An Integrated Modelling Approach for Assessing Land Use Change and Water Allocation Policy Options

Juliet Karla Gilmour

January, 2003

A thesis submitted for the degree of Doctor of Philosophy
of the Australian National University

I certify that this thesis does not incorporate without acknowledgment any material previously published. This work has not been previously submitted for a degree or diploma in any institution of higher education.

Juliet Gilmour.

Juliet Gilmour

Acknowledgments

I would like to thank Tony Jakeman for his continuing support during the Phd. A very special thankyou to Barry Croke and Rebecca Letcher who have given extensive help throughout the entire project. In particular, Tony has ensured the direction and timely submission of the thesis. His guidance has been of great benefit in all aspects of the PhD process. Barry Croke has worked very closely with me to develop the hydrology component of the thesis. His time and thoughts have been provided instantaneously; always placing my thesis requirements above his own work commitments. Rebecca has helped extensively with the development of the conceptual framework and agricultural production model. Her input has been highly valued at all stages in the project. She has helped to ensure a timely submission of the thesis. I have built a valuable friendship with her that will last well beyond the submission of the PhD. Thanks Bec, Bazz and Tone!!.

Thanyou to Bill Watson, Michelle Scoccimmaro and Nigel Hall who helped with the development of the thesis in the early days. Thankyou also to Bill Young who provided targeted guidance in the development of the hydrology component. A special thankyou to Jess Spate for helping me code the model in Matlab.A very special thankyou to Trent for his complete support and understanding of the PhD process. Thanks to Lach and Wendy for their continual light hearted humour thoughout the past three years. Sue Kelo has become a great friend, always willing to talk at any time. Thanks to Emma for those many, many ,many coffees at the Purple Pickle Café.

The following people and Organisations have also contributed to the thesis;

- The Department of Land and Water Conservation; Yass and Leeton. In particular John Scown who provided me with GIS data.
- The CRC for Viticulture for agricultural production system data on viticulture.
- The Department of Agriculture for their information on agricultural production systems in the Murrumbidgee.

Financial support for this work has been provided by The Australian National University and CSIRO Land and Water. Financial support for travel has also been provided by RIRDC.

Abstract

The need to measure or predict impacts spatially as well as temporally throughout a catchment as a result of applying multiple water and land use policy options has evolved as an important aspect of water resources management. In the current climate of water reform in Australia, not only are the economic impacts required to be assessed, but also environmental and social impacts of implementing reform.

This thesis developed a quantitative, integrated modelling approach for assessing several current water policy options at the catchment scale. Yass catchment, a dryland unregulated river system in the Upper Murrumbidgee, is selected to develop the integrated model. Three Water Reform policy options that are currently being implemented in the catchment are selected for analysis. They are the Farm Dams Policy, Salinity Management Policy and Volumetric Conversions Policy.

In treating the environment as a legitimate stakeholder in water resources management under the Water Reforms Process, the modelling approach uses the hydrological system as a foundation for development of the integrated model. Specific attention is paid to conceptualising the hydrological system module with similar complexity to the agricultural production system module. This also ensures the process of conceptualisation, model development and integration is balanced from an interdisciplinary perspective. The complexity of the integrated model is also tailored to the available data. The importance of the conceptualisation is its ability to provide a tool to measure spatial trade-offs and impacts (direct and indirect) between three systems components: the hydrological system, the policy system and the agricultural production system at the catchment scale.

A regionalisation of the hydrological model is developed and applied to the Yass catchment tributary system. The aim is to develop an integrated model that could be applied to unregulated systems where environmental information, and particularly streamflow data, is sparse. The testing of the approach is carried on parts of the unregulated river system of the Macquarie catchment with good results for use in the integrated model.

An agricultural production systems model is also developed as part of the integrated model. The agricultural production system is modelled using a three tiered hierarchy. The hierarchy consists of Activities, Land Management Units and Nodes. The hierarchy is used to define consistent and distinct points of integration between the hydrological system and the agricultural production system. It also provides a framework for integrating the three policy options selected for analysis in the integrated model. Additionally, a set of key indicator outputs, showing the impact of various scenarios are produced at these nodes.

A major outcome of the thesis is the development of the integrated model to concurrently run multiple policy scenarios. The scenarios considered in this thesis focus upon imposing policy options and examining associated land use changes in the hydrological system and changes in agricultural production system output. The results are examined by considering the ability of the model to produce appropriate direction, magnitude and thresholds of change. Consequently, evaluation of the integrated model results moves away from examining absolute numbers. Limitations of the model for examining policy issues is also carried out by a sensitivity analysis of the integrated model. The general approach can be applied to an analysis of policy options and agricultural production systems other than those considered specifically in this thesis. In particular, the ability of the hydrological component to predict streamflow in ungauged areas makes the methods especially useful when applied to unregulated and/or data sparse catchment systems.

List of Acronyms

The list of acronyms does not include those used for model names or parameters contained within the models.

ABS	Australian Bureau of Statistics
ABARE	Australian Bureau of Agriculture and Resource Economics
AFFA	Agriculture, Forestry, Fisheries of Australia
ANZECC	Australia and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australian and New Zealand
ASC	Allowable Storage Capacity
Assoc.	Association
AWA	Australian Wine Association
BEE	Bulk Extraction Entitlement
BEL	Bulk Extraction Limit
CMB	Catchment Management Board
CMC	Catchment Management Committee
CMD	Catchment Moisture Deficit
COAG	Council of Australian Governments
CTP	Commence to Pump/Cease to Pump Rules
CRCV	Co-operative Research Centre for Viticulture
DEM	Digital Elevation Model
DLWC	Department of Land and Water Conservation
Dept. Ag.	New South Wales Department of Agriculture
EA	Environment Australia
ET	Evapotranspiration
ESD	Ecologically Sustainable Development
GCV	Generalised Cross Validation
GIS	Geographic Information System
Ha	Hectares
HR	Harvestable Right
IA	Integrated Assessment
IAG	Independent Audit Group

IAM	Integrated Assessment and Modelling
ICM	Integrated Catchment Management
IPART	Independent Pricing and Regulatory Tribunal
LMU	Land Management Unit
LP	Linear Programming
LWRRDC	Land and Water Resources Research Development Corporation
MDBC	Murray Darling Basin Commission
ML	Megalitre
mm	Millimetres
NCDC	National Capital Development Commission
NCP	National Competition Policy
NDSP	National Dryland Salinity Management Plan
NSESD	National Strategy for Ecologically Sustainable Development
NSW	New South Wales
NRM	Natural Resource Management
NSW EPA	New South Wales Environment Protection Authority
PET	Potential Evapotranspiration Rate
RFO	River Flow Objective
RIRDC	Rural Industries Research and Development Council
RMC	River Management Committees
SA	South Australia
SRMP	Site Resource Management Plans
TCM	Total Catchment Management
WQO	Water Quality Objective
Vic	Victoria

Table of Contents

Table of Figures

Table of Tables

Chapter 1 Natural Resources Management

1.1 Introduction

In many parts of the globe, water is considered a scarce resource in catchment systems. This is true over much of the Australian continent. Annual runoff from Australian catchments is among the lowest per unit area in the world (Ghassemi *et al.*, 1995).

Water is shared between urban, industrial and agricultural users. However, human use of water continues to increase, with the largest projected demand for water being from the agricultural sector, followed by industry and domestic uses (Ghassemi *et al.,* 1995). Agricultural activities are estimated to constitute 62% of total world water demand. Water use across all sectors has increased by a factor of ten since 1900 and is expected to continue to increase (UNEP, 1992).

In Australian catchments, the community and water managers have identified that current systems of water use are unsustainable, resulting in numerous problems within the landscape (DLWC, 2000a). Perhaps the most abundant and documented problem is one of rising water tables associated with the spread of salinity within the landscape. The Murray Darling Basin Commission estimates the socio-economic damage as a result of the salinisation of catchments to be $400 million per annum (MDBC, 2000b). Clearing for grazing and irrigation agricultural practices has been the major cause of salinity. Instream salinity trends are expected to continue to increase in all major river systems within the Murray Darling Basin with an average increase of 33mg l^{-1} yr^{-1} (Schofield and Ruprecht, 1989). To date, revegetation programs such as the establishment of forestry activities as an alternative agricultural enterprise have been favoured among several other options to reduce instream and land salinisation. Schofield and Ruprecht (1989) estimated that at least 50% of salt-affected catchments in Australia would need to be revegetated to halt the rise in salinity trends. Potential conflicts among water users as a result of pursuing such a management option include the reduction in runoff and hence streamflow available for irrigation extraction. The commercial viability of forestry as an alternative activity in low rainfall areas

(400mm/yr) has also been raised as a reason for pursuing alternative water management options (Dumsday, 1999).

Irrigation is the major user of water in regional areas of Australia covering a total area of 1.85 million hectares (ABS, 1999). In the state of NSW alone there are 60 000 water licenses currently administered, with the largest volume of extractions occurring within the Murrumbidgee and Murray catchments (DLWC, 1999a). Of the total volume of water extracted for irrigation, 71% is used for flood irrigation, which contributes to rising water tables and often results in salinisation.

Regulation and extraction of surface water and groundwater through conjunctive use schemes has resulted in not only an alteration to the quantity of water available to river systems, but a disruption to the pattern and timing of streamflow. Extractions for the purpose of irrigation have increased from 100 000 ML/yr to 600 000 ML/yr between 1989 and 1995 alone in the major regulated irrigation regions of the Murray, Murrumbidgee, Darling, Central West and Barwon systems (DLWC, 1999b). Given the increase in water demand, a major problem has been the over-allocation of water resources in catchment systems. Past mechanisms to allocate water have not dealt with competing water uses; instead allocating licenses on an ad-hoc basis. In Australia at present the phenomena, where water demand exceeds water supply, has been labelled as the maturing of the Australian water industry (Smith, 1998). Thus, new mechanisms, rules and systems of management are required to prevent environmental problems, such as salinity and the degradation of instream habitat, as a result of flow alteration and over extraction of surface and groundwater resources.

In unregulated river systems, particularly the upper catchments of the Hunter, Murrumbidgee and Murray systems in New South Wales, the construction of farm dams in addition to unchecked instream extraction has resulted in land and water degradation in dryland systems. Since the inception of the *Water Act 1912*, there has been no restriction placed upon the number or size of farm dams constructed, until recently. Studies by Scown (2000) and Schreider *et al.,* (2002) have estimated the runoff reduction as a result of farm dam construction can be as high as 27% and 30% respectively. Scown (2000) suggests that runoff reduction of this magnitude may have an impact on the river systems during prolonged low rainfall periods.

1.2 The Water Reforms Process in Natural Resource Management

In response to problems within Australian catchments, the past decade in Australian water resources management has been largely devoted to the evolution of a complex system of water management and allocation rules to meet the needs of all users. Arguably, the largest step in adjusting the way in which we use water has been the inclusion of the environment as a legitimate user of water (DLWC, 1997d).

The Federal Government has responded to the seriousness of water management problems in Australian catchments by introducing a series of Water Reforms (COAG, 1994). Ensuring the needs of water users in conjunction with meeting the basic health requirements of the biophysical environment is the main aim and challenge of the Water Reforms Process. The Reforms, commenced in 1995, are the responsibility of the Australia New Zealand Environment and Conservation Council (ANZECC) and the Coalition of Australian Governments (COAG) (AFFA, 2000). Various state Government Departments have developed their own short and long term strategies to solve water management problems. Water quality and quantity related aspects have been the focus. The major changes to water management under the COAG have been (COAG 1994):

- An Integrated Catchment Management (ICM) approach to water management including the use of water within the social, ecological and physical constraints of the catchment system
- The separation of water rights from land or property rights
- Recognition of the environment as a legitimate user of water and therefore entitlement to an allocation of water
- Implementation of water trading as a major end point of the Water Reforms Process.

Since the inception of the Water Reforms Process, the need to manage the entire hydrological cycle has been recognised. The Water Reforms agenda has since developed a holistic framework to water management. This framework is focused on the catchment as the unit at which management of the water resource is carried out. This is known as the Total Catchment Management (TCM) approach (COAG, 1994).

The *Water Act 1912* has, up until the Water Reforms Process, been utilised to administer water management. It was designed to administer the 'development phase' of irrigated agriculture in Australia and does not recognise the environment as a user of water. In addition, the size of a water allocation was tied to the land holding size. This Act does not take into consideration the actual quantity of water physically available from the catchment system at any point in time (DLWC, 1999b). In 1986, the *Water Administration Act* was introduced as one of the first steps in changing the mechanisms by which water is allocated. Since that time, states and territories have introduced their own mechanisms. In NSW this has included the *NSW Water Conservation Act, 1997* and, most recently, the *White Paper: A proposal for updated and consolidated water management legislation in New South Wales* (DLWC, 2000d).

1.3 Scientific tools to manage water resources within Australian catchments

Lack of scientific information, both biophysical and socio-economic, has been one barrier to developing a set of successful management strategies within the Water Reforms Process. In the first instance, lack of biophysical information has prevented the implementation of a set of water management options that are deemed suitable to meet the water requirements of the physical environment. Where comprehensive scientific or consensus-forming studies have taken place to identify the water needs of the physical environment, the process of adjustment and long term economic impact upon water users (such as irrigators) is often unknown. In addition to this, there is currently little understanding of both the magnitude and nature of socio-economic-hydrological-environment interactions. Many frameworks and studies have been proposed for investigating ways of assessing what is an appropriate environmental allocation given the current water resource in the Murray Darling Basin. See, for example, Banens *et al.*, (1996), Banens *et al.*, (1994), Young *et al.*, (1995), Davis and Young (1998), and Young *et al.*, (1998). Similarly, a plethora of studies has investigated economically optimal water allocation options. See, for example, Brennan and Scoccimarro (1999), Dudley (1998), and Hall *et al.*, (1994). However, how users of water impact upon each other and the water resource through economic actions is a basic question that has not been answered in the majority of catchments. Developing a successful management strategy is further hindered by the lack of conceptual frameworks available to document system interactions and aid the decision making process. Arguably then, it is fair to say that the Water Reforms Process is in its infancy.

Nevertheless, significant progress has been made in New South Wales (NSW) and other States. In NSW, the responsibility for implementing the Water Reforms Process was shared initially by the Environment Protection Authority and the NSW Department of Land and Water Conservation. Recently, additional legislative changes have brought other State Government Departments as well as Local Councils under the Water Reforms management umbrella, making the Water Reforms agenda a potentially powerful management tool.

Given the progress of the Water Reforms to date, many questions remain unanswered, preventing the main aim of the reform process from being achieved. Questions that need to be answered focus around, firstly, identifying the nature of human-hydrological-environment interactions? Once this systems-focused question is answered, managers can begin to ask specific questions that relate to the implementation of a tailored system of water rights.

This would develop the water managers understanding of the costs and benefits (social, economic and environmental) of providing access to water resources under rules determined by the Reform Process. For instance, how is a system of water rights to be defined by managers? How are managers to design adaptive and robust conceptual frameworks to meet the water needs of all users in the future? How do the actions of water users affect other users, the environment and the hydrological cycle, spatially and temporally? The Water Reforms Process requires a range of tools and techniques to implement a new set of water allocation rules.

The primary aim of this thesis seeks to develop an approach for assessing water allocation rules, developed by the Water Reform agenda, at the catchment scale. This approach is developed and tested in the Yass river catchment in the Upper Murrumbidgee. It is largely a dryland, unregulated system that suffers from over extraction of streamflow and land clearing. Consequently, the catchment has a very severe salinity problem in both its land and water systems. In addition, Farm Dam development has been prolific due to not only traditional activities such as grazing, but recently introduced intensive land uses that can be highly viable economically in the catchment.

1.4 Aims of the Thesis

The main aim of this thesis is to design and develop a catchment-scale modelling approach for assessing impacts of implementing multiple Water Reforms policy options. Aspects of this development are:

1. Identify the magnitude and nature of human-environment interactions that relate to the introduction of multiple water reform policies. This will facilitate the identification in the catchment of integration points between the agricultural production and hydrological systems in the catchment.
2. Design a conceptual framework for assessing economic (agricultural production) and environmental water policy tradeoffs resulting from the introduction of multiple options.
3. Design a modelling and analytical approach for assessing the impact of land and water policies on both the agricultural production and hydrological catchment systems.

The model developed is then used to run multiple policy scenarios, with the aim of identifying impacts of implementing water policy options (as identified by the Water Reforms Process). These scenario runs serve as a useful vehicle for assessing the advantages and limitations of the approach developed. This assessment has three components:

1. Model impacts, on catchment land use and hydrological systems, associated with agricultural production decisions as a result of policy imposition
2. Model spatial trade-offs between land, water and human systems as a result of agricultural production decisions and policy options
3. Assess the usefulness and limitations of the modelling approach developed for analysing the land and water issues selected for analysis.

A second aim of the thesis is to demonstrate how a general procedural approach for carrying out an integrated assessment study at the catchment scale may be developed.

The approach should be broad enough to assist decision makers answer catchment scale land and water policy questions of the type identified so far. The thesis serves to map out a general procedure for conducting such studies by way of:

1. Selecting the question(s) to be addressed
2. Using data and question information to build the model
3. Designing an appropriate conceptual framework
4. Identifying model complexity and key points of integration
5. Constructing the model formulation
6. Running scenarios and testing the model
7. Iterating back to refine the previous steps as necessary

1.5 Thesis Outline

Chapter 1 has described broadly the major natural resource management problems currently faced in Australian catchments, with a particular emphasis upon water-related issues at the catchment scale. It introduced The Water Reforms Process and approaches to dealing with such problems to date. Chapter 2 is a review of the Water Reforms Process in Australian catchments with a specific emphasis on the state of New South Wales within which the thesis case study is located. It indicates the current state and magnitude of the problem at present in NSW catchments. In approaching the problem from a quantitative analysis perspective, a review of integrated water allocation models and current gaps in modelling approaches is also presented. Chapter 3 is a review of the case study catchment. The main aim is to identify land and water problems in the Yass catchment. Secondly, it identifies the details of the three water policy questions to be modelled. A third section is devoted to identifying types of data sets and limitations of data quality and availability. The chapter concludes by identifying specific questions to be addressed in Yass catchment by the modelling approach. Chapter 4 describes the conceptual framework developed to represent the catchment system and its land and water policy issues. Chapter 5 develops the hydrological modelling component and presents results obtained for predicting streamflow in unregulated catchments as a result of land use changes. In Chapter 6 the agricultural production model is formulated, describing aspects of integration in space and time with the elements of the hydrological cycle that need to be modelled. Chapter 7 presents the scenario analysis and results form running the integrated model. Chapter 8 is a sensitivity analysis of the integrated model. It identifies advantages and major limitations of the modelling approach. Chapter 9 contains the conclusions of the thesis.

Chapter 2 The Water Reform Process

2.1 Introduction

This Chapter introduces the Water Reform Process in Australia and its implementation in the state of New South Wales. The aim is to identify the management and policy processes currently utilised to address water problems. It sets the scene as to the current magnitude and specific nature of the problem considered in the thesis. The identification of these two aspects is central to the thesis in that they determine what aspects will be selected for analysis and how its treatment will be structured. A review of integrated modelling studies applied to water allocation issues is also given in order to support, and provide insight into, recent approaches to modelling water allocation options at the catchment scale.

