = 0.459 \) and \( R^2 = 0.448 \), were also close to this level. At three sites, 410067, 410076 and 410711, model performance \(( R^2 \) ) improved relative to the calibration period. In all catchments the magnitude of the bias increased relative to that of the calibration period. Figures 4-11, 4-12 and 4-13 show flow duration curves for available observed and modelled streamflow. These three flow duration curves show the range of behaviour for all catchments simulated.
Figure 4-11 Observed and modelled flow duration curves for model simulation period at gauge number 410067. Simulation $R^2 = 0.615$.

Figure 4-12 Observed and modelled flow duration curves for model simulation period at gauge number 410107. Simulation $R^2 = 0.556$.
58

4.5.4 IHACRES Rainfall-Runoff Modelling Discussion

The IHACRES rainfall-runoff model generally provided adequate simulation of streamflow for catchment management applications. Calibration of the model in 14 of the 17 subcatchments was successful. Simulation on independent data outside of the calibration period was successful in 11 of those subcatchments ($R^2 > 0.5$).

Difficulties in modelling streamflow can primarily be apportioned to difficulties in estimating catchment areal rainfall. Because of the low density of rain gauges in the catchment it is unlikely that all rainfall events are adequately reproduced. According to Hall and Barclay (1975), areal rainfall estimates based on point measurements should only be regarded as an index of the true mean rainfall, and errors between 10 and 20% can be regarded as normal. This is the major limitation to rainfall-runoff modelling.

As discussed in Section 4.4.1, attempts were made to improve catchment areal rainfall estimation. A hybrid approach using Theissen polygon methods and weighting of individual
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rainfall gauges by an annual average rainfall surface was used. The method proved successful. However, the potential exists to introduce inconsistent catchment areal estimates because rainfall data is available at individual rain gauge locations over different intervals of the modelling period. The result is that different rainfall gauges exert varying influence on the catchment areal rainfall estimate. Problems occur where the level of influence of individual rainfall gauges changes between the calibration and simulation period. The obvious solution is to attempt to increase the density of rainfall measurements. A potentially more useful approach would be to select individual rainfall stations with an appropriate length of record and measurement quality prior to calculating catchment areal rainfall. Thus the benefit of reducing the number of rainfall gauges to reduce bias is at the expense of the estimation of the distribution of flows and measures of model performance of the calibration fits.

The availability of rainfall and temperature data determines the limits to which the results can be further extended. In the upper Murrumbidgee catchment, historic rainfall records generally do not extend prior to the beginning of the 20th Century.

4.6 Streamflow Routing

Streamflow routing is the procedure whereby the time and magnitude of streamflow at a point on a stream is determined from data at one or more points upstream (Chow, 1964). A capacity to estimate downstream flow from upstream data (and vice versa) is essential in many catchment modelling applications. Whilst there is a need for routing techniques for general catchment modelling applications, many of the techniques that have been developed have focused on flood routing.

In general, routing techniques may be classified into two categories: hydraulic routing and hydrologic routing. Hydraulic routing techniques are based on the solution of the partial differential equations of unsteady open channel flow, often referred to as the Saint Venant Equations (United States Army Corps of Engineers, 1994b). These equations describe the conservation of mass and momentum in gradually varied open channel flow. The equations are difficult to solve, even numerically, and it is often necessary to neglect certain terms and make assumptions in their use (Lettenmaier, 1993).

Hydrologic routing, on the other hand, employs an analytical or empirical relationship between storage within the reach and streamflow at the outlet. Hydrologic routing models offer the advantages of simplicity, ease of use and computational efficiency (United States Army Corps of Engineers, 1994b). The accuracy of hydrologic methods in calculating streamflow hydrographs is normally comparable with hydraulic methods. Lettenmaier (1993) has identified two drawbacks of hydrologic routing techniques. The first is that forecasts can
only be made at sites when parameters have been calibrated from observed streamflow. The second identified drawback is that hydrologic routing methods are not applicable to catchments that respond rapidly relative to the timestep of the modelling.

4.6.1 Model Description

A technique was required in this research for routing flow from upstream to downstream gauge sites. A hydrologic routing method based on a lag-route model with a non-integer delay was selected for ease of use, computational efficiency, modest data requirements, and the potential for identifiability with reach characteristics. The model described below is intended for general application across a range of tasks, not specifically for flood routing. It is representative of a class of models similar to the Muskingum method (Chow, 1964) and has the following characteristics:

- ease of use and programming;
- minimal data requirements;
- small number of parameters; and
- potential for parameter identifiability from physical characteristics.

Using the lag-route model, flow is calculated as a function of time at a particular location according to the following equation:

\[ Q_{n+1}^{t+1} = C_1 Q_{n+1}^t + C_2 Q_n^t + C_3 Q_{n+1}^t \]

where \( Q \) is streamflow; \( n \) indicates the node (\( n + 1 \) is the downstream node); \( t \) is the timestep and \( C_1, C_2 \) and \( C_3 \) are parameters of the routing model. The model can also be written as:

\[ Q_{n+1}^{t+1} = \alpha Q_{n+1}^t + (1 - \alpha)\left( \gamma Q_n^t + (1 - \gamma) Q_{n+1}^t \right) \]

where \( \alpha \) can be physically related to the temporal broadening of the hydrograph peak and \( \gamma \) can be associated with the delay between \( Q_n^t \) and \( Q_{n+1}^t \).

For short reach lengths where \( \gamma \cong 1 \),

\[ Q_{n+1}^{t+1} = \alpha Q_{n+1}^t + (1 - \alpha) Q_n^t \]

and \( \alpha \) and \( \gamma \) are related to \( C_1, C_2 \) and \( C_3 \) as follows:

\[ \alpha = C_3 \]
The lag-route model described above is in many respects similar to the Muskingum-Cunge routing model (Haan et al., 1993). The main difference is that the parameters of the lag-route model take positive values only.

4.6.2 Routing Parameter Selection

A grid search program has been used to select a set of parameters for use in the routing model. The parameter estimates of the model are constrained to be physically realistic and conserve total streamflow i.e. parameters take only positive values and \( C_1 = 1 - C_2 - C_3 \).

Upstream to downstream flow is compared after the scaling of flow based on the ratio of total upstream to total downstream flow for the calibration period. Observed streamflow data were used to calibrate the model so that changes to upstream rainfall-runoff models can be readily incorporated within the system. The scaling is made to account for losses and gains across the reach. Following scaling, measures of model performance are calculated for each combination of an exhaustive search of parameters. A resolution of 0.01 is used in the search. Parameters are selected on the basis of several statistics of model performance, primarily \( R^2 \), but also \( R_{agr}^2 \) and \( R_{inv}^2 \). These statistics of model performance have previously been described as part of the IHACRES calibration in Section 4.5.1.

Parameters can be selected directly from the output file produced by the grid search program or alternatively contour plots representing the value of the objective functions across the parameter space can be used to select the routing parameters. A description of this method of streamflow routing can also be found in Croke and Newham (in prep).

4.6.3 Streamflow Routing Results

Fixed parameter routing was generally successful in estimating streamflow at downstream nodes of the Murrumbidgee River system. The routing model results are shown in Table 4-8. The table presents \( R^2 \), \( R_{agr}^2 \) and \( R_{inv}^2 \) measures of model performance. Additionally, results are displayed in Figures 4-16 to 4-21 where measures of model performance are shown as contour plots across the range of routing parameter values for various upper Murrumbidgee reaches.
Table 4-8 Routing model results for upper Murrumbidgee River reaches. Routing parameters, reach lengths and measures of model fit are presented for each reach.

<table>
<thead>
<tr>
<th>Upstream Gauge</th>
<th>Downstream Gauge</th>
<th>Proportion of Downstream Flow</th>
<th>Reach Length (km)</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( R^2 )</th>
<th>( R^2_{\text{hyp}} )</th>
<th>( R^2_{\text{inv}} )</th>
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<td>0.00</td>
<td>0.31</td>
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</tr>
<tr>
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<td>0.591</td>
<td>24.1</td>
<td>1.00</td>
<td>0.00</td>
<td>0.64</td>
<td>0.78</td>
<td>0.84</td>
</tr>
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<td>410101</td>
<td>0.022</td>
<td>34.3</td>
<td>0.39</td>
<td>0.00</td>
<td>0.55</td>
<td>0.74</td>
<td>0.81</td>
</tr>
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<td>410101</td>
<td>0.035</td>
<td>86.0</td>
<td>0.54</td>
<td>0.02</td>
<td>0.70</td>
<td>0.73</td>
<td>0.71</td>
</tr>
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<td>99.0</td>
<td>0.00</td>
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<td>0.75</td>
<td>0.70</td>
<td>0.58</td>
</tr>
<tr>
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<td>410101</td>
<td>0.587</td>
<td>70.4</td>
<td>0.80</td>
<td>0.20</td>
<td>0.94</td>
<td>0.94</td>
<td>0.93</td>
</tr>
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<td>18.1</td>
<td>0.00</td>
<td>0.63</td>
<td>0.55</td>
<td>0.74</td>
<td>0.83</td>
</tr>
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<td>0.85</td>
<td>0.90</td>
<td>0.93</td>
</tr>
<tr>
<td>410713</td>
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<td>0.044</td>
<td>8.5</td>
<td>0.00</td>
<td>0.68</td>
<td>0.58</td>
<td>0.62</td>
<td>0.61</td>
</tr>
<tr>
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<td>410035</td>
<td>0.103</td>
<td>1.6</td>
<td>1.00</td>
<td>0.00</td>
<td>0.39</td>
<td>0.37</td>
<td>0.26</td>
</tr>
<tr>
<td>410090</td>
<td>410026</td>
<td>0.295</td>
<td>68.5</td>
<td>0.31</td>
<td>0.66</td>
<td>0.79</td>
<td>0.78</td>
<td>0.34</td>
</tr>
<tr>
<td>410088</td>
<td>410024</td>
<td>0.545</td>
<td>35.2</td>
<td>0.99</td>
<td>0.01</td>
<td>0.94</td>
<td>0.96</td>
<td>0.96</td>
</tr>
</tbody>
</table>
\*410160       | 410026           | 0.008                       | 50.0             | 0.29 | 0.47 | 0.75 | 0.72           | 0.61           |
\*410851       | 410026           | 0.050                       | 80.8             | 0.19 | 0.61 | 0.84 | 0.76           | 0.39           |
\*410050       | 410035           | 0.538                       | 89.5             | 0.64 | 0.00 | 0.89 | 0.88           | 0.89           |
\*410033       | 410101           | 0.324                       | 94.5             | 1.00 | 0.00 | 0.63 | 0.75           | 0.80           |

* These reaches are not explicitly modelled in the stream network but are included to make a more robust estimation of routing parameters based on reach characteristics (as described in the following section).
4.6.4 Estimation of Routing Parameters Based on Reach Characteristics

The selection of routing parameters using the methods described in the previous section are appropriate when routing from a single upstream catchment that is hydrological representative of the downstream node. In practice such examples are rare and difficulties arise using this method where streamflow from multiple upstream inputs, from ungauged sites or from sites without overlapping periods of data are to be routed. This was one of the major limitations identified by Lettenmaier (1993). The following techniques to estimate routing parameters based on reach characteristics were developed to address this deficiency in the case study catchment.

As described in Section 4.6.1 for the lag-route model, the selected routing parameters represent attributes of the change in streamflow characteristics along a reach. The $\alpha$ parameter can be related physically to the temporal broadening and attenuation of the hydrograph peak along the stream reach, whereas the $\gamma$ can be associated with the delay in the flow peak between upstream and downstream reaches. In this study the $\alpha$ and $\gamma$ parameters were related to the physical characteristics of the stream reach. Relationships between mean channel slope, stream length, stream roughness and others were investigated. It was found however that the length of the stream was the main determinant of the routing parameters.

In the analysis only data from reaches with an $R^2$ greater that 0.7 are used. The result from one other reach is also excluded from the analysis: the parameter $\gamma$ was estimated to equal 1 between gauges 410050 and 410035, representing a zero delay over a 89.5 km reach. Figures 4-14 and 4-15 show the results of $\alpha$ and $\gamma$ plotted against stream length respectively.

From this data a linear regression was fitted and routing parameters based on this relationship were used. Regressions were constrained to have an intercept at 0 and 1 for $\alpha$ and $\gamma$, respectively. Table 4-9 shows the linear regression parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slope</th>
<th>Intercept</th>
<th>$R^2$</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.003</td>
<td>0</td>
<td>0.20</td>
<td>8</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-0.0084</td>
<td>1</td>
<td>0.68</td>
<td>8</td>
</tr>
</tbody>
</table>

$\alpha$ and $\gamma$ parameters and hence $C_1$, $C_2$ and $C_3$ values were calculated using the regression relationship above. Table 4-10 shows the modelled routing parameters and a comparison of
$R^2$ values between the optimum and modelled parameter values. The observed parameter values already shown in Table 4-8 are presented to allow comparison with the fitted routing parameters.

Figure 4-14 Routing parameter $\alpha$ plotted against stream length for sites in the upper Murrumbidgee catchment. The linear regression line fitted to this data is also shown.

Figure 4-15 Routing parameter $\gamma$ plotted against stream length for sites in the upper Murrumbidgee catchment. The linear regression line fitted to this data is also shown.
Table 4-10 Observed and modelled routing parameters and comparison of $R^2$ values.

<table>
<thead>
<tr>
<th>Upstream Gauge</th>
<th>Downstream Gauge</th>
<th>Observed</th>
<th>Fitted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$C_1$</td>
<td>$C_2$</td>
</tr>
<tr>
<td>410105</td>
<td>410100</td>
<td>0.96</td>
<td>0.04</td>
</tr>
<tr>
<td>410075</td>
<td>410062</td>
<td>0.54</td>
<td>0.02</td>
</tr>
<tr>
<td>410100</td>
<td>410062</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>410067</td>
<td>410050</td>
<td>0.45</td>
<td>0.12</td>
</tr>
<tr>
<td>410062</td>
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<td>0</td>
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<td>0</td>
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<td>410081</td>
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<td>0</td>
</tr>
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<td>410050</td>
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</tr>
<tr>
<td>410141</td>
<td>410101</td>
<td>0.39</td>
<td>0</td>
</tr>
<tr>
<td>410076</td>
<td>410101</td>
<td>0.54</td>
<td>0.02</td>
</tr>
<tr>
<td>410077</td>
<td>410101</td>
<td>0</td>
<td>0.45</td>
</tr>
<tr>
<td>410050</td>
<td>410101</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>410731</td>
<td>410101</td>
<td>0</td>
<td>0.63</td>
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<td>0</td>
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<td>410035</td>
<td>0</td>
<td>0.68</td>
</tr>
<tr>
<td>410700</td>
<td>410035</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>410090</td>
<td>410026</td>
<td>0.31</td>
<td>0.66</td>
</tr>
<tr>
<td>410088</td>
<td>410024</td>
<td>0.99</td>
<td>0.01</td>
</tr>
<tr>
<td>*410160</td>
<td>410026</td>
<td>0.29</td>
<td>0.47</td>
</tr>
<tr>
<td>*410851</td>
<td>410026</td>
<td>0.19</td>
<td>0.61</td>
</tr>
<tr>
<td>*410050</td>
<td>410035</td>
<td>0.64</td>
<td>0</td>
</tr>
<tr>
<td>*410033</td>
<td>410101</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

† Reaches used to estimate routing parameters based on reach length. * Reaches not explicitly modelled in the stream network.
The decline in $R^2$ values between routing using modelled parameters and those selected directly from grid search program is generally small. This is because the routing parameters are relatively insensitive to change near their optimum value, as can be seen in the following plots of model performance across the range of parameter values. In the following plots the fitted routing parameters are shown in red. The number following the point is the measure of model performance for the fitted set of routing parameters.

![Contour Plot](image)

**Figure 4-16 A contour plot of the $R^2$ surface in routing parameter space. The example is for a 68.5 km reach of the Yass River (410090 - 410026).**

In Figure 4-16 above, because of the broad peak of the $R^2$ surface close to the optimum, the reduction in model performance resulting from the use of a fitted set of routing parameters is small - decrease in $R^2$ is from 0.79 to 0.77. The following figures show similar features for the $R^2_{agr}$ and $R^2_{inv}$ measures of model performance for the Yass River reach. Figures 4-19, 4-20 and 4-21 show $R^2$ surface plots for other example study catchment reaches.

The decline in the performance between the fitted and optimised routing models is greatest in models with low $R^2$ values initially. This indicates problems primarily associated with routing between reaches with different hydrologic characteristics, but may also be due to timing errors and/or streamflow measurement errors.
Figure 4-17 A contour plot of the $R_{sur}^2$ surface in routing parameter space. The example is for a 68.5 km reach of the Yass River (410090 - 410026).

Figure 4-18 A contour plot of the $R_{inv}^2$ surface in routing parameter space. The example is for a 68.5 km reach of the Yass River (410090 - 410026).
It can be seen in Figures 4-16 to 4-18 that the routing parameters for each objective function may have optimum values at a number of different parameter combinations. This dichotomy can be explained by the travel time of a flood wave being a function of streamflow (Ponce and Yevjevich, 1978) and that each objective function is weighted towards a different flow level. For general applications, the $R_{inv}^2$ measure of model performance (weighted toward low flows) is generally of less importance than $R_{sqy}^2$ and $R^2$.

The $R^2$ plots across the parameter space for three other reaches of the upper Murrumbidgee are shown in the following figures.

Figure 4-19 A contour plot of the $R^2$ surface in routing parameter space. The example is for a reach of the Murrumbidgee River (410101 - 410035).
Figure 4-20 A contour plot of the $R^2$ surface in routing parameter space. The example is for reaches of both the Numeralla and Murrumbidgee Rivers (410067 - 410050).

Figure 4-21 A contour plot of the $R^2$ surface in routing parameter space. The example is for a reach of the Numeralla River (410100 - 410062).
4.6.5 Streamflow Routing Discussion

A hydrologic routing method was selected for application in this research for ease of use, computational efficiency, modest data requirements, and the potential for parameter identifiability with reach physical characteristics. The model was successfully applied across the study catchment. The development of the routing method where parameters are selected based on reach characteristics has overcome the inherent limitations of the lag-route model. The use of parameters selected based on reach characteristics reduces performance of the model only slightly in the majority of catchments. This is due to the generally broad range of parameter values with comparable measures of model performances close to the optimum value.

The difference in optimum parameter combinations for each of the measures of model performance may provide a rationale for the use of a variable parameter model where parameters are varied according to streamflow. The variable parameter model of Ponce and Yevjevich (1978) was investigated. However, because of the need to provide detailed physical data to parameterise the model and associated difficulties in obtaining this information for a large number of reaches, the routing parameters were fixed using the grid search program. The selection of a fixed parameterisation in preference to a variable parameterisation may be justified not only by data availability but also by the nature of the hydrologic problem in question. For example, when investigating in-stream sediment transport, where high flow conditions mobilise the majority of the total sediment load (e.g. Olive and Rieger, 1984), selection of parameters based only on $R_{surf}^2$ or $R^2$ is most appropriate. Similarly, when investigating issues concerning water allocation, selection of parameters based on consideration of the range of measures of model performance may be most appropriate.

Error in the lag-route model with parameters selected from reach characteristics can be attributed to four main sources. The first is from the contribution of ungauged areas with different rainfall and hydrologic response characteristics. The second is from error in measurement (or modelling) between upstream and downstream stream gauges. The third source of error can be attributed to the process representation of the model. The final source is from the fitting of the actual routing parameters from channel characteristic inputs. It is difficult to apportion the relative source of error. However, the performance of the routing model appears to be most influenced by differences in the hydrologic characteristics and flow estimation between upstream and downstream catchments.
4.7 Murrumbidgee Integrated Catchment Management System (ICMS)

This section describes the development of the Murrumbidgee ICMS (Integrated Catchment Management System) and presents results from the application. The Murrumbidgee ICMS has been developed because previous streamflow modelling efforts are inadequate at useable temporal or spatial scales for examination of many resource management issues (Newham et al., 2000, 2001b). The collective models packaged within the ICMS are designed to provide a general tool and data archive for hydrologic investigations by resource managers across the upper Murrumbidgee catchment. The Murrumbidgee ICMS incorporates a subset of the IHACRES rainfall-runoff and streamflow routing models for selected subcatchments, described previously in this chapter.

4.7.1 Integrated Catchment Management System

ICMS is an object-oriented modelling environment incorporating typical models and data used in catchment management modelling (Reed et al., 1999). The ICMS modelling platform is designed for the rapid development of DSS. It caters for three types of users - scientists, managers and stakeholders. The first layer is for scientists who require tools to develop catchment management models. The second layer provides managers with a DSS to compare model outputs with respect to a variety of scenarios. This layer can incorporate all the complexity of environmental processes, yet provides the user with a simple and clear visual representation of the catchment processes involved. The third layer of ICMS is for stakeholders who require a simple model representation with results that are easy to interpret, understand and base decisions.

ICMS allows for the building and combination of models incorporating temporal, spatial and other data. The structure of ICMS allows for inheritance of components and building libraries of models, thus increasing speed of construction by reducing duplication of effort.

The ICMS was developed collaboratively between CSIRO Land and Water and the Australian National University. The Murrumbidgee ICMS was one of several prototype applications of the ICMS. Study in other catchments has demonstrated that the ICMS is a useful tool for water quality investigation (e.g. Croke et al., 2000) and also for integrated economic and social assessments (e.g. Gilmour, 2000; Letcher et al., 2000).

4.7.2 System Development

The Murrumbidgee ICMS uses a nodal system based on subcatchment streamflow gauges. Calibrated rainfall-runoff and streamflow routing models that have been described in previous sections of the chapter are used as the basis of the Murrumbidgee ICMS. Inputs to the rainfall-runoff models remain unchanged. The streamflow routing parameters used in the
Murrumbidgee ICMS were selected based on stream reach characteristics. An ICMS system view of the Murrumbidgee network is shown in Figure 4-22. The view shows the links, models and data inputs to the system.