2.2 The Water Reform Process: The National Context

The National Competition Policy (NCP) was adopted by the Federal and State Governments in 1995 (NCP, 2002). The NCP is a suite of reforms, of which the principle aim is to provide an integrated, national approach to microeconomic reform. A part of these reforms has the aim of creating sustainable systems and one of these is water related (COAG, 1994). The Coalition of Australian Governments in responsible for developing a strategy to define a new system of water access rights. It comprises State and Federal Government Departments and Agencies responsible for water management. In 1994, COAG requested that the Agricultural and Resource Management Council of Australia and (ARMCANZ) and the Australia New Zealand Environment and Conservation Council (ANZECC) oversee the reform process at the level of State Governments (ICESD, 1996).

2.3 Evolving Water Reform in NSW

The NSW Government began implementation of the Water Reform package in 1995. Prior to this, steps had already been taken to develop an integrated system of policies devoted to sustainable water resource use. This is evident in the adoption of the Total

Catchment Management Policy in 1984 and the *Total Catchment Management Act 1989*. Under this policy umbrella, Catchment Management Committees (CMCs) were established to oversee policy implementation at the local level. Since 1995, the CMCs have been responsible for a large part of Water Policy Reform adoption and implementation (DLWC, 1999a). Subject to review in 1999, the role of CMCs was largely judged to be inadequate given the decision to implement all reforms by 2005. River Management Committees (RMCs) superseded the CMCs in their role as water managers. In 2000, the CMC structure was overhauled from community-based project implementation to one of a largely Government Department driven policy vehicle (DLWC, 1998c).

In addition, RMCs were to be disbanded once preliminary water management goals for 2005 had been established. Now known as Catchment Management Boards, the change runs parallel to a series of legislative changes making Local and State Government fully accountable for the progress of Water Reform implementation, and hence reflecting the seriousness of Government in pursuing the aims of the National Strategy for Ecologically Sustainable Development (NSESD) and the National Competition Policy (NCP) Agreement, both introduced in 1995. Having identified the evolving nature of Water Policy in NSW, the next section introduces the mix of water management mechanisms introduced to manage water problems in NSW. This illustrates the state of water management problems and the structure of current policy instruments being utilised.

2.4 Changes to the Water Act 1912: Existing Allocation Problems

Water allocation rules were first adopted under the *Water Act 1912*. This is currently the main Act used for water resources management in NSW. The Act provides a framework for licence allocations, and the nature and timing of water diversions. It has not been changed since its inception. The NSW Government White Paper (2000) acknowledges that the *Water Act 1912* does not provide a framework for implementing the Water Reform objectives (DLWC, 2000a). The *Water Administration Act 1986* is an attempt to streamline water administration by allowing conditions on licences to be varied for environmental purposes. This Act was changed in 1997 to incorporate the principles of ecologically sustainable development into the licensing and administrative system (DLWC, 2000b).

In response to this, the new *Water Management Act 2000* was introduced to the New South Wales Parliament. The main changes aim to assist the Water Reform process by providing a clearer definition of water for environmental purposes. It has also resulted in the introduction of a new system of water rights and access conditions on licences, and the development of *Water Management Plans* for determining specific water allocation limits in NSW catchments. Changes to the legislation are ongoing to meet the aims of the Water Reforms. Current major shortcomings of the legislation identified by the *NSW White Paper 2000* and *NSW Water Conservation Strategy 1999* include little or no mechanism for the needs of the ecosystem to be met. Secondly, there is no current mechanism to consider the cumulative effect on the whole catchment in terms of environmental impacts and impacts on other users of water (DLWC, 1999e).

Over-allocation of water in both groundwater and surface water environments has been identified as one of the larger problems in the current system of licence administration (DLWC, 1999b; DLWC, 1999g and DLWC, 2000a). This has reduced the security of tenure for licence holders and has been exacerbated by the activation of unused licences at any time without any requirement to lodge an intention to use the licence (DLWC, 1999b). The Water Reform process has responded to the problem of over-allocation and reduction in security of supply by the placement of an embargo upon all new licences during the reform period.

In the past in unregulated river reaches, access to water was tied to land holdings. This has reduced the ability to obtain an environmental share of water. Water was unable to be distributed consistently with the objectives of Ecologically Sustainable Development. The allocation of water, based on land holding size, restricted the ease of transfer to new agricultural activities within the catchment. A key objective of the Water Reform Process has been to develop an allocation system that caters to the transfer of water entitlements under structural adjustment (DLWC, 1998f). Under the new legislation, the development of water management plans has the aim of setting extraction limits for the catchment under a new licence system. It is hoped that the new mechanism will increase security of access and provide a mechanism for defining a clear set of water rights for users (DLWC, 1997c).

In administering a new water management system, a major aim, consistent with the National Competition Policy is the development of a mechanism for easily transferring water entitlements, either through water trading or a system of water transfers. Transfers and third party access rights must be consistent with an environmental share of water. The aim of the *Water Management Plans* is to set sustainable, harvestable allocation rules to meet this need. The new rules are to be reviewed at the end of five years, in 2005 (DLWC, 1999a; DLWC, 1999e). Current legislative changes are designed to meet this goal of the Water Reform Process. Given these problems, the next section identifies the current mechanisms in place for allocating water under the evolving nature of the Reform Process. It reveals how far the Water Reforms to date have solved problems of allocation identified by the NSW and Federal Governments. This also sets the scene for selection of the water management problem in Yass catchment as a topic of the thesis.

2.5 NSW Water Reforms Mechanisms: The Current Situation

This section identifies the main areas of focus under the NSW Water Reform package. A discussion of the current mechanisms follows with particular attention paid to issues and problems that the Water Reforms face in the future.

Table 2.1 identifies the main areas of focus contained within the NSW Water Reforms. It also lists the mechanisms used to manage water to date at the catchment scale. The table illustrates the complex set of mechanisms that have been implemented under the Water Reforms in New South Wales. Each mechanism has associated with it a series of rules defining the type and level of extraction permitted given economic, climatic, hydrological and environmental conditions of the catchment. In NSW, since 1995, a temporary set of rules has been adopted and implemented through policy mechanisms attached to allocation rules.

The rules are to be reviewed in 2005. In line with the National Competition Policy Agreement, the review is to be of an integrated nature, capable of assessing impacts between systems or areas of focus identified in Table 2.1. To date, the development of conceptual frameworks to measure the impact of introducing these new rules upon land and water systems, other concurrent policies and economic units have only been partially developed. Any assessment of the Water Reform Process must:

- address issues at the catchment scale
- assess the progress of reforms for assisting or reducing viability of agricultural activities
- consider socio-economic and hydrological relationships both spatially and temporally (for instance, this would include the relationship between preserving in-stream river flows and the economic impact upon water users).
- address potential inter-policy impacts as a result of implementation
- adopt a framework specific to the Water Reform Process.

The last two points fulfill the National Competition Policy Agreement that an integrated approach should be taken to assist with water resources management. The remainder address questions of long term sustainability for land, water and economic units, a key aim of the National Strategy for Ecologically Sustainable Development.

2.6 Structure of the Current System

This section discusses the current mechanisms, under the Reform Process, to manage water resources in NSW. It concludes with a summary of current water management problems to be investigated. This will allow the selection in Chapter 3 of the problem topic to be analysed in the thesis.

2.6.1 The Water Resource and Management Structure

Two main sources of water in NSW are surface water, consisting of direct runoff into rivers and overland, and groundwater, consisting of all water contained in aquifers. The distribution of water is highly skewed across the state, with 75% of all rainfall occurring within the coastal zone and 25% inland (DLWC, 1997b). However, 80% of all surface

Table 2.1: Water Reform Mechanisms and Policy options currently being implemented in NSW catchments

Water Management Focus under the Water Reforms	Current Mechanisms
Water Quality Objectives	Interim water quality objectives
Water Quantity Objectives	Interim water flow objectives
Water Pricing Reforms	Water trading between catchments Permanent/temporary transfers IPART (Independent Pricing Tribunal) bulk rural water prices
Third Party Access Rights	Water trading (inter-valley and interstate trading) Bulk water entitlements
Groundwater Allocation	Moratorium on extractive licences Sustainable yield extraction limits (Low and high yield licences) Water harvesting by 'Zones' (allowable extraction densities, restrictions on transfers of rights) Volumetric allocation Continuous accounting: 'Access' versus 'use right' Conjunctive use licence
Surface Water Allocation	Hierarchical licence structure Separation of water share and access rights Murray Darling Basin Commission Cap Volumetric conversions Commence to pump, Cease to pump rules High, low and general security licences High flow licences Off allocation access Moratorium on extractive licences Sleeper and dozer licences Ghost licences Riparian licences Embargo on new issue licences Dam store release rules Continuous accounting
Run Off Capture	10% Farm dam policy Licences for large dams
Water Use efficiency	Flood plain harvesting Structural adjustment assistance for technological change Tax rebate for technological change Water savings
Ecosystem Health	Environmental flow rules Flood pulse/continuous flow rules Contingency environmental flow Exclusion of trading/transfers in 'stressed' catchments
Water Industry Socio-economic Structural Reform	Structural adjustment assistance Assistance (through trade) for value added industries

and groundwater extraction occurs within inland catchments (DLWC, 1997c). The States water resources are divided into three management systems: groundwater, unregulated and regulated systems. In an effort to overcome the insecurity of supply that characterises Australian catchments, NSW has constructed 16 major dam storages. Dam storage releases have occurred under a predetermined set of access rights to guarantee security of supply for a hierarchy of users. Surface river systems below the dam storage are known as *Regulated* river systems. Surface water systems above the dams (often associated with the upper catchment) are free from regulated river releases and are known as *Unregulated* systems. The *Groundwater* system is the third management unit, pertaining to all groundwater held in aquifers.

There is an estimated 5 billion megalitres (ML) of groundwater contained in NSW aquifers and an estimated surface water dam storage capacity of 14 million ML, in addition to two dams that supply urban water. Access to the groundwater resource is limited to an estimated 5 million ML being available for extraction on a sustainable basis. Surface water access is also a smaller proportion of total storage capacity (between 7 million and 12 million ML) owing to climate-related insecurity of supply. There are currently 60 000 water licence holders licenced to capture 7.2 million ML per annum (MDBC, 1999). Of this, 7 million ML is captured for the purpose of irrigation with the majority of licences operating in the inland catchments (DLWC; 1997d and DLWC, 1998b). This illustrates the current tensions between supply of water and user demand in NSW catchments. The NSW Water Reform Process has recognised that the water system is at a minimum, fully allocated, and more likely to be over-allocated in many catchments. Users continue to lobby for increased access and security of supply. In addition to this, since the inception of the National Competition Policy, the environment has been declared a legitimate user of water.

2.6.2 Water Sharing: Environmental Responsibility versus User Security?

Water dependent users continue to degrade the environment through changes in size, timing and frequency of flows within regulated rivers. Water entitlement allocations have perpetuated environmental degradation for a number of reasons. The pre-reform water licensing system does not allow for an environmental allocation of water. The allocation of licences has, up until the Water Reform Process, been allocated on a needs basis for users. The result is a large number of *sleeper* and *dozer* licences (DLWC, 1999d). These are licences that have been issued but are not currently utilised. It is the activation of these licences in drier years that has resulted in over-extraction from the river system. In addition, the licence system has traditionally allocated licences based on the property size to be used for irrigation. The entitlement, based upon water demand rather then available supply, has resulted in near 100% extraction in dry periods.

Where surface water resources have been exhausted, many licences have allowed extraction of water from the groundwater system to secure water supply. These are known as *conjunctive* licences. Conjunctive licences have resulted in unsustainable extraction of groundwater resources. The timing and duration of groundwater extraction has not been monitored. As a result, over-extraction of groundwater has resulted in problems such as salinity, reducing water quality and increasing salt delivery to land systems. Off-allocation entitlements occur when there is a surface water supply after which all licences have been fulfilled. It allows unrestricted access to water by users above the entitlement. Water is extracted and often stored within farm dams. This has been another mechanism aimed at increasing security of supply for water users. However, the result has been environmental degradation even in times where available water has the potential to satisfy both environmental and user needs (DLWC, 2000d).

In response to acknowledging the unsustainable nature of the current water management system, rivers have been classified according to the level of 'stress' experienced by the extraction of water under the current licensing system. The *Stressed Rivers Assessment Report* has formed the basis for designing a new set of sustainable allocation rules. The next section outlines major changes to allocation rules in NSW under the Water Reform Process (DLWC, 1997c).

2.6.3 A Response: The CAP and Embargo

As additional water users have been allocated licences, the activation of sleeper and dozer licenced has continued to increase. In times where water supply has been enough to satisfy both licenses and environmental needs, access to off-allocation water has compromised the environmental share of water available. In 1995, the Murray Darling Basin Commission announced a Cap on all extractions from surface water. The Cap is a ceiling on the volume of water that can be taken from a catchment regardless of the number of licences (MDBC, 1996 and DLWCc). The Cap volume recognised an environmental share of water as well as the volume of water required for downstream users. Specifically, the Cap limits the amount of water able to be extracted to the volume extracted in the year 1993/94 (MDBC, 1999).

The Cap and embargo have prevented any further environmental stress by maintaining water extraction levels at 1993/1994 levels (IAG, 1997). It is now argued that the implementation of the Cap was the first step in introducing a new set of access and water property rights under the Reform Process. Although establishing a benchmark, it does not meet the needs of the environment from the perspective of flow requirements. Similarly, the Cap on extractions at a 1994 level does not allow for adjustment of the water allocation system to meet long term sustainable needs of new and existing users in NSW catchments (DLWC, 1998d; MDBC, 2000a). Meeting the Cap by licence restrictions has resulted in annual management outcomes, reducing security of supply to users. It is clear that the Cap and embargo have increased security to regulated system users by preventing further extraction on unregulated (upper catchment) rivers. However, the Reform Process still needs to address entitlement volumes on specific catchments (according to the 'stressed' status) (DLWC, 1998c). In many ways, the Cap and embargo reflect the current state of the Water Reform Process in that continued depletion of the water resource has been halted (MDBC, 2000b). Now the reforms are in the stage of defining what are acceptable extraction volumes that meet the needs of the environment, and increase security for users that is long term, dynamic and sustainable (IAG, 1998). The next section describes those aspects of the Reform Process that have attempted to achieve this.

2.6.4 Environmental Objectives

The establishment of Unregulated, Regulated and Regulated River Management Committees (RMCs) was one of the first steps toward defining sustainable extraction volumes. Each committee had the responsibility of developing a set of River Flow Objectives (RFOs) and Water Quality Objectives (WQOs). The objectives must balance both environmental and economic needs in the long term. The first set of flow rules defined in accordance with the objectives were implemented in 1998/1999 for regulated river systems. Known as Interim Flow Objectives, the set of objectives developed for the Murrumbidgee Regulated River System, of which Yass is a catchment, are given in Table 2.2 (EPA, 2001; EPA, 1999).

Table 2.2: River Flow Objectives (RFOs): Examples from the Murrumbidgee regulated river system

Interim RFOs	Example from the Murrumbidgee Regulated System
Protect natural water levels in pools and riffles during low flows	Release of 615 ML per day from Burrinjuck and 560 ML from Blowering. All releases equal to inflows
Restore a portion of high flows and fresh flows	Between April-October release a portion of inflows in accordance with climate variation
Restore the natural inundation patterns and distribution of floodwaters	Water is to be stored to buffer natural flow patterns and restore inundation
Ensure enough water for contingent environmental events	Reserve 250 000 ML for water quality needs and algal bloom suppression

The regulated river systems and the Barwon-Darling system were the first to define RFOs. For each river system, a set of twelve flow rules were developed to restore natural river flows and maintain the ecological function of the river. RMCs had the responsibility of setting the flow objectives in conjunction with community involvement. At this stage of the Water Reform Process, there is little information for assessing the likely impact of introducing RFOs, both economically and environmentally. In general there is considerable debate as to what types of flows benefit ecological river function and habitat. In light of this limitation, RFOs are to be revised for the first two years with another revision in 2005. Although potentially providing the means for an environmental allocation that is sustainable, knowledge as to the likely trade-offs for agricultural production systems is limited. Given this limitation, the impact of the proposed environmental flow rules have been limited to 10% of all diversions in 1994. The limit on implementation to 10% of the Cap has the objective of guaranteeing security of supply for users. This illustrates the current lack of understanding in identifying the magnitude and type of environmental impacts and trade-offs between economic and environmental systems as a result of implementing rules under the Water Reform Process. The limit is in place until 2005. Under the Water Reform Agenda, it is envisaged that the five year cooling-off period will facilitate water trading, a main objective of the reform process.

RFOs provide the foundation to develop an environmentally sustainable set of allocation rules while meeting the NCP's goal of facilitating trading in accordance with defining a new set of water property rights through third party access. Striking the balance between developing a system to legitimise the environment as a user of water and facilitating economic sustainability by water trading are considered mutually obtainable under a new set of water allocation rules and access rights (DLWC, 1999b). The next section identifies current progress and problems in defining such a system of allocation rules.

2.6.5 Water Sharing Arrangements: Volumetric and hierarchy

The water sharing framework is currently being targeted for implementation at several decision making levels. Water must be shared between users and the environment while the second level defines access rights between extractive and non-extractive users. Defining access rules for both annual and long term sustainable entitlements is an ongoing process. In light of this, a draft set of Water Sharing Principles provides an interim policy platform for the NSW Government to proceed with the Water Reform Process. The water sharing principles are identified in Table 2.3 (DLWC, 1998d).

The first step in introducing a water right that is secure, yet adaptable to changing river flows has been to separate an access right from a use right. Under the previous system, an allocation and the right to immediately access the allocation under the use right were a single licence (DLWC, 1998e). The separation of each allows for an environmental flow before access is determined. However, security of tenure is not compromised as the access right licence contains the potentially larger allowable extraction limit, pending climate variability.

Prior to the Water Reform Process, water extraction licences were revised and renewed every five years. This reduced security of tenure and increased risk associated with investment opportunities in the water industry. There is still considerable debate as to whether the new rules, separating access from use rights, could allow a fixed licence agreement, thus increasing economic security of tenure for users. Under the Water Reform Process, six options for securing water entitlements over the long term are under review. These range from a fixed access right to issuing a perpetuity licence with conditions to be renewed every five years.

Table 2.3: Interim Water Sharing Principles to determine allocation rules in NSW

Principle 1	The environment and extractive users have a legitimate claim on water
Principle 2	Water sharing arrangements should ensure the maintenance of surface and groundwater systems (this is prior right to extractive use)
Principle 3	Water Sharing should allow Ecologically Sustainable Development
Principle 4	Community and Government should work together to determine access rules
Principle 5	Any changes to access rules should not act to diminish current water use rights
Principle 6	Water rights should be separated from land title
Principle 7	Rights should be easily specified in terms of tenure, obligations and definition
Principle 8	Water sharing should be based on a consistent licensing system
Principle 9	The benefits of water efficiency gain are held with the land holder
Principle 10	The market for water rights needs to maximise opportunities for the productive use of water with environmental equity and efficiency constraints.

The Department of Land and Water Conservation identified various benefits of the new allocation framework, including facilitating a more consistent assessment of the impacts upon the environment and capable of adjusting to new requirements, improved demand management in stressed systems, clearer processes for new water-based enterprises and encouraging the movement of water to higher value industries. The separation of use rights from access rights has been proposed to facilitate both temporary and permanent transfers of water, encouraging water trade (see Section 2.7). The Water Reforms are committed to facilitating greater security of tenure for water users in catchments. In addition to separating access from use rights, the Reforms Process will introduce a new set of rules known as *Continuous Accounting*.

Under the current water allocation system, users who do not make use of a full water entitlement lose any surplus water for the next year. The unused water is forfeited by the user and returned to the catchment manager (the Department of Land and Water Conservation) and re-allocated for the next year among all users. The *NSW Water Conservation Strategy* (DLWC, 2000a) has identified this system as encouraging inefficient use of water. Licenced users that do save water are not rewarded with any greater security of access than those who do not conserve the water resource. In addition, the extent of supply security is restricted to the catchment capacity over the period of one year only, arguably raising uncertainty in business investment decisions. Under the Water Reform Agenda, structural change to water allocation rules involves the introduction of a *Carryover Capacity*, also known as *Continuous Accounting*. A carryover provision attached to licences would entitle water users to obtain part of any unused water for use in the next year. Continuous accounting provides an incentive to save water in wet years and provides security of tenure to users in drier years. A recent addition to this rule under the Water Reform Process has been the introduction of *Capacity Sharing*. This has the aim of increasing security of tenure for water users. Under capacity sharing, licenced entitlement users obtain a share in tributary inflows, outflows and storage capacity of dams.

In summary, the separation of access and use rights, while facilitating the environment as a legitimate user of water, reduces security of supply for users. Two main changes to water allocation rules seek to legitimise the environment as a user of water, namely restrictions on floodplain harvesting and a hierarchical system of allocation (DLWC, 2000d). To allow environmental and other users to operate in time, the Water Reform Process introduces new rules under a hierarchy of access rights. These changes have been made under the new *Water Act 1999* (DLWC, 1999e). At the moment the hierarchy of use does not apply to groundwater users.

The previous section has introduced broad structural changes to the water industry under the Water Reforms. The next sections focus on specific changes and problems associated with water management units in the catchment: the regulated and unregulated river systems. It identifies how the Water Reform Process is currently addressing this problem as well as identifying current shortfalls and questions to be answered.

2.6.6 The Regulated System

One of the main mechanisms used to date to manage water within regulated systems has been through a series of volumetric conversions. A volumetric conversion ties the enterprise to a volume in the river, ensuring that the river is not over-allocated regardless of climate variation (DLWC, 1998f). The modelling approach in this thesis examines the impact of volumetric conversions and the impact of a new system of water licences under structural adjustment.

Within regulated rivers, there are two types of licences: high security and general security. High security licences have access to water in all cases with the exception of extreme drought events. High security licences include town water supply, stock and domestic supply and irrigation operations that involve permanent planting such as viticulture and fruit trees. A separate set of rules activating dam storages ensures that the needs of high security licences are met above that of the Cap and environmental flow rules. General security licences include all other forms of water use such as irrigation. Prior to the Water Reform Process, general security licences gained access to water after high security licences had been fulfilled (DLWC, 1999a). Since the Water Reform Process, these licences are now subject to the Cap and environmental flow rules, raising the argument that general security licences have been reduced in security of supply, resulting in the raising of risk for investment in water-based industries.

The Water Reform Process has been reluctant to address the problem for the following reason. The current embargo prevents the expansion of water entitlements. A characteristic of high security licences is that the entitlement is rarely used in its entirety on an annual basis. The Reform Process has encouraged temporary transfers of water between high and general security licences to correct the short fall. This has the aim of facilitating permanent and temporary water trade within valleys and catchments (see Section 2.7.3).

2.6.7 The Unregulated System

Unlike the regulated river system, unregulated systems are not subject to controls over the volume and timing of water extracted from the river. Irrigated areas are still subject to a licence. However, what characterises these systems is the level of in-stream extraction for the purpose of drought proofing by storage in small dams. Extraction from the riparian zone is the second major characteristic of unregulated systems. A key problem that the Water Reforms seek to address in unregulated systems is the growth of extraction from the stream and capture of run-off in farm dams (DLWC, 1998g; DLWC, 1999h). The growth has resulted from the movement of traditional agricultural activities such as grazing to water intensive alternative activities such as viticulture and horticulture (see Section 2.7.3). In addition to adversely impacting upon water availability in the downstream regulated systems, unregulated systems are subject to both the Cap and environmental flow rules. Clearly, over-allocation of the unregulated system has a major impact on water sharing arrangements.

The Water Reform Process aims to reduce water use in over-allocated unregulated systems by introducing two mechanisms: volumetric conversions and assigning access classes to each licence. Volumetric conversions are currently being carried out in all unregulated catchments. In addition, the volumetric licence is assigned an A, B or C access level. An 'A' class is the highest security licence, allowing access to water at low flows. Similarly, 'B' class licences have access during times of moderate flows only, while 'C' class licences are the lowest security licences. This last category has access only during moderate and largely high flow periods. To date, various discussion papers by the Department of Land and Water Conservation have identified specific classes of flows to be trialed under the new water allocation system (DLWC, 1997c; DLWC, 1999g; DLWC, 2000d). As yet, there is little information on the likely economic impact upon water users as a result of introducing a system of volumetric conversions.

In contrast to regulated river systems, unregulated river systems have a large number of *sleeper* and *dozer* licences. Sleeper licences are those that have not been used for a long period of time while dozer licences are activated in times of drought to maintain water access in addition to the active entitlement. A potentially adverse affect of implementing volumetric conversions within unregulated systems is the activation of sleeper and dozer licences if users are suddenly restricted to water access under the new hierarchy system. There is also the possibility of the sale and/or activation of sleeper and dozer licences under market conditions with the introduction of water trading. In this case, the implementation of new rules could cause additional extraction from both groundwater and surface waters.

A second problem associated with unregulated rivers is the development of farm dams for use in alternative agricultural enterprises. Although the *NSW Strategy for Water Conservation 1999* has encouraged the transition into value-added industries (see structural adjustment in Section 2.7.3), unrestricted capture of run-off in farm dams has the potential to reduce recharge to groundwater and surface water discharge to streams. For this reason, the Farm Dams Policy was introduced as part of the Water Reforms package in 1995 (DLWC, 1999e). The policy restricts the capture of runoff to 10% of runoff from a property. Dams constructed that are above seven megalitres are subject to a licence administered through the Department of Land and Water Conservation. Debate as to the appropriate percentage has been ongoing throughout the reform implementation. In light of the debate, there is little information as to the impacts upon streamflow and hence the operation of volumetric rules as a result of introducing a 10% cap upon all runoff capture. Alternatively, enforcement of a 10% runoff rule also has the potential of reducing diversification into alternative agricultural activities for those value-added industries such as horticulture and viticulture that are high users of water.

2.6.8 Groundwater Systems

Groundwater licences are issued for extraction of water from bores and have only been subject to volume restrictions since 1972. Similar to unregulated systems, the Water Reform Process has attempted to identify areas that are currently over-allocated or are at risk from over-extraction by classifying groundwater systems into high, medium and low risk areas. In some parts of NSW, groundwater zones have been introduced to limit groundwater extraction. For example, in the Namoi catchment allocations have been reduced in line with a set of sustainable yields to limit the occurrence of over-extraction. At best, preliminary estimates of a sustainable yield have been suggested (NGERP, 1999 and DLWC, 1999i).

2.7 Water Trading

The introduction of the new licence structure, including the development of River Management Plans by the River Management Committees and conversion of all licences to a volumetric allocation is part of the Water Reforms framework to implement water trading. Water trading has been offered as the solution to both economically and environmentally inefficient use of water resources, primarily by providing a mechanism for transferring water away from economically unviable uses to 'value-added' industries. In addition, trade has been identified as a mechanism to move water away from uses that have been environmentally damaging by way of 'trading out' of the industry. There are several key features and rules that underpin the development of water markets in NSW catchments (DLWC, 1998d; and Topp and McClintock, 1998). This section seeks to explore this and identify economic and environmental questions that water trading raises.

2.7.1 Water Markets: A Short Profile

The first trade in water took place in 1985 in South Australia. Since that time, NSW catchments have been subject to water trading. Water trading is now the primary source of water transfers between activities. In 1997-98 10% of the total consumptive water entitlement was traded in NSW catchments. During this time 832 149 ML was traded in NSW, all of which occurred in regulated systems. The distribution of trade is highly skewed with 35% of all NSW trade occurring in the Murrumbidgee Irrigation Area and 27% in the Murray Irrigation Areas (DLWC, 1999a)

The amount of 'real trade' occurring is much less then 10% owing to the fact that trade has been split between temporary and permanent transfers. Permanent trade involves the transfer of the entitlement in exchange for a fixed one-off payment for the water entitlement. Given the immature nature of Australian water markets, 90% of all trade has occurred in the form of temporary transfers. Temporary transfers involve transferring the water entitlement for a short amount of time, usually over an annual time period. At the end of that time the water entitlement is taken back by the original custodian. Despite the largely 'temporary' nature of water trading in NSW catchments, the value of trade has been estimated at between $60 million and $100 million for the 1997/98 year with at least $30 million being attributed to trade in NSW catchments. Trade has been carried out in the regulated river systems only (Marsden Jacob and Associates, 1999).

2.7.2 Facilitation of structural adjustment

Potential long term benefits of implementing a trading framework have been identified. The facilitation of structural adjustment is fundamental to introducing the framework. A main aim of introducing trading is to allow new water users to obtain water for value added industries such as viticulture and horticulture. Trading will allow the exit of older industries for these new industries without placing pressure upon the State Government for additional water entitlements. In this sense, structural adjustment under water trading will not jeopordise the state's commitment to a set of environmentally sustainable flow rules (Marsden Jacobs and Associates, 1999).

Providing a mechanism for securing third party access rights for new industries has been identified as an important element in increasing water trading. A problem that has been identified with the exit of traditional enterprises is the loss of economies of scale due to 'stranded' irrigation technology once the water entitlement has been sold. The Water Reforms Agenda strongly recommends government subsidies to facilitate structural adjustment, or the incurrence of an exit fee for the new user to ensure trade does not produce large inequities and economic loss under structural adjustment. In this sense, the development of a water market is not expected to evolve from a purely free market approach (NSW Rural Assistance Authority, 2000).

As for the current situation, a review of the NSW Government trading framework conducted by Marsden Jacob and Associates (1999) has suggested that trade is being hampered by the current administrative system in which a permanent transfer may take up to 12 months to complete. This has been suggested as the major impediment to developing a mature water market. In addition, approval is based upon a case-by-case assessment subject to provisions and flow rules contained in the *River Management Plans*. This ensures that all trade adheres to the principles of Ecologically Sustainable Development in meeting the environmental goals of the water reforms. As a result, the current framework has yet to provide a mechanism to facilitate movement toward new industries such as viticulture by permanent transfers of water. Value-added industries have no other mechanisms of gaining access to water with the embargo upon new water entitlements. Given these current impediments, the type of buyers and sellers in the market indicate whether or not trade will facilitate structural adjustment. Table 2.4 suggests this is the case, with demand for water derived from higher value industries.

Table 2.4: Demand for water based on trade in southern states between 1987-1993. Source: Bjornlund and McKay (1998)

Activity	% of sellers	% of buyers
Viticulture	6.4	26.9
Citrus horticulture	0.9	8.7
Stone fruit horticulture	4.4	0.5
Other horticulture	1.7	38.1
Vegetables	13.6	16.4
Dairy pastures	12.3	0.4
Lucerne and Grains	49.3	6.9
Other	11.4	2.1
Total	100	100

2.7.3 Reform rules governing valley and inter-valley trade

To prevent purely price-driven water trade options that could result in adverse environmental consequences, a series of rules and regulations will govern any trade that takes place. Unless water trade was consistent with Ecologically Sustainable Development, trade could dry out river reaches, damaging both land and water resources. Recent studies suggest that where the property rights system is poorly defined, damaging third party effects are common in addition to generating adverse externalities (Beare and Rosalyn, 1998).

River and groundwater management plans will identify boundaries on trading for the purpose of trading within the requirements of Ecologically Sustainable Development. Site Resource Management Plans (SRMPs) will extend Land and Water Management Plans and River Management Plans development by the River and Catchment Management Committees. The aim will be to set a system of site use licence regulations. SRMPs will detail technical provisions relating to water releases and volume available for trade within and between valleys.

2.8 Problems and Potential Research Questions

This review has set the scene as to the current magnitude and nature of water reform questions and problems that are yet to be solved. Table 2.5 is a summary of these aspects of the Water Reforms, having the purpose of identifying potential areas of research for investigating a water reform-related question. The table illustrates the broad range of topics and their associated questions that could be analysed as part of a modelling approach to investigate water allocation issues. The questions have two characteristics in common that is also a feature of the approach developed in this thesis. They are all focused at the catchment scale. The questions also require an approach to investigating trade-offs and impacts in order to address the question appropriately.

Table 2.5: Issues and potential research areas within the Water Reform Agenda

Issue yet to be addressed	Question or topic area for research
Environmental Water Allocation	What are appropriate environmental flow rules for catchments?
Unregulated Rivers	What will be the impacts of conversion of licences to a volumetric rule?
Run-off Rules	What is an appropriate run-off rule for land capture of water? What are the impacts on streamflow?
Community Involvement	What role should the community play in development of long-term water management strategies?
Legislation	How will the *Water Act 1912* accommodate the new Reform Process? What Aspects of the Water Conservation Strategy are consistent with the reform agenda?
Groundwater	What is an appropriate set of sustainable yield limits for catchments? What is the affect of implementing conjunctive use rules? What is the impact of volumetric conversions upon groundwater access?
Regulated Rivers	What will be the effect of separating access from use rights within allocation rules? How are sleeper and dozer licences to be managed? How is access to off-allocation water to be implemented that is consistent with environmental and economic access rules?
Economic	What is the long term economic impact of encouraging trade and transfer to 'value added industries'? What affect will this have on the catchment environmental system?
Policy	What is the inter-policy impact as a result of introducing multiple reform agendas simultaneously into catchments? How are RFOs and RQOs to be utilised while allowing security of access to water by users? What are the long-term economic impacts on introducing the Cap and embargo?
Environmental	What are the ecological impacts upon the river system of introducing the new system of water allocation rules
Water Security for Users	How effective is the new set of rules in increasing security of supply for users in the water industry? This includes management of hierarchy of licences, carryover rules, transfer and trade entitlements and access under volumetric allocation given climate uncertainty
Climate Contingency	What is the effect upon economic and environmental users of water given climate uncertainty under the new set of water allocation rules? How flexible is the Reform Agenda in providing security and flexibility under climate change?
Management	How effective is the existing management framework for implementing the reform objectives?

2.9 Identification of the Thesis Approach to the Problem

As the literature review has identified, catchment managers and decision makers have identified the development of sustainable agricultural systems as a key aspect of managing human activities in the Australian environment. The Water Reforms seek to facilitate a transition to sustainable land and water use. Definitions as to what is sustainable agriculture are abundant, yet there are relatively few methods or mechanisms for identifying what constitutes a sustainable agricultural activity in the landscape and even fewer methods for defining the sustainability of an activity from the perspective of catchment impacts (economic and biophysical). For the purpose of analysing catchment scale Natural Resource Management (NRM), sustainability has been defined as the ability to continue within identified limits (Pezzey *et al.*, 1992).

Sustainable ecosystem identification and management is one of several key areas associated with the NSW Water Reform Process. Decision makers in the policy environment are required to make decisions that reflect a balance between the socio-economic and environmental systems. The evaluation of alternative options followed by an implementation stage is no longer the final step in effective policy making. Attributes that comprise a sustainable option require the consideration of the current situation in addition to long-term trade-offs. This second component requires decision makers to understand the impacts of change and dynamic system processes in order to identify sustainable limits of water extraction and agricultural land use. Under the Water Reform Process, the introduction of new flow allocation rules in catchments is one response to delivering sustainable systems.

Single disciplinary research is unable to consider system interactions to measure sustainability. Integrated assessment techniques attempt to overcome this problem by considering impacts and potential response options using a form of systems analysis. Techniques and methods developed and utilised for this purpose are numerous. Parson (1995) identified integrated assessment as consisting of numerous methods, from formal scientific analytical methods to techniques that rely upon stakeholder consultation.

2.10 Use of Integrated Assessment Models and Frameworks

Integrated Assessment Models (IAMs) have been widely utilised by the scientific community to answer systems-oriented questions. The use of IAMs is dependent upon the question drivers. These may be scientifically driven through process-related questions or policy driven through behavioural questions (Rotmans and Van Asselt, 1996).

The use of IAMs has largely been applied to assessments of the impact of climate change. The most evident and generic problem in utilising these models is the trade-off between physical systems understanding and its representation in the model, and the representation of impacts associated with policy options. Models that are overly complex in structure suffer from being too specific for policy questions to be answered. Transparency is a key requirement for justifying and interpreting model outputs for policy based decisions. Secondly, these complex models are limited in that outputs consist of quantitative detail that are not consistent with time or space scales or interpretation required for decision making. Model transparency reduction has reduced the ability of these models to be utilised in a policy environment (Hope *et al.*, 1993; Peck and Teisburg, 1993; Dowlatabadi and Morgan 1993; Ravetz, 1997). Jakeman and Letcher (2001) provide a summary of IAM features and these are reproduced in Table 2.6.

Table 2.6: Common features of Integrated Assessment. (Source: Jakeman and Letcher (2001))

• A problem-focussed activity, needs driven; and likely project-based
• An interactive, transparent framework; enhancing communication
• A process enriched by stakeholder involvement and dedicated to adoption
• Linking of research to policy
• Connection of complexities between natural and human environment; recognition of spatial dependencies, feedbacks, and impediments
• An iterative, adaptive approach
• A focus on key elements
• Recognition of essential missing knowledge for inclusion
• Team-shared objectives, norms and values; disciplinary equilibration
• Science not always new but intellectually challenging
• Characterisation and reduction of uncertainty in predictions

Recent developments in the field of integrated assessment have attempted to build systems that integrate models with tools such as Geographic Information Systems (GIS) to communicate model outputs. GIS allows model data outputs to be interpreted easily by viewing the spatial impact of model outputs. Other modules have been able to incorporate dynamic decision making as part of model integration. The result is that optimal decision making paths have been identified for long-term sustainability (Van den Bergh, and Nijkamp, 1994 and Taylor *et al.*, 1999). Earlier work focused upon climate change has attempted to represent systems processes in a complex way, yet policy decision options have been static. Dynamic modules developed in integrated assessment and modelling allow policy decisions to be changed or incremental through time. This is a significant step in IAMs, although it appears to be in its early stages.

Given the past development and application of IAMs, the use of integrated assessment provides a potentially useful and relevant tool to answer land and water questions of the type identified in Table 2.5. An integrated assessment model, applied to answering selected water reform questions of the nature identified in the literature review, could be of benefit to the policy environment where the following are considered:

- The policy resolution dictates the modelling resolution. Policy questions to be answered under the Water Reforms Agenda are focused at the larger catchment and regional scale. The resolution of the modelling exercise must be sufficiently coarse and broad-scale to capture essential processes. Processes selected for model development must be targeted to the question. In this case model development must produce the following outputs as a minimum:

    - changes in broad hydrological characteristics such as volume of flow through the catchment or tributaries
    - changes in broad economic characteristics such as economic return by industry (or activity) at the catchment scale

- Given the necessity to consider trade-offs between systems, integration between economic (agricultural production in this case) and hydrological systems can only occur at that process scale coarse enough to allow effective model integration. Simplicity in the conceptual foundation and model construction is therefore desirable to avoid problems in integrating across disciplinary boundaries. However, the trade-off is to ensure that model complexity is significant enough to capture these processes accurately enough to answer the policy question of interest.