A total of 24 nodes are included in the network. There are three node types in the system:

- IHACRES rainfall-runoff modelling nodes;
- streamflow routing nodes; and
- observed streamflow input nodes.

The system was constructed to reproduce streamflow for a 20-year period beginning at the start of 1960. This period was selected on the basis that the majority of streamflow gauges have data recorded in that period and that a relatively high proportion of rainfall gauges have recorded data.

Figure 4-22: System view of the Murrumbidgee ICMS. Nodes of the system are displayed as square icons labelled with stream gauge numbers (prefixed by 410). A legend is shown on the right hand side of the figure.
A map of the corresponding subcatchments and stream reaches is shown in Figure 4-23.

Figure 4-23: Upland subcatchments of the Murrumbidgee ICMS. Routing nodes are indicated by triangles. All subcatchments and routing nodes are labelled with their respective gauge numbers. The locations of major centres in the catchment are also shown.

4.7.3 Results

Results for the IHACRES model simulations for the period are presented in Table 4-11. Note that the 20-year simulation period from the beginning of 1960 may include periods used for calibration of each of the models. No observed data was available to enable comparison at the Michelago Creek site (410141) over the Murrumbidgee ICMS simulation period.
The results of the simulations presented in Table 4-11 show that streamflow is generally well estimated over the 20-year simulation period using the IHACRES models. The $R^2$ value representing agreement between modelled and observed streamflow over the simulation period is greater than 0.5 at all sites except 410077.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>$R^2$</th>
<th>Bias (mm/y)</th>
<th>$R_{sqr}^2$</th>
<th>$R_{inv}^2$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>7.9</td>
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<td>410067</td>
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<td>0.602</td>
<td>-0.028</td>
</tr>
<tr>
<td>410075</td>
<td>0.635</td>
<td>0.1</td>
<td>0.690</td>
<td>-0.067</td>
</tr>
<tr>
<td>410076</td>
<td>0.660</td>
<td>15.9</td>
<td>0.678</td>
<td>-1.938</td>
</tr>
<tr>
<td>410077</td>
<td>0.485</td>
<td>135.5</td>
<td>-0.071</td>
<td>-3.974</td>
</tr>
<tr>
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<td>0.521</td>
<td>-11.1</td>
<td>0.463</td>
<td>-0.104</td>
</tr>
<tr>
<td>410090</td>
<td>0.660</td>
<td>8.2</td>
<td>0.615</td>
<td>-4.429</td>
</tr>
<tr>
<td>410105</td>
<td>0.669</td>
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<td>0.694</td>
<td>-0.869</td>
</tr>
<tr>
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<td>0.154</td>
</tr>
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<td>0.647</td>
<td>-0.202</td>
</tr>
<tr>
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<td>0.559</td>
<td>19.0</td>
<td>0.277</td>
<td>-3.755</td>
</tr>
</tbody>
</table>

The routing parameters used in the Murrumbidgee ICMS were those estimated from stream reach attributes. Measures of model performance for each of the streamflow routing sites have already been described in Section 4.6.4 and no further consideration is given here. Table 4-12 shows the measures of model performance for downstream nodes of the Murrumbidgee ICMS using simulated streamflow inputs to the routing models.

It can be seen in Table 4-12 that daily streamflow is generally not well reproduced at downstream nodes of the Murrumbidgee ICMS. However, total monthly streamflow volumes show much closer agreement between observed and modelled totals. This may indicate inconsistencies in the timing of data collection between streamflow gauges. The level of bias in the comparison is generally acceptable. Flow duration curves presented later in this section show that the distribution of flow is generally well reproduced in the Murrumbidgee ICMS.
Figures 4-24 and 4-25 show example stream hydrographs for two downstream nodes of the modelling system: Murrumbidgee River at Cotter Crossing and the Yass River at Yass. Both of these figures have been prepared using the plotting tools incorporated within the ICMS platform. The example hydrograph for the Murrumbidgee River site (the furthest downstream node of the system) shows that streamflow is generally well reproduced across a range of flow levels. At the Yass River node the flow is not as well simulated. In the Yass River instance, where flow is routed from a single and relatively small upstream catchment, the influence of ungauged areas is potentially significant. The influence of ungauged areas can be seen in the underestimation and overestimation of several streamflow peaks.

Table 4-12 Measures of model performance for downstream nodes of the Murrumbidgee ICMS.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>$R^2$ (daily)</th>
<th>$R^2$ (Monthly)</th>
<th>Bias (%)</th>
<th>Number of Days to Calculate Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>410024</td>
<td>0.47</td>
<td>0.55</td>
<td>-2.9</td>
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</tr>
<tr>
<td>410026</td>
<td>0.69</td>
<td>0.83</td>
<td>11.2</td>
<td>3771</td>
</tr>
<tr>
<td>410035</td>
<td>0.24</td>
<td>0.94</td>
<td>4.4</td>
<td>1209</td>
</tr>
<tr>
<td>410050</td>
<td>0.46</td>
<td>0.90</td>
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</tr>
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</tr>
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<td>0.65</td>
<td>-23.1</td>
<td>1460</td>
</tr>
<tr>
<td>410101</td>
<td>0.47</td>
<td>0.93</td>
<td>-8.5</td>
<td>1986</td>
</tr>
</tbody>
</table>

Figures 4-26 and 4-27 show streamflow duration curves at the Murrumbidgee River at Cotter Crossing and the Numeralla River at Numeralla. These two catchments have the largest and smallest upstream contributing areas respectively. The catchments also show the best and worst agreement between modelled and observed streamflow duration curves.
Figure 4-24 Example stream hydrograph for the Murrumbidgee River at Cotter Crossing (410035).

Figure 4-25 Example stream hydrograph for the Yass River at Yass (410026).
Figure 4-26 Flow duration curve for the Murrumbidgee River at Cotter Crossing (410035).

Figure 4-27 Flow duration curve for the Numeralla River at Numeralla (410100).
As discussed in the following chapter an ability to reproduce the distribution of streamflow is a key requirement for the successful modelling of water quality. The distribution of streamflow is particularly well estimated at node 410035. At node 410100 high streamflow conditions are slightly overestimated whereas low streamflow conditions are highly underestimated.

4.7.4 Murrumbidgee ICMS Discussion

The Murrumbidgee ICMS is successful at estimating flows at various scales across the upper Murrumbidgee catchment. This can be attributed to the system including robust, carefully calibrated rainfall-runoff and routing models. The system provides not only an estimation of streamflow across the catchment but also a tool to investigate a host of water related issues and plays an additional role in archiving streamflow data.

In the study catchment the ICMS has proven to be a suitable tool for the construction of network systems. The ICMS provides an excellent system for the display and manipulation of catchment data. The structure of the Murrumbidgee ICMS is very flexible and allows for ongoing improvement and experimentation on the models and data held within the system. The advantages of use of the ICMS are the ease of constructing and changing models and an ability to incorporate new spatial nodes quickly and easily. Much of the work for the construction of the Murrumbidgee ICMS was involved in data collection and modelling external to the ICMS platform. The details of this work have already been described in previous sections of the chapter. Further development of the ICMS platform to include an ability to customise individual applications, such as for the Murrumbidgee ICMS, should be investigated. Such work would improve the dissemination of results to stakeholders.

The Murrumbidgee ICMS has successfully simulated the overall distribution of streamflow and in the majority of cases provided reasonable estimates of total streamflow volume. The modelling system was most constrained by error in catchment areal rainfall estimates and from timing errors between streamflow gauges. Problems with producing catchment areal rainfall estimates have already been discussed in Section 4.5.4. The problem of timing error between streamflow gauges has limited the apparent success of the simulation of daily streamflow at downstream nodes. In addition to increasing the regularity and hydrologic range of streamflow gauging, it is recommended that attention also be directed to improving the associated timing of data collection.

The network routing approach of the Murrumbidgee ICMS allows for the propagation of error from upstream nodes through the stream network. For the Murrumbidgee ICMS this appeared to be only a minor problem and its effect was limited by careful calibration of the routing models between individual sites in the stream network. Consideration of the problem of error
propagation in linked network systems should be considered in future applications. A similar issue is addressed in Chapter 6 where the routing of sediment is considered.

4.8 Rainfall-Runoff Model Comparison

The final section of this chapter presents a comparison between the SIMHYD model (Peel et al., unpublished) applied as part of the Australian National Land and Water Resources Audit and the IHACRES model applied as part of this research. Six sites are available for comparison. The comparison is useful but also tenuous in the respects that different data inputs, model calibration periods and calibration techniques were used in the separate applications. The models are also compared at only a limited number of sites. However there are many similarities between the applications: both models are conceptually based, have a similar number of parameters and reproduce streamflow from inputs of rainfall and temperature or potential evapotranspiration.

The SIMHYD model is described below, the corresponding description of the IHACRES model has been given previously in Section 4.3. Following the description of SIMHYD, a summary table showing a comparison of performance of the each model is presented and then discussed.

4.8.1 SIMHYD Description

SIMHYD is a simplified version of the conceptual daily rainfall-runoff model HYDROLOG described in Chiew et al. (2002). The model has been applied to 331 catchments in Australia as part of the NLWRA (Peel et al., unpublished). The SIMHYD model uses a total of seven parameters to model streamflow from inputs of potential evapotranspiration and daily rainfall. The model incorporates three conceptual stores: an interception store, a soil moisture store and a groundwater store. Runoff is modelled to result from the contribution of infiltration excess runoff (from interception store), interflow and saturation excess runoff and baseflow from the groundwater store. Within the Peel et al. (unpublished) study the routing of streamflow is not considered as streamflow is modelled at monthly timesteps. Figure 4-28 shows the structure of the SIMHYD model, a description of model parameters and the equations used to predict streamflow.
Figure 4-28 Structure of the SIMHYD model (source Peel et al., unpublished).

4.8.2 Model Comparison

Table 4-13 presents results of the comparison between SIMHYD and IHACRES models at commonly modelled sites in the upper Murrumbidgee catchment. Statistics for the IHACRES model are calculated using the 20-year simulation period of Section 4.7. To enable comparison between the models, the measures of model performance for the IHACRES modelling are also calculated monthly.

The comparison shows that the IHACRES models used in this research reproduce streamflow of a comparative performance to the SIMHYD models at common sites. The $R^2$ of the IHACRES model is equal or greater in simulation of streamflow at three of the five sites. Bias is comparable across both models. It should however be noted that the IHACRES model has achieved comparative performance with fewer parameters than the SIMHYD model (IHACRES uses three parameters in the non-linear module compared to seven parameters in
In this comparison the IHACRES models have generally been calibrated on a shorter length of record than the corresponding SIMHYD models.

Table 4-13 Comparison of rainfall-runoff model performance at commonly modelled sites - IHACRES and SIMHYD models.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Validation $R^2$ IHACRES</th>
<th>Validation $R^2$ SIMHYD</th>
<th>Validation bias (%) IHACRES</th>
<th>Validation bias (%) SIMHYD</th>
</tr>
</thead>
<tbody>
<tr>
<td>410067</td>
<td>0.722</td>
<td>0.600</td>
<td>-13.4</td>
<td>0.978</td>
</tr>
<tr>
<td>410077</td>
<td>0.479</td>
<td>0.656</td>
<td>5.8</td>
<td>-11.349</td>
</tr>
<tr>
<td>410105</td>
<td>0.783</td>
<td>0.911</td>
<td>-13.6</td>
<td>-5.348</td>
</tr>
<tr>
<td>410705</td>
<td>0.761</td>
<td>0.761</td>
<td>4.3</td>
<td>-3.682</td>
</tr>
<tr>
<td>410731</td>
<td>0.559</td>
<td>0.490</td>
<td>1.3</td>
<td>-4.369</td>
</tr>
</tbody>
</table>

It is difficult to draw conclusions about the relative predictive performance of either of the models from this limited comparison. A separate comparison between the IHACRES model and another variant of the HYDROLOG model, MODHYDROLOG, has been made previously by Chiew et al. (1993).

It is worth noting that the modelling described in Chapter 6 uses results from the Peel et al. (unpublished) study for the basis of the hydrologic parameterisation of the SedNet model. It will be seen later in that chapter that hydrologic model inputs have important implications for pollutant load calculations.

4.9 Chapter Discussion

This chapter has described the construction of daily hydrologic simulation models at catchment scales for the investigation of water quality and other issues in the upper Murrumbidgee River catchment. The modelling of streamflow in some circumstances provides the only information for effective catchment management and resource allocation. Where this information can be supplied with a high spatial and temporal resolution its value is much increased. Such hydrologic modelling provides a key for the examination of water quality issues and also the integration of biophysical, social and economic assessment and modelling.

The results presented in the chapter demonstrate that appropriately constructed rainfall-runoff models can successfully reproduce streamflow across a range of scales. The IHACRES model has been successfully calibrated at 14 of 17 sites and has successfully simulated streamflow.
from independent data at 11 of those sites. Outputs from the IHACRES model has also been compared with the SIMHYD model and has shown comparable performance, which has been achieved using fewer model parameters and a generally shorter calibration period.

The streamflow routing technique described in the chapter shows that the estimation of daily streamflow is possible at downstream sites where upstream streamflow is known. A method of estimating the parameter values of the simple routing model based on stream reach characteristics has been described in the chapter. In the majority of situations the decline in the performance of the model is minimal when parameters are selected based on stream reach characteristics.

The development of the Murrumbidgee ICMS has also been described in the chapter. The system has incorporated a subset of the IHACRES rainfall-runoff and lag-route routing models. The Murrumbidgee ICMS provides not only an estimation of streamflow across the catchment but also a tool to investigate a host of water related issues, and plays an additional role in archiving streamflow data. The development of the Murrumbidgee ICMS has improved the potential delivery of the research presented in this chapter to catchment stakeholders.

Limitations to the development of hydrologic models in the catchments have been identified to stem primarily from inadequate rainfall input data. These were probably improved by developing an interpolated rainfall surface. Substantial improvement would require more dense measurement of point rainfall data.
Chapter 5 Subcatchment Pollutant Load Estimation

'In rivers, the water that you touch is the last of what has passed and the first of that which comes'. DA VINCI

5.1 Introduction

Effective management strategies to reduce the impact of environmental pollutants require information on the pollutant contribution of subcatchments. Knowing the relative pollutant contributions of subcatchments enables identification of areas that require concentration of remediation efforts, more intensive monitoring and/or study. Quantification of the export of pollutants also allows comparison with predictive modelling approaches such as those discussed later in Chapter 6.

This chapter is focused on pollutant load estimation using observed pollutant concentration data. As background, a review of techniques for load estimation is presented at the beginning of the chapter. A background discussion of the level and type of expenditure on water quality monitoring in the upper Murrumbidgee catchment is made and the inadequacies of these programs for load estimation are discussed. A water quality monitoring program established as part of this research is then described. The program was developed to address some of the inadequacies of current approaches. In the final section of the chapter sediment loads are estimated at two sites using three regression-based load estimation techniques. Modelled streamflow data generated in exercises covered in Chapter 4 are used for estimating loads. The effects of changes in the temporal resolution of data inputs and the use of modelled versus observed streamflow inputs on resultant pollutant loads are also explored. The final section of the chapter presents a discussion of the results and an overall summary.

5.1.1 Load Estimation Techniques

This review is concerned with techniques for estimating pollutant loads using a combination of observed in-stream pollutant concentration and streamflow data. Pollutant loads are not generally observed in-stream. Instead, they are inferred from measurements of pollutant concentrations and streamflow. The latter are more easily measured (Mimikou, 1982). A comprehensive review, applicable in the Australian context, on development of functional relationships between pollutant concentration and streamflow for the estimation of loads is provided by Letcher et al. (1999). That work is cited frequently through the following section.
A wide range of techniques to estimate pollutant loads are presented in the literature. These can be conveniently placed into three categories:

- averaging techniques;
- ratio estimators; and
- regression techniques (rating curves).

**Averaging Techniques**

Averaging methods are generally considered to be the simplest available techniques for pollutant load estimation. Calculations of load over a given time period are made by using averages of streamflow, concentration or load for a given sub-interval and then summing these over the entire period (Letcher *et al.*, 1999). Whilst these methods are easy to apply, the assumptions implicit behind such calculations, including independent and identically distributed data, are rarely met (Letcher *et al.*, 1999). This leads to potential bias in the estimation of loads, especially if the sampling program does not collect data from the entire range of streamflow and concentration variability.

Hollinger *et al.* (2001) have applied an averaging technique described by Dann *et al.* (1986) to estimate the export of sediment and nutrients from a market garden near Sydney.

**Ratio Estimators**

Ratio estimators use the correlation within a sample for estimating pollutant loads. The ratio estimate is calculated as:

\[ Y_R = (y / q) Q \] (5-1)

where \( y \) and \( q \) are the sample means of concentration and streamflow respectively, \( Y_R \) is the ratio estimate of load and \( Q \) is the streamflow (Letcher *et al.*, 1999).

The ratio estimator is the best linear unbiased estimator under two conditions: that the relationship between concentration and streamflow is a straight line passing through the origin, and the variance of the mean concentration about the line is proportional to the mean streamflow. These two conditions are rarely met and use of ratio estimators generally leads to bias in the results (Letcher *et al.*, 1999). Ratio estimators are described in detail by Preston *et al.* (1989).
Regression Techniques

Regression estimates are based on extrapolating a limited number of pollutant concentration measurements by developing a functional relationship between pollutant concentration and streamflow (Letcher et al., 1999). Regression-based techniques have been widely applied to estimating pollutant loads. For example it has been commonly found that suspended sediment load is a power function of streamflow (Mimikou, 1982). Regression techniques have come into widespread use because data requirements are modest and load estimates can be produced for periods beyond when concentration data were collected (Robertson and Roerish, 1999).

Examples of the use of regression-based techniques for estimating suspended sediment loads can be found in Mimikou (1982), Ferguson (1986) and Letcher et al. (2002). For other pollutants, examples include Kronvang and Bruhn (1996), who have used regression-based techniques for calculating nitrogen and phosphorus loads, and Frey (2001) who have calculated loads of pesticides using regression-based techniques.

Parameter values for power functions are typically derived using a linear regression to the logarithm of the input data (Croke, 2002). Ferguson (1986) describes problems of bias (usually underestimation) of sediment loads using such methods. The problem is that the use of a linear regression on logarithms of the data results in the geometric mean of the modelled data being equal to the geometric mean of the observed values, rather than the arithmetic mean. Ferguson (1986) proposes the use of a bias correction factor to account for such problems.

Summary

No optimal method of load estimation has been found in the literature, and advantages and disadvantages can be associated with any method. The selection of an appropriate load estimation technique depends on not only the availability of concentration data, but also on the desired accuracy of estimates and the preferred complexity of the load estimation technique (Letcher et al., 1999). The choice of technique will depend on the characteristics of the available data and to a lesser extent the nature of the catchment under consideration.

Generally less confidence may be placed on loads estimated using data with a wide sampling interval or a sampling program that does not characterise flood events. Infrequent sampling is often inadequate to describe directly the changes in water quality and usually misses the highest concentration events (Sanders et al., 1983).
5.2 Upper Murrumbidgee Water Quality Monitoring

Water quality data are collected over the upper Murrumbidgee catchment by a variety of organisations to serve multiple purposes. There is much diversity in the types of pollutant analyses made. Examples include:

- The NSW Department of Land and Water Conservation has funding of $1.6 million over six years for monitoring the unregulated parts of the Murrumbidgee River catchment. For the upper Murrumbidgee catchment, approximately $95,000 is invested annually for physical and chemical water quality sampling and analysis.

- Environment ACT invests approximately $26,000 in monitoring chemical and physical water quality of streams and rivers within the upper Murrumbidgee per year. Environment ACT is improving the utility of the data they collect by shifting from a predominantly routine sampling program to include more event based sampling.

- Actew AGL’s activities in water quality monitoring are primarily concerned with the provision of residential water supply to the Canberra region.

- The ACT Department of Health, Housing and Community Care has a bacteriological water quality monitoring program in place to assess the quality of water for recreational purposes, in the urban lakes of the ACT.

- The National Capital Authority conducts water quality monitoring in Lake Burley Griffin and its inflows. Their testing includes physical, biological and chemical analysis. Selected swimming sites are targeted with additional bacteriological sampling.

The catchment is also an important study area for research by organisations that do not have direct management roles. Several universities and research organisations collect water quality information in the catchment. Community based Landcare and associated groups also collect water quality data from within the catchment. However, it is difficult to quantify their total investment. Each of the organisations has a predominantly routine stream sampling program in place. Routine samples are collected at set intervals and generally take no account of the hydrologic or antecedent conditions. Routine sampling is largely ineffective for the purposes of load estimation due to the predominance of sampling at low flow conditions (Letcher et al., 1999). Generally only the prevailing ambient quality of a water body is determined by these means.

In summary, more than $150,000 is invested annually in water quality investigations for the catchment. It will be shown later in the chapter that the catchment has few sites with data of an appropriate standard for effective estimation of pollutant loads. There are few sites to
estimate loads because of the routine nature of the sampling programs in place and inappropriate siting of data collection locations. Alternate approaches are needed.

### 5.3 An Improved Water Quality Monitoring Program

Cost-effective and targeted water quality monitoring programs are required to quantify properly the total loads of environmental pollutants at catchment scales. This section describes the development of a monitoring program in tributaries of the upper Murrumbidgee River. The objective of the monitoring program was to provide water quality data on which to base sediment load estimates. The limiting factor on the quality of pollutant load estimation is commonly the nature of concentration data (Littlewood, 1995).