- Given the abovementioned tension in deriving a conceptual foundation and model construction for analysis of a question, the model must be able to produce outputs that are easily understood and of relevance to informing decision makers as to the outcome for a given question of interest. For instance, in answering a Water Reform question as to what is an adequate environmental flow, a set of model outputs detailing number of invertebrates or changes in daily streamflow presents two problems. The first has too narrow a relevance to answering the question of interest while the second may produce overly complex data (especially where a 20-year simulation is carried out) that is cumbersome to manage and difficult to interpret. Selection of the integrating scale and process resolution must be tailored to produce model outputs for answering Water Reform Agenda questions.
- Given these specific considerations and the potential to apply integrated assessment models to the Water Reforms Agenda, a literature review is given in the next section on the state of the art in integrated assessment in order to illustrate the suitability of IAM for answering the sorts of questions to be identified in Chapter 3, the scene setting chapter for the case study. From this, a set of specific thesis questions from the list created in Table 2.5 can be identified. This sets the context for development of an approach in Chapter 4, the conceptual framework.

2.11 The use of Integrated Assessment Models to Assess Catchment-Scale Water Allocation Issues

McKinney *et al.,* (1999) suggested that integrated economic-hydrological modelling approaches are best equipped to assess water management issues at the basin scale and are of two types. At this scale, integrated models aimed at examining water allocation issues are divided into compartmental model approaches and holistic model approaches. Compartmental approaches are characterised by a loose connection between the economic and hydrological modelling components. This is often seen in the use of one model (the hydrology for instance) output data simply used as input data to a more sophisticated economic model. In contrast, holistic models involve tighter interaction (seen in the conceptual and analytical frameworks) between the economic and hydrology systems. An ideal holistic river basin model is made up of three components; 1) An in-stream environment, 2) a supply component (the hydrological system) and 3) a demand component (the economic or irrigation system). Design of interaction between these components and the complexity within them is the function of the integration. This review has the aim of demonstrating how the modelling approach developed in the thesis is a holistic approach.

Integrated models developed by Dandy and Crawley (1992), Fedra *et al.,* (1993), Lee and Howitt (1996), Stockle *et al.,* (1994) and Varis *et al.,* (1994) are examples of integrated models designed to examine water quality or biophysically-related policy options under various cropping and land use irrigation patterns. In these studies, the biophysical modelling component is of a high level of detail with regard to processes such as throughflow and evapotranspiration.

In contrast, other integrated water resource models have focused upon the economic system and related policy options. Dinar and Letey (1996), Williams *et al.,* (1989), Young (1996), Schneider and Whitlach (1991) and Hewitt and Hanemann (1997) are examples of integrated models that have focused upon estimating agricultural water demand as a series of optimisation functions. These models have focused upon policy options that are related to the economic system, and therefore, are typically concerned with answering water allocation or property rights-based issues.

Griffin and Hsu (1993) attempt to bridge the gap between economic and biophysical model detail by presenting an integrated model to assess water markets where in-stream flows are given value. The approach is based upon varying economic policies and water consumption, using an optimisation algorithm. These approaches solve the water allocation problem from the demand component of the integrated model. Other integrated water allocation models that are focused on adjusting demand side parameters by using an objective function of demand include McCarl *et al.,* (1999), Characklis *et al.,* (1999), Oweis and Hachum (2001), Berbel and Gomez-Limon (2000), Kruseman and Bade (1998) and Raju and Kumar (1999). These are examples of integrated water allocation models that solve the problem by optimising a demand component parameter (typically a water demand function or price function from irrigators) to solve the water allocation issues. These approaches, while having great benefit for economic policy instrument evaluation associated with water reform, are limited in their representation of the interaction between production systems and the hydrological system.

Additionally, the studies cited above assume one point of integration, that being extraction of flow from the stream for irrigation. Such models typically integrate at just one point in the hydrological cycle and are criticised for being focused at too narrow a spatial and temporal point that does not represent in adequate detail the response of one system component to another. Bouman *et al.*, (1999) argue that addressing problems of aggregation of spatial and temporal scales is a key requirement to furthering integrated modelling that balances the hydrology and economic component. Rogers *et al.*, (1993) developed an integrated model to link the basin-level integrated model with a macroeconomic model in order to link the water resource use to the national economic sector, while Giannias and Lekakis (1997) developed an integrated model to assess inter-country water allocation policies. Addressing the opposite direction of scale, Greiner and Hall (1995) and Collins *et al.*, (1996) are examples of integrated water allocation models that examine impacts of larger reforms upon farm-level income. Once again however, the policy focus is on extractive water use only.

Even where new approaches call for integration at various spatial and temporal scales (see Fresco, 1995; Jansen, 1995; and Crissman *et al.*, 1997 for a discussion of scale issues in integrated water allocation models) to improve the balance of supply (hydrology) and demand (economic) side representation as identified by Bouman *et al.*, (1999), there is little evidence of an integrated approach that has several points of integration between the economic and hydrological system. An approach of this nature would not only have the potential to answer water policy issues that were not specifically focused upon extraction of water, but also facilitate the balancing of the economic and hydrology model components. Wherever a single point of integration occurs, modellers run the risk of oversimplifying a component to facilitate model integration. A single point of integration also makes it problematic to model a more complex representation of the policy environment given that a suite of water policy options cannot all be measured through the point of integration where water extraction occurs.

However, studies by Dudley and Hearn (1993), Dudley (1998) and Dudley and Scott (1993) recognise the failure of most integrated models to fully integrate the management of water demand and water supply. These studies have even gone so far as to test which variables are critical to be included in the optimisation in an effort to identify the appropriate level of detail of system components with which to integrate. These papers indicate the relative benefits of increasing the number of variables such as farm dam holding capacity or surface water evaporation. Once again, the representation of the policy environment is limited to that of extractive water use or defining a system of property rights by altering demand or supply side variables.

Simonovic (1999) proposes a new modelling approach for water policy analysis using integrated models. The model utilises object-oriented modules to structure the water policy analysis process to best address the policy choice. While the approach develops a flexible integration environment for analysing a range of water policy issues, the approach does not allow for the analysis of land and water policy-related issues in tandem. A limitation of the current state of the art in integrated water resources modelling is the assumption that only a single policy is implemented at an any given point in space or time (water extraction for instance). Given that there are considerable and desirable benefits for policy makers in analysing policy options in isolation, a new approach in integration could go further to also examine interpolicy impacts.

Amir and Fisher (2000) used a deterministic linear optimisation procedure to assess the impacts of introducing multiple policy options and found that a mix of pricing and quantity restrictions can have unintended side effects as opposed to assessing each policy in isolation. The limitation of the study from a holistic perspective was its very limited use of hydrological modelling. A time series seasonal volume of water was used as input to the economic model. In later studies, Salman *et al.*, (2001) use the SAWAS model in a similar way to the work by Amir and Fisher (2000) to investigate the importance of temporal factors upon water allocation. Studies such as this, and by Vedula and Kumar (1996), highlight the importance that temporal integration serves, particularly when examining irrigation-related water allocation questions. Integrated water resource models that consider temporal policy impacts are numerous and use various efficient algorithms to optimise timing in water supply policies. Varis and Lahtela (2002), and Varis (1997) are examples of well developed analytical frameworks for examining integrated water resources options using a Bayesian network approach. In addition, the consideration of temporal aspects of integration is well studied in the literature (Evers *et al.*, 1998; Mehrez *et al.*, 1992; Philbrick and Kitanidis, 1998; Mahendrarajah *et al.*, 1992; Mahendrarajah *et al.*, 1996; Bryant *et al.*, 1993; and Chatterjee *et al.*, 1998 are recent examples that focus upon timing).

Less attention has been given to water policy issues that are spatial in nature, although recent developments in Geographic Information Systems have allowed integrated models to investigate spatial impacts of water allocation policies. Chakravorty and Roumassest (1991) and Bouman *et al.*, (1999) for example consider spatial impacts as part of an integrated water modelling approach.

2.12 Conclusions

The literature review of the Water Reform Process has shown the current state of water resources management in Australia and especially in New South Wales. The review has served to identify the scope of current policy issues that could be examined in the thesis. However, the review also highlights the evolving nature of Water Reform in New South Wales' catchments. The relevance of policy questions selected for investigation in the thesis is quite likely to change during the period of time elapsed for completion of the task. The review has served to illustrate that the type of water policy issue selected is not generic for all catchments. Rather, the first distinction in identifying a problem for analysis is made between regulated and unregulated systems. Subsequent policy issues important in implementing the Reforms on a catchment-by-catchment basis depend upon past land and water management exercised by agricultural production systems. These factors shape what are considered to be 'current priority issues' for a catchment. The task in Chapter 3 is to identify specific questions of the nature identified in Table 2.5 and apply them to a case study of Yass catchment in the Upper Murrumbidgee.

A current limitation of the Water Reform Process is lack of scientific information, both biophysical and socio-economic, for assessing the impact of introducing the Water Reforms. As demonstrated in Chapters 1 and 2, very little information is available as to what is an adequate environmental flow volume or groundwater sustainable yield for instance. It is not surprising therefore that studies so far on the Water Reform Process have not examined in detail catchment-scale impacts upon the biophysical system as a result of agricultural production system operation and vice versa. However, integrated approaches of this nature are required in order to begin developing tools to examine the impact of the reforms from the perspective of creating sustainable catchment systems - one of the aims of the National Competition Policy. This requires approaches to link land, water and socio-economic systems to analyse the whole system.

The review of Integrated Assessment was focused on exploring the current state of the art in using modelling approaches to examine water allocation issues. The review showed that although a variety of approaches have been devised to investigate water policy issues, very few have examined multiple issues concurrently. Where this is the case, approaches have tended to rely upon a single point of integration between the biophysical and agricultural production system. These have often involved building a relatively sophisticated agricultural production model and simply using biophysical data as input, or vice-versa, depending on the disciplinary bias. Improved approaches for investigating water allocation issues are to be found in balancing and integrating each disciplinary input to model construction, taking into account the specific nature of the question being asked, the modelling objectives and the knowledge and data available to construct and test the model. Balanced approached of this sort are only beginning to emerge (e.g. Letcher, 2002).

Chapter 3 Study Site and Modelling System

3.1 Introduction

This Chapter is divided into three parts. The first part (Sections 3.2 to 3.12) is a review of land, water and agricultural production systems in the Yass catchment. It defines the types of land and water problems that are specific to the catchment. The second part (Sections 3.13 to 3.14) identifies those land and water policy issues in the catchment that are to be modelled. The extent to which the system can be conceptualised and models constructed depends on the availability of datasets, their quality and resolution. Therefore, the third part of the chapter is devoted to these issues pertaining to data sets (see Section 3.15 to 3.22). The chapter concludes with a problem statement and questions to be addressed (see Sections 3.23 and 3.24). These three parts of Chapter 3 provide the foundation for development of the conceptual framework in Chapter 4, its scale, resolution and crucial points of integration required to investigate the policy issues identified in this chapter.

Section 3.14 describes processes that could be included as system parameters and variables in the approach. All other considerations including the conceptualisation of the system to answer policy questions of interest, and integration of system parameters and variables are dealt with in Chapters 4, 5 and 6 respectively as part of the model conceptualisation and formulation.

3.2 Profile of Yass Catchment Case Study Area

Yass catchment has been identified as a 'highly stressed catchment' in that it suffers from severe degradation of its land systems as well as in-stream water quality and quantity problems (DLWC, 2000d). Yass catchment has a unique set of human-imposed land uses that determine catchment condition. Conceptual design of an integrated assessment model must represent the key land uses and processes responsible for the current catchment condition in order to be effective in aiding decisions to influence improved outcomes. In Yass catchment, there are two main processes that are contributing to a deterioration in catchment condition. In the Upper Yass catchment, water extractions for the purpose of crop production and farm dam development to capture run-off have reduced river flow, having the greatest impact on low flow conditions (see Section 3.13 for further detail).

The second driver of change is the rate of rural residential subdivision in the upper and lower catchment. In particular, subdivision in the lower catchment has resulted in the development of a viticulture industry. The demand for rural-residential allotments is increasing given an economically buoyant viticulture industry. Land use change is also a result of the catchment proximity to Canberra. As a result, high land prices and falling production prices for land uses such as grazing provide an incentive to subdivide land for hobby farms or attract value-added activities such as viticulture (Yass Shire Council, 1997). Land use change in the catchment is therefore a key factor that is likely to contribute to changes in catchment condition in the future.

3.3 Demographic Characteristics

The Yass catchment is located in the headwaters of the Murray-Darling Basin, covering an area of 160 000 hectares. It is part of the upper Murrumbidgee catchment immediately upstream of Burrinjuck dam (location at 149'9', 34'9) as shown in Figure 3.1. The Yass plains were settled in 1821 and in the past have largely been used for grazing of cattle and sheep (Bayley, 1973). Yass shire includes the townships of Yass, Gundaroo and Murrumbateman (Yass Shire Council, 2000 and ABS, 1996).

3.4 Climate and Hydrology of Yass Catchment

Yass River is the trunk stream within the catchment and is a tributary of the Murrumbidgee river system, flowing from the headwaters at Gundaroo through the catchment and into Burrinjuck dam. Table 3.1 shows the tributaries that run off the main Yass Arm and their associated areas. Figure 3.2 depicts the twelve tributaries and locations where they meet Yass trunk stream. The contribution that each tributary makes to total stream flow in the Yass arm is a function of several factors. These include precipitation, catchment area draining the tributary, ground water loss and vegetation cover within a subcatchment. In the upper catchment area, Brooks Creek drains a large part of the upper Yass catchment. Similarly, Murrumbateman Creek drains a larger section of the Lower Yass Catchment. Smaller tributaries include Dicks Creek, also known as Sawpit Creek. However, these smaller tributaries contribute a significant amount of saline water to the lower catchment system (NCDC, 1981).

Elevation ranges from 520m at the lowest part of the catchment to a maximum of 820m. Average annual rainfall varies between 550mm and 700mm. Tributary stream flow is ephemeral, as illustrated by Figure 3.3. A large reduction in stream flow occurred during the 1970's as a result of farm dam development (Scown, 2000).

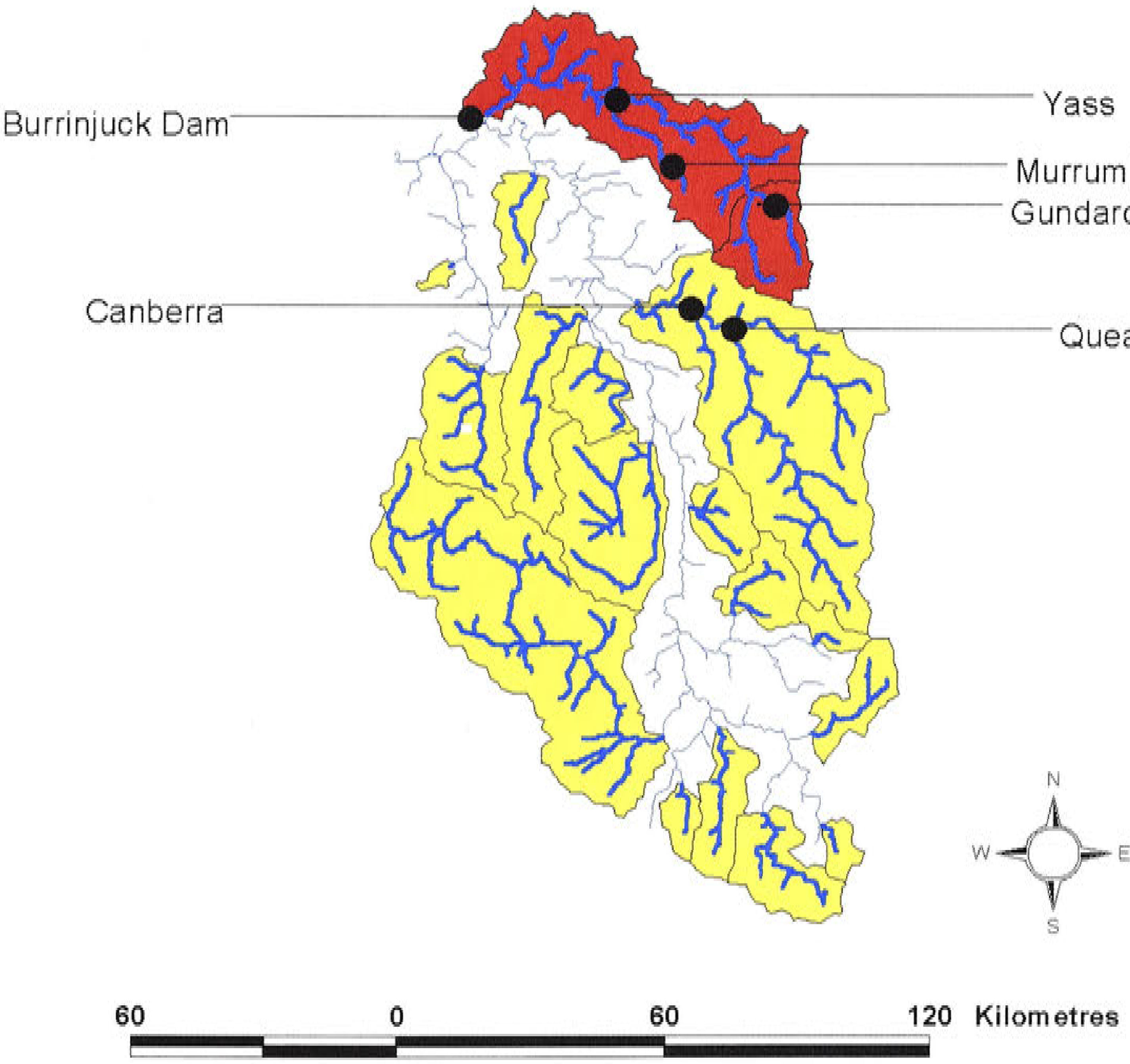

Figure 3.1: Location of Yass Catchment (shown in red) and major townships in relation to the remainder of the Upper Murrumbidgee Catchment (shown in Yellow) and the Murrumbidgee trunk stream (shown in white)