Field water quality monitoring programs and their associated laboratory analyses are expensive (Moore and Gallant, 1991). The methods used in this research attempt to overcome some of the methodological and design inadequacies of water quality monitoring programs for the estimation of pollutant loads. The tools, techniques and sites of a sampling program in four subcatchments of the upper Murrumbidgee are described. Included are modifications to the design of Graczyk et al. (2000) for an inexpensive, rising stage water quality sampler suitable for Australian conditions.

#### Site Selection

For the program described here sites for monitoring of water quality were selected based on the following criteria:

- it was necessary that sites be co-located with a continuously recording stream gauge to ensure that streamflow could be determined at the time of sampling;
- it was preferable that sites were telemetered and access to this data was available;
- sites were required to have vehicular access in wet weather; and
- preference was given to sites close to Canberra to reduce travelling time.

A short list of catchments was made. To ensure variety in physical characteristics, attributes such as topography and land use were also considered. Nested catchments were preferred to enable potential investigation of pollutant transport through river reaches. Four sites were selected, these are presented below in Table 5-1. A map showing the locations of the sites is shown in Figure 5-1.
Table 5-1 Upper Murrumbidgee subcatchments chosen for investigation.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>410705</td>
<td>Molonglo River at Burbong</td>
</tr>
<tr>
<td>410711</td>
<td>Gudgenby River at Nass</td>
</tr>
<tr>
<td>410731</td>
<td>Gudgenby River at Tennent</td>
</tr>
<tr>
<td>410759</td>
<td>Molonglo River below Carwoola</td>
</tr>
</tbody>
</table>

Figure 5-1 Map of water quality sampling sites including name and number of gauge.
Sampling Strategy

There are two crucial design factors in the construction of water quality monitoring programs. These are the location of sampling stations (Sanders et al., 1983) and the type and frequency of sampling. The previous section has outlined the selection of water quality monitoring locations for this study. These catchments have highly variable rainfall and streamflow typical of Australian environments (Smith, 1998). The catchments also have fast hydrograph rise and recessions rates typical of Australian conditions (Croke and Jakeman, 2001). Due to these hydrologic characteristics, rising stage conditions in particular are generally not adequately sampled with a manual sampling program. However, water quality sampling during runoff events is important as the bulk of pollutants are exported from catchments during these periods (Olive and Rieger, 1984).

According to Sanders et al. (1983) clear objectives for water sampling programs need to be established prior to commencement of sampling. The sampling program was expected to run for a maximum of 18 months. Robertson and Roerish (1999) suggest that for a program of this length a combined event based and monthly routine sampling be used. This was established. Event based sampling programs collect discrete samples throughout runoff events across both rising and falling limbs of the stream hydrograph. The program uses a siphon sampler (described in the following section) to collect rising stage samples; routine and falling stage samples have been collected by manually.

Rising Stage Water Quality Sampler

Siphon samplers are low-cost alternatives to automatic mechanical samplers for collecting event based water quality samples. This section describes a rising stage siphon sampler and the deployment of such samplers in the field. The design of the sampler was modified for Australian conditions from Graczyk et al. (2000). This improved design is shown in Figure 5-2. The approximate cost of materials for each of sampler is $60. The samplers are easy to construct using simple tools.
Figure 5-2 Schematic design of a rising stage automatic water quality sampler (source: modified from Graczyk et al., 2000).

The operation of the samplers is very simple. As water level rises to the elevation of the intake tube, water enters the 8mm vinyl tube. As the stream continues to rise, water continues to move up the intake tube until it reaches the top of the loop; at this point a siphon is created and the bottle starts to fill. The sample collection bottle fills rapidly under a hydraulic head with displaced air escaping through the exhaust tube. Once full, changes in the stream level do not affect the contents in the bottle. Following an event, the bottles are collected and the contents analysed. Several samplers can be installed at different levels at each site to collect samples throughout the anticipated range in water levels.

A simple comparison of the water quality data collected by mechanical automatic samplers and siphon samplers was made in the study of Graczyk et al. (2000). No systematic biases are evident in the comparison of data. The methods used suggest that variation in pollutant loads between mechanical and siphon samplers were predominantly due to the mis-timing of sample collection.
The siphon samplers are essentially sealed following collection of a sample on the rising limb of the hydrograph and do not collect samples when the stream stage is decreasing. Hence manual samples are required for analysis of the water quality during this period. Decreases in stage, however, are generally more protracted than increases in stage and can be adequately manually sampled (Graczyk et al. 2000).

A prototype of the sampler was trialed in the Sullivan's Creek catchment of the ACT for a runoff event. Experience from the deployment of the prototype sampler in the Sullivan's Creek led to design modifications for Australian conditions and the sampling program presented here. The modifications include:

- increasing the length of the intake loop to 150mm to increase the depth at which the sample is taken, this also having the desirable effect of decreasing the sample collection time resulting from the greater hydraulic head;
- securing the intake loop for a better estimation of the height at which a sample is taken, thus reducing errors in the corresponding estimation of streamflow;
- increasing the size of the collection bottle to 1L to allow a greater range of water quality attributes to be analysed;
- adding a screw cap and coupling at each end to strengthen the unit and allow ease of access;
- strengthening of the intake and exhaust tube connections; and
- painting of the body of the sampler to protect from ultraviolet light deterioration and to aid in concealment.

In this research samplers were positioned at stream gauge sites with continuous monitoring of streamflow. Figure 5-3 shows the height of samplers marked on a stage height recurrence interval plot for each of the catchments of this study. Five samplers were installed at each site. At each site, the stage height, at which each of the samplers captures a sample, was determined accurately using a dumpy level and marked stream gauge heights. By use of a rating curve, instantaneous streamflow at the time of sampling can be determined and this data used to calculate pollutant loads. As can be seen in Figure 5-3 samplers are positioned at levels with a bias toward high flow conditions. Generally the recurrence interval of flow extended to the one in two year flood event.
Subcatchment Pollutant Load Estimation

Figure 5-3 Stage height recurrence interval plots. The height of individual samplers are marked on the plots and labelled with their corresponding individual sampler number.

Table 5-2 summarises a number of hydrologic attributes for each of the water quality sampling sites and lists the streamflow record length used to construct the plots of Figure 5-3.
Table 5-2 Summary of hydrologic attributes of water quality sample sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Maximum Recorded Stage Height (m)</th>
<th>Maximum Recorded Streamflow (m$^3$s$^{-1}$)</th>
<th>Record Length (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>410705</td>
<td>4.265</td>
<td>682.0</td>
<td>71.5</td>
</tr>
<tr>
<td>410711</td>
<td>3.100</td>
<td>183.0</td>
<td>38.4</td>
</tr>
<tr>
<td>410731</td>
<td>5.376</td>
<td>361.7</td>
<td>35.7</td>
</tr>
<tr>
<td>410759</td>
<td>5.705</td>
<td>446.9</td>
<td>27.3</td>
</tr>
</tbody>
</table>

Figure 5-4 A siphon sampler (with modifications) secured in-stream adjacent to stream gauge marking (site 410711 - Gudgenby River at Nass).
5.3.2 Sampling Results

Samplers were positioned at each of the four sites from early March 2001 until late September 2002. Over this period streamflow was generally low because of low average rainfall. A total of 21 samples were collected across the four sites. Of these only six were collected by siphon samplers. A summary of results is shown in Table 5-3.

Table 5-3 Water quality data collected from water quality sampling sites.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Collection Date</th>
<th>Time</th>
<th>Method</th>
<th>Stage Height (m)</th>
<th>Suspended Solid Concentration (mgL⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>410705</td>
<td>28/07/01</td>
<td>12.05</td>
<td>Manual</td>
<td>0.11</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>24/09/01</td>
<td>-</td>
<td>Auto</td>
<td>0.53</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>12/10/01</td>
<td>11.15</td>
<td>Manual</td>
<td>0.09</td>
<td>0.50</td>
</tr>
<tr>
<td>410711</td>
<td>8/07/01</td>
<td>13.32</td>
<td>Manual</td>
<td>0.49</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>26/07/01</td>
<td>14.00</td>
<td>Manual</td>
<td>0.49</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>13/09/01</td>
<td>13.30</td>
<td>Manual</td>
<td>0.59</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>10/02/02</td>
<td>-</td>
<td>Auto</td>
<td>0.85</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>10/02/02</td>
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<td>Manual</td>
<td>0.72</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
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<td>Manual</td>
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<td>2.0</td>
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<td>Auto</td>
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</tr>
<tr>
<td>410731</td>
<td>8/07/01</td>
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<td>Manual</td>
<td>0.88</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
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<td>Manual</td>
<td>0.97</td>
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</tr>
<tr>
<td></td>
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<tr>
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<td>5.9</td>
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<td>Manual</td>
<td>0.49</td>
<td>3.3</td>
</tr>
<tr>
<td>410759</td>
<td>28/07/01</td>
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<td>Manual</td>
<td>0.32</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>24/09/01</td>
<td>-</td>
<td>Auto</td>
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<td>41.0</td>
</tr>
<tr>
<td></td>
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<td>Manual</td>
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<td>1.10</td>
</tr>
</tbody>
</table>
Suspended sediment concentrations ranged from 0.5 to 280 mgL⁻¹ across all the collected samples. Samples collected manually had a much narrower range of relatively low concentrations: 0.5 to 9.1 mgL⁻¹. Samples at the Molonglo River sites (410705 and 410759) showed generally lower suspended sediment concentrations in both manual and automatically collected samples than at the Gudgenby River sites.

Over the course of the sampling program, due to the low flow conditions, the number of routinely measured samples was reduced. Practically no new information was added with collection of additional data at low flow conditions.

On several occasions fouling of the intake tube by insects resulted in failure to collect a sample. In an attempt to overcome this problem a surface insecticide was applied to both intake and exhaust tubes and also to the sample collection bottle. Several samplers at site 410731 were vandalised over the course of the sampling program.

5.3.3 Sampling Program Discussion

The alternate program described in this section of the chapter is presented to stimulate improved methods of water quality sampling. The cost and importance of these programs necessitates that good quality data is collected, for the appropriate purposes, at the appropriate sites, over a sufficient range of hydrologic conditions. This section has demonstrated that water quality data can be collected simply and cost-effectively if programs are appropriately designed.

The alternate program presented here is a step towards improved water quality sampling. The salient features of the program presented are:

- data are collected with a specified objective;
- sampling sites have been selected to achieve the objective of the program;
- rising stage samples are collected automatically; and
- the program is cost-effective.

A shortcoming of the monitoring program is that falling stage water quality samples need to be collected manually. Research into the design of cost-effective, simple falling stage samplers is required. The limitations to designing mechanical devices are that: they require a double trigger to start sample collection; they must be robust enough to be deployed in-stream for long periods; they must be simple to construct from readily available materials; and they should be inexpensive to produce. Alternatively, collection of falling stage samples across a range of widely distributed sites could be coordinated through local data collection teams or with the assistance of people living close to the measurement site.
It is disappointing that so few samples were collected over the duration of the research because of the generally low rainfall and streamflow conditions experienced over the period of data collection. Rainfall deficiencies over this period are well documented. In the 18-month period from the 1st June 2001 to the 30th November, total rainfall was in the lowest decile recorded - a 500mm departure from the 18 month mean (Australian Bureau of Meteorology: http://www.bom.gov.au). This demonstrates that a routine sampling program over this period would result in sampling across a very narrow range of hydrologic conditions. Subsequent load estimation from this data would result in high uncertainties.

Further testing of the siphon sampler beyond the methods used by Graczyk et al. (2000) is suggested to ensure that there are no systematic errors resulting from sample collection. This could be undertaken by a comparison between samples collected by submersion of a siphon sampler (to simulate rising stage conditions) and samples collected using standard methods. A wide range of alternative uses are possible for siphon samplers of the type described here. This includes investigation of a range of in-stream pollutant transport dynamics and is limited only by the imagination of the researcher.

### 5.4 Sediment Load Calculations

This section describes the estimation of pollutant loads in the upper Murrumbidgee River catchment. The data generated here is used for the comparison with landscape based modelling approaches in Chapter 7, and more broadly for investigating load estimation techniques and their role in support of pollutant load modelling. The application of three regression-based methods of load prediction (discussed in Section 5.1.1) are presented. The section begins by describing the process used to select subcatchments for load assessment. Following this, a discussion of the characteristics of each of the catchments and of the available data is made. The results for each of the load estimation techniques are tabulated and discussed.

#### 5.4.1 Subcatchment Selection Process

To ensure that pollutant loads were calculated with an acceptable level of accuracy a set of criteria were established to select appropriate sites. Sites selected for pollutant load estimation were required to meet the following criteria:

- be co-located with a continuously recording stream gauge with streamflow data of an appropriate quality in terms of record length, temporal resolution and stream gauging regularity and quality;
- have water quality measurements spanning a range of hydrologic conditions;
have more than 30 observed samples; and

- have minimal influence from upstream regulation or significant pollutant point sources.

Only two sites were found that satisfied the criteria for load estimation across the whole of the upper Murrumbidgee River catchment. The sites are Burra Creek at Burra Road (410744) and Jerrabomberra Creek at Hindmarsh Drive (410790). This result is concerning given the investment in water quality monitoring made in the catchment (see Section 5.2). At the beginning of the research it was anticipated that sufficient data would also be available at each of the Molonglo and Gudgenby River sampling sites described in Section 5.3. As has been discussed previously, due to low rainfall and streamflow over the monitoring period load estimates were not possible from that data.

**Burra Creek Catchment**

Burra Creek is a tributary to the Googong Dam, an important water supply for the ACT and Queanbeyan, and a subcatchment of the upper Murrumbidgee. Due to increased rural residential development within the catchment there are concerns over the quality of water flowing to the Googong Dam (Carter et al., 1994). The predominant land use within the catchment is extensive grazing. However, there are also significant areas of remnant and regrowth native forest across the catchment. At the stream gauge and monitoring site (410774), the subcatchment has an area of approximately 68 km².

**Jerrabomberra Creek Catchment**

The Jerrabomberra Creek drains to Lake Burley Griffin, an important urban lake in the centre of Canberra. There are concerns over the influence of both agricultural and rural residential development on water quality within the catchment (Carter et al., 1994). These concerns prompted Environment ACT to establish a water quality monitoring program for the catchment. Groundwater-related concerns also led to a study by Croke et al. (2001a) that investigated the sustainable groundwater resource of the subcatchment. The Croke et al. (2001a) publication provides additional background to the water resources of the catchment. The Jerrabomberra Creek catchment is used predominantly for the extensive grazing of sheep and cattle and limited horticultural activities. Approximately 11% of the catchment is urban, 2% woodland, 18% open forest and the remainder (69%) is grassland. At the stream gauge and monitoring site (410790), the Jerrabomberra Creek catchment has an area of approximately 121 km².
5.4.2 Data

Event based water quality data collected by ACTEW on behalf of Environment ACT has been used for estimating sediment loads in the Burra and Jerrabomberra Creek subcatchments. At the Burra Creek site, water quality was sampled across nine separate flow events between January 1994 and June 1997. The total number of water quality samples analysed was 115. The peak flows of the sampled events ranged from 0.74 to 7.40 m$^3$s$^{-1}$.

At the Jerrabomberra Creek site water quality was sampled across 12 flow events that occurred between May 1996 and August 1998. A total of 85 individual water quality samples were analysed. The peak flows of the sampled events ranged from 0.72 to 9.35 m$^3$s$^{-1}$.

Figure 5-5 compares the daily streamflow duration curve against streamflow at the time of event based sampling at the Burra Creek site. It can be seen in the figure that the streamflow at the time of event based sampling is above the highest decile of the flow duration curve. This is due to two factors: that the collection of samples during events has predisposed sampling to the higher end of the duration curve; and that the duration of a typical hydrograph peak is less that one day. Similar features can be seen in the comparison for the Jerrabomberra Creek catchment.

Observed streamflow data is available for approximately 14 years (beginning in March 1985) and for approximately five years (beginning in March 1995) for Burra Creek and Jerrabomberra Creek subcatchments respectively. Observed data at both hourly and daily temporal resolution is available for both sites. The IHACRES model has also been used to simulate daily streamflow for both catchments over a ten-year period beginning at the start of 1988. Full details of the streamflow modelling are reported in Chapter 4.

5.4.3 Methods

Two regression-based methods are used in this study to relate sediment concentration to streamflow. Regression-based methods were selected for use because of the limited number of samples on which this analysis is based and the need to extrapolate beyond the period where samples were measured. For the same reasons the use of regression-based methods is also appropriate for future application to other catchments of the upper Murrumbidgee.

Two functional forms were used to relate suspended sediment concentration to streamflow:

\[
[SS] = aQ + c \quad 5-2
\]

\[
[SS] = aQ^b \quad 5-3
\]
where \([SS]\) is suspended sediment concentration, \(Q\) is streamflow and \(a\), \(b\) and \(c\) are constants (not to be confused with those of the IHACRES model in Chapter 4).

![Daily Flow Duration Curve](image1.png)

![Event Based Sampling](image2.png)

**Figure 5-5** A comparison between the daily streamflow duration curve(a) and streamflow at the time of event based sampling (b) for the Burra Creek site.

For Equation 5-2, parameters were selected to minimise the sum of the squares of the residuals. This is referred to as Method 1 in the proceeding text. To estimate parameters for Equation 5-3, two methods were used. The first approach referred to as Method 2, estimated parameter values using linear regression of the logarithm of the input data. The second approach (Method 3) used a non-linear regression package to select the set of parameters. Use of Methods 3 overcomes the problems identified by Ferguson (1986) without the need to estimate a bias correction factor.
Figure 5-6 Example event hydrographs at the Burra Creek site showing corresponding sediment concentration data, (a) Event 6 – 29 November 1995 and (b) Event 8 – 20 September 1996.
5.4.4 Results

Parameter Estimation

Tables 5-4 and 5-5 show the parameters, standard errors and the $R^2$ values for each model in the Burra and Jerrabomberra catchments respectively. The $R^2$ statistic is used to show the ability of each model to fit the observed data.

Figures 5-6 and 5-7 show the observed concentration data and fitted regression curves for each subcatchment.

Table 5-4 Parameter values (with standard errors) for each parameter estimation method in the Burra Creek catchment.

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameter</th>
<th>Value</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$a$</td>
<td>58±3</td>
<td>0.749</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td>150±40</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$a$</td>
<td>129±14</td>
<td>0.658</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>0.71±0.07</td>
<td></td>
</tr>
<tr>
<td>3 - Non-Linear Regression</td>
<td>$a$</td>
<td>193±19</td>
<td>0.714</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>0.65±0.06</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-5 Parameter values (with standard errors) for each parameter estimation method in the Jerrabomberra Creek catchment.

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameter</th>
<th>Value</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$a$</td>
<td>57±8</td>
<td>0.368</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td>75±27</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$a$</td>
<td>112±11</td>
<td>0.279</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>0.55±0.10</td>
<td></td>
</tr>
<tr>
<td>3 - Non-Linear Regression</td>
<td>$a$</td>
<td>144±14</td>
<td>0.318</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>0.53±0.10</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-7 Observed concentration data and model fits to observed data for Burra Creek catchment.

Figure 5-8 Observed concentration data and model fits to observed data for Jerrabomberra Creek catchment.
Load Calculation

The total suspended sediment loads exported from both the Burra and Jerrabomberra Creek subcatchments were calculated for the 10-year period from the 1st January 1988 to the 31st December 1997 using each of the three methods described in the previous section. The period of load estimation spans the majority of the event based data collection and also enabled the use of modelled streamflow data. Loads were modelled using streamflow data estimated using the IHACRES rainfall-runoff model described previously in Chapter 4. Results are presented in Table 5-6.

The streamflow inputs used for estimating pollutant loads have potentially important implications on load estimates. Two investigations of the influence of streamflow inputs are made in this section. The first is an investigation of the influence of the temporal resolution of streamflow data on the predicted loads in the Burra Creek subcatchment. Results for that investigation are presented in Table 5-7. The second investigation compares the use of modelled versus observed data in the same catchment. Table 5-8 shows the results of that comparison. The Burra Creek catchment was selected for these two additional investigations as it has observed streamflow data at hourly and daily resolution spanning the load modelling period.

Table 5-6 Calculated suspended sediment loads for Burra and Jerrabomberra Creek subcatchments.

<table>
<thead>
<tr>
<th>Method</th>
<th>Sediment Load (ty⁻¹)</th>
<th>Ratio Burra / Jerrabomberra</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Burra Creek</td>
<td>Jerrabomberra Creek</td>
</tr>
<tr>
<td>1</td>
<td>$3.00 \times 10^3$</td>
<td>$3.09 \times 10^3$</td>
</tr>
<tr>
<td>2</td>
<td>$2.40 \times 10^3$</td>
<td>$1.99 \times 10^3$</td>
</tr>
<tr>
<td>3</td>
<td>$3.23 \times 10^3$</td>
<td>$2.48 \times 10^3$</td>
</tr>
</tbody>
</table>

The results presented in Table 5-6 show that there is close agreement between the estimate of the total suspended sediment load exported from each catchment irrespective of the calculation method. Using the linear estimation technique (Method 1), the export from the Burra Creek was estimated slightly lower than for Jerrabomberra Creek whereas for non-linear techniques (Methods 1 and 2) the Burra Creek estimate was higher. The total loads predicted using Method 3 are consistently higher than those predicted by Method 2. This illustrates the potential problem of underestimation that Ferguson (1986) identified when models are fit to the logarithm of pollutant concentration inputs.
Further consideration of these results, including a comparison with the load estimates modelled in Chapter 6, is made in Section 7.2.5.

Table 5-7 Comparison of the influence of the temporal resolution of data inputs on the suspended sediment load for the Burra Creek subcatchment. Streamflow inputs are observed data.