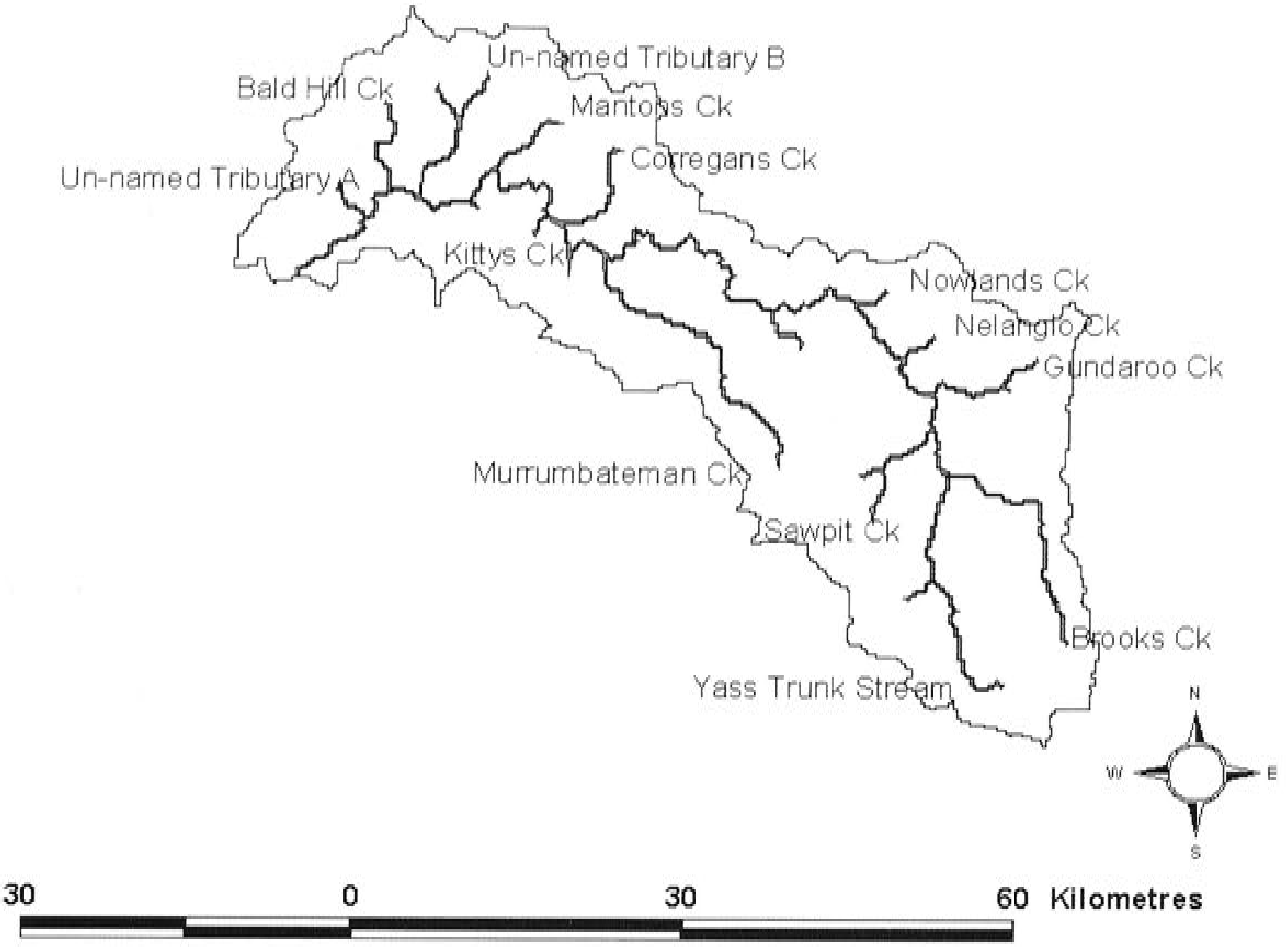

Figure 3.2: Trubutaries of Yass Catchment

Table 3.1: Tributaries of the Yass catchment

Name	km²	Elevation	Latitude	Longitude
Mantons Ck	62.87	456	148.9	-34.82
Kittys Ck	24.37	501	148.94	-34.86
Corregans Ck	56.25	503	148.96	-34.86
Murrumbateman Ck	187.37	512	148.96	-34.89
Sawpit Ck	1.25	515	149.09	-34.91
Nelanglo Ck	25.31	548	149.24	-34.97
Nowlands Ck	33	539	149.2	-34.93
Bald Hill Ck	73.56	408	148.81	-34.83
Gundaroo Ck	113.93	575	149.25	-35.03
Brooks Ck	134.12	579	149.28	-35.07
Un-named catchment near Bald Hill Ck	92.93	499	148.85	-34.82
Un-named catchment south of Bald Hill	20.5	400	148.78	-34.85
Trunk stream above Gundaroo	388.0	520	147.78	-34.67

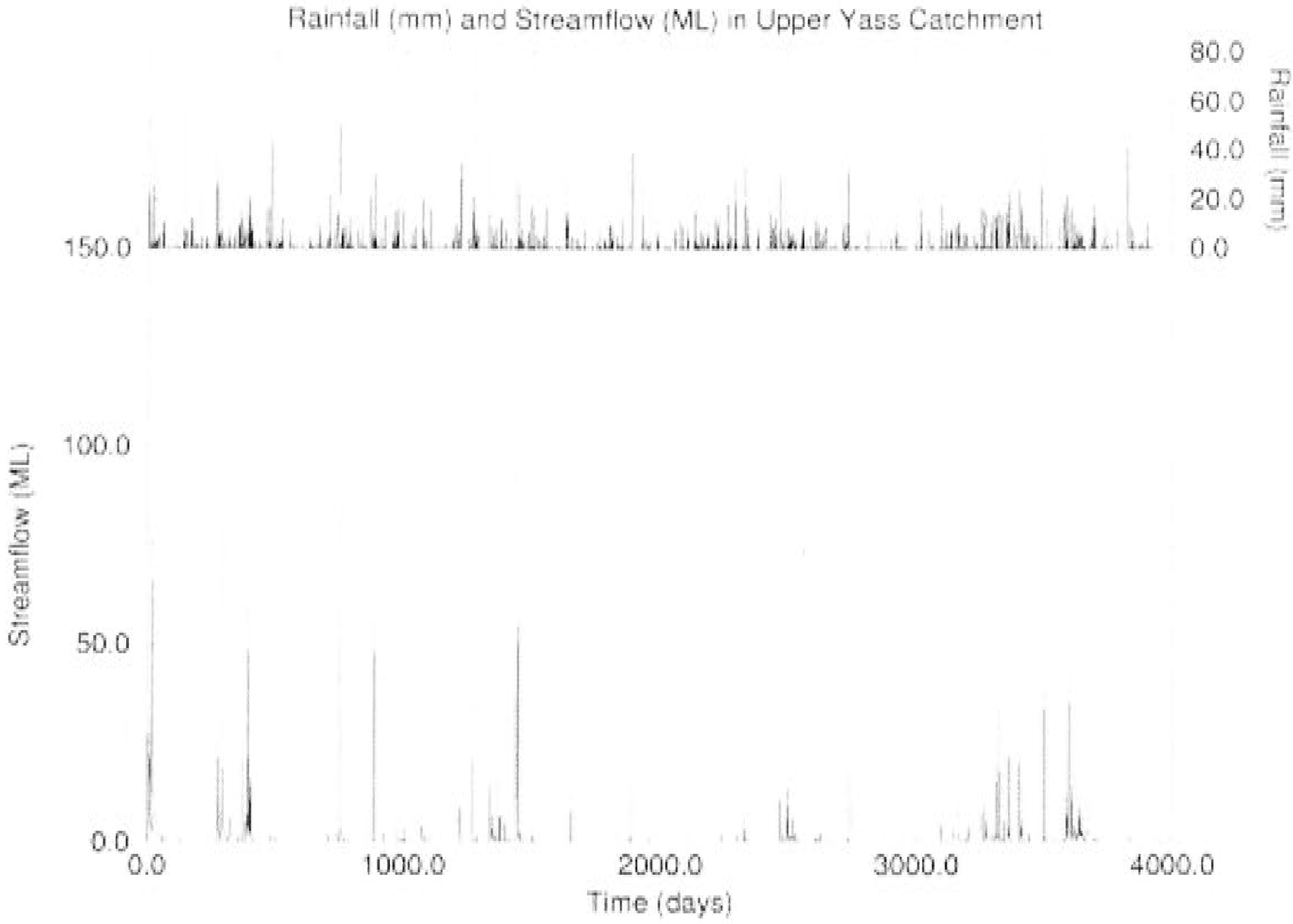

Figure 3.3: Streamflow and rainfall variation in the Yass catchment (Period of record: 28/5/1965 to 19/6/1976)

3.5 Groundwater Recharge Areas

Sawpit Creek and the confluence of Brooks Creek with Yass trunk stream are two major areas where surface water contributes to groundwater. Table 3.2 illustrates recharge areas and recharge rates in the catchment. Where streamflow gauges are utilised for water balance calculations, the addition of groundwater to streamflow may or may not be captured in the water balance depending on the location of the stream gauge. Hence, knowledge of recharge and discharge areas in the catchment is particularly important in developing flow models, especially in ungauged catchments.

Table 3.2: Regional recharge areas in Yass catchment. (Source: DLWC, 1993)

Recharge Areas	Geology	Recharge rate per year (mm)
Mount Spring	Silurian Volcanics	9
Millpost Hill	Sedimentary	253
Picaree Hill	Sedimentary	66
Barton Highway	Silurian Volcanics	49
Gums Flat Road	Silurian Volcanics	17

3.6 Land and Water Management Issues in Yass Catchment

The catchment suffers from water quantity problems as a result of the over-extraction of surface water, and water quality problems as a result of dryland salinisation (DLWC, 2000c; Soil Conservation Service of NSW, 1986). Figure 3.4 illustrates a salt scald in the catchment. Stream salinity concentrations are exacerbated by the extraction of surface water for crop irrigation. Figure 3.5 illustrates the typical farm dam construction in the catchment. The catchment has a high density of farm dams (see Section 3.8) for stock and domestic water supply associated with grazing activities. Land use in the catchment has resulted in clearing and associated erosion problems as illustrated in Figure 3.6. In-stream extraction is the result of land use activities such as rotational cropping and lucerne irrigation. These activities have contributed to stream bank deterioration as depicted in Figure 3.7. However, value-added 'intensive' land use activities such as horticulture and, in particular, viticulture have experienced prolific growth in the catchment in the past decade (see Figures 3.8 and 3.9).

Figure 3.4: Salinity problems as a result of clearing

Figure 3.5: Construction of farm dams to capture runoff

Figure 3.6: Typical erosion problem in Yass

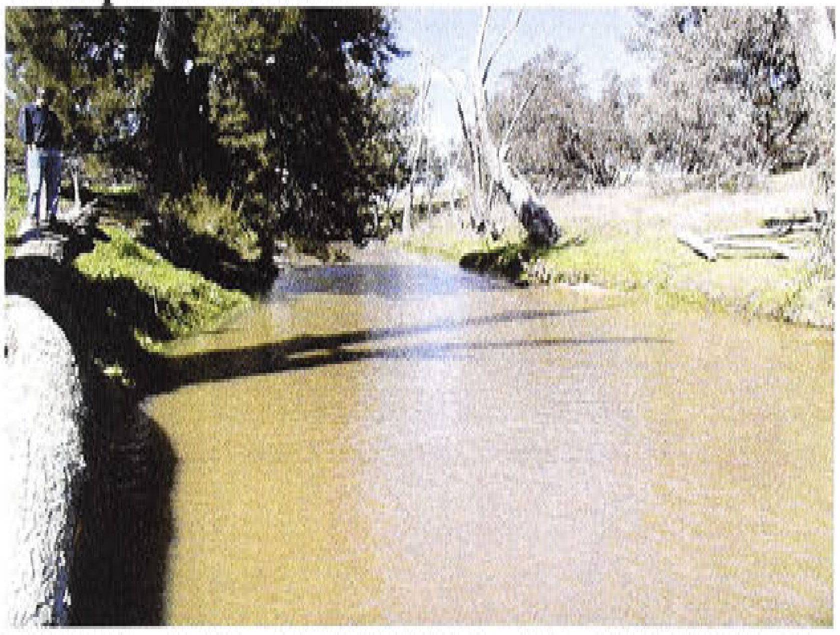

Figure 3.7: Extraction of streamflow has reduced stream and bank condition

These activities rely on a larger water supply than 'traditional activities' such as grazing. In Yass, viticulture activities occur on soil types that are well-drained and slightly sloping. This precludes these activities from the river flats. As a result, supplementary irrigation is solely from farm dams in Yass for these relatively new land uses (pers. comm. Watson, 1999).

Figure 3.8: A typical small scale viticulture activity in the catchment

Figure 3.9: An example of intensive horticultural activities recently introduced into the catchment

3.7 Extractions from Yass River

The Yass tributary system is unregulated in that it is upstream of Burrinjuck Dam. Unregulated catchments have not been subject to volumetric limits on water extracted in the past. As a result, information as to the level of water extractions are estimates only (DLWC, 2000c). Table 3.3 provides the annual water extractions and irrigation area for each land use.

Table 3.3: Estimated annual water extraction from Yass River for the year 2000 (Source: DLWC 2001c)

Industry type	Total Licensed	Total hectares Irrigated	Draft Conversion factor	Theoretical Volume Extracted (ML)
Lucerne	35	569.5	6	3417
Viticulture	42	270	3.5	945
Domestic/Stock	5	N/A	6	30
Industrial	1	N/A	20	20
Town Water	1	N/A	N/A	1400
Recreation	5	N/A	4	20
All irrigation	89	839.5	N/A	4362

Unregulated systems such as Yass are subject to conversion of area-based licences to volume-based licences by a draft conversion factor (DLWC, 2001a). The conversion rates determine the amount of water utilised by the activity per hectare. The draft conversion rate is then used to determine the entire extractive proportion for the activity at the catchment scale. The volumetric allocation is still being determined for the catchment. Estimates of the volume of extractions from the river, especially from Yass weir, were required for the modelling in this thesis to estimate ungauged streamflow in the absence of abstraction.

3.8 Farm Dam Development

According to Scown, (2000) Yass catchment has a high level of farm dam development with an average of 4.5 dams per 100 hectares. The number of dams below a holding capacity of 5 ML is 6381. Larger dams above a capacity of 10 ML total 585. Dams between 5-10 ML capacity are smaller in number, totaling 185. Tributaries that have the highest concentration of farm dam development are located in the upper Yass catchment on Brooks Creek and Yass arm itself (see Figure 3.2). The highest concentration of farm dam development per hectare occurs immediately south of Murrumbateman where intensive land use activities such as viticulture are increasing. These are rain-fed dams only. Larger in-stream reservoirs occur along the Murrumbateman and Sawpit Creeks in the lower Yass catchment.

Studies by Scown and Nicoll, (1993) have measured the impacts of farm dam development upon stream flows in the catchment by using surface area to determine storage capacity of individual dams. The holding capacity of dams within the catchment has been estimated at 27,909.9 ML. Using dam holding capacity and rainfall measurements, it is estimated that the loss of stream flow due to farm dam capture is approximately 20% of total runoff produced in the catchment (Scown, 2000). This excludes loss from residential activities. Loss of stream flow by farm dam development is distributed across land use types within the catchment. Table 3.4 indicates the loss attributed to land use type in Yass (DLWC, 2000c).

Table 3.4: Estimated runoff loss by farm dam capture from land use in Yass catchment (After DLWC, 2000c)

Enterprise	Area covered in Yass (Ha)	Water requirement (ML/Ha	Volume Utilised (ML)
Lucerne, dryland crops	445.54	6	2673.24
Viticulture	147.56	3	442.68
Orchards (apples)	48.47	7	339.29
Horticulture	1.40	6	8.4
Total use in Yass Catchment	642.97		3463.61

3.9 Geology, Soils and Vegetation

Yass catchment exists within the Lachlan Fold Belt geological formation. Parent material consists of three types: Silurian sediments, Ordovician and Acid Volcanic groups. Granitic outcrops are also known to occur at higher elevations in the catchment. Volcanic shales and cherts are interbeded with quartz sandstone to form what is the Pittman formation in Yass. The formation is a syncline, dipping away from the south of the catchment. Consequently, the Ordovician parent formation is found north of Yass arm from Sutton to Yass township. Soils derived from the parent material are podzolic. The podzolic soils in the upper catchment are sandy in texture due to the parent derivation. Deeper soils are found on the lower slopes of the catchment and often consist of a massive clay B horizon, although the clay layer is relatively permeable.

Yass catchment has been extensively cleared for the purpose of grazing. Over 75% of the catchment consists of grassland communities (Moore, 1970). Native forest areas occupy a small area in the middle catchment area, consisting of Dry Sclerophyll species. Of the native shrublands, 80% are located along the northern catchment boundary of the catchment.

3.10 Spatial Occurrence of Land Uses In Yass Catchment

The main land use is cattle and sheep grazing. These activities cover 75% of the catchment. Clearing of the catchment, up to 83%, has occurred in pursuit of an expanding grazing industry, up until the last decade (Yass Shire Council, 2000). Since this time, wool and cattle prices have fallen. The result has been pressure to subdivide for the purpose of rural-residential allotments, in addition to the introduction of intensive land uses in the form of horticulture and, more recently, an expanding viticulture industry.

Irrigation from in-stream sources occurs in the upper catchment for the purpose of lucerne production and rotational cropping. Irrigation enterprises are continuous along the main Yass stream in the upper catchment between Sutton and Gundaroo townships. The tributaries of Nelanglo in the north east of the catchment and Murrumbateman Creek south of Yass arm also support irrigation land uses. Viticulture enterprises are found in the lower Yass catchment around the Murrumbateman Creek tributary. Although small in number, the rate of viticulture development in lower Yass catchment is higher than that of any other enterprise owing to the recent development of viticulture activities. Table 3.5 lists the land uses and their areas in Yass catchment.

Table 3.5: Land use in Yass catchment (modified from Scown, 2000 and DLWC, 2000c)

Land Use	Area	Percentage of catchment area
Riparian Zones (stream channel and wetlands)	1850	1.12
Softwood plantations	740.82	0.46
Cultivation Area	5 126.89	3.21
Grasslands	122 498.61	76.8
Horticulture	49.87	0.031
Viticulture	147.56	0.092
Urban Area	774.94	0.48
Irrigated Land	445.54	0.27
Native Tree Cover	26 734.02	16.77
Other (modified land including dams)	1 087.21	0.68

3.11 Land Use Change: Structural Adjustment and an Economic Profile

In Yass catchment, the rate of rural residential subdivision has increased by 70% since 1970 (Yass Shire Council, 2000). In particular, new industries such as horticulture and viticulture have been introduced. In the 1990s alone, the growth of viticulture enterprises trebled. Given the intensive water requirements of establishing a viticulture enterprise, this section will describe growth statistics and set the scene as to the likely path of viticulture establishment in the catchment.

New South Wales and South Australia have recorded the highest rate of growth in viticulture of all Australian States within the last 5 years. However, production growth is concentrated on existing wineries with 10 of the 276 wineries being responsible for 68% of total production in NSW (ABS, 1999a). Viticulture enterprises resulted in 40 000 hectares of new vines being planted in the past 6 years in Australia (ABS, 1999b). The number of hectares planted for new vines is given in Table 3.6. As indicated, the land area devoted to vineyards in 1999 is seven times the area of land devoted to grape growing in 1992.

Table 3.6: Viticulture expansion in NSW by hectares (Source: ABS, 1999a)

Year	1992	1993	1994	1995	1996	1997	1998	1999
New plantation	239	326	546	1090	1081	2290	2510	1768

New South Wales accounts for 20.4% of all wine-grape production in Australia (SA 52.4% and Vic 24.3%). The wine-grape outlook is for an increase in NSW production by as much as 16% between the 1998-99 and 2000-01 growing years (ABARE, 1999). The projected growth areas in NSW are illustrated in Table 3.7. The projected increase in industry growth is attributable to the production of premium wine-grapes (ABARE, 2000).

Table 3.7: Projected growth rate (kilotonnes) of the viticulture industry. (Source: ABARE, 1999)

NSW regions	1998/99 kt	Projected 99/00 kt	Projected 00/01 kt	% Change
Hunter Valley	28	29	30	7
MIA	119	128	131	10
Sunraysia	20	28	34	71
Rest of NSW	29	38	39	31
Total	197	224	234	19

Vines for the purpose of grape growing require moderately well drained soils. Quartz or leached podzolic B horizon soils are highly suitable. Irrigation is often essential for vine establishment and fruit production. A minimum water availability of 20 litres per vine per week is essential. A mature vine will require 100 to 300 litres per week, varying throughout the production season.

3.12 Studies Conducted in Yass catchment

Several studies in Yass catchment have focused on processes related to groundwater movement. Wagner (1987) carried out a study of processes and sources of salinisation in the south east of the Murrumbidgee catchment. Yass catchment sites of high salinisation were identified and processes contributing to rising salinity in Yass were identified. Land management practices have mobilised the naturally high concentration of salt that is contained in the Ordovician bedrock of the catchment.

Acworth *et al.*, (1997) developed a conceptual model to measure the impact of debris flow upon salt loads in Yass catchment. Sawpit Creek has been the focus of this work. Jankowski and Acworth (1997) investigated catchment attribute relationships to determine processes responsible for water logging and subsequent salinisation at Sawpit Creek. The subcatchment of Sawpit Creek has been a focus area owing to its rising salinity levels. Brad *et al.*, (1991) have continued to investigate sources of salt and groundwater processes within this tributary.

A case study by Scown and Nicoll (1993) identified overland flow as the process driver of stream flow in Sawpit Creek catchment. The study found no significant relationship between streamflow and nutrient or salt loads, indicating that groundwater is the source of salt in this subcatchment. However Brad *et al.*, (1991) found that overland flow contributed to as much as 65% of the salt load during peak rainfall events, indicating that baseflow was an important source of nutrients during dry months (given antecedent conditions).

The study by Scown and Nicoll, (1993) focused upon water quality issues as related to salinisation. Subcatchment areas investigated as case studies included Sawpit Creek and Yass River. In addition, six other treated and untreated saline sites in the catchment were the subject of a groundwater and water quality investigation to determine salt loads and sources. The outcome was a set of management options for agricultural activities and water use within the recharge areas of these sites.

Xihua *et al.*, (1998) developed a GIS modelling methodology to simulate movement of nutrient pollutants through the river system. The main aim of the study was to predict the movement of nutrients downstream from point source pollution. Specific tasks undertaken in the project were the estimation of nutrient travel times with flow rates, pollution spread throughout the hydrograph peak and the effect of weirs and other obstructions upon travel and dispersion. A hydrological flow network was defined upon which point sources of pollution were identified and incorporated into the network. A similar study of the erosion potential of Sawpit Creek catchment was conducted by Ellis (1998). The study utilised decision tree analysis in conjunction with a GIS to predict erosion, given land use or management changes. It was noted that the predictive capacity of using such a modelling technique at the tributary scale was restricted in predicting all erosion processes.

The Regional Water Quality Study of the Upper Murrumbidgee used a modelling methodology to indicate catchment impacts as a result of land use changes. The AQUALM model uses export coefficients generated from various land uses and rainfall conditions to simulate water quality changes (DLWC, 1998). A hydrological network defining stream lengths and channel characteristics was utilised in conjunction with a GIS to simulate impacts upon water quality.

Scown (2000) has conduced a detailed land use mapping study in Yass catchment. The impact of farm dams upon runoff to streams was quantified. Yass is a first case study among several others planned in the upper Murrumbidgee. A spreadsheet-based decision support system (DSS) was also developed to identify the health of the catchment given land use in the catchment. The DSS structure is based upon qualitative relationships between land use type and water quality and quantity parameters. More recently, Schreider *et al.*, (2002) used a rainfall-runoff model to examine the impacts of farm dam development upon Yass catchment, suggesting an annual average increase in farm dams capture of 3.3% of mean annual flow from 1970 to 1999.

3.13 Land and Water Policy Issues in the Catchment

There are three new water policies that will be introduced into Yass catchment under the Water Reform Process. They are a series of Volumetric Conversions, The Farm Dams Policy and a Salinity Management Strategy. This section describes these policies and options within them. Each of these are included in the modelling approach to represent drivers of, and constraints to, land and water use change as well as important interactions within the catchment system.

3.13.1 Volumetric Conversions

In-stream water users in the Yass catchment have been allowed to take an unlimited amount of water from the catchment over time. It is estimated that a larger proportion of these licences are not activated annually (DLWC, 1999f). As a result, the system has the potential to be over-allocated in that there are more licences available then water available in the river on a volume basis. This will largely affect low flows within the river if licences are activated. To avoid this problem, a re-allocation of water is to take place by converting all licence entitlements from an open entitlement based upon land size to a volume based upon in-stream volume available. This is known as a volumetric entitlement (see Section 2.6.5).

In order to structure a defined set of property rights to encourage future trading and prevent over-extraction, especially at low flow conditions, a set of extraction limits and a hierarchy of access rules are attached to the volumetric entitlement. New water users will only be allowed into the system if there are excess extraction volumes or if they purchase extraction volumes from other users. The volumetric entitlement must be below the Murray-Darling Basin Cap (see Section 2.6.4) level, and it must conform to environmental flow rules. These will be included in the base case scenario for modelling in this thesis.

The aim of the volumetric conversions is to ensure that volume and variability of flow are preserved for ecological purposes. This includes preserving high flow events, low flows that are continual and a fresh flow that is typical of the natural flow regime.

3.13.1a Commence to Pump Thresholds with no extraction limit/multiple extraction limits

The first set of options suggests a single extractive limit. Extraction of water from Yass catchment predominantly affects low flow conditions, with 60% of all low flows being extracted. The first policy option suggests imposing a single commence to pump threshold (CTP). A single CTP entails that extraction is not permitted until the river reaches a predefined volume.

Implementing multiple CTP thresholds is a second option proposed for implementation of the volumetric rule. Above the threshold any volume may be extracted from the river. However, the threshold rule reduces moderate flow events and also reduces flow variability over the entire regime. Although simple to implement, a daily flow extraction rule allows any volume to be extracted above the CTP rule. Where the system is fully allocated, this could result in loss of all pulse flow events, reducing the river flow to the CTP threshold at all times. An alternative is to set a CTP threshold with multiple extraction limits. The system prevents over-allocation by also imposing a hierarchy of users to extract certain volumes, above which a single bulk entitlement would apply to all users.

In setting multiple flow classes above the CTP threshold, the problem of securing supply for users is overcome by allowing for even a small level of extraction in the majority of cases. A number of extraction limits are tied to flow classes. For example, a typical unregulated river may have an extraction volume of 7 ML per day where flows are between 5 to 20 ML per day. This may increase through several classes to a maximum of 24 ML extraction where peak events occur for example. Multiple extraction limits have the added benefit of securing supply for users over the entire flow regime. However, the major disadvantage is that the total volume in the river is reduced evenly over the entire flow range (DLWC, 2000a).

3.13.1b A hierarchy of users for the volumetric entitlement

A series of flow classes will be tied to a hierarchy of users as determined by the water entitlement. This are divided into A, B and C licences. The main features of the hierarchical system is that class A licences may pump at a threshold of low flow periods and above. These represent high security licences. Class A licence holders have the greatest security for water access, being able to pump over a range of flows from low to high flow events.

A bulk entitlement is to be set for the entire catchment over all flow conditions. Within a bulk entitlement limit for the catchment under a given flow regime, the threshold for the A, B and C class licences is determined. The hierarchy is then applied to determine how extraction will take place. Within the bulk extraction entitlement (BEE), a Bulk Extraction Limit (BEL) is applied to each flow class for which licences are attached (see DLWC, 2000b). Table 3.8 illustrates the class license limits for unregulated rivers in NSW. Table 3.9 illustrates the rules for calculation of the Bulk Extraction Limits for NSW Rivers.

Table 3.8: Flow classes within unregulated rivers of NSW. (Source : DLWC, 2000a)

Class	Description
A	Low flow conditions- between the "commence to pump" threshold and the 80th percentile (usually only exists in permanently flowing streams)
B	Low to median flows - between the 80th and 50th percentiles (may not exist in ephemeral streams)
C	Median to high flows - above the 80th percentile but may be further subdivided depending on water demand (usually exist in ephemeral catchments)

Table 3.9: Interim BEL for NSW Rivers. (Source: DLWC, 2000b)

Subcatchment	Recommended Interim BEL as a percentage of flow
Peak Daily Demand<40% flow	30% of flow
Peak Daily Demand = 40-70% of flow	SUM of Peak Daily Demand (PDD) minus 10%
Peak Daily Demand>70% of flow	60% of flow

3.13.2 The Farm Dams Policy

The Farm Dams Policy has been introduced partly in response to downstream user concerns at the rate and type of development in upper catchments in NSW. This policy places restrictions on the total amount of runoff that is allowed to be captured for small scale irrigation use in unregulated areas. Land uses that are most likely to be affected by the policy are small-scale and often intensive activities such as viticulture.

The policy has been effective since January 1999. The so-called '10% rule' is a revision of the policy designed to reflect varying runoff under regional climates. The policy restricts use of runoff to 10% of rainfall within a property boundary (dams that capture a larger amount are subject to a licence). This is known as the harvestable right (HR). The HR is not transferable between properties and is tied to the property size (unlike volumetric entitlements).

The HR does not automatically translate to a storage capacity. Once the 10% runoff amount is calculated from rainfall, the amount is multiplied by a series of indexes that relate the HR to geology, annual climate and other catchment characteristics to arrive at an allowable storage capacity (ASC). The ASC is a coefficient applied at the regional scale (as opposed to the farm scale that determines the HR). The ASC determines the size of the dam that is allowed to be built on the property. The ASC is mapped by a series of contour coefficients that land holders may use to determine the size of the dam. Studies by Schreider *et al.*, (2002) have suggested that the reduction in runoff as a result of farm dam construction is as high as 30% in some upper catchment areas.

3.13.3 Salinity Management Policy Options

The National Dryland Salinity Management Program (NDSP) was developed to manage human-induced processes that continue to facilitate the rise in dryland salinity in agricultural production regions. Since its establishment in 1993, NSW has adopted a state-wide strategy for the management of salinity. In NSW it is estimated that 120 000 ha of agricultural land is affected by high salt levels (LWRRDC, 1997 and LWRRDC, 1998). Agricultural costs are estimated at $130 million annually to the state. Several studies have been conducted in Yass catchment investigating salinity-focused problems (Scown, 2000; DLWC, 2000c; Soil Conservation Service of New South Wales, 1986). In the Sawpit Ck subcatchment, areas of land are subject to salt scald with a larger proportion unfit for agricultural production.

The most popular option to date has been to replant salt-affected areas in an effort to reduce watertable rise. Options for managing salt-affected landscapes include: (a) adapting to the high water tables with new enterprises; (b) prevention of further recharge by replacement of existing activities with those that use a similar level of water to native vegetation; and (c) revegetation. In Yass catchment, a salinity abatement program conducted by local institutions has focused on option (b).

3.14 Catchment-scale land and water processes for consideration in the modelling approach

In conducting the review of the Yass catchment and its issues in this Chapter, Table 3.10 illustrates potential variables and attributes that could be considered in constructing the modelling system.

Table 3.10: Potential variables and attributes to be included in the modelling approach

Catchment System Components	Potential Model Variables or Attributes	Included in modelling approach
Climate	Rainfall, Streamflow, Temperature	Rainfall-runoff model
Terrain	Soil, Substrate, Geology, Slope	Studies relating catchment soil and vegetation to catchment water balance
Land Cover	Vegetation, Evapotranspiration, Land cover changes	Effects on the water balance
Land Management	Farm Dams	Effects on runoff interception
River Hydrology	Streamflow through subcatchments, recharge to groundwater	Dissaggregation of flows, Recharge module in the rainfall-runoff model
Extractions	Flow Diversions	Agricultural modelling component
River Ecology	Stream characteristics	Habitat and environmental flow policy component. Changes in flow requirements with stream characteristics
Land use and agricultural production systems	Characteristics of the current land use and tenure system	Agricultural production model formulation
Land use change	Economic characteristics of alternative land use practices	Agricultural production and hydrological model formulation
Catchment Water Policy	Water policy options	Agricultural production model formulation

Streamflow on a daily basis is required to be considered given in-stream policy options operate at the daily time scale. For this, a model component capable of simulating daily flows would be required. In addition, the operation of the Farm Dams Policy would also require a modelling component capable of examining changes in evapotranspiration, effective rainfall and runoff at the catchment scale. Given that a priority issue in the catchment is that of land use change to intensive activities and its resultant impact upon catchment hydrology, the modelling component utilised must also be capable of relating land use change to changes in catchment hydrology. Agricultural production system operation and land use change to activities such as viticulture are prominent in the catchment. The modelling approach must therefore utilise a modelling component capable of representing agricultural production systems and any potential land use and production changes that may take place. The component would need to relate agricultural production (and forestry plantation) to streamflow diversions by irrigators, and interception of runoff by farm dams. Thus, the review has served to identify policy issues and characteristics of the agricultural production and hydrology systems that are required to be represented in building a modelling approach of Yass catchment. This tentatively allows the identification of appropriate spatial and temporal data sets required to carry out the model formulation and its construction, the subject of Section 3.15.

3.15 Data Sets

This section introduces potential spatial and temporal data to be used in the modelling approach as well as relevant aspects of data quality and quantity. The identification of data sets, their resolution and quality has two objectives. Firstly, it determines how each variable will be treated in the conceptual framework developed in Chapter 4. Secondly, it identifies issues, advantages or problems for inclusion and treatment within the analytical techniques in Chapters 5 and 6.

3.15.1 Streamflow data

Three streamflow gauges are located in the Yass catchment as indicated by Figure 3.10. Spatial location of the gauges enables characteristics to be identified that limit data use. Gauge 26 is located below Yass weir and drains an area of 1290 km^2. The weir is responsible for the extraction of the town water supply. Streamflow data at the gauge contains a small baseflow component as a result of the extractions above the gauge. Data on extracted flows were obtained and added to the gauged data to give a reasonable estimate of the hydrograph at the gauge (see Chapter 5).

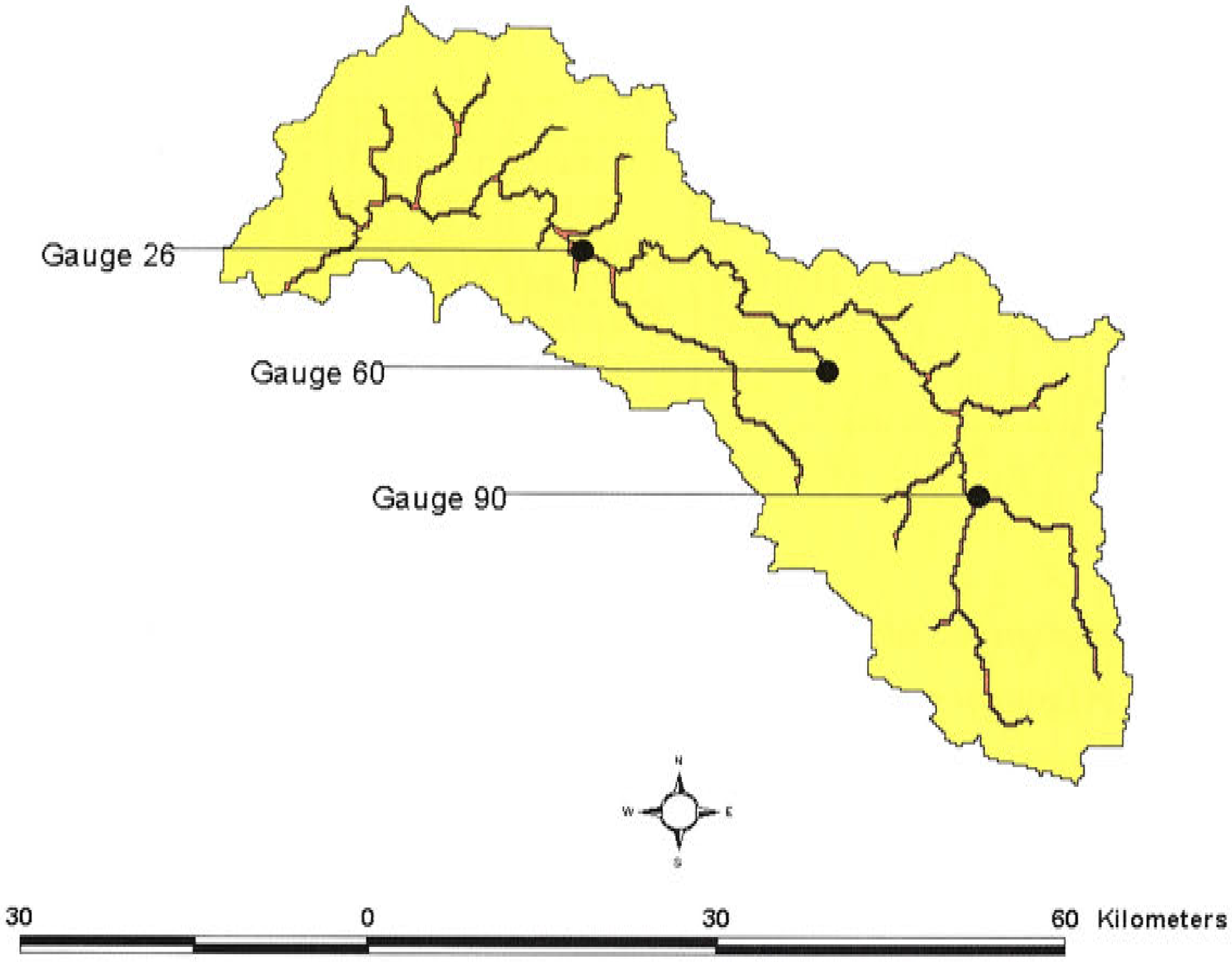

Figure 3.10: Streamflow gauges in Yass catchment

Gauge 60 is located off the trunk stream, draining a small catchment area of 9.94 km^2. Gauge 90 is located in the upper catchment draining 388 km^2. The gauge is not subject to extractions or other impediments to flow. Gauge 90 is the furthest upstream gauge and best represents natural flow conditions in the catchment. Table 3.11 illustrates the temporal quality of the stream gauge data sets. Missing data periods occur at both Gauges 90 and 26. Although Gauge 26 does not have any data gaps and is located on the trunk stream, it is downstream of Yass weir. Gauge 60 and 26 have overlapping periods of recorded flow. These factors will have to be dealt with to avoid potential problems in developing a network of flows for the catchment.

Table 3.11: Temporal data set quality for the stream gauges in Yass catchment

	Gauge 90	Gauge 60	Gauge 26
Location (Longitude, Latitude)	149.27, -35.07	149.15, -34.94	148.97, -34.88
Catchment Area	388 km^2	9.94 km^2	1229 km^2
Controls	Limited irrigation extraction. Area of groundwater recharge	None	Yass weir, irrigation extraction
Record Period	28/5/1965-19/6/1985	3/2/1989-7/4/1998	31/7/1969-4/7/1998
Missing Data	22/10/1971-21/1/1972 15/9/1972-1/1/1973 1/7/1973-25/9/1974	None	24/6/1973-7/7/1973

3.15.2 Rainfall data

In order to produce areal estimates of rainfall for each of the ungauged subcatchments, availability of point data was investigated for the modelling exercise (Figure 3.11). A total of 480 rain gauges were selected from the Metaccess database by selecting all gauges within a 100 km radius from the middle of the Upper Murrumbidgee catchment. Gauges with missing data or records with less then 5 years of data (which is the minimum period to effectively produce rainfall surfaces) were omitted. Of the total number of rain gauges, 128 were selected for use in the modelling approach. All 128 data sets spanned at least a 20-year period of rainfall and had no missing data values.