<table>
<thead>
<tr>
<th>Method</th>
<th>Sediment Load (ty⁻¹)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hourly Streamflow</td>
<td>Daily Streamflow</td>
</tr>
<tr>
<td>1</td>
<td>$5.79 \times 10^3$</td>
<td>$3.41 \times 10^3$</td>
</tr>
<tr>
<td>2</td>
<td>$3.97 \times 10^3$</td>
<td>$2.61 \times 10^3$</td>
</tr>
<tr>
<td>3</td>
<td>$4.91 \times 10^3$</td>
<td>$3.39 \times 10^3$</td>
</tr>
</tbody>
</table>

Table 5-7 presents a comparison of the influence of the temporal resolution of streamflow data inputs to each of the models. Significant differences can be seen between loads calculated using hourly and daily streamflow inputs. Loads calculated using hourly streamflow data are higher than those calculated using daily streamflow (up to a factor of 1.7). The variation occurs because streamflow events typically have a duration of less than one day.

Hourly streamflow data should give a more reliable estimate of pollutant loads. However, hourly observed streamflow data is available for only a limited period at most sites and modelled streamflow estimates are generally unavailable at hourly resolution because of the difficulties in obtaining appropriate rainfall inputs. Further research is required to investigate how to correct loads estimated using daily streamflow data in catchments where events are typically of a duration of less than one day. Such methods may involve correction of streamflow inputs based on the analysis of the streamflow distribution using flow duration curves. Modifications to streamflow inputs are needed that change the distribution of daily flows so that they match more closely the distribution of flows at hourly time intervals.

The final comparison made in this section investigates the use of modelled versus observed streamflow data for calculating sediment loads. The results of the comparison are presented in Table 5-8. There is generally close agreement between loads calculated using modelled and observed streamflow in the Burra Creek subcatchment. To develop good pollutant load estimates, inputs of modelled streamflow data must reproduce both the total volume of streamflow and also the distribution of flow across the simulation period. It was seen in Chapter 4 that generally both the total streamflow volume and the distribution of flow across
the simulation period were well represented using the IHACRES model. Therefore these data are appropriate for basing pollutant load calculations.

**Table 5-8 Comparison of the influence of modelled versus observed data inputs on the suspended sediment load for the Burra Creek subcatchment.**

<table>
<thead>
<tr>
<th>Method</th>
<th>Sediment Load (ty⁻¹)</th>
<th>Ratio (Observed / Modelled)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed Streamflow</td>
<td>Modelled Streamflow</td>
</tr>
<tr>
<td>1</td>
<td>$3.41 \times 10^3$</td>
<td>$3.00 \times 10^3$</td>
</tr>
<tr>
<td>2</td>
<td>$2.61 \times 10^3$</td>
<td>$2.40 \times 10^3$</td>
</tr>
<tr>
<td>3</td>
<td>$3.39 \times 10^3$</td>
<td>$3.23 \times 10^3$</td>
</tr>
</tbody>
</table>

Comparison of the results of Table 5-7 and Table 5-8 shows that the temporal resolution of the streamflow inputs rather than the source of streamflow data (observed or modelled) is of greater importance in determining pollutant loads.

### 5.4.5 Load Calculation Discussion

In this section three methods were applied to estimate the suspended sediment export from both the Burra and Jerrabomberra Creek subcatchments. A linear regression method relating suspended sediment concentration to streamflow (Method 1) showed the highest agreement with observed concentration data in both subcatchments. Using Method 1, the export of suspended sediment from the Burra and Jerrabomberra Creeks was estimated for a 10-year period beginning in 1988, yielding values of $3.00 \times 10^3$ and $3.09 \times 10^3$ ty⁻¹ respectively. The comparison of these results with the SedNet-UM model is presented in Chapter 7.

An investigation of the implication on loads calculated using streamflow data with an hourly rather than a daily resolution was also investigated. The use of daily data has the effect of underestimating total pollutant loads relative to hourly data. Hourly data are thought more appropriate for load calculation and research has been suggested to establish methods for correction of loads calculated using daily data. A second investigation of modelled inputs argued that, provided the total flow volume and the distribution of flow is adequately reproduced in modelled streamflow data, there is little difference in resultant load estimates.

### 5.5 Chapter Discussion

Pollutant load estimates provide important information on which to base remediation efforts and support more sophisticated pollutant load modelling. A literature review of a variety of
techniques of load estimation has been made in this chapter. Regression-based techniques were thought most appropriate in situations of limited concentration data and where there is a need to extrapolate outside of the data collection period. The accuracy of any estimate of pollutant load depends on both the applicability of the method used and the volume and collection characteristics of the available concentration data. A common requirement for each load modelling technique is water quality data spanning a range of hydrologic conditions. Section 5.2 described how the water quality collection programs currently in place in the upper Murrumbidgee are severely limiting for anything other than assessing ambient water quality i.e. low flow conditions. This is illustrated by the fact that only two sites in the study catchment satisfied the criteria established in Section 5.4.1 for undertaking pollutant load estimation.

Work needs to be done to bridge the gap between those who collect such water quality data and those who use it for research and management. The conclusions reached by Letcher et al. (2002) and Croke et al. (2000) with respect to water quality monitoring are to a large extent supported by the research presented here:

- improved coordination of monitoring activities is necessary to ensure that the data is useful for answering management questions and progressing associated model development;
- design of monitoring programs needs to be coordinated with collection agencies and researchers;
- implementation of longer monitoring periods over a broad range of hydrologic conditions is necessary for accurate modelling of pollutant loads;
- nested networks of streamflow and water quality collection programs are required to allow in-stream processes to be investigated; and
- short term high temporal frequency monitoring of rainfall, streamflow and pollutant concentration are required to assess better the relationship between storm intensity, rate of river rise and pollutant generation.

A cost-effective monitoring program using siphon sampling equipment in the Molonglo and Gudgenby Rivers has been described in this chapter. The program illustrates the potential for the collection of useful data with only modest investment. Unfortunately, due to generally low rainfall over the monitoring period, insufficient data was collected to generate reliable estimates of suspended sediment loads and the full potential of the program was not realised.

Using existing event based water quality data together with modelled streamflow data at two sites in the upper Murrumbidgee catchment, an estimate of the suspended sediment load has
been made. Under the assumption that water quality at the time of sampling is representative of the modelled period, suspended sediment exports from the Burra and Jerrabomberra Creek catchments have been estimated at \(3.00 \times 10^3\) and \(3.09 \times 10^3\) ty\(^{-1}\) over the monitoring period. It should be noted that the calculation of sediment loads in the Burra and Jerrabomberra Creek subcatchments has neglected the bedload component of the sediment budget as the available data was limited to suspended sediment concentration.

The results from this chapter are discussed further in Chapter 7 where a comparison is made with the results from application of the SedNet-UM model in the study catchment. This chapter has illustrated the scarcity of appropriate pollutant concentration data. For this reason models are required that can provide useful information on pollutant loads with only sparse data inputs. In the following chapter a conceptual semi-distributed modelling approach that has modest data requirements is presented for quantifying pollutant load export. The chapter provides a description of the model and the sensitivity analysis methods developed for testing it.
Chapter 6 Landscape Based Modelling

The introductory chapters of this thesis discussed the significant alteration of catchments, streams and associated ecosystems of Australia that has occurred since European settlement. These changes have resulted in the extensive degradation of aquatic habitat and water quality. Remediation is time consuming, expensive and often poorly focussed. For the effective focusing of on-site work to repair degradation of riparian ecosystems, an improved understanding and quantification of the generation of fluxes from upland catchments is required. Particularly important in land and water management applications are tools that spatially identify sources and transport of pollutants.

The recently developed Sediment River Network Model (Prosser et al., 2001a; Prosser et al., 2001c) provides a new and promising approach to estimating the sources and transport of sediment at catchment scales. However, systematic testing of the complete model and some of its components is lacking. Such testing is required to develop an improved understanding of the behaviour of the model, to assist in prioritising model development activities and to gauge the level of confidence in the outputs from the model.

This chapter describes the SedNet model and sensitivity analysis methods used to improve understanding of the model. Results of an application of the model in the upper Murrumbidgee catchment and sensitivity analysis of the model are presented. The final sections of the chapter suggest improvements to the model.

6.1 Sediment River Network Model

SedNet, the Sediment River Network Model, is a model used to estimate the propagation and deposition of sediment sourced from riverbanks, gully and hillslope sources through a river network. The SedNet model is fully described by Prosser et al. (2001a) and Prosser et al. (2001c). The model was specifically developed for application at the continental scale for the Australian National Land and Water Resources Audit (NLWRA) (see: http://www.nlwra.gov.au).

Management Applications

Outputs from the SedNet model are intended to be used to address catchment scale resource management questions, such as determining which subcatchments dominate the supply of sediment, where sediment is stored in a catchment, the proportion of sediment supplied by
various erosion processes and, importantly, how management change may alter downstream sediment yields (Prosser et al., 2001a; Prosser et al., 2001c). The results from the SedNet model, when displayed within a GIS, show spatial patterns of sediment entrainment, stream sediment loads and deposition across a catchment. In this form results enable land managers to prioritise effectively on-ground works aimed at reducing sediment loads where necessary.

6.1.2 Model Description

The basic unit of calculation of the SedNet model is a link in a river network. A river link is the reach of a river between any two stream junctions (or nodes) as shown in Figure 6-1. Each river link has an internal catchment, from which sediment may be delivered from hillslope and gully erosion sub-models. Using physical attributes associated with the link, streambank erosion, floodplain deposition and sediment transport capacity sub-models are used to estimate the propagation of sediment through the river network. Also shown in Figure 6-1 is the Shreve stream magnitude number (Shreve, 1966) corresponding to each river link. SedNet processes river links in increasing order of their magnitudes.

The SedNet model is intended for application at catchment to continental scales. For example, in application in the NLWRA (Prosser et al., 2001a), first-order streams had contributing areas of 25-50 km² and streams were broken into reaches of approximately 10 km in length. Drainage-division-specific parameterisation of the model was used in that application.

The model has been applied widely within Australia to estimate long-term sediment loads for individual river reaches, using simple conceptual and empirical models of sediment detachment, transport and deposition. SedNet is a steady-state model. The SedNet model incorporates three sediment-source (erosion) sub-models: hillslope, gully and streambank. Suspended sediment load delivered to the river network is estimated from all three source models. Bedload sediment is sourced from only the gully and streambank models; hillslope erosion is assumed to deliver no bedload sediment to the stream network. The transport and deposition of suspended and bedload sediment fractions are modelled separately through the river network. Suspended sediment is removed from the stream network by deposition, estimated using floodplain and reservoir deposition sub-models. All suspended sediment that is not deposited is routed downstream through the stream network. Bedload is routed through the river network using a sediment transport capacity sub-model. Streamflow regimes are represented within SedNet using a simple sub-model that estimates key hydrologic variables for each link in the stream network. These variables represent the various influences of river hydrology on sediment transport, and are thus a critical component of the model. Greater detail on each of the sub-models is presented in Section 6.1.3.
Figure 6-1 Elements of the SedNet model - river links, stream magnitude and internal catchment areas. Diagram modified from Prosser et al. (2001a).

Model implementation

SedNet is coded in the Arc Macro Language (AML), the scripting language of the ARC/INFO GIS program. Several separate sub-programs are used to define river networks and their subcatchments, import data, implement the model and compile the results (Prosser et al., 2001a). Figure 6-2 shows the order of processing and functionality of the sub-programs of the SedNet model.

The principal input to the first SedNet sub-program is elevation data in the form of a DEM. The DEM data are used to define river networks and to attach physical attributes to each stream link, for example length and average slope. The first sub-program also intersects reservoir and lake coverages with the river network to label links corresponding to reservoirs and lakes; these links are then modelled differently. The second sub-program numbers river links defined in the first sub-program. A consistent numbering system is necessary to order the processing of the model links. The third SedNet sub-program is used to attach to each river link data about its corresponding internal subcatchment. Input data to this sub-program
includes spatial hillslope erosion estimates, riparian vegetation, rainfall surfaces, gully density and floodplain data, generally in the form of raster based data. The final sub-program implements the sub-models as described in the following sections. The final sub-program works sequentially through the river network beginning with first order streams. Working sequentially from lower-order streams enables upstream tributary contributions to be used as inputs to the modelling of downstream links.

**Figure 6-2 Diagram of the sub-programs and data inputs to the SedNet model.**

**Suspended Load Versus Bedload**

The SedNet model estimates the propagation of suspended load and bedload separately. Prosser *et al.* (2001a) describes suspended load as suspended textured sediment carried at relatively uniform concentration through the water column during flows. The supply of sediment rather than the transport capacity of a river generally limits the transport of suspended sediment (Lawson and O'Neill, 1975). With respect to suspended sediment, it is assumed that because of the relatively high velocities, and hence low residence times, river systems have reached steady state conditions (Prosser *et al.*, 2001a). Supply of suspended sediment is estimated from the sum of hillslope, gully and riverbank erosion sub-models. Suspended sediment is removed from the stream network by deposition, estimated using a floodplain deposition sub-model. All suspended sediment not deposited is routed downstream through the stream network.

Bedload is sediment transported in greatest proportions near the bed of a river. The relatively high residence time of bedload sediment in river networks results in transient deposition as sediment is moved through a river network (Prosser *et al.*, 2001a). Excess supply of bedload sediment is modelled as stored (deposited) on the bed of the river.
6.1.3 Sub-Model Description

This section describes each of the seven SedNet sub-models.

**Gully Erosion Sub-Model**

The contribution of sediment to a river link \((x)\) from gully erosion is estimated by:

\[
G_x = \frac{1000 \times A_x \times \alpha \times P_r \times \rho}{\tau}
\]

where \(G_x\) is mean annual sediment delivery to the river link \((\text{ty}^{-1})\); \(A_x\) is the area of the link internal subcatchment \((\text{km}^2)\), \(\alpha\) is mean cross sectional area of gullies \((\text{m}^2)\); \(P_r\) is the gully density of the internal subcatchment; \(\rho\) is bulk density of eroded sediment \((\text{t} \cdot \text{m}^3)\) and \(\tau\) is the age of the gully \((\text{years})\).

**Hillslope Erosion Sub-Model**

The contribution of suspended sediment from the internal catchment of a river link resulting from sheet wash and rill erosion (hillslope) is estimated by applying a hillslope sediment delivery ratio to the results of total hillslope erosion modelling (total hillslope erosion estimates are generally generated using USLE based models). The contribution of suspended sediment from hillslope erosion to a river link \((x)\) is given by:

\[
H_x = Y \times H_{E,x}
\]

where \(H_x\) is hillslope erosion delivery to the river network, \(Y\) is the sediment delivery ratio and \(H_{E,x}\) is the total hillslope erosion estimate across the internal subcatchment of individual river links.

**Streambank Erosion Sub-Model**

Streambank erosion for each river reach is estimated using a lateral bank erosion rate together with attributes of the river link. Parameters for calculating the lateral erosion rate are taken from the review of Rutherfurd (2000). The following equation is used to calculate the sediment mass contributed to the river link from streambank erosion:

\[
B_x = a \times Q_{1.58,x}^{c} \times L_x \times h \times \rho \times (1 - V_x)
\]
where $B_X$ is the mass of sediment sourced from bank erosion over the reach, $a$ and $c$ are lateral migration constants, $Q_{1.58,x}$ is the estimated 1.58-year-recurrence interval flow (used as an estimate of bankfull streamflow for the link), $L_x$ is the link length (km), $h$ is bank height (m), $\rho$ is the in situ sediment bulk density and $V_x$ is the proportion of intact riparian vegetation along the river link.

**Sediment Transport Capacity Sub-Model**

The capacity of a link to transport bedload sediment is estimated using the following equation:

$$T_x = \frac{k S_x^{1.3} \sum Q_x^{1.4}}{\omega w_x^{0.4}} \quad 6-4$$

where $k$ is a constant, $S_x$ is the energy gradient (approximated as the sine of the channel slope), $\sum Q_x^{1.4}$ is the mean annual sum of daily values of $Q_x^{1.4}$, $w_x$ is the mean channel width of the link and $\omega$ is the settling velocity of bedload particles (ms$^{-1}$).

**Floodplain Deposition Sub-Model**

Deposition of sediment on the floodplain adjacent to each river link is estimated using the following equation:

$$D_x = \frac{Q_{f,x}}{Q_x} F_x \left( 1 - e^{-\left( \frac{v d_{f,x}}{Q_{f,x}} \right)} \right) \quad 6-5$$

where $D_x$ is the total deposition on the flood plain over the reach (ty$^{-1}$), $Q_{f,x}$ is the floodplain streamflow of the link, $Q_x$ is total streamflow of the link, $F_x$ is the total suspended sediment delivered to the river link, $v$ is sediment settling velocity, $A_{f,x}$ is the floodplain area of the corresponding river link.

**Hydrology Sub-Model**

The following hydrologic variables are required for each individual river link:

- mean annual flow ($\bar{Q}_x$);
• sediment transport capacity discharge ($\sum Q_x^{1.4}$);

• bankfull streamflow ($Q_{BF}$); and

• median overbank streamflow ($Q_{OB}$).

The Prosser et al. (2001a) application of the SedNet model in the NLWRA used a rudimentary hydrology sub-model. This was necessary to provide the requisite broad coverage of Australia. Inputs for the NLWRA application were mean annual rainfall calculated from grids of daily rainfall provided by the Queensland Department of Natural Resources (Prosser et al., 2001a).

Mean annual flow estimates were made from upstream catchment area and spatially averaged mean annual rainfall for each link according to the following equation:

$$\bar{Q}_x = k A_u^m R_u^n$$

where $\bar{Q}_x$ is mean annual flow of the link, $A_u$ is upstream area, $R_u$ is spatially averaged mean annual rainfall of the upstream area and $k$, $m$ and $n$ are constants.

As detailed previously, calculation of sediment transport capacity for each river link requires input of the mean annual sum of $Q_x^{1.4}$. The value of $\sum Q_x^{1.4}$ for each river link is estimated from the following equation:

$$\sum Q_x^{1.4} = t A_u^p R_u^b$$

where $t$, $p$ and $b$ are constants.

Prosser et al. (2001a) has expressed $\sum Q_x^{1.4}$ as a function of mean annual flow ($\bar{Q}_x$) rather than using the above equation. In practice, for analysis of the model, the value of $\sum Q_x^{1.4}$ is determined, as it is in the SedNet code, using the above equation.

Bankfull streamflow is used in the SedNet model to predict the rate of bank erosion and to separate flood flows from in-channel flows. Bankfull streamflow has also been expressed as a function of $\bar{Q}_x$ by Prosser et al. (2001a). Again for practical reasons, its value is determined using the following equation:

$$Q_{BF,x} = r A_u^d R_u^f$$
Median overbank streamflow, used to predict mean annual floodplain deposition, is estimated using the following equation:

\[ Q_{OB,x} = y A_u^z R_u^l \]  \hspace{1cm} (6-9)

**Reservoir Deposition Sub-Model**

Where applicable, the SedNet model includes a reservoir/lake trap efficiency sub-model based on the model of Brune (1953) to estimate sediment deposition in reservoirs. Reservoirs are represented as a link in the river network corresponding to the reservoir. No bedload is passed through a reservoir by the model. The proportion of suspended load that is trapped by the reservoir is calculated using the following equation:

\[ T_E = -22.0 + \frac{119.6 C/I}{0.012 + 1.02 C/I} \]  \hspace{1cm} (6-10)

where \( T_E \) is trap efficiency (%), \( C \) is the volume of the reservoir (ML) and \( I \) is the mean annual input streamflow (ML).

**Parameter Values**

The SedNet model has approximately 20 parameters. All parameter values are provided from empirical or theoretical prior knowledge, and they are not (as yet) calibrated against field measurements (Prosser *et al.*, 2001c). A discussion of each of the SedNet parameters, including description of their probable ranges, is found in the following sections. Table 6-1 lists the SedNet parameters, their current value and probable ranges. The estimated range of parameter values will be used to guide the sensitivity analysis and interpretation of the results.

**Gully Cross Sectional Area \( \alpha \)**

Prosser *et al.* (2001c) uses a value of 10m\(^2\) as an estimate of gully cross sectional area. That value has been used in this study. A mean gully cross sectional area of 14.3m\(^2\) has been estimated from 14 observations in the nearby Ben Chifley Dam catchment (Letcher *et al.*, 2001), however, with only a limited number of gullies surveyed, it is difficult to draw inferences for the upper Murrumbidgee catchment.
Landscape Based Modelling

Gully Age $\tau$

An average gully age of 100 years is used as a parameter in the SedNet model (Prosser et al., 2001c). For the upper Murrumbidgee catchment this appears to be a reasonable estimate when historic reports on gully initiation are considered. The main gully erosion phase in the upper Murrumbidgee catchment was in the period between European settlement (the mid-1820's) and late 1800's (Starr et al., 1999). During that time most gullies are thought to have reached close to their maximum depth and width (Starr et al., 1999). In the upper Murrumbidgee, the first aerial photography dates from the mid-1940's and, when compared with more recent photography, confirms that the majority of gullies had reached their maximum headward extent before the mid-1940's (Eyles, 1977). Gully initiation is however still occurring at a limited number of sites in the catchment (Starr et al., 1999).

Sediment Bulk Density $\rho$

Experimental data on sub-soil bulk density has been used as a basis for fixing a value for the $\rho$ parameter. A mean sub-soil bulk density of approximately 1.5$\text{m}^{-3}$ has been calculated from Australia-wide sampling; the associated 95% confidence interval has a range between 1.0 - 1.9 $\text{m}^{-3}$ (N. McKenzie pers com 31/1/02). A parameter value of 1.5 $\text{m}^{-3}$ is used for $\rho$.

Suspended to Bedload Ratio $\delta$

SedNet does not distinguish between suspended and bedload on the basis of a particular particle size threshold (Prosser et al., 2001c). Because of the lack of a particle size threshold, measurements of soil texture provide only a guide to the probable range of the ratio. The suspended to bedload ratio may also have significant spatial variation through a river network. A value of 0.5, apportioning suspended and bedload fractions equally, is used.

Bank Erosion Constants $a, c$

The review of Rutherfurd (2000) was used as the basis for evaluating the bank erosion constants $a$ and $c$. The bank erosion constants of Rutherfurd (2000) were constructed from a worldwide data set that included only 3 data points from Australian river systems.

Bank Height $h$

In the absence of comprehensive data on bank heights of Australian rivers an estimate of streambank height of 3m is used as a parameter value.
A sediment delivery ratio of 0.05 has been used for parameterisation of the SedNet model (Prosser et al., 2001c). This parameter is applied to total hillslope erosion estimates for individual internal subcatchments. Conceivably the ratio can take any value between 0 and 1. Unfortunately, there are few reported values of sediment delivery ratios in Australia and these are all to a large extent dependent on the method used for hillslope erosion modelling or measurement. Because of this uncertainty, \( Y \) was used as a calibration variable in the NLWRA application to match observed sediment loads in rivers.

In a comprehensive review of the sediment transport capacity exponents \( \beta \) and \( \gamma \) made by Prosser and Rustomji (2000), it was observed that 95% of all published values ranged between 1 and 2 for both parameters. Values of 1.4 are used for parameterisation of both \( \beta \) and \( \gamma \) within SedNet.

The model of Dietrich (1982) is used for parameterisation of the settling velocity of sediment on the floodplain environment. The settling velocity used is that estimated for silt sized particles: \( 1 \times 10^{-6} \text{ ms}^{-1} \). For SedNet-related applications the major determinant of settling velocity in the Dietrich (1982) model is the assumed size of the sediment particle.

The hydrologic parameters of SedNet have been estimated by Young et al. (2001) from simulated daily flows generated by Peel et al. (unpublished). The simulated flows were used by Young et al. (2001) to derive regional relationships for \( Q_s \) and then these were related to the other hydrologic parameters assuming a power law relationship. The regionalisation of rainfall-runoff modelling is described in Peel et al. (unpublished). Discussion and comparison of Peel et al. (unpublished) research with this study has already been made in Section 4.8. Refer to Table 6-1 for the values of the SedNet hydrologic parameters.

The errors reported by Young et al. (2001) in estimating the hydrologic parameters of SedNet do not take account of the errors in the hydrologic models on which they are based. The importance of the hydrologic parameters will become apparent later in the thesis and will be discussed in some detail (see Chapter 8).
### Table 6-1 Summary of SedNet parameters and probable ranges.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-model</th>
<th>Description</th>
<th>Prosser <em>et al.</em> (2001a) Value</th>
<th>Estimated Range of Mean</th>
<th>SedNet Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Gully</td>
<td>Gully cross section area</td>
<td>10 m$^2$</td>
<td>5 - 20</td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>Gully</td>
<td>Gully age</td>
<td>100 yrs</td>
<td>70 - 150</td>
<td></td>
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<tr>
<td>$\rho$</td>
<td>Gully &amp; Bank</td>
<td>Sediment bulk density</td>
<td>1.5 tm$^3$</td>
<td>1.0 - 1.9</td>
<td>rho</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Gully &amp; Bank</td>
<td>Suspended to bedload ratio</td>
<td>0.5</td>
<td>0.3 - 0.7</td>
<td>pcs</td>
</tr>
<tr>
<td>$a$</td>
<td>Bank</td>
<td>Constant</td>
<td>0.008</td>
<td></td>
<td>bank_a</td>
</tr>
<tr>
<td>$c$</td>
<td>Bank</td>
<td>Exponent</td>
<td>0.6</td>
<td></td>
<td>bank_c</td>
</tr>
<tr>
<td>$h$</td>
<td>Bank</td>
<td>Bank height</td>
<td>3 m</td>
<td>1 - 5</td>
<td>bheight</td>
</tr>
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<td>$Y$</td>
<td>Hillslope</td>
<td>Sediment delivery ratio</td>
<td>0.05</td>
<td>0.01 - 0.5</td>
<td>hsrdr</td>
</tr>
<tr>
<td>$\beta$</td>
<td>STC</td>
<td>Exponent</td>
<td>1.4</td>
<td>1 - 2</td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>STC</td>
<td>Exponent</td>
<td>1.4</td>
<td>1 - 2</td>
<td></td>
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<tr>
<td>$v$</td>
<td>Flood plain</td>
<td>Sediment settling velocity</td>
<td>$10^{-6}$ ms$^{-1}$</td>
<td>$10^{-7}$ - $10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>$k$</td>
<td>Hydrology</td>
<td>Constant - mean annual flow</td>
<td>$1.62 \times 10^{-5}$</td>
<td>-</td>
<td>k8</td>
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<tr>
<td>$m$</td>
<td>Hydrology</td>
<td>Area exponent - mean annual flow</td>
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<td>-</td>
<td>s</td>
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<td>$n$</td>
<td>Hydrology</td>
<td>Rainfall exponent - mean annual flow</td>
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<td>-</td>
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<td>$t$</td>
<td>Hydrology</td>
<td>Constant - mean annual sum $Q^{1.4}$</td>
<td>$1.25 \times 10^{8}$</td>
<td>-</td>
<td>k2</td>
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<td>$b$</td>
<td>Hydrology</td>
<td>Rainfall exponent - mean annual sum $Q^{1.3}$</td>
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<td>$p$</td>
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<td>Area exponent - mean annual sum $Q^{1.4}$</td>
<td>1.31</td>
<td>-</td>
<td>b</td>
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<td>$r$</td>
<td>Hydrology</td>
<td>Constant - bankfull streamflow</td>
<td>$7.62 \times 10^{8}$</td>
<td>-</td>
<td>k4</td>
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<td>$f$</td>
<td>Hydrology</td>
<td>Rainfall exponent - bankfull streamflow</td>
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<td>-</td>
<td>f</td>
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<td>$d$</td>
<td>Hydrology</td>
<td>Area exponent - bankfull streamflow</td>
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<td>-</td>
<td>c</td>
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<tr>
<td>$y$</td>
<td>Hydrology</td>
<td>Constant - median overbank streamflow</td>
<td>$6.84 \times 10^{7}$</td>
<td>-</td>
<td>k7</td>
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<tr>
<td>$l$</td>
<td>Hydrology</td>
<td>Rainfall exponent - median overbank streamflow</td>
<td>0.91</td>
<td>-</td>
<td>h</td>
</tr>
<tr>
<td>$z$</td>
<td>Hydrology</td>
<td>Area exponent - median overbank streamflow</td>
<td>2.48</td>
<td>-</td>
<td>g</td>
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</table>
6.2 Upper Murrumbidgee Application

The SedNet model has been applied over the upper Murrumbidgee River catchment as a tool for improving land and water management and also to enable further analysis and development of the model. The application of SedNet made in this research has been called SedNet-UM to distinguish it from the NLWRA application of Prosser et al. (2001a). The application is used as the focus of sensitivity analysis described in Section 6.3. In addition to the sensitivity analysis, the model has been applied to compare with data collected, analysed and described in Chapter 5. The accuracy assessment and comparison with this and other data is made in Chapter 7.

Input data for the application in the upper Murrumbidgee catchment was based on data sets used in the NLWRA and described by Prosser et al. (2001a). This included hillslope erosion estimates sourced from Lu et al. (2001). Some catchment specific modifications have been made:

- A DEM with a 25m cell size has been used in preference to the 250m DEM used in the NLWRA. This finer resolution data enables stream networks to be more accurately defined spatially, resulting in changes to some link characteristics. Of particular note is that when using 25m data, estimates of stream length and elevations are improved.

- Measurements of stream width from the Murrumbidgee catchment were used as an input to the model (unpublished data from P Rustomji). Stream width was predicted as a function of upstream area using the following equation:

\[
w = 2.4 \times A_u^{0.43} \quad 6-11
\]

where \( w \) is channel width and \( A_u \) is upstream contributing area (km\(^2\)).

- Catchment specific parameterisation of the hydrology of the upper Murrumbidgee was used in the calculation of \( \sum Q_s^{1.4} \):

\[
\sum Q_s^{1.4} = 1.26 \times 10^{-8} A_u^{1.31} R_u^{3.47} \quad 6-12
\]

- Gully erosion mapping extending over the catchment was used as input for estimating gully erosion density. This was in preference to the inputs of the NLWRA (modelled density estimates). Mapped data was sourced from the NSW Department of Land and Water Conservation, with mapping undertaken at a nominal scale of 1:100 000.
6.2.1 Results

The SedNet-UM model has been applied using the parameter values of Table 6-1 and data inputs as described previously. Model outputs at a variety of sites are shown in Table 6-2. For consistency between chapters, the sites selected correspond to established stream gauge locations. Estimates of bedload, channel deposition, suspended sediment load and the amount of floodplain deposition are presented in the table. Note that estimates for the gauge locations correspond to the outputs for the corresponding stream reach.

Not surprisingly, sediment load estimates generally increase with increasing area. However, there are several exceptions at sites in Table 6-2. The exceptions are in the most part due to the influence of up-stream reservoirs and in-channel deposition of bedload sediment. An example is the influence that the Cotter Dam has on bedload sediment output at site 410700. Because of the relatively undisturbed catchment of the Goodradigbee River, outputs of the SedNet-UM model at site 410088 also show relatively low sediment loads. Whilst considering Table 6-2 it is worthwhile to note that the floodplain deposition depth presented in the Table has such a limited range of different values because of rounding.

Figures 6-3 to 6-5 show spatial results from the application of the SedNet-UM model in the upper Murrumbidgee River catchment. Figures showing mean annual bedload sediment outputs (Figure 6-3), mean annual sediment loads (Figure 6-4) and the depth of in-channel deposition (Figure 6-5) are presented. The figures show the features discussed in the previous paragraph. The influence of sediment deposition on the bedload export can be seen by comparing Figure 6-3 with Figure 6-5. Where in-channel deposition occurs, the corresponding bedload sediment export is reduced.

Using the SedNet-UM model the total delivery of bedload sediment to Burrinjuck Dam from Mountain and Warroo Creeks and the Yass, Murrumbidgee and Goodradigbee Rivers has been estimated to be a total of $2.15 \times 10^5$ ty$^{-1}$. The corresponding suspended load delivery to the Burrinjuck Dam is $4.13 \times 10^5$ ty$^{-1}$.

The results from application of SedNet-UM in the study catchment are discussed in some detail in Chapter 7 where they are compared with other observed and modelled results. The comparison includes discussion of the spatial patterns of the results.
## Table 6-2 SedNet-UM model outputs at various sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Approximate Area (km²)</th>
<th>Bedload (kt/y)</th>
<th>In-Channel Deposition (m)</th>
<th>Suspended Load (kt/y)</th>
<th>Floodplain Deposition (mm/y)</th>
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<td>410024</td>
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<td>0</td>
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Figure 6-3 Modelled annual average bedload sediment budget from application of the SedNet-UM model.
Figure 6-4 Modelled annual average suspended load sediment budget from application of the SedNet-UM model.
Figure 6-5 Modelled depth of in-channel sediment deposition from application of the SedNet-UM model.
6.3 Sensitivity Analysis

The following sections describe sensitivity analysis of the SedNet-UM model. The sensitivity analysis is used to develop an improved understanding of the behaviour of the model. This work, together with the comparison of the application of SedNet-UM with collateral data, assists in prioritising model development activities. This section begins with a review of sensitivity analysis approaches to provide a context for examination of the SedNet-UM model.

6.3.1 Background

Sensitivity analyses are formalised procedures to identify the impact of changes in model inputs and components on a model's output (Rose, 1993; Thornton, 1993). Sensitivity analysis forms an important part of the model validation process through evaluating where model development and data gathering activities should be focused. Beres and Hawkins (2001) point out that recommendations based upon a model without an explicit sensitivity analysis lack foundation. Along similar lines, Saltelli (2000) contends that sensitivity analysis is a prerequisite for model building in any setting and in any field where models are used.

Sensitivity analysis can be used to give insights to the following types of questions:

- Does the model resemble the system or process under study (Saltelli, 2000)?
- Which of the parameters, data inputs and model components exert a significant influence on the output variables (Beres and Hawkins, 2001)?
- Which parameters, data inputs and model components are inconsequential (Beres and Hawkins, 2001)?
- Do changes in specific combinations of model parameters produce unexpectedly large influences on results i.e. are there interactions between model components?

Parameters or processes to which the model output is sensitive and which have significant uncertainty may require special attention in estimation. Conversely, it is also important to identify those parameters or processes that have little influence on the behaviour of the model, and that may be aggregated, modified or removed. As a whole, sensitivity analysis is used to increase confidence in a model and its predictions, by improving understanding of the behaviour of a model (Saltelli, 2000).

A wide range of model sensitivity analysis techniques are described in the literature. Saltelli (2000) and Campolongo et al. (2000) provide complementary and comprehensive introductions to the topic. Several environmental modelling applications are also described in the wider literature. Examples include:
Rustomji and Prosser (2001) have investigated the sensitivity of a sediment transport capacity model used to predict the spatial patterns of sediment delivery to valley floors.

Crosetto et al. (2000) have described the use of sensitivity analysis on a GIS-based, distributed hydrologic model.


Beres and Hawkins (2001) have illustrated various sensitivity analysis methods on an ecological population model.

Baginska et al. (2001) have applied the non-linear parameter estimation code (PEST) for sensitivity testing to determine and assess the importance of parameters of the AnnAGNPS model.

Dorner et al. (2001) have performed Monte Carlo simulations to investigate the influence of parametric uncertainty on the results of a non-point source pollution model.

Spear and Hornberger (1980) have carried out sensitivity analysis on a phosphorous-based model of eutrophication processes in the Peel-Harvey Inlet of Western Australia.

van der Perk (1992) have investigated accuracy and uncertainty of a series of phosphate concentration water quality models using Monte Carlo simulations.

Wade et al. (2001) have used general sensitivity analysis to model the mechanisms that control in-stream phosphorus, macrophyte, and epiphyte dynamics using the Kennet model.

Even with numerous example applications, there is a general paucity of literature reviewing the methods of sensitivity analysis. Further, despite the acknowledged importance of sensitivity analysis, there is no single, well-accepted procedure on how it should be performed (Beres and Hawkins, 2001). This reflects the difficulty in generating sufficiently general approaches for sensitivity analysis across a broad range of model types and also difficulties in transfer and communication across scientific disciplines.

Campolongo et al. (2000) have identify three main settings where sensitivity analysis may be applied:

- *factor screening*, where the task is to identify influential factors in a system with many factors;

- *local sensitivity analysis*, where the emphasis is on the local impact of the factors of the model and involves the use of partial derivatives; and
- *global sensitivity analysis*, where the emphasis is on apportioning the output uncertainty to the uncertainty in the input factors.

There is redundancy in the above classification in the sense that many methods may be allocated to more than one category. Nonetheless, the classification provides a useful means of structuring the current review.

**Factor Screening**

Screening designs are preliminary numerical experiments whose purpose is to identify the most important factors from amongst a large number that may affect a particular model response (Campolongo *et al.*, 2000). Screening methods are useful for dealing with models containing a large number of factors. Often parameters are varied one at a time around standard (control) values and the magnitudes of residuals, defined as the difference between the perturbed experimental results and the control, are compared in order to evaluate the factors to which the model is significantly sensitive (Campolongo *et al.*, 2000). This type of screening method is similar in many respects to local sensitivity analysis techniques.

**Local Sensitivity Analysis**

Local sensitivity analysis is usually carried out by computing partial derivatives of model outputs with respect to the input factors. In order to compute the derivatives numerically, the input factors are varied within a small interval around a nominal value (Campolongo *et al.*, 2000). This is done by either mathematical analysis of a model or by running a model with perturbed values of the variable items. Commonly, individual model parameters and/or inputs are varied by some constant percentage whilst all others retain their original values. The relative change in model outputs is noted to determine the sensitivity of the model to the parameter change (Thornton, 1993). In this instance local sensitivity is defined as the gradient of output with respect to parameters and/or inputs, normalised by the ratios of their sizes so as to relate proportional, rather than absolute changes:

\[
\frac{\partial y}{\partial \theta_i} = \frac{\theta_{i0}(y_i - y_{i0})}{\delta \theta_i y_{i0}}
\]

where, \( \frac{\partial y}{\partial \theta_i} \) is the local sensitivity; \( y_i \) is the perturbed output; \( y_{i0} \) is the reference (control) output and \( \delta \theta_i \) is the perturbation of the \( i^{th} \) parameter.

The conceptual and practical simplicity of local sensitivity analysis accounts for its popularity, but it has limitations. Firstly, ratios of output changes to input or parameter
perturbations are useful only if the extent of the uncertainties in the input or parameter values are known fairly precisely, allowing representative perturbation sizes to be chosen. Failing that, if the relations between perturbed and output variables can be assumed linear, then effects scale with perturbation size and the combined influence of changes in two or more parameters or inputs can be found by superposing their individual effects. Sometimes neither is true: uncertainties often cannot be confidently quantified in advance, and perturbation-output relations are generally non-linear, perhaps sharply. A third limitation of local sensitivity analysis techniques is that for non-linear models gradient information is local (gradient is independent of where it is measured for linear models). Knowing a sensitivity for given perturbations about a given nominal parameter value does little to answer questions such as whether some quite different values would produce similar output behaviour, or what range of parameters or inputs would yield output behaviour which meets given conditions. Further information on general sensitivity analysis is given in a later section.

**Parameter Interactions**

Even when the sensitivity of an output to all individual parameters is investigated, investigating only one parameter at a time does not uncover potentially important interactions between parameters (Beres and Hawkins, 2001). Possibly significant effects could be produced by several parameters interacting in concert; such interaction effects can potentially be greater than the sum of the individual effects in question (Beres and Hawkins, 2001). Furthermore, these interactions may be caused by sets of what were not otherwise considered sensitive parameters (Beres and Hawkins, 2001).

These limitations of one at a time perturbation techniques, particularly for large or complex models, point to the need for alternative methods. Experimental designs that can reveal otherwise unknown parameter interactions are required. One method used for examining the effects of parameter interactions is the construction of a Hessian matrix which contains the second derivatives of the output:

$$h_{ij} = \frac{\partial^2 y}{\partial \theta_i \partial \theta_j}$$

(6-14)

where, $h_{ij}$ is element $(i, j)$ of the Hessian matrix $H$, $y$ model output; $\theta_i$ and $\theta_j$ are the $i$th and $j$th elements of the parameter vector respectively.
Construction of the Hessian matrix requires \( \frac{n(n-1)}{2} + n + 1 \) model runs to investigate interactions between \( n \) parameters. The matrix \( H \) is constructed as follows:

\[
\frac{\partial^2 y}{\partial \theta_i \partial \theta_j} \equiv \frac{y_{ij} - y_j - y_i + y_0}{\delta \theta_i \delta \theta_j}
\]

where, \( y_{ij} \) is the output from the model with perturbation of the \( i \) th and \( j \) th parameter, \( \delta \theta_i \) and \( \delta \theta_j \) are the perturbations in the \( i \) th and \( j \) th parameters respectively.

Whereas the first-order derivatives give the effect of individual parameter changes on the output, second-order derivatives allow investigation of parameter interactions. In addition, second-order derivatives can also be used to determine if the results of perturbations of individual parameters are linear.

**Global Sensitivity Analysis**

Global sensitivity techniques apportion uncertainties in model outputs to uncertainties in each input factor (Campolongo et al., 2000). Known or assumed uncertainty distributions for each factor provide the input for the analysis. The concept of global techniques is to find the set of values of the uncertain quantities over which model outputs remain within a specified range or satisfy a list of requirements more generally.

**6.3.2 Methods**

The complete SedNet-UM model, although widely applied, lacks a systematic testing of the sensitivities to its components and data inputs. This section describes how sensitivity analysis has been used to focus development of the SedNet-UM model. Research on model sensitivity has been undertaken to improve understanding of the behaviour of the model. This information will be used to simplify and improve the structure and parameterisation of SedNet-UM where possible. It is important to assess, for example, the extent to which errors in parameterisation of streambank and sediment transport sub-models in SedNet-UM flow through to estimates of sediment load. The application of SedNet-UM in the upper Murrumbidgee is used as a basis for the investigation.

Local sensitivity measures of the impacts of perturbations of the model parameters have been investigated. Trials have been carried out where sensitivities are investigated both one at a time and also where parameter interactions are investigated. In addition to developing understanding of the model, reference to this research will guide future sensitivity assessment.
To quantify the relative sensitivities, each individual parameter was perturbed one at a time by a constant proportion of its value whilst all others were fixed at their original value. The initial values of each parameter are those presented in Table 6-1. Four sets of perturbations around the value of each parameter were made (90%, 95%, 105%, and 110% of the original value). The estimated value of both the suspended and bedload sediment loads predicted with individually perturbed parameter values were written to file for each of the sites detailed in Table 6-3. The agreement in the pattern of sediment deposition in the outputs of each reach of the perturbed model runs was compared with the pattern in the non perturbed output. The overall agreement was expressed as a percentage of the total number or reaches.

To investigate potentially significant effects of parameter interactions, interdependencies between parameters of the SedNet-UM model were also investigated. This was undertaken by sequential perturbation of two parameters at a time. The corresponding outputs were recorded and analysed using local sensitivity measures already detailed in Section 6.3.1, Parameter Interactions.

The scope of the sensitivity analysis has been constrained for practical reasons. The analysis is confined to the SedNet-UM model parameters, i.e. no consideration is made of data inputs. The SedNet-UM model parameters investigated are those listed in Table 6-1. The reservoir deposition sub-model is not considered in the sensitivity analysis. It has been excluded because:

- the model has been well tested and is generally widely accepted (Ward et al., 1981);
- the reservoir deposition sub-model generally acts on only a limited number of river links within any stream network; and
- when modelling at catchment scales, the processes of sediment deposition and nutrient cycling occurring within lakes and reservoirs generally require detailed temporal modelling.