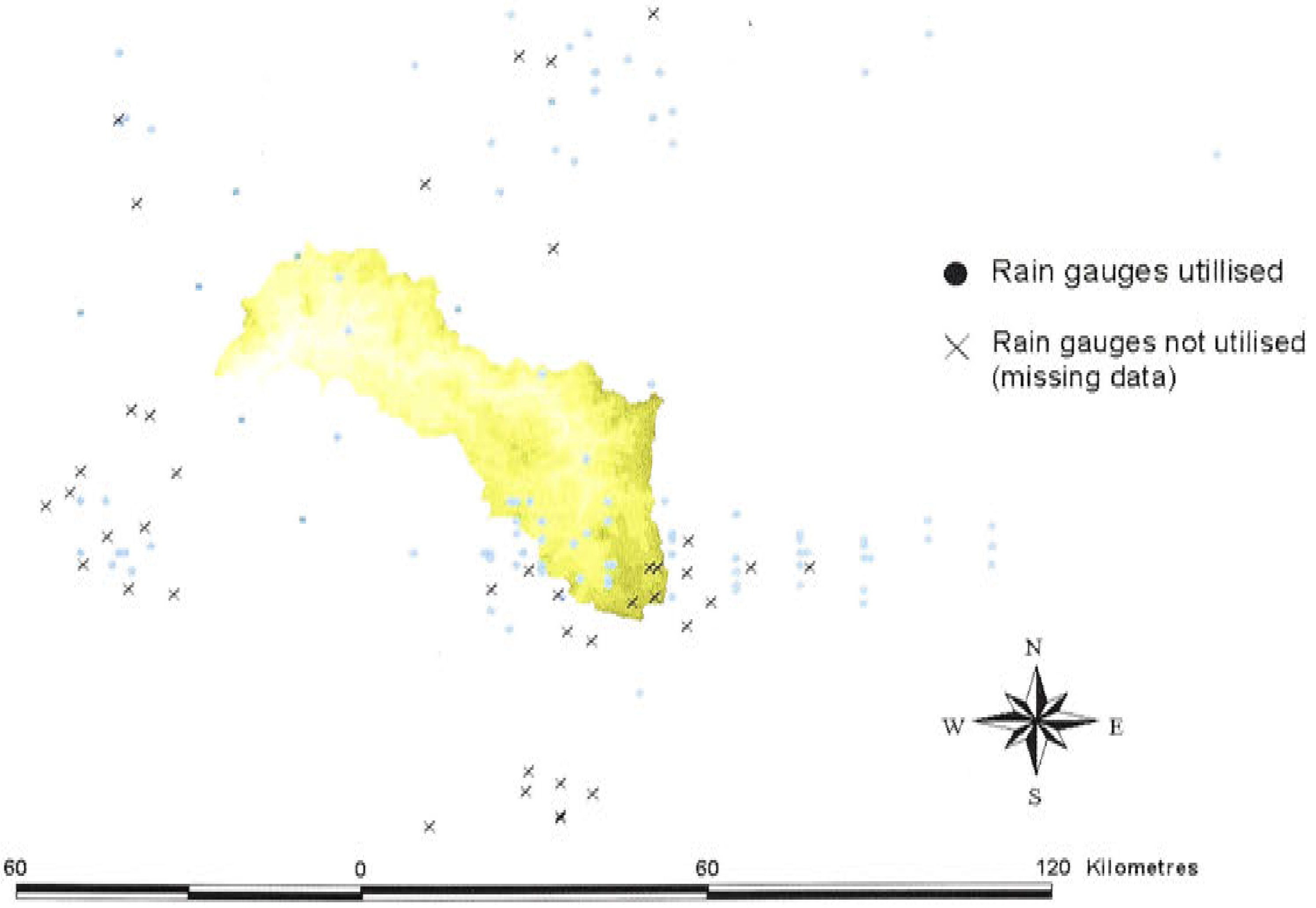

Figure 3.11: Distribution of rainfall gauges used for Yass catchment

To check the validity of zeros contained within the data sets, a cross correlation between all rain gauges in the catchment and between streamflow and rain gauge data was carried out. A correlation analysis between rainfall gauges was carried out in order to identify the distribution of rain days at every gauge. For example, where a rainfall event is being recorded by one gauge and not at other gauges, this could indicate that the spatial distribution of gauges is too coarse to capture all rainfall events occurring in the catchment. It may also indicate that the data has been recorded incorrectly at a gauge. This has implications for partitioning rainfall for streamflow upon ungauged subcatchments in Chapter 5, where multiple gauges are used to identify daily rainfall in the subcatchment of interest.

The correlation analysis is used to determine if there is a timing problem within the data. Table 3.12 displays the results of running a correlation analysis between daily gauged rainfall and daily streamflow for a given gauge. The results indicate a 1 day time delay in the data. This suggests that the rainfall data has a time error of 1 day given that the catchment draining to the gauge is small enough to elicit a streamflow response within hours after a rainfall event. This will have to be considered in using a rainfall-runoff model to simulate streamflow using the rainfall time series developed from the surfaces.

Table 3.12: Correlation between precipitation and streamflow indicating a 1 day time delay between rainfall and streamflow

Delay	Precipitation	Streamflow
-3	0.194844	0.187661
-2	0.163763	0.135459
-1	0.106064	0.398835
0	0.426908	1.5059
1	1	0.395741
2	0.556467	0.134651
3	0.333579	0.182765
4	0.32675	0.181107
5	0.221791	0.11376

3.16 Digital Elevation Model (DEM)

A Digital Elevation Model was obtained and used for determining spatial rainfall characteristics. The source of the digital elevation model (DEM) was the ANUDEM geodata mapped at 1:250 000 resolution. This resulted in a grid coverage of 250 meters. For the purpose of this thesis, all mapping and spatial data manipulation was carried out in the ARCINFO based system and ARCVIEW Geographic Information Systems (GIS) software. In ARCINFO a 40 metre sink level was utilised to fill major changes in elevation A flow accumulation function determined how rainfall would be transported over the surface once the sinks were filled. Figure 3.12 illustrates the DEM and elevation classes.

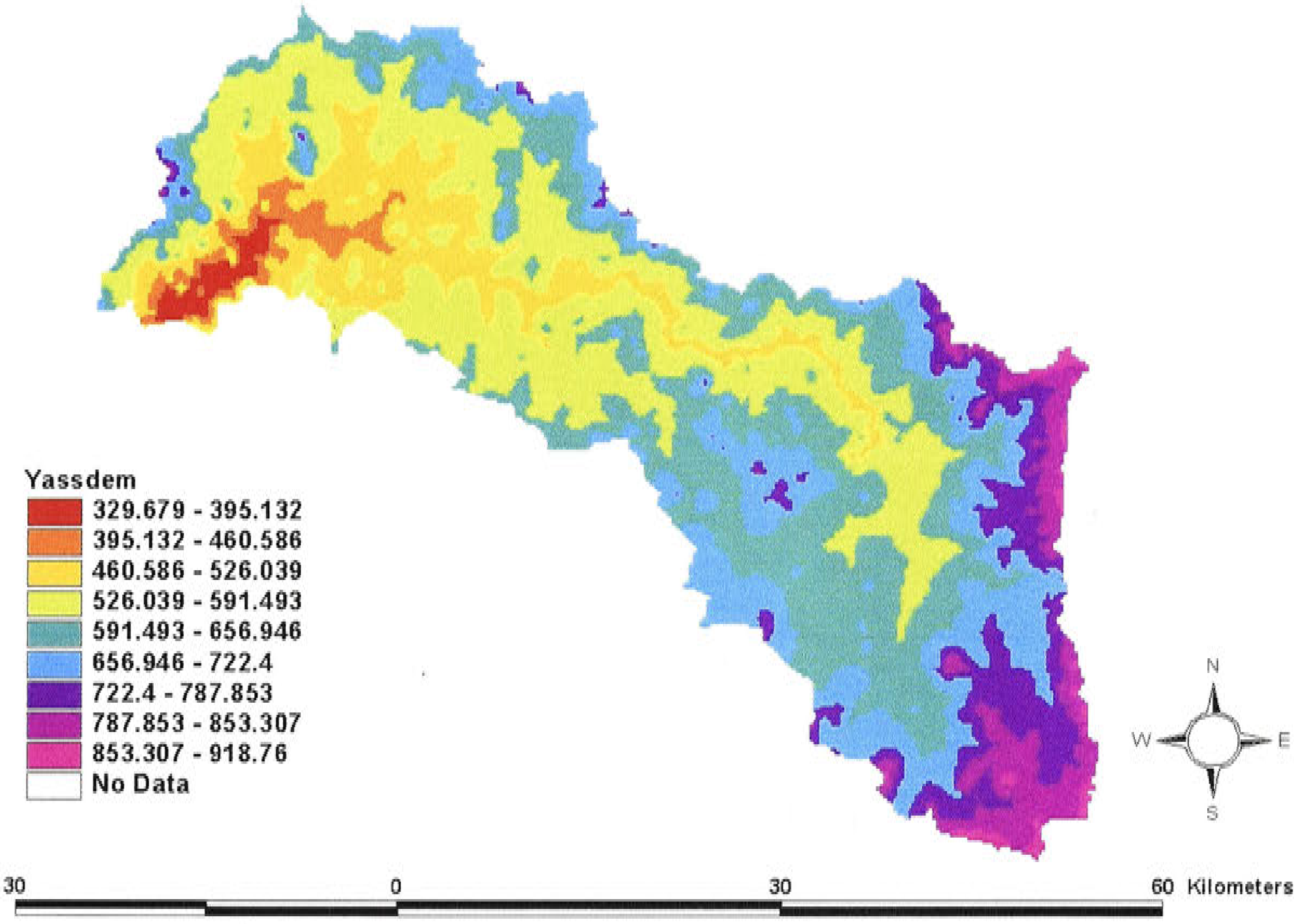

Figure 3.12: Yass catchment DEM derived from ANUDEM

3.16.1 Stream Network and Subcatchment Generation

ARCINFO was utilised to generate a streamflow network in the catchment. Latitude and longitude limits were defined to determine the lowest and highest elevation points in the catchment. A flow accumulation threshold was then defined to create a stream network. Finally, a pour threshold (defines the depth a channel will fill before streamflow begins to fill downstream tributaries) was defined to determine at what depth water would flow from the tributary to the trunk stream. A watershed function was utilised to snap individual streams together to form the catchment network.

From the stream network, latitude and longitude co-ordinates were obtained from ARCVIEW to generate subcatchments along the stream network. Figure 3.13 illustrates the thirteen subcatchments calculated from the DEM. A flow accumulation level was trialed numerous times but failed to generate the small subcatchment. The 250m DEM was not of sufficient resolution to generate the subcatchment (Gauge 60) given its area of just 9.94 km^2. A pour level was set at just 15 metres given the shallow elevation of some of the subcatchments. However, the result also generated two sub catchments that do not exist as a result of the low elevation selected for subcatchment generation. A finer resolution DEM would benefit further studies on smaller catchments such as Yass.

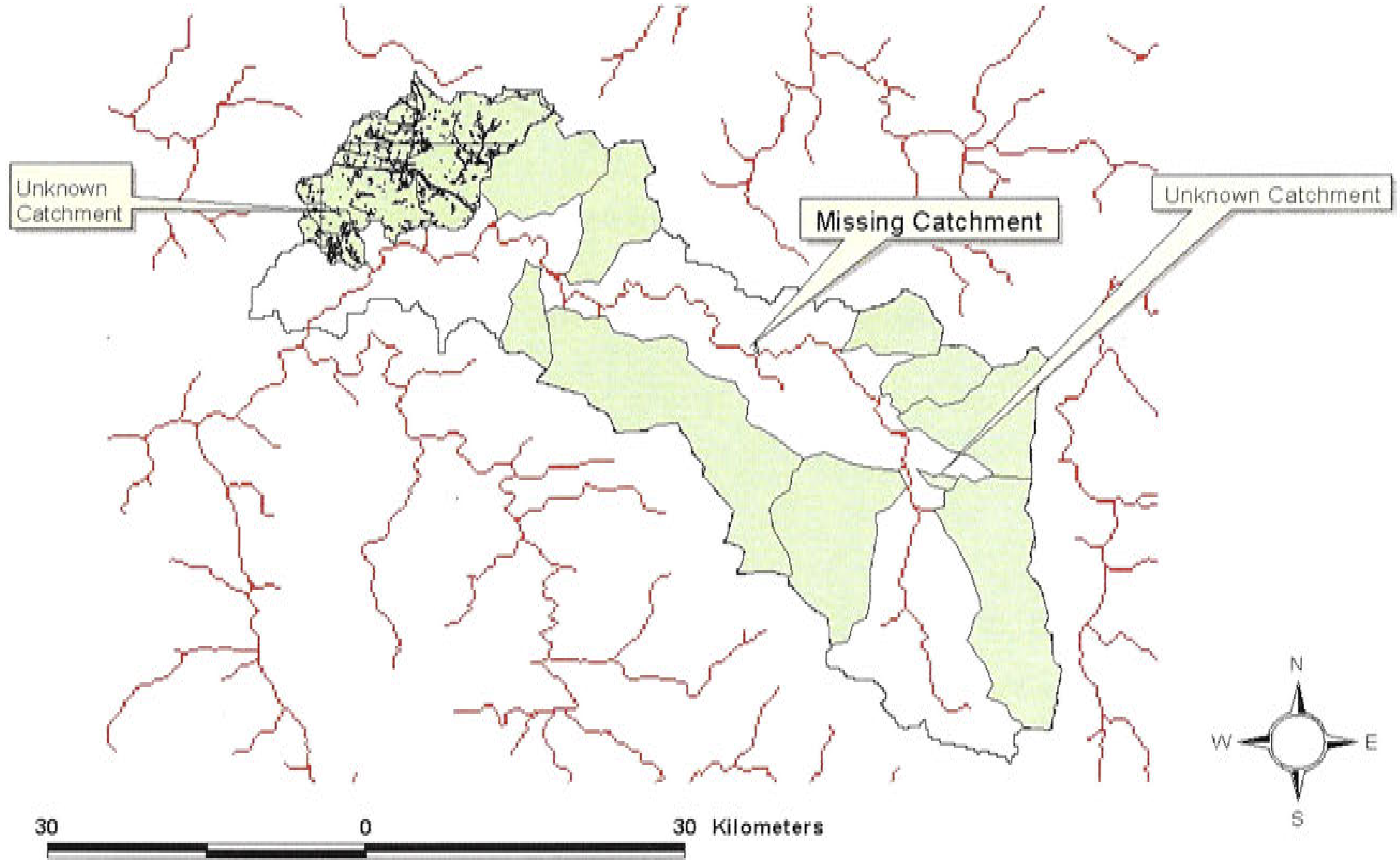

Figure 3.13: Subcatchments derived from the DEM

The subcatchment grid resolution was poor on smaller subcatchments as indicated by Figure 3.14. However, for the purpose of developing an aggregated regional agricultural production model, the resolution was judged to be sufficient. Figure 3.14 shows that there is a significant change in elevation for these catchments. This has implications for the land use potentially able to operate within these subcatchments. This is important where, as is the case in this thesis, the modelling approach is used to examine land use change options under policy scenarios. Therefore, a higher resolution digital elevation model would be useful to improve the reliability and plausibility of any spatial modelling results generated by the approach in this thesis.

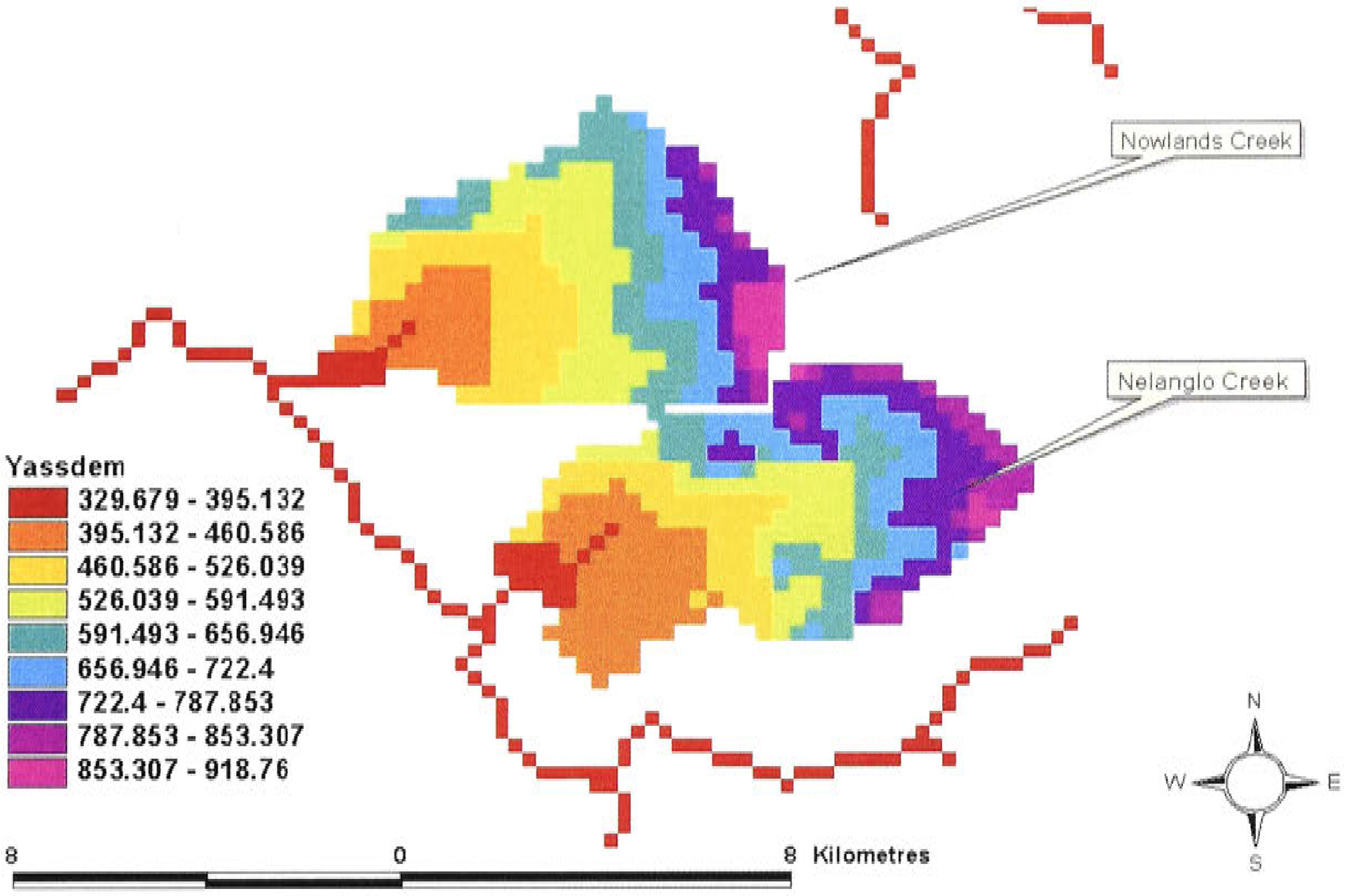

Figure 3.14: DEM resolution (metres) for two small subcatchments in Yass

3.17 Land Use and Land Cover

In order to represent the current system with regard to water use, the following were required: a land cover map that identified extractions from the river, the number and size of farm dams and the location of forestry operations. A land use map containing all of this information was obtained from the Department of Land and Water Conservation in digital form. Grids were cut to the Yass catchment boundary in ARCINFO as shown by Figure 3.15. Figure 3.16 shows the level of detail from an example catchment (Murrumbateman Creek subcatchment). The land cover map was utilised to construct the base case agricultural production model in Chapter 7.