Output Evaluation

Testing the outputs of the SedNet-UM model is challenging. The model has multiple outputs across a large number of river links. For the sensitivity analysis, evaluation of the outputs of the model was made at a variety of sites. Because of the differences in the modelling of the sources and propagation of suspended and bedload sediment by SedNet-UM, analysis of these outputs (suspended load and bedload) has been considered separately.

The selection of reaches for assessment of sensitivity based on scale alone was not sufficient to characterise the response of the model because of the spatial nature of the outputs of
SedNet-UM. For example, if investigating the sensitivity of the model using the deposition as an output, selection of only sites with relatively large streamflow volume and steep channel slope would bias the sensitivity assessment. This is particularly problematic when considering the bedload sediment fraction that has thresholds when deposition patterns are changed. Details of the sites used in the analysis are provided in Table 6-3.

**Table 6-3 River links used in the sensitivity analysis of SedNet-UM.**

<table>
<thead>
<tr>
<th>Record Number</th>
<th>Selection Attribute</th>
<th>Stream</th>
<th>Shreve Order</th>
<th>Upstream Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>153</td>
<td>Large scale</td>
<td>Murrumbidgee River</td>
<td>139</td>
<td>963806</td>
</tr>
<tr>
<td>395</td>
<td>Median scale</td>
<td>Goodradigbee River</td>
<td>3</td>
<td>20705</td>
</tr>
<tr>
<td>511</td>
<td>Small scale</td>
<td>Unnamed tributary of Numeralla River</td>
<td>1</td>
<td>5174</td>
</tr>
<tr>
<td>184</td>
<td>Highest gully per unit internal subcatchment area</td>
<td>Murrumbidgee River</td>
<td>135</td>
<td>943315</td>
</tr>
<tr>
<td>424</td>
<td>Highest hillslope input per unit internal subcatchment area</td>
<td>Murrumbidgee River</td>
<td>62</td>
<td>508927</td>
</tr>
</tbody>
</table>

The first three sites listed in Table 6-3 were selected on the basis of scale alone, the individual river reaches selected were those with the largest, median and smallest upstream contributing areas. The remaining two evaluation sites were those having the largest contribution of gully and hillslope erosion per unit of internal subcatchment area.

**Assessing Spatial Pattern Change**

Because of the spatial outputs of SedNet-UM, potentially important information about the behaviour of the model is not uncovered by focusing testing at only a limited number of sites. To overcome this limitation each individual link of the control model run was compared with the corresponding link of a perturbed model run. For comparison, links were classified as either depositing or non-depositing reaches. The overall agreement between model runs was calculated and expressed as a percentage. In this study only deposition and non-deposition categories were investigated.
6.3.3 Results

One at a Time Perturbations

A summary of results for the sensitivity analysis of the SedNet-UM model is shown over the following pages. For one at a time parameter perturbations of the model, Table 6-4 shows summary sensitivity results for the bedload component, Table 6-5 shows results for suspended load and Table 6-6 shows results for the total load. These results are for the large scale reach (number 153).

Firstly, by examining the expected direction of change in model outputs resulting from each parameter perturbation it can be concluded that the model is coded correctly and behaves as expected. As an example, decreasing the hillslope delivery ratio (parameter: hsdr) decreases the amount of hillslope sediment delivery to the stream network. Thus, it would be expected that suspended sediment outputs would similarly decrease. Bedload erosion would remain unaffected by the change in the hsdr parameter because of the structure of the model. This result is confirmed in Table 6-4 and Table 6-5 - suspended sediment output is decreased and no change is recorded in the bedload component.

The results from one-at-a time perturbations reveal that the outputs of the model are most sensitive to perturbations of the hydrologic parameters. Outputs show greatest sensitivity to perturbations in parameters $a$, $b$, and $f$ for the bedload fraction and parameters $f$, $g$, and $c$ for the suspended sediment fraction. For the total sediment load, outputs show greatest sensitivity to perturbations in a similar set of parameters ($a$, $f$ and $g$).
Table 6-4 Sensitivity analysis results for bedload sediment output from one at a time parameter perturbations. Results are shown for reach number 153 (large scale). The reference (control) bedload output is 133.82 kty$^{-1}$.

<table>
<thead>
<tr>
<th>Param</th>
<th>Perturbation: -10%</th>
<th>Perturbation: -5%</th>
<th>Perturbation: +5%</th>
<th>Perturbation: +10%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bedload Sed. (kty$^{-1}$) % Change</td>
<td>Bedload Sed. (kty$^{-1}$) % Change</td>
<td>Bedload Sed. (kty$^{-1}$) % Change</td>
<td>Bedload Sed. (kty$^{-1}$) % Change</td>
</tr>
<tr>
<td>hsdrt</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
</tr>
<tr>
<td>sedvcl</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
</tr>
<tr>
<td>bheight</td>
<td>132.79 -0.78</td>
<td>133.31 -0.39</td>
<td>134.35 0.39</td>
<td>134.87 0.78</td>
</tr>
<tr>
<td>rhol</td>
<td>132.79 -0.78</td>
<td>133.31 -0.39</td>
<td>134.35 0.39</td>
<td>134.87 0.78</td>
</tr>
<tr>
<td>pcsl</td>
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<td>129.73 -3.06</td>
<td>137.93 3.07</td>
<td>142.03 6.13</td>
</tr>
<tr>
<td>bank_a</td>
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<td>133.31 -0.39</td>
<td>134.35 0.39</td>
<td>134.87 0.78</td>
</tr>
<tr>
<td>bank_c</td>
<td>131.26 -1.92</td>
<td>132.45 -1.03</td>
<td>135.43 1.20</td>
<td>137.29 2.59</td>
</tr>
<tr>
<td>k8</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
</tr>
<tr>
<td>s</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
</tr>
<tr>
<td>r</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
</tr>
<tr>
<td>a</td>
<td>23.62 -82.35</td>
<td>69.52 -48.05</td>
<td>218.55 63.31</td>
<td>258.78 93.37</td>
</tr>
<tr>
<td>b</td>
<td>66.19 -50.54</td>
<td>114.00 -14.82</td>
<td>165.56 23.71</td>
<td>211.40 57.97</td>
</tr>
<tr>
<td>k2</td>
<td>128.64 -3.87</td>
<td>131.23 -1.94</td>
<td>136.41 1.93</td>
<td>139.00 3.87</td>
</tr>
<tr>
<td>f</td>
<td>126.94 -5.14</td>
<td>129.47 -3.25</td>
<td>141.32 5.60</td>
<td>154.21 15.23</td>
</tr>
<tr>
<td>c</td>
<td>130.07 -2.81</td>
<td>131.73 -1.56</td>
<td>136.46 1.97</td>
<td>139.80 4.46</td>
</tr>
<tr>
<td>k4</td>
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<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
</tr>
<tr>
<td>g</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
</tr>
<tr>
<td>h</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
<td>133.82 0</td>
</tr>
</tbody>
</table>
Table 6-5 Sensitivity analysis results for suspended load sediment output from one at a time parameter perturbations. Results are shown for reach number 153 (large scale). The reference (control) bedload output is 311.09 kty⁻¹. SS - suspended sediment.

<table>
<thead>
<tr>
<th>Param</th>
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<th>Perturbation:</th>
<th>Perturbation:</th>
<th>Perturbation:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-10%</td>
<td>-5%</td>
<td>+5%</td>
<td>+10%</td>
</tr>
<tr>
<td></td>
<td>SS (kty⁻¹)</td>
<td>% Change</td>
<td>SS (kty⁻¹)</td>
<td>% Change</td>
</tr>
<tr>
<td>hsdrr</td>
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<td>-4.00</td>
<td>304.86</td>
<td>-2.00</td>
</tr>
<tr>
<td>sedvel</td>
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<td>2.86</td>
<td>315.48</td>
<td>1.41</td>
</tr>
<tr>
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<td>-0.86</td>
<td>309.75</td>
<td>-0.43</td>
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<td>-0.86</td>
<td>309.75</td>
<td>-0.43</td>
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<td>5.81</td>
<td>320.13</td>
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<td>311.00</td>
<td>-0.03</td>
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<td>c</td>
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<td>h</td>
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<td>-5.04</td>
</tr>
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</table>
Table 6-6 Sensitivity analysis results for the total sediment output from one at a time parameter perturbations. Results are shown for reach number 153 (large scale). The reference (control) sediment output is 444.92 kty⁻¹.

<table>
<thead>
<tr>
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<th>Perturbation:</th>
<th>Perturbation:</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>-10%</td>
<td>-5%</td>
<td>+5%</td>
<td>+10%</td>
</tr>
<tr>
<td></td>
<td>Total Sed.</td>
<td>% Change</td>
<td>Total Sed.</td>
<td>% Change</td>
</tr>
<tr>
<td></td>
<td>(kty⁻¹)</td>
<td></td>
<td>(kty⁻¹)</td>
<td></td>
</tr>
<tr>
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<td>0.99</td>
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<td>443.06</td>
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<td>443.06</td>
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<td>443.06</td>
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</tr>
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<td>b</td>
<td>376.11</td>
<td>-15.46</td>
<td>424.46</td>
<td>-4.60</td>
</tr>
<tr>
<td>k2</td>
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<td>-1.20</td>
<td>442.24</td>
<td>-0.60</td>
</tr>
<tr>
<td>f</td>
<td>383.48</td>
<td>-13.81</td>
<td>404.92</td>
<td>-8.99</td>
</tr>
<tr>
<td>c</td>
<td>414.61</td>
<td>-6.81</td>
<td>428.24</td>
<td>-3.75</td>
</tr>
<tr>
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<td>-1.32</td>
<td>442.02</td>
<td>-0.65</td>
</tr>
<tr>
<td>k7</td>
<td>439.56</td>
<td>-1.20</td>
<td>442.29</td>
<td>-0.59</td>
</tr>
<tr>
<td>g</td>
<td>397.37</td>
<td>-10.69</td>
<td>410.05</td>
<td>-7.84</td>
</tr>
<tr>
<td>h</td>
<td>415.23</td>
<td>-6.67</td>
<td>429.23</td>
<td>-3.52</td>
</tr>
</tbody>
</table>
Figure 6-6 presents the percentage output change in total sediment load to perturbations of the most sensitive parameters of the model. It can be seen that output response is non-linear across the parameter space examined.

![Graph showing non-linear behaviour in total sediment output. Results are shown for reach number 153 (large scale).](image)

Table 6-7 shows the overall agreement between perturbed model outputs and the control model run expressed as a percentage agreement of river links. The overall agreement compares the pattern of sediment deposition of the perturbed run against a reference (control) model output. It can be seen that the parameters $a$, $b$ and $k2$ have the greatest influence on the pattern of sediment deposition when compared with the control model output.
Table 6-7 Calculated overall agreement (%) for comparison of perturbed model outputs against a reference output (control). Results for comparison of depositing and non depositing reaches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Perturbation:</th>
<th>-10%</th>
<th>-5%</th>
<th>+5%</th>
<th>+10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>hsdri</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>sedvel</td>
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<td>100</td>
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<td>100</td>
<td>100</td>
</tr>
<tr>
<td>bheight</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
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<td>rho</td>
<td></td>
<td>100</td>
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<td>100</td>
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<tr>
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<td></td>
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<td>99.45</td>
<td>99.82</td>
<td>99.45</td>
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<tr>
<td>bank_a</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>bank_c</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>99.82</td>
</tr>
<tr>
<td>k8</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>s</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
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<td>r</td>
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<td>100</td>
<td>100</td>
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<td>100</td>
</tr>
<tr>
<td>a</td>
<td></td>
<td>72.64</td>
<td>84.84</td>
<td>90.76</td>
<td>88.72</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td>89.65</td>
<td>95.93</td>
<td>96.86</td>
<td>92.61</td>
</tr>
<tr>
<td>k2</td>
<td></td>
<td>99.45</td>
<td>99.82</td>
<td>99.45</td>
<td>98.34</td>
</tr>
<tr>
<td>f</td>
<td></td>
<td>99.82</td>
<td>99.82</td>
<td>99.63</td>
<td>99.26</td>
</tr>
<tr>
<td>c</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>99.82</td>
</tr>
<tr>
<td>k4</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>k7</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>g</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>h</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Parameter Interactions

Figures 6-7 to 6-12 show the Hessian matrices for the series of river links presented in Table 6-3. Displaying the results of the parameter interactions in this form enables presentation of the numerous model sensitivities and interdependencies between parameters.

The parameter interaction diagrams also reveal useful information about the change in sensitivities with respect to scale. Sensitivity patterns for the suspended load show very similar patterns across all scales. It can be seen at all scales that important interactions occur between parameter sets \( r \) and \( s, f \) and numerous other parameters (particularly \( c, g \) and \( h \)) and between the three parameters \( c \) and \( g \) and \( h \). The influence of the hydrologic parameters is dominant. This could be expected following the examination of the one at a time sensitivities as presented in the preceding section. Interactions between non-hydrologic parameters appear insignificant.

The pattern of the Hessian matrix is also similar across a range of scales for the bedload fraction. Important parameter interactions occur between the \( a \) and \( b \) parameters which are the rainfall and area exponents used to calculate the mean annual sum of \( Q^{1.4} \). The exception to this general pattern for bedload is for the median scale reach (see Figure 6-9). At the median scale site low input of sediment, because of a near-pristine catchment, changes the pattern of sensitivities and parameter interactions. The dominance of the interaction between hydrologic parameters is far less significant in relative terms at this reach.
Figure 6-7 Parameter interactions for the bedload sediment output at a large scale (reach number 153).

Figure 6-8 Parameter interactions for the suspended sediment output at a large scale (reach number 153).
Figure 6-9 Parameter interactions for bedload sediment output at a median scale (reach number 395)

Figure 6-10 Parameter interactions for the suspended sediment output at a median scale reach (reach number 395)
Figure 6-11 Parameter interactions for the bedload sediment output for a small scale reach (reach number 511)

Figure 6-12 Parameter interactions for the suspended sediment fraction at a small scale reach (reach number 511)
Figure 6-13 Parameter interactions for the bedload sediment output for a high hillslope input reach (reach number 424).

Figure 6-14 Parameter interactions for the suspended fraction for a high hillslope input reach (reach number 424).
Figure 6-15 Parameter interactions for the bedload sediment output at a high gully erosion reach (reach number 184).

Figure 6-16 Parameter interactions for suspended sediment output for a high gully erosion reach (reach number 184).
Significance of Parameter Interactions

In this section the importance of parameter interactions in the SedNet-UM model is quantified. The Taylor series expansion of the model about the reference parameter values $\theta_0$ is:

$$y(\theta) = y(\theta_0) + \sum_i \frac{\partial y}{\partial \theta_i} (\theta_i - \theta_0) + \frac{1}{2} \sum_i \sum_j \frac{\partial^2 y}{\partial \theta_i \partial \theta_j} (\theta_i - \theta_0)(\theta_j - \theta_0) + ...$$  \hspace{1cm} (6-16)

The $\sum_i \frac{\partial y}{\partial \theta_i} (\theta_i - \theta_0)$ term is the linear response of the model to perturbations in the parameter set. The next term is the second order response taking into account the quadratic response to a change in a single parameter ($i = j$), and the interaction between parameter pairs ($i \neq j$). The significance of the quadratic response and parameter interactions in the total effect of parameter $i$ can be determined by calculating the ratio of these terms:

$$R_i = \frac{1}{2} \sum_j \frac{\partial^2 y}{\partial \theta_i \partial \theta_j} (\theta_j - \theta_0) \frac{\partial y}{\partial \theta_i}$$  \hspace{1cm} (6-17)

The parameter interaction is significant when the absolute value of $R_i > 1$. It can be seen in Table 6-8 that $R_i$ is significant for both the bedload and suspended load for all $\theta_i$'s. This indicates that second order interactions are very significant. The result shows that a simple gradient sensitivity analysis is not adequate to fully understand the model behaviour. Ignoring the second degree terms in Equation 6-16 can give potentially misleading results. There may also be potentially important contributions due to higher degree terms not considered here.

Similar results are obtained at the other river links used in the sensitivity analysis of SedNet-UM.
Table 6-8 Ratio of second to first order terms for the suspended and bedload sediment fractions for reach number 153.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Suspended</th>
<th>Bedload</th>
</tr>
</thead>
<tbody>
<tr>
<td>hsd</td>
<td>3.32</td>
<td>-</td>
</tr>
<tr>
<td>sedvel</td>
<td>7.42</td>
<td>-</td>
</tr>
<tr>
<td>bheight</td>
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<tr>
<td>rho</td>
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</tr>
<tr>
<td>pcs</td>
<td>6.50</td>
<td>6.40</td>
</tr>
<tr>
<td>bank_a</td>
<td>16.59</td>
<td>15.64</td>
</tr>
<tr>
<td>bank_c</td>
<td>21.94</td>
<td>19.32</td>
</tr>
<tr>
<td>k8</td>
<td>18.44</td>
<td>-</td>
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<td>s</td>
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<tr>
<td>r</td>
<td>17.01</td>
<td>-</td>
</tr>
<tr>
<td>a</td>
<td>28.41</td>
<td>7.13</td>
</tr>
<tr>
<td>b</td>
<td>26.62</td>
<td>7.63</td>
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<tr>
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<td>24.79</td>
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<td>f</td>
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<td>16.44</td>
</tr>
<tr>
<td>k7</td>
<td>9.52</td>
<td>-</td>
</tr>
<tr>
<td>g</td>
<td>9.52</td>
<td>-</td>
</tr>
<tr>
<td>h</td>
<td>9.50</td>
<td>-</td>
</tr>
</tbody>
</table>

6.3.4 Sensitivity Analysis Summary

If reliable conclusions are to be drawn from predictive models such as SedNet-UM, it is crucial that the sensitivity of outputs to uncertainty in inputs, parameters and features of the model structure be properly assessed. In this research, sensitivity analysis of the SedNet-UM model has been undertaken to assess sensitivities of individual parameters and the influence of parameter interactions. SedNet-UM interconnects a large number of relatively simple models for individual river links, forming a complex structure with a very large number of potential interactions. The sophistication and complexity of SedNet-UM stems from its
structure and method of application, rather than from the complexity of its component parts. The multiple and spatially distributed outputs of SedNet-UM challenge sensitivity analysis.

Results of the sensitivity assessment presented here clearly show that the hydrologic parameters of the SedNet-UM model are most sensitive to perturbations of the input parameters. This was generally the case for each of the total sediment outputs and for the bedload and suspended load fractions, across a range of spatial scales and representative reach types. Parameter interaction investigations using a Hessian matrix of local sensitivities also showed that the interactions between parameters were most prevalent among the hydrologic parameters of the SedNet-UM model. These results have important implications for focusing future research associated with the model. Improving the structure or focusing efforts on estimation of the SedNet-UM hydrologic parameters should be the primary focus of such study.

Because of the limitations of local measure of sensitivity identified in Section 6.3.1 and the practical complexity of the SedNet-UM model, the sensitivity analysis presented here could be extended potentially to gain additional insight into the behaviour of the model. Local sensitivity analysis approaches described here are useful for providing a guide to future assessment using general sensitivity techniques. Approaches such as finding the set of values of uncertain quantities over which the outputs remain within a specified range are appropriate for future assessment of variants the SedNet-UM model. Such trials should attempt to identify the boundaries, in the space of selected significant parameters, of the regions within which any parameter values give rise to sediment loads meeting specified criteria (which need not be simple). For example, it will be of interest to find the ranges of erosion parameter values over which observed sediment depositions are matched by the model to within a chosen tolerance; this would allow assessment of how far erosion rates may be inferred from deposition, and whether any erosion mechanisms may be omitted or combined. The computing requirements of any such work will require the re-coding of the SedNet-UM model into a faster computing language.

For future sensitivity work on the SedNet-UM and similar variants, investigation of sensitivities across a range of spatial scales and sites is required. To complement selection of sites according to scale, future sensitivity assessment should also focus analysis at sites of management significance, for example, reservoirs, estuaries or wetlands.
6.4 Chapter Discussion

SedNet and similarly structured variants have much potential to address common resource management issues with respect to pollutant source, propagation and fate. The SedNet-UM model is particularly suited to identifying critical source areas where remediation is likely to be most effective for reducing sediment delivery to particular sites of a stream network.

This chapter has described the SedNet model and has presented an application of the model in the upper Murrumbidgee catchment. The study application has been used as a basis for sensitivity analysis of the model. The sensitivity analysis has been undertaken to improve understanding of the model and as a guide for shifting the scale of model application. The SedNet model was originally developed for application at the continental scale. Because of this, the focus in developing the SedNet model was to estimate correctly the large-scale regional patterns of sediment propagation and deposition. This research has focused on applying the model to predict sediment propagation and deposition patterns at catchment scales. This requires more detailed spatial resolution of the sediment sources and estimation of model input parameters. Also, some factors that vary strongly at the continental scale can be relatively constant within a catchment, for example, rainfall erositivity. For catchment scales, improved data inputs, improved representation of processes and consequent improvements in accuracy are required.

An attractive feature of SedNet is its ability to predict both total loads of sediment and to map the patterns of sediment delivery and transport. Because of this there are two particular features of inaccuracy to consider with respect to the model - the prediction of total loads and the ability to reproduce the patterns of sediment delivery and transport. If the load at a point in a river network is correct when compared with collateral data this does not mean that the pattern of load generation is also correct and vice versa. From a management perspective, an ability to reproduce the patterns of sediment delivery accurately is most valued. These issues are further considered in this research in Chapter 7 where a comparison with estimated pollutant loads is presented, and also in Section 8.3 where improvements to model testing are discussed.

Because of the steady state structure of the SedNet model no account is taken of temporal variation in sediment delivery to streams from erosion sources. This is a shortcoming of the model. For example, the structure of the gully erosion sub-model implies a constant annual volume of sediment delivered from gully systems. In upland humid-temporal regions, sediment yield from channel incision (of both streambanks and gullies) generally shows at first a rapid rise, then a decline as gullies and streambanks progressively stabilise (Wasson et al., 1996). In practice attempts to include increased temporal complexity in the gully erosion
sub-model may be constrained by inadequate quantification of temporal sediment delivery for all but a few intensively studied gullies.

Prosser (2002) has also described directions for ongoing development of the model potentially to include:

- automated generation of hydrologic variables including regulated flows;
- improved nutrient modelling capacity;
- parameterisation of the bank erosion model from Australian data;
- incorporation of a wider range of land management scenarios;
- simple disaggregation of mean annual loads to daily loads using daily flow series;
- an ability to model anastomosing streams;
- specification of particle size characteristics; and
- incorporation of variable channel geometry and variable sediment delivery from gullies and hillslopes from streams.

Whilst not attempted as part of this thesis, further development of the modelling capacity of SedNet to include economic optimisation based on the costs of management intervention in order to prioritise management effort is warranted. Also worthy of additional research is how the results of the SedNet-UM modelling described here can be better disseminated to those responsible for developing policy for land and water management. Extra detail on some of these issues can be found in Newham and Field (2001).

Improved parameterisation of the hydrologic components of the model in particular is needed. More intensive work in individual catchments with rainfall-runoff and routing model can potentially provide improved estimates of flow for each river link. For the Murrumbidgee catchment a predictive capacity at subcatchment scale has already been constructed and described in Chapter 4 and in part in Newham et al. (2000). Regionalisation techniques based on relationships between landscape attributes and calibrated flow model parameters will be required to re-scale subcatchment scale estimates to the individual river link scale. Details of how this may be achieved are discussed in Chapter 8: Elements of an Improved Pollutant Export Model. Coupling semi-distributed models such as SedNet-UM with data provided by conceptual modelling shows much promise.

Parameters of the streambank erosion sub-model were taken from the review of Rutherfurd (2000) who related lateral erosion rates of rivers with either bankfull or mean annual flood streamflow. In Rutherfurd's review a worldwide data set was used. It included approximately 70 data points, with only three from Australian river systems.
Accuracy assessment of the SedNet-UM model will be used to assist in prioritising improvements in model structure, parameterisation and data acquisition. These improvements are important to continue the development of methods for predicting the sources, transport and potential impacts of environmental pollutants in catchments. The proceeding chapter makes a comparison of modelling approaches that have been developed in this and previous chapters. The performance of the SedNet-UM model is assessed against field measured and other modelled data.
Chapter 7 Comparison of Estimated Pollutant Loads

7.1 Introduction

An important component of evaluating and improving pollutant load modelling is to compare and assess accuracy through comparison with collateral knowledge. Accuracy assessment is important to gauge confidence in model outputs. In the case of the SedNet-UM model, accuracy assessment is required to assess confidence in both the predicted total sediment loads and also in the patterns of sediment transport. Comparison with collateral knowledge will also assist general sensitivity analysis techniques by enabling realistic bounds to be attached to model outputs needed for identification of uncertainties in model inputs and parameters (details can be found in Section 6.3.4).

According to Wasson (1994) the prediction of sediment fluxes through components of a sediment budget for large basins is an ideal against which to measure the success of models of basin wide sediment transport. This chapter presents a comparison between the outputs of the pollutant load estimation techniques presented in this study with published sources of pollutant load information. The overall comparison is focused on accuracy assessment of the SedNet-UM model. Details of the application of the SedNet-UM model used for comparison here are discussed in Section 6.2.

Potential sources on which to base the comparison include:

- loads modelled using in-stream pollutant concentration and streamflow data such as described in Chapter 5;
- sediment budgets constructed using a variety of reconnaissance techniques, for example: examination of aerial photo interpretation, assessing historic change in stream cross sections, strategic establishment of erosion pins etc. For examples, see Reid and Dunne (1996);
- reservoir sedimentation studies, for example United States Army Corps of Engineers (1994a); and
- magnetic and radionuclide sediment tracing techniques, for example Wallbrink et al. (1998).
7.2 Load Comparisons

Five separate comparisons are presented in this chapter. The first is a comparison between the outputs of SedNet-UM with load estimates from a variety of sources compiled in the publication of Wasson (1994). The second comparison enables evaluation of the pattern of sediment transport predicted by SedNet-UM against data from the sediment tracing study of Wallbrink and Fogarty (1998). The third compares a detailed small-scale sediment budget with outputs from the SedNet-UM model. The reservoir sedimentation study of Wasson et al. (1999) is then compared with the outputs of SedNet-UM in the fourth comparison. The final comparison is between modelled suspended sediment load estimates from Burra and Jerrabomberra Creeks (presented in Chapter 5) with corresponding estimates from SedNet-UM.

7.2.1 Southern Upland Sediment Yield Comparison

Wasson (1994) has collated sediment yield data from a variety of sources for the southern uplands of Australia in order to build upon previous compilations of sediment load made by Olive and Walker (1982) and Olive and Rieger (1986). Additional data includes published and unpublished load estimates from sedimentation studies of farm dams and reservoirs, mining sites and tracer based studies. The data used in the analysis of Wasson (1994) are primarily sourced from suspended load estimates. It is argued by Wasson (1994) that the exclusion of the bedload fraction in estimation of sediment yield introduces uncertainty that is small relative to other uncertainties. However, excluding the bedload component will obviously underestimate the true stream sediment load.

Figure 7-1 shows a plot of the data on which Wasson (1994) based his analysis and the associated regression line. Also shown on the same plot are the predicted total sediment outputs from each reach of the SedNet-UM application in the upper Murrumbidgee catchment. Several of the reported sediment yield data are sourced from the upper Murrumbidgee catchment. The bulk of these are the yields from small-scale farm dam sedimentation studies. The cluster of the dam sedimentation data can be seen in the region of the graph corresponding to catchment areas of 0.01 - 1 km². Comparatively few of Wasson's data points are from studies at scales similar to application of the SedNet-UM model.

The outputs from SedNet-UM for the upper Murrumbidgee system show good general agreement with the results compiled by Wasson (1994). It can be observed in the plot that the majority of the predicted outputs from reaches of SedNet-UM lie above the regression line fitted to the Wasson (1994) data. This is because either the SedNet-UM estimates are on average too high, or more likely, neglecting the bedload component of the sediment budget has led to an underestimate by Wasson (1994).
Figure 7-1 Mean annual sediment yield versus catchment area for the southern upland areas of Australia. Source: Wasson (1994). Also shown are the SedNet-UM load estimates for reaches of the upper Murrumbidgee catchment.

7.2.2 Radionuclide and Magnetic Sediment Tracing Comparison

Wallbrink and Fogarty (1998) have undertaken sediment tracing work in the Molonglo River subcatchment of the upper Murrumbidgee. Their research applied both magnetic and radionuclide tracing techniques at stream confluences to determine the relative contribution of sediment from each confluence. Sediment tracing techniques may be used to indicate the relative proportions of sediment flux to the confluence channel from the contributing tributaries.

Three common stream confluences are available for comparison with the results of SedNet-UM. Wallbrink and Fogarty (1998) analysed two sediment size fractions. For the purposes of assessing the SedNet-UM model the <63µm fraction has been compared with the suspended load, and the 125-250µm fraction with the bedload. Results of the comparison are presented
Comparison of Estimated Pollutant Loads

in Table 7-1. For this purpose only the relative contributions from each of the stream confluences are presented.

Table 7-1 Comparison of relative contribution of stream confluences: Wallbrink and Fogarty (1998) tracing and SedNet-UM modelling comparison. The application and parameterisation of the SedNet-UM model used for comparison is discussed in Section 6.2.

<table>
<thead>
<tr>
<th>Confluence</th>
<th>Suspended load</th>
<th>Bedload</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tracing (%)</td>
<td>SedNet-UM (%)</td>
</tr>
<tr>
<td>Molonglo River/</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ballalaba Creek</td>
<td>100±60</td>
<td>44</td>
</tr>
<tr>
<td>Yandygunulah Creek</td>
<td>40±17</td>
<td>31</td>
</tr>
<tr>
<td>Hoskinstown Creek</td>
<td>38±21</td>
<td>41</td>
</tr>
</tbody>
</table>

Caution must be exercised when comparing the results of sediment tracing and the SedNet-UM modelling. Sediment tracing techniques are based on assumptions and are influenced by errors in measurement. Tracing results can be strongly influenced by individual sediment transport events that do not reflect the relative tributary supply over long time periods. In contrast, the steady state SedNet-UM model attempts to effectively aggregates the influence of such events.

The comparison presented in Table 7-1 shows general agreement between modelled results and sediment tracing estimates. With the exception of the bedload estimate for Hoskinstown Creek, all SedNet-UM relative contributions are within the uncertainty estimated for the sediment tracing. These results give confidence that the SedNet-UM model is reproducing the pattern of sediment transport, at least within the range of uncertainty of the sediment tracing at these sites. The results of the tracing comparison reveal nothing of the quantities of sediment transported by any of the tributaries.

7.2.3 Detailed Small Scale Sediment Budget Comparison

Wasson et al. (1998) have published a detailed sediment budget for the Jerrabomberra Creek subcatchment of the upper Murrumbidgee River. Data sourced from farm dam sedimentation surveys were used as the basis of calculating sediment yields for subcatchments of the Jerrabomberra Creek.

In constructing the sediment budget, Wasson et al. (1998) considered hillslope areas separately from channels and associated floodplains. For the analysis, the Jerrabomberra Creek catchment was subdivided on the basis of its stream network into subcatchments using
Comparison of Estimated Pollutant Loads

a similar method to what is automated in SedNet-UM. Data from sedimentation rate surveys of 50 farm dams (sourced from the publication of Neil and Galloway, 1989) were extrapolated using regression analysis across each of the subcatchments. The contribution of channel incision to the sediment budget was considered separately. These channel incision components of the sediment budget were estimated based on the stratigraphy of the valley floors and hillslope valleys, and the farm dam surveys (Wasson et al., 1998).

A summary diagram of the sediment budget constructed by Wasson et al. (1998) for the Jerrabomberra Creek is shown in Figure 7-2.

Figure 7-2 The sediment budget constructed by Wasson et al. (1998) for the Jerrabomberra Creek catchment post European settlement (source Wasson et al., 1998).

The post European settlement sediment budget of Wasson et al. (1998) has been compared directly with the outputs of the SedNet-UM model for Jerrabomberra Creek catchment.
Meaningful comparison can only be made between the total hillslope erosion estimate, the sum of streambank and gully erosion and the total catchment load. Table 7-2 shows the comparison between the results of the SedNet-UM application and the sediment budget. It was necessary to multiply the annual average outputs from the SedNet-UM model to allow direct comparison with the work of Wasson et al. (1998). Annual average outputs were multiplied by the gully age parameter \( \tau \) (100 years).

**Table 7-2 Comparison of SedNet-UM and Wasson et al. (1998) sediment budgeting for the Jerrabomberra Creek catchment.** Note that the SedNet-UM results are multiplied by 100 years to enable comparison with the post-European sediment budget of Wasson et al. (1998). All measurements are in tones.

<table>
<thead>
<tr>
<th>Budget Element</th>
<th>SedNet-UM</th>
<th>Wasson et al. (1998)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gully erosion input</td>
<td>(1.1 \times 10^6)</td>
<td>(7.24 \times 10^6)</td>
</tr>
<tr>
<td>Streambank erosion input</td>
<td>(2.9 \times 10^4)</td>
<td></td>
</tr>
<tr>
<td>Total hillslope erosion</td>
<td>(1.3 \times 10^7)</td>
<td></td>
</tr>
<tr>
<td>Hillslope erosion input</td>
<td>(6.6 \times 10^5)</td>
<td>(3.38 \times 10^5)</td>
</tr>
<tr>
<td>Total sediment input</td>
<td>(1.8 \times 10^6)</td>
<td></td>
</tr>
<tr>
<td>In-channel and floodplain deposition</td>
<td>(3.7 \times 10^5)</td>
<td></td>
</tr>
<tr>
<td>Suspended sediment yield</td>
<td>(8.6 \times 10^5)</td>
<td></td>
</tr>
<tr>
<td>Bedload sediment yield</td>
<td>(5.6 \times 10^5)</td>
<td></td>
</tr>
<tr>
<td>Total sediment yield</td>
<td>(1.4 \times 10^6)</td>
<td>(3.42 \times 10^6)</td>
</tr>
</tbody>
</table>

The data presented in Table 7-2 shows that sediment inputs from gully and streambank sources are estimated within one order of magnitude for both approaches (\(1.1 \times 10^6\) and \(7.2 \times 10^6\) for SedNet-UM and Wasson et al., 1998, respectively). Hillslope erosion estimates for SedNet-UM are higher, however again less than one order of magnitude than the corresponding estimate made by Wasson et al. (1998). Hillslope erosion data for the application of the SedNet-UM model was sourced from continental scale mapping of Lu et al. (2001). Increasing the spatial resolution of the hillslope erosion modelling used in SedNet-UM may result in better agreement with the estimate of Wasson et al. (1998).

The total sediment yield predicted by Wasson et al. (1999) is approximately 2.5 times higher than the yield predicted using the SedNet-UM model. More careful consideration of the time periods of each approach may result in closer agreement.
Within the SedNet-UM model the Jerrabomberra Creek catchment was modelled as only two links in the stream network. A comparison at this scale is at the lower limit of the SedNet-UM model in terms of spatial resolution. On the other hand, the scale of the detailed sediment budgeting of Wasson et al. (1998) is approaching its upper limits. Construction of a similarly detailed sediment budget would be impractical at the scale of the upper Murrumbidgee catchment without substantial investment. Certainly such detailed studies would be not be possible at continental scales.

Caution needs to be exercised when drawing conclusions from this particular comparison. The scale of the comparison is very small for the SedNet-UM model and potentially influenced greatly by data inputs such as gully erosion mapping and hillslope erosion modelling. A second, potentially significant factor influencing the results is the use of the gully age parameter to sum the results of the SedNet-UM modelling. Summing the SedNet-UM modelling over a longer period would result in the outputs showing closer agreement.

### 7.2.4 Dam Sedimentation Comparison

Reservoir sedimentation data are often useful for checking modelled estimates of sediment yield (Reid and Dunne, 1996). Wasson et al. (1999) have compiled an estimate of the total sediment input to the Burrinjuck Reservoir since its construction in 1912. Their budget is based on analysis of the distribution of sediments on the bottom of the reservoir. The approach of the study was to combine information captured from aerial photography (taken at low water levels) with field measurements of sediment thickness (also collected at low water levels) and data collected remotely in submerged areas using an adapted oceanographic seismic profiler. This data was used to produce both a map of the distribution of accumulated sediment in the reservoir and to estimate the total volume of sediment delivered since construction. Wasson et al. (1999) estimate that $2.26 \times 10^7$ m$^3$ of sediment have been deposited in the reservoir since construction. Using a sediment bulk density of 1.5 t/m$^3$ this equates to a total deposition of $3.39 \times 10^7$ t. As the bulk of the data on which Wasson et al. (1999) based their calculations were collected in 1985, the deposition has occurred over approximately 73 years. Assuming a sediment trap efficiency of 100% as Wasson et al. (1999) have, the annual average sediment delivery over that period is $4.6 \times 10^5$ t/yr.

As presented in Section 6.2.1, the total SedNet-UM estimate for sediment delivery to Burrinjuck Dam from its catchment is $2.15 \times 10^5$ t/yr and $4.13 \times 10^5$ t/yr for the bedload and suspended loads respectively. This represents a total of sediment supply of $6.3 \times 10^5$ t/yr.
The results from SedNet-UM and from the Wasson et al. (1999) study show reasonably close agreement. The result is encouraging and shows that at large scales the estimation of quantities of sediment transported in SedNet-UM are reliable.

Cross sectional data held by Environment ACT for several other reservoirs in the catchment have also been investigated. It was found that because of the cross sectional survey methods used to estimate sediment accumulation, the uncertainties in the sedimentation estimates are potentially larger than the information latent in the data. No comparison is possible for loads at these other reservoir sites.

### 7.2.5 Suspended Load Estimates

This section presents a comparison between outputs of the SedNet-UM model and suspended sediment estimates calculated in Chapter 5 for two upper Murrumbidgee subcatchments. The suspended sediment loads calculated in Chapter 5 for the Burra and Jerrabomberra Creek subcatchments were $3.00 \times 10^3$ ty$^{-1}$ and $3.09 \times 10^3$ ty$^{-1}$ respectively. A 10-year period beginning at the start of 1988 was used for the calculation of sediment yield. The suspended sediment loads presented in Chapter 5 were estimated using a linear regression method from observed suspended sediment concentration data (see Section 5.4 for further details).

The corresponding estimate of the suspended sediment fraction at these two sites from the SedNet-UM model were $7.4 \times 10^3$ ty$^{-1}$ and $8.6 \times 10^3$ ty$^{-1}$. In relative terms the suspended sediment load calculated in Chapter 5 for Burra Creek was 97% of the load for Jerrabomberra Creek over the same time interval. For the SedNet-UM model the sediment load of Burra Creek was estimated to be 86% of the load of the Jerrabomberra Creek subcatchment.

Results show general agreement between the SedNet-UM model and the load estimates of Chapter 5 in terms of estimating the relative contribution from each subcatchment. The total loads predicted in Chapter 5 are however lower than the load predicted by SedNet-UM. One explanation to account for the variation is that the use of daily rather than hourly data has led to an underestimation of the sediment load calculated in Chapter 5. A second explanation is that the comparison is influenced by the time periods of the load estimation. In the case of the SedNet-UM estimates the modelling time period is 100 years whereas for the load calculations of Chapter 5 the period was only 10 years. The loads calculated in Chapter 5 are based on recently sampled concentration data (mid 1990's) and thus have declined from the peak of sediment yields that followed European settlement as described by Wasson et al. (2000). Also, as discussed in Chapter 5, loads are influenced by the prevailing climatic and hydrologic conditions at the time of sampling.
Chapter Discussion

Accuracy assessment is an important component of evaluating pollutant load modelling techniques. This chapter has presented a comparison between outputs of the SedNet-UM model with collateral knowledge from five separate pollutant load studies. In each case, careful consideration was made of the inherent limitations in comparing modelling techniques.

The comparison presented in Section 7.2.1 shows that there is reasonable agreement between outputs of the SedNet-UM model with the Wasson (1994) compilation of sediment yield data from the southern uplands region of Australia. In Section 7.2.2, it was seen that the patterns of sediment loads estimated using the SedNet-UM model show agreement (within the uncertainties of sediment tracing techniques), for a limited number of sites in the Molonglo River subcatchment. The third comparison, described in Section 7.2.3, showed that at very small scales relative to the overall application of the SedNet-UM model, outputs do not show close agreement with a detailed sediment budget constructed by Wasson et al. (1998). However, problems with the time periods used for the comparison are thought to have influenced the result. At large scales relative to the described SedNet-UM application, the model shows close agreement with an estimate of reservoir sedimentation made by Wasson et al. (1999) (see Section 7.2.4). The final comparison of the SedNet-UM model with the results of the load calculations made in Chapter 5 show that SedNet-UM predicts the relative source strength of the catchments well. The total loads may be underestimated in Chapter 5 because of the use of daily data and different time periods for the comparison (see Section 7.2.5 for further details).

From the comparisons it can be cautiously concluded that the SedNet-UM model is generally performing well at predicting both the patterns and quantities of sediment source and transport at catchment scales. Further testing is required before more definitive conclusions can be reached. The following chapter discusses suggested changes to the SedNet-UM model that should improve the prediction of the patterns and quantities of sediment transport.
Chapter 8 Elements of an Improved Pollutant Export Model

8.1 Introduction

The fundamental requirement of a pollutant export model is to encapsulate the primary drivers of pollution source, transport and fate at catchment scales. The drivers include: climatic, hydrologic, topographic factors and landuse and riparian management practices. This thesis has identified through review, application and testing of various water quality and quantity models the required elements of a pollutant export model applicable for catchment scale application.

The research has focused on sediment export modelling in the Australian context. A sediment model must be able to simulate the dominant processes of sediment source and transport. This includes, in addition to modelling the inputs from hillslope areas, the ability to simulate the processes of gully and streambank erosion. Models are required to account for the effects of land and water management activities to enable the evaluation of management change scenarios. Modelling systems should be sensitive to climate variability, but not necessarily operating dynamically. The complexity of a model should be commensurate with the data available to underpin the application. For widespread acceptance such models need to be easy to use and should have the facilities for comprehensive testing of its outputs and internal behaviour. These general principals above also apply to other catchment scale pollutant source and transport models.

The SedNet model was developed to assist in identifying critical sediment source areas and the transport of sediment at catchment scales. The model incorporates many of the desirable features of pollutant export models identified above. Thus it provides a useful basis for ongoing development of pollutant export modelling techniques.

The potential for the use of SedNet to aid in improving the focus of remediation efforts was demonstrated by application in the upper Murrumbidgee catchment in Chapter 6. Chapter 6 also identified, by way of sensitivity analysis, components of the model that require additional study to improve the accuracy and hence reliability of the model for aiding management decisions. In Chapter 7 the predictive accuracy of SedNet was assessed by comparison with several other studies. It was found that the model showed reasonably close agreement with these other studies, however improvements were recommended.
This chapter discusses several of the identified limitations of the SedNet model and makes suggestions for modification to components of the model. The suggested modifications aim to improve both the capabilities for accurate prediction of the patterns of sediment source and transport and also quantification of total sediment loads. The chapter consequently investigates several topics:

- improving hydrologic representation within the model;
- improving the hydrologic simulation of land use change; and
- appropriate techniques for model testing.

### 8.2 SedNet Hydrologic Modelling

A key component for estimating the transport of sediment through a river network is the spatial and temporal distribution of streamflow. As described in Chapter 6, SedNet uses five hydrological variables to characterise the distribution of flow for each link of a river network:

- Bankfull streamflow \( Q_{BF} \) - used as a predictor of bank erosion and floodplain deposition \( Q_{BF} \) is assumed to correspond to the 1.58-year average recurrence interval flood event;)
- Mean annual flow \( \overline{Q} \) - used to model reservoir deposition;
- Median overbank streamflow \( Q_{OB} \) - used to model floodplain deposition; and
- Sediment transport capacity discharge \( \sum Q^{1.4} \) - used to estimate the transport capacity of the bedload sediment fraction \( \sum Q^{1.4} \) is calculated as the mean value of the annual sum of daily streamflow raised to the 1.4 power).

In the Prosser et al. (2001a) application of SedNet and for the modelling presented in Chapter 6, regional relationships for each streamflow variable were used in order to provide the broad spatial coverage required of the modelling. The regionalisations derived by Young et al. (2001) for use in SedNet were based on analysis of streamflow data from 314 sites. Observed streamflow records from 32 sites and simulated streamflow at 282 sites were used. Thus, the regionalisations were heavily biased towards simulated streamflow. The simulated streamflow used in the study of Young et al. (2001) was sourced from application of the SIMHYD model by Peel et al. (unpublished) (see Section 4.8.1 for a description of the SIMHYD model).

While the SIMHYD model was applied on a daily timestep in the study of Peel et al. (unpublished), the model was calibrated using statistics calculated on a monthly basis. Thus the modelled streamflow should give reasonable estimates of monthly streamflow, and hence
mean annual flow. However, the critical hydrologic variables required by SedNet depend on accurate estimates of at least daily and, as discussed later, potentially hourly streamflow. Deriving values for the hydrologic variables from SedNet from modelled streamflow time series should give reliable estimates of these variables, but only if the simulated flows adequately represent the dynamic response of the catchment, and the relationship is well defined (Croke et al., 2002).

The advantage of using modelled flows is that a continuous set of flow data can be generated. In the study of Young et al. (2001) 100 years of simulated flows were used. The use of modelled flow avoids complications arising from the different time periods for which observed streamflow is available at different stream gauge sites.

As described in Chapter 6, the hydrological variables regionalised by Young et al. (2001) are of the form:

\[ X = kA^r P^s \]

where \( X \) is either \( Q_{BF}, \bar{Q}_s, Q_{OB} \) or \( \sum Q^{1.4} \), \( A \) is the catchment area, \( P \) is the mean annual rainfall, and \( k, r \) and \( s \) are constants that vary according to the hydrologic variable calculated. Using this method the parameterisation of the SedNet model depends only on the contributing area and the mean annual rainfall. Other influencing factors such as land use, soil characteristics and topography are not explicitly included.

### 8.2.1 Improving Hydrologic Parameterisation

Improving the hydrologic parameterisation of the SedNet model is supported by the results of sensitivity analysis presented in Chapter 6. It was concluded in Chapter 6 that the outputs of the model are most sensitive to perturbations of the hydrologic parameters and thus should be an initial focus of improvements to the model. There are two reasons for improving the parameterisation of the hydrologic variables used by SedNet. Firstly, improving the accuracy of the estimates of the variables should improve the accuracy of the SedNet model, particularly for the prediction of the spatial patterns of sediment source and transport. Secondly, as discussed in the previous section, the current parameterisation is sensitive only to rainfall and contributing area and there is no sensitivity in the hydrologic variables to other catchment attributes. This constrains SedNet to simulating only limited land use change scenarios because the hydrologic impacts of such changes cannot be explicitly modelled. This also results in the underestimation of catchment-to-catchment variability. For example there is no differentiation in the hydrologic parameter values between subcatchments that are fully forested in comparison to subcatchments that have been cleared for pasture production. Thus,
changes are required to enable development of more reliable simulation of management change scenarios.

Two primary methods are available for improving the regionalisation of the streamflow variables used in SedNet: using observed streamflow data to determine relationships for the existing land use or using modelled daily streamflow data.

Using observed data has the advantage of limiting accuracy to the errors in the observed values only. However, there are drawbacks to using observed streamflow data. First, the data provides an indication of the response of a catchment for the conditions in the catchment over the time that the data was collected. As a result, the response of the same catchment to a different set of imposed management conditions cannot be determined easily. The second drawback of using observed data is that the number of sites with continuously recorded streamflow over a sufficient length of record is limited (a particular problem within Australia). Use of observed streamflow data would result in a shorter period of data, increasing that uncertainty resulting from climatic variability. Thus the influence of model errors are avoided, at the cost of introducing uncertainty due to only that climate variability in the record, as well as limiting analysis to existing land use (Croke et al., 2002).

For catchments with a relatively rapid hydrologic response, even daily streamflow will not adequately represent the true range or distribution of streamflow. In many cases, hourly streamflow will be needed to obtain the true distribution. Unfortunately, very few streams have a long record of hourly data available. Therefore, combined use of hourly and daily data may be needed to estimate the values of the streamflow variables adequately. An investigation of the influence of the temporal resolution of data inputs on the hydrologic parameterisation is discussed in the following section.

The second option for improving the regionalisation of streamflow is to use modelled streamflow data calibrated on a daily timestep, with an additional criterion that the observed streamflow duration curve be adequately reproduced. It is necessary to reproduce the streamflow duration curve to estimate accurately the hydrologic variables of SedNet (similar requirements were also discussed in Chapter 5 as necessary for accurate pollutant load estimation).

Use of modelled values will enable regionalisation of the hydrologic variables and potentially allow incorporation of catchment attributes in that regionalisation. However as discussed in Chapter 4, the simulation of streamflow is dependent on the quality of rainfall inputs to a model. This is particularly true when long periods of simulated streamflow are required, as the number of available rain gauges is limited (particularly early in the century). The error in the streamflow variables derived from simulated streamflow will be a combination of errors
Elements of an Improved Pollutant Export Model

in the rainfall record, error in the rainfall-runoff model representation of the catchment and the effect of a finite period of record.

Croke (2002) has investigated the hydrologic parameterisation of the SedNet model for application across the Murray-Darling Basin. The study investigated in detail the regionalisation of the hydrologic inputs to the SedNet model. It was summarised that the distribution of streamflow can be estimated through regionalisation of the runoff coefficient and the slope of the flow duration curve. In the Croke (2002) study the runoff coefficient (and hence the $\bar{Q}_s$) was estimated from the mean annual rainfall, the woody vegetation cover and potential evaporation. For the study the slope of the flow duration curve was estimated from the modelled runoff coefficient. Further consideration of the work of Croke (2002) is recommended for future applications of the SedNet model. The possibility of regionalisation of $\bar{Q}_s$, and hence the other SedNet hydrologic variables $Q_{BF}$, $Q_{OB}$ and $\sum Q^{1.4}$, overcomes the inherent limitations of the present formulation of SedNet. This allows improved simulation of landuse change in the model by improving the hydrologic representation.

8.2.2 Influence of Data Inputs on Model Parameterisation

There are potentially significant implications regarding the effects of error in the data inputs used to parameterise the SedNet model. In the previous section the use of both observed and modelled streamflow data and the use of data of different temporal resolutions were discussed. This section investigates the influence of data inputs on the hydrologic parameterisation of the SedNet model. Two comparisons are made. The first investigates the influence of the temporal resolution of data inputs by presenting a comparison between daily modelled and observed data. Only a subset of available sites is used in the comparison due to the limitations of finding sites with an appropriate length of record. The modelled data used in the comparison is sourced from the simulations of the IHACRES model in Chapter 4. The first comparison is presented in Table 8-1.

The second investigation compares the influence of the temporal resolution of data inputs. The influence on the hydrological parameterisation of SedNet of using observed hourly versus observed daily data is compared. Results of that comparison are presented in Table 8-2.

Table 8-1 shows the values of each of the hydrologic variables of the SedNet model calculated from observed and modelled streamflow data inputs. It can be seen that the modelled and observed values of $\bar{Q}_s$ show close agreement in all cases. This is because the parameters of the IHACRES models have been calibrated to minimise bias (see Chapter 4 for details). For the same reason the values of $\sum Q^{1.4}$ also show generally close agreement. The
values of the hydrologic variables $Q_{BF}$ and $Q_{OB}$ are however dependent not only on the total flow volumes being equal but also on the distribution of flows. It can be seen that potentially significant variation in these variables is possible if the streamflow model does not adequately represent the distribution of flow. The largest discrepancy occurs at gauge number 410077 where the variables calculated from observed and modelled streamflow vary by factors of 1.1 to 4.0 for $Q_{BF}$ and $Q_{OB}$ respectively.

Table 8-1 A comparison between observed and modelled data inputs on the hydrologic parameterisation of the SedNet model. Modelled data is sourced from Chapter 1.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>$Q_{BF}$ (ML/day)</th>
<th>$Q_{OB}$ (ML/day)</th>
<th>$\sum Q^{1.4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Modelled</td>
<td>Observed</td>
</tr>
<tr>
<td>410076</td>
<td>5112</td>
<td>3199</td>
<td>27296</td>
</tr>
<tr>
<td>410077</td>
<td>890</td>
<td>3575</td>
<td>15475</td>
</tr>
<tr>
<td>410088</td>
<td>11016</td>
<td>7963</td>
<td>194279</td>
</tr>
<tr>
<td>410713</td>
<td>7638</td>
<td>4582</td>
<td>66586</td>
</tr>
</tbody>
</table>

Table 8-2 A comparison between hourly and daily data inputs on the hydrologic parameterisation of the SedNet model. The ratio columns represent the ratio of hourly to daily data.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Area (km$^2$)</th>
<th>$Q_{BF}$ (ML/day)</th>
<th>$Q_{OB}$ (ML/day)</th>
<th>$\sum Q^{1.4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hourly</td>
<td>Ratio</td>
<td>Hourly</td>
</tr>
<tr>
<td>410705</td>
<td>505.1</td>
<td>16354</td>
<td>2.1</td>
<td>8349</td>
</tr>
<tr>
<td>410711</td>
<td>376.7</td>
<td>6115</td>
<td>2.0</td>
<td>3367</td>
</tr>
<tr>
<td>410713</td>
<td>223.9</td>
<td>7271</td>
<td>2.4</td>
<td>2681</td>
</tr>
<tr>
<td>410731</td>
<td>684.2</td>
<td>11056</td>
<td>2.0</td>
<td>8707</td>
</tr>
<tr>
<td>410759</td>
<td>415.4</td>
<td>11251</td>
<td>2.3</td>
<td>6382</td>
</tr>
<tr>
<td>410774</td>
<td>68.0</td>
<td>3778</td>
<td>3.6</td>
<td>1900</td>
</tr>
</tbody>
</table>
Table 8-2 shows the values for the three non-linear hydrological variables derived using hourly data, and the ratio of hourly/daily derived values. Calculation of $Q_k$ does not depend on the timestep used and is not considered here. The hourly derived values for both $Q_{BF}$ and $Q_{OB}$ are based on daily maximum flow values obtained from hourly mean flow values, while the daily-derived values are based on daily mean flow values. Both these variables show significant sensitivity to the temporal resolution of data used, with up to a factor of 4 increase in value when hourly data is used. Such an increase would result in a corresponding increase in streambank erosion by a factor of approximately 2.3. In comparison, the value of $\sum Q^{1.4}$ was derived directly from hourly or daily mean flow data, and is less sensitive to the temporal resolution of the data used. The impact of this sensitivity with temporal resolution on the output from the SedNet model depends on the sensitivity of the SedNet model to these variables. It has already been discussed in Chapter 6 that the SedNet model has significant sensitivity to the hydrologic variables. For example a 10% increase in the value of the $f$ parameter (rainfall exponent for the calculation of $Q_{BF}$) results in a 35% increase in the total sediment output at the largest reach in the modelling network.

### 8.3 Improving Model Testing

It was discussed in Chapter 7 that accuracy assessment is an important component of evaluating and improving pollutant load modelling. In Chapter 6 two particular components of accuracy were identified as being important for testing the SedNet model - the prediction of the quantities of the total loads, and also the ability to reproduce the patterns of sediment delivery and transport. It is thought that for the majority of management applications an ability to reproduce accurately the spatial patterns of sediment delivery is more valuable than an ability to predict the total sediment loads. Thus, future testing of the SedNet model should focus firstly on a comparison with the patterns of sediment source and transport and, to a lesser extent, the quantification of total loads.

The comparison of the sediment tracing study of Wallbrink and Fogarty (1998) with the outputs of the SedNet model, presented in Section 7.2.2, is an example of the type of model testing required to assess effectively the performance of the SedNet model. For future sediment tracing studies key stream confluences should be identified a priori to ensure that the maximum information is gained for a given investment. Another method of assessing the pattern of pollutant transport is the use of aerial photo techniques to determine reaches with and without bedload sediment deposition.
The lack of appropriate widespread observed pollutant concentration data over longer time periods, as recognised in Chapter 5, limits the validation of total loads of pollutants for models such as SedNet. However, it is possible to establish programs to collect useful data for model validation with the resources presently allocated to water quality monitoring. Innovative programs for event based sampling and consolidation of disparate programs are required. Guidelines for establishment of such water quality monitoring programs were discussed in Chapter 5 (Sections 5.3.3 and 5.5). An aspect of the establishment of monitoring and testing programs that should be considered is that models of the type discussed in this research can assist in maximising the effectiveness of experimental programs and ensure the right kinds of data are collected (Moore and Gallant, 1991).

Testing of future variants of SedNet, and other similar models, should be with data collected and/or analysed at comparable spatial scales. Limited discussion of this issue was made in Section 7.2.3. Of the comparisons presented in Chapter 7, the dam sedimentation study of Wasson et al. (1999) was at an appropriate spatial scale for the upper Murrumbidgee application. Additional testing in the upper Murrumbidgee is suggested at subcatchment scales. This would be possible with studies similar to the type presented by Wasson et al. (1999) at other reservoirs in the catchment, and through use of sediment tracing techniques such as described by Wallbrink and Fogarty (1998) at additional stream confluences.

8.4 Chapter Discussion

Through sensitivity analysis, changes in the hydrologic modelling invoked by SedNet have been identified as important (Newham et al., in prep; Newham et al., 2001c) and are necessary to enable the simulation of the influence of land management change. This chapter has presented an analysis of observed and modelled streamflow for selected catchments in the upper Murrumbidgee catchment.

Using observed data removes the contribution to uncertainty due to modelling errors, and errors in the input climate time series used by the model. In addition, observed streamflow data enables use of higher temporal resolution (as only daily rainfall estimates are available for most catchments in Australia). The cost is the limited duration of streamflow data for many sites, as well as variability between catchments in the period covered.

Using a rainfall-runoff model enables generation of a long period of simulated streamflow, limited only by the availability of the necessary climate data. This allows for averaging out of climate variability, as well as production of a homogeneous temporal coverage for all catchments so that variations in temporal coverage of streamflow do not affect the results. The recommendation of this study is that both observed and simulated streamflow time series
should be used in regionalising the hydrological response of the catchments. In future studies consideration should be made of the approach used by Croke (2002). Such improvements will enhance simulation of the physical processes of erosion and deposition at catchment scales. 

Research into the hydrologic parameterisation of the SedNet model undertaken by Croke (2002) shows promise for overcoming the inherent limitations of the present hydrologic modelling invoked by SedNet. In that work the distribution of streamflow was estimated through regionalisation of the runoff coefficient and the slope of the flow duration curve. In the study $\bar{Q}_x$ was estimated from the mean annual rainfall, the woody vegetation cover and potential evaporation. This has the advantage of enabling the simulation of the hydrologic effects of changes in land cover and hence sediment source and transport. 

Methods for testing the SedNet model have also been discussed in this chapter. The spatial outputs of the model are of greatest value for prioritising management. Thus, future testing should focus on comparisons with techniques such as sediment tracing where the effectiveness of the model for predicting the pattern can be discerned. Other sediment budgeting techniques are also useful but need to be undertaken at similar spatial scales to the application of the model. Refinement of modelling techniques and monitoring activities is an iterative process. Information from models may complement monitoring programs and assist in planning monitoring activities. Similarly monitoring can be useful to refine modelled estimates.
Chapter 9 Conclusions

Clever management of catchments and riparian zones is essential as the resources allocated to their management are small in relation to what is required for their remediation. Improved land management and the effective focusing of remediation to address the widespread degradation of catchments and their riparian environments requires modelling tools for the identification of critical sources of environmental pollutants. Models are increasingly needed by managers to meet the legislative demands and societal expectation of sustainable land and water resource use, to integrate our scientific understanding of the impacts of management change and to give broader and longer term perspectives to management intervention.

The development of suitable water quality and quantity models is a difficult task. Few models exist that are appropriate for providing catchment scale prediction of pollutant loads and identification of critical pollutant source areas. Simple approaches to calculating pollutant loads such as using observed pollutant concentration and gauged streamflow data are limited: the effects of climate and land management change cannot be discerned; sampling programs are expensive (and often ineffective); and their estimation is fixed spatially. At the other end of the spectrum more complex models are often no more successful. A range of problems often constrains their use. These problems include model over-parameterisation, onerous data requirements, unsuitability of model assumptions and inappropriate structure.

This research has investigated water quality and quantity modelling through literature review and the development, application and testing of several hydrologic and pollutant export models. The research has achieved its three aims:

- A capacity for catchment scale hydrologic modelling has been developed for the upper Murrumbidgee. This has been achieved through the construction of the Murrumbidgee ICMS. As part of its development, the IHACRES rainfall-runoff model has been used to model daily streamflow at various subcatchment scales across the study catchment. The rainfall-runoff modelling is suitable for investigation of a wide range of issues (including pollutant load estimation). The model was compared with an application of the SIMHYD rainfall-runoff model (used for the NLWRA) at several commonly modelled locations. The IHACRES models performed well in comparison with SIMHYD, requiring shorter calibration periods and using fewer model parameters to achieve comparable results. A simple streamflow routing model with parameter values based on reach characteristics was also developed and tested as part of the development of the Murrumbidgee ICMS.
The routing model performed well, enabling estimation of downstream flow from modelled upstream streamflow.

- Techniques have been developed and refined to estimate the export of environmental pollutants from upland catchments. In Chapter 5 pollutant loads were calculated for two case study subcatchments. Regression based techniques were used to estimate sediment export from a combination of streamflow data (simulated using the IHACRES model) and measured suspended sediment concentration data. Such techniques were judged appropriate for widespread application to catchments with similar physical environments and constraints on available data. Novel techniques were also developed and trialed in this research to improve water quality sampling in four case study subcatchments. These cost-effective methods involved the use of rising stage siphon sampling equipment to overcome the inherent limitations of sampling of event based water quality.

- The techniques of sediment generation and transport modelling at catchment scales have been improved in this research. Techniques for estimating sediment generation have been developed and refined through application, analysis and testing of the SedNet-UM model. Application of the model has provided a capacity to quantify sediment source, transport and management implications at catchment scales. The investigation of the SedNet-UM model has also included rigorous examination of the behaviour of the model through sensitivity assessment. The major conclusion reached through the sensitivity assessment was that the hydrologic parameters of the model are most sensitive to input change. Hence, investigation of those hydrologic components of the model should be the initial focus of model improvements.

In addition to reaching the three broad aims of the research, other important outcomes have also been achieved. Incorporating the strengths of the conceptual IHACRES rainfall-runoff model (e.g. the ability for hydrologic prediction and regionalisation) and the strengths of the semi-distributed SedNet model (e.g. the simple representation of sediment source and transport processes) is potentially very useful for the future prediction of environmental pollutant export. Both models have complexity commensurate with data availability and the potential for widespread application. The SedNet-UM application has demonstrated that it is possible to construct stream pollutant models that assist in prioritising management across catchment scales. It can be concluded that SedNet and similar variants have much potential to address common resource management issues requiring the identification of the source, propagation and fate of environmental pollutants.
Conclusions

9.1.1 Summary of Contributions

This thesis has attempted to make a number of contributions to the development of water quality and quantity modelling methods for the purpose of improving catchment and riparian management. A summary of the contributions of this research include:

- the construction and testing of the IHACRES rainfall-runoff model across a variety of catchment scales and physical environments;
- the development and testing of a simple streamflow routing model using parameter values estimated from reach characteristics;
- the development of an integrated network of daily streamflow simulation models at various scales across the upper Murrumbidgee (the Murrumbidgee Integrated Catchment Management System);
- the demonstration of cost effective water quality monitoring techniques using rising stage siphon samplers at several upper Murrumbidgee sites;
- the identification and application of appropriate pollutant load calculation methods for use with event based water quality data and modelled streamflow;
- the development of a capacity to estimate sediment source and transport across the upper Murrumbidgee through application of the SedNet-UM model, incorporating catchment specific data;
- the identification of improvements to the SedNet-UM model through comprehensive sensitivity assessment, model testing and comparison of outputs with other studies; and
- the description of methods to integrate improved hydrologic input into the SedNet model and similarly structured variants.

9.1.2 Further Research

Several areas of further research have been identified over the course of the study. They include:

- investigating methods used to estimate catchment areal rainfall from sparse point measurements;
- more broad application and testing of the routing method developed in this research;
- research into the design of cost-effective, simple falling stage samplers;
- investigation of methods to estimate pollutant loads, using inputs of mean daily streamflow, for catchments where events are typically of a duration of less than one day;
Conclusions

- consideration of economic aspects of management change as part of pollutant load modelling to further assist in prioritising management expenditure;

- detailed testing using pollutant tracing techniques to assess the spatial results of modelling applications;

- development of improved gully and streambank erosion models to better reflect current management; and

- identification of the most appropriate set of strategies for the dissemination of the results of modelling to catchment managers and other stakeholders.
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