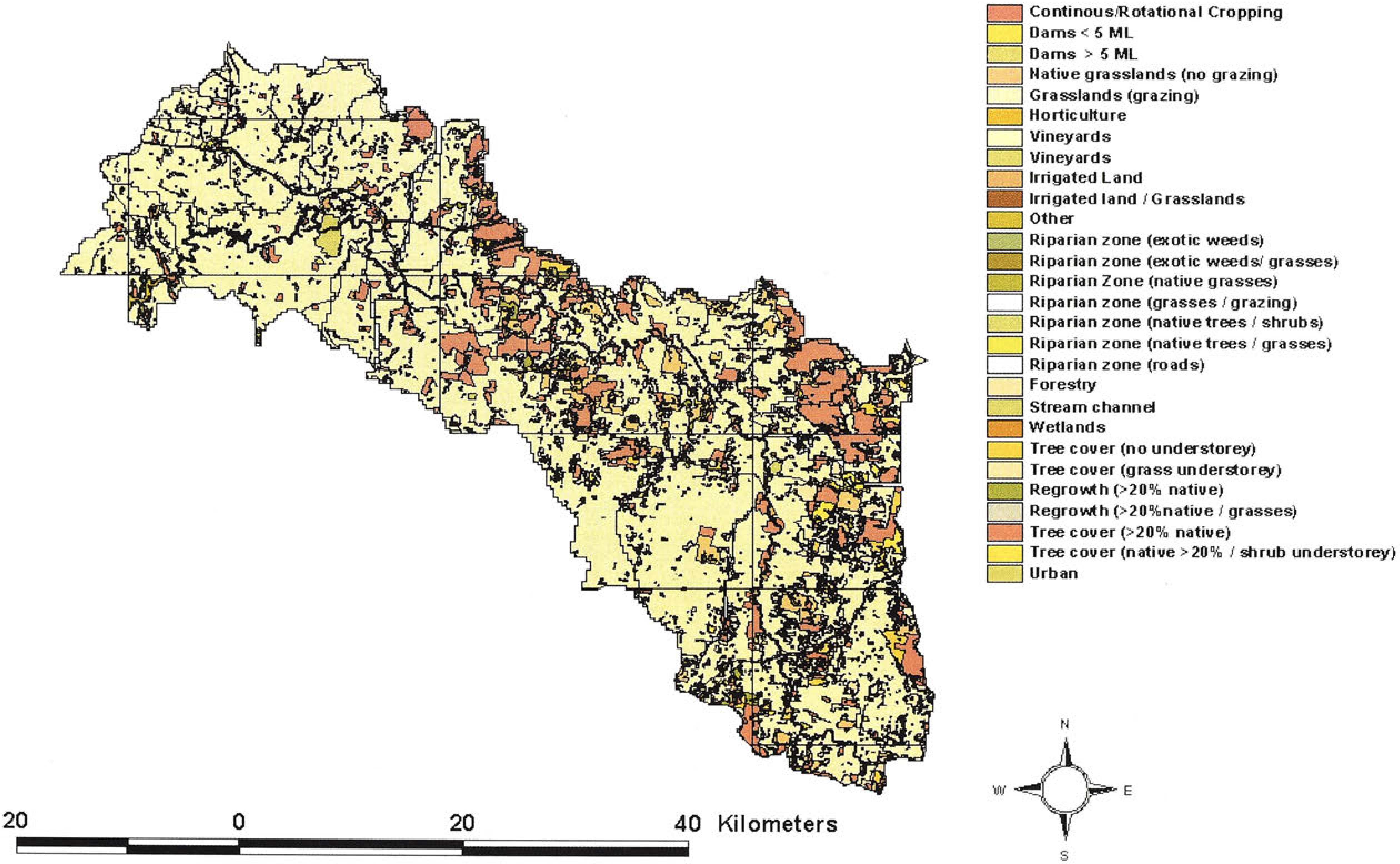

Figure 3.15: Land use map for Yass catchment (Source: DLWC, 2001b)

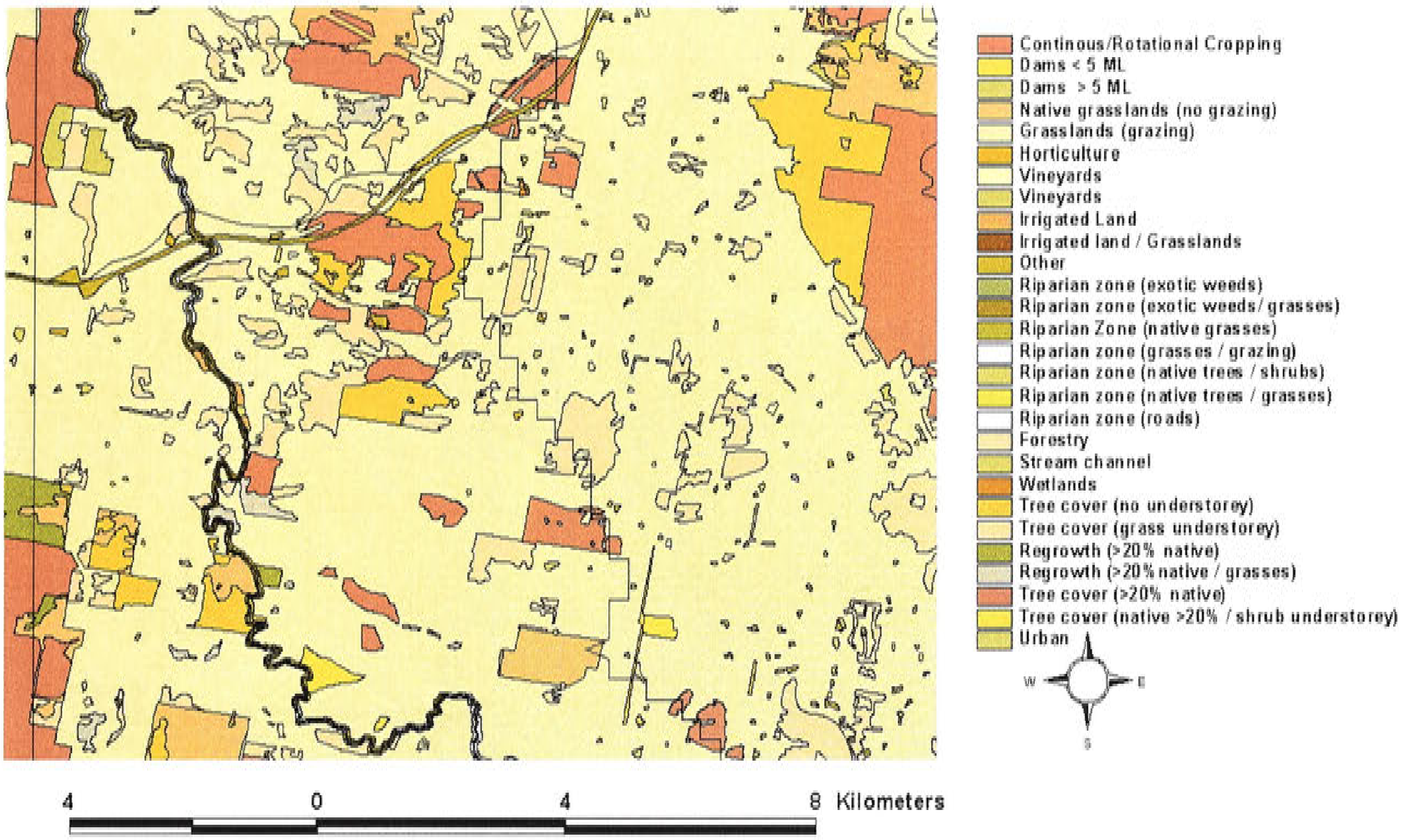

Figure 3.16: Land use map for part of the Murrumbateman subcatchment illustrating farm dams, irrigated areas and forestry

3.18 Soil Type, Land Capability, Aspect and Slope

Biophysical maps were obtained largely for the purpose of identifying agricultural production regions (see Chapter 6). A soil map was required for the hydrological modelling component (see Chapter 5). It was obtained from the NSW Department of Agriculture in digitised form. A Land Capability map was obtained from the Department of Land and Water Conservation. The soil map was cut to the catchment boundary in ARCVIEW. The resolution of the soil map for Yass, given the source was a statewide map, was low with just four soil classes being identified. This placed assumptions upon both the hydrological and agricultural production model component. Given that region definitions and options chosen under the scenario analysis in the agricultural production model were dependent upon the detail of the biophysical map features, the soil map may limit the accuracy of the integrated model results. Secondly, partitioning of rainfall for recharge to runoff-ratio estimates was dependent upon soil fraction estimates (see Chapter 5). The resolution of the soil map may have reduced the ability to identify land area of appropriate suitability for land use activity selection by the model simulation. Slope and aspect were derived from the DEM in ARCINFO. Figures 3.17 and 3.18 illustrate the maps utilised.

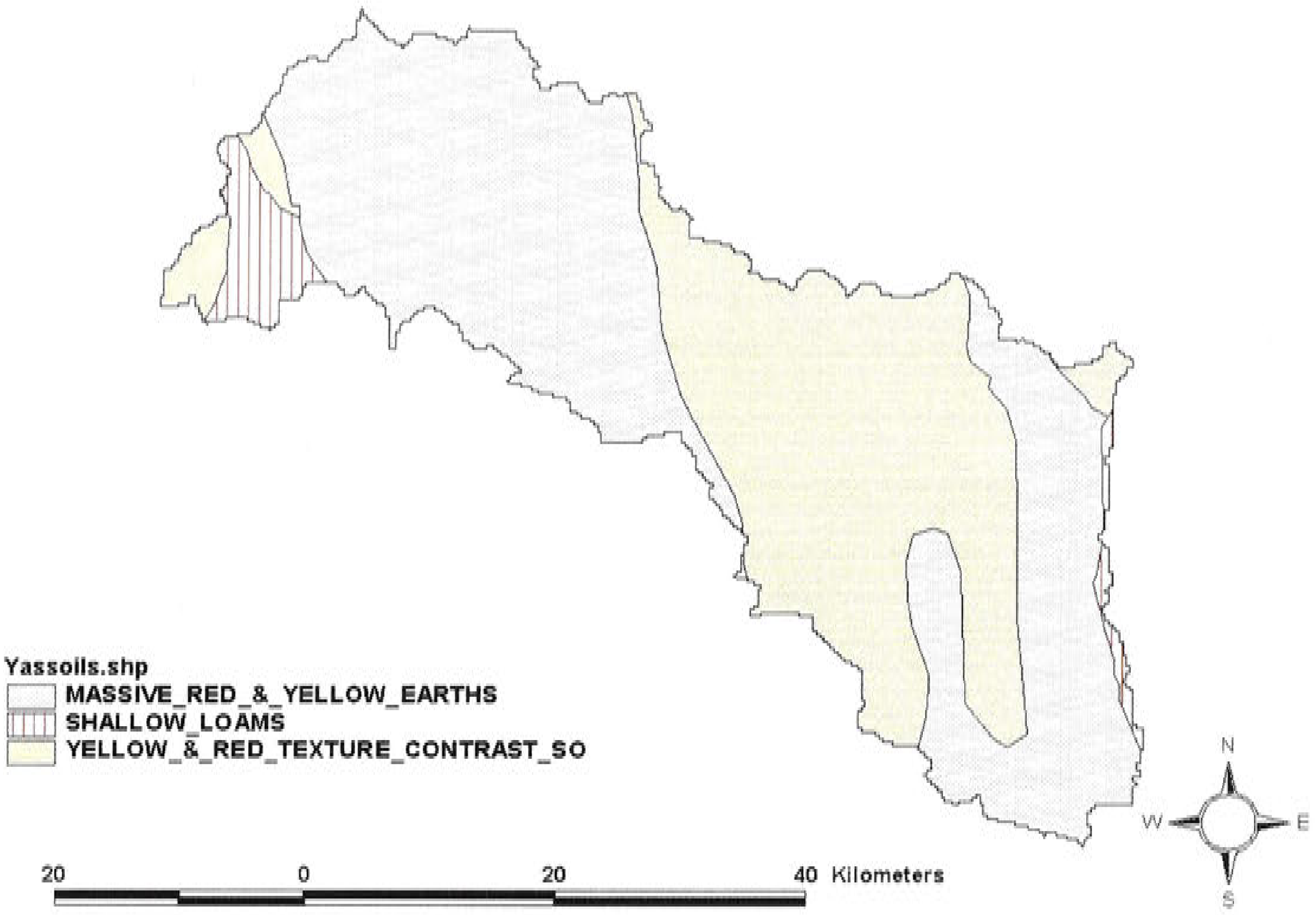

Figure 3.17: Soil type in Yass catchment. (Source: NSW Department of Agriculture, 2000)

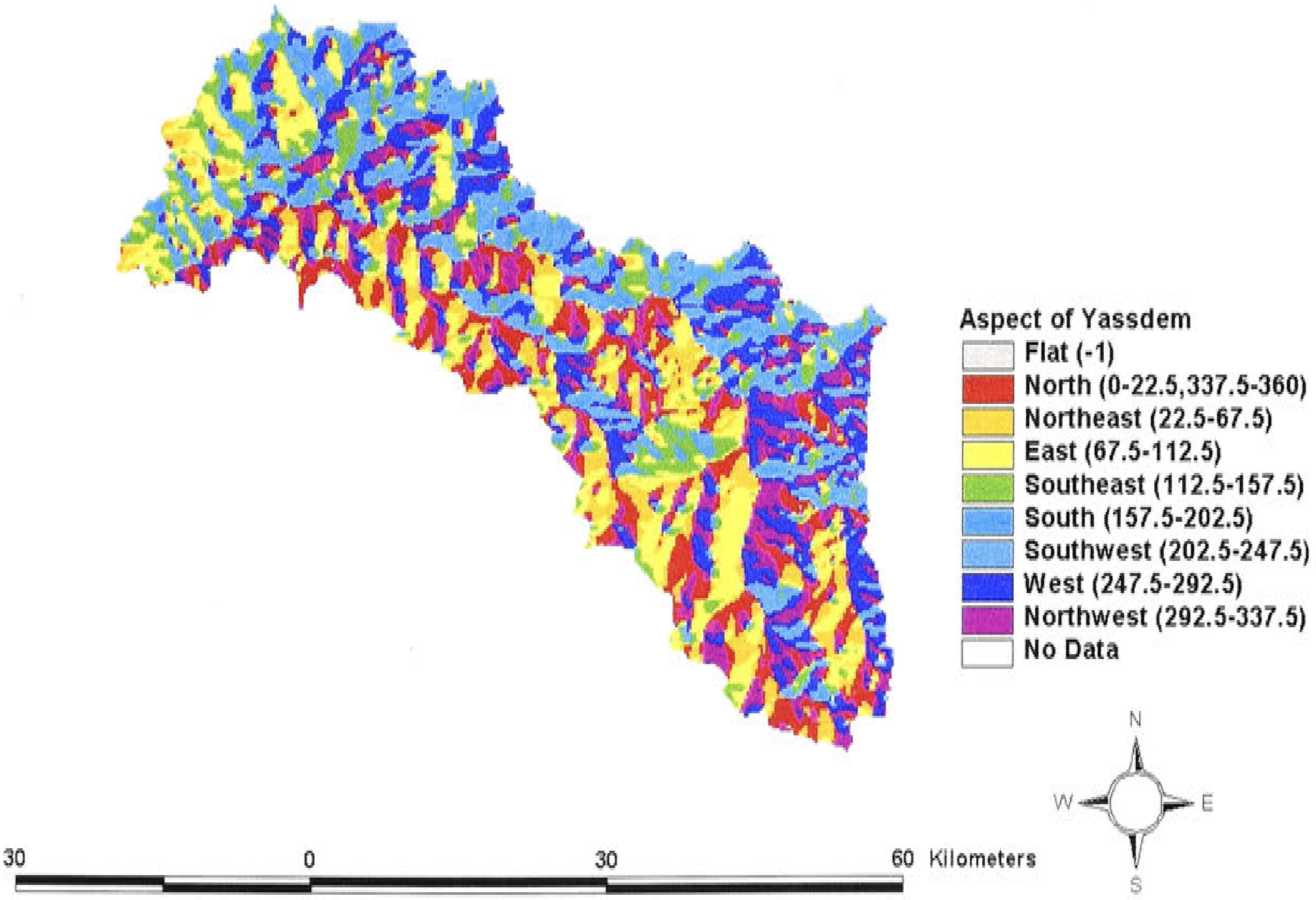

Figure 3.18: Slope and aspect described from the DEM of Yass catchment

3.19 Temperature Data

Time series temperature data was required for the purpose of calibrating streamflow models on the three gauged catchments and simulating flows in the ungauged catchments. Time series temperature data was also required for the agricultural production model.

Temperature data was obtained for Yass catchment and surrounding areas from the Metaccess database. Temperature variation with elevation is 6.5°C for every 1000m (Brutsaert, 1982). In Yass catchment the difference between minimum and maximum elevation is 589 meters suggesting a maximum variation of 3°C across the catchment. To check this, a comparison between temperature in Canberra and at Burrinjuck Dam was carried out. The comparison is shown in Table 3.13. Given this result, it was decided to use temperature records from a single time station for the entire modelling approach.

Table 3.13: Correlation of temperature between two stations within the vicinity of Yass catchment

	Minimum Temperature	**Maximum Temperature**	**Mean Temperature**	**Standard Deviation**
Burrinjuck	5.90	40.5	20.5	7.22
Canberra	5.80	40.0	19.78	6.74

3.20 Hydrology Model and Water Allocation Data Sets

Extraction limits set by the Coalition of Australian Governments (COAG) require a method to identify the appropriate allowable extraction from the stream discharge time series data. Extraction within regulated systems (and some unregulated systems) is controlled by the commence to pump and cease to pump rules (CTPs). CTP rules were split between the three classes identified in Sections 3.13.1a and 3.13.1b. A bulk extraction limit is then set, being the total amount of water available for extraction from each class on any given day. An Excel spreadsheet program was used to determine the daily available water to irrigators. It involved the following steps:

- Daily streamflow in Yass catchment was simulated for 20-years at each of four nodes (to be defined in Section 4.7)

- Zero values were removed from the data set
- Percentile class values were removed
- An Excel routine was written to calculate the percentile values of each class
- A bulk extraction limit and its percentage of flow was also calculated.
- The end result was a set of CTP's for each class and a 20-year streamflow record containing available water for extraction.

3.21 Economic Data Sets for the Agricultural Production System Model Component

In addition to biophysical spatial data sets required to develop the agricultural production regions, temporal economic data sets were required to specify the agricultural production systems within the catchment. Tables 3.14 and 3.15 illustrate the characteristics of the data sets obtained for dryland and irrigated activities respectively. A data set of existing water licence holders and estimated extractive use were also obtained from the Water Licensing Officer at the Department of Land and Water Conservation, Leeton.

Data sets for the six agricultural production activities listed included gross margins and annual prices as well as fixed and variable costs of investment. Discount factors were used to calculate annuitised economic returns. Major input data identified for the model were restricted to land, water and labour. Labour units required to produce a given commodity were obtained, as were daily, monthly and annual water use volumes. Qualitative information on the nature and length of each production cycle was also acquired to represent the production cycle in the model formulation

Table 3.14: Data sets utilised for the dryland activities (Sourced for years 1995-2001)

Activity	Commodity	Data Set	Source
Sheep Grazing	Lambs	1. Prices 2. Gross margins 3. Yield per hectare 4. Meat yield per lamb 5. Fixed Investment cost 6. Variable costs (fodder)	NSW Department of Agriculture
Cattle grazing	Cattle grazing yearling and 2 year olds	As above	NSW Department of Agriculture Australian Meat Industry Assoc.
Forestry	Softwood production	1. Prices 2. Gross Margins 3. Fixed investment costs 4. Water Use 5. Labour use 6. Land use constraints 7. Variable cost inputs 8. Yield per hectare 9. Yield per soil type	Australian Bureau of Statistics RIRDC and NSW Department of Agriculture

Table 3.15: Data sets utilised for the irrigated activities (Sourced for years 1995-2001)

Activity	Commodity	Data Set	Source
Viticulture	Red wine	1. Prices 2. Gross Margins 3. Fixed investment costs 4. Water Use 5. Labour use 6. Land use constraints 7. Variable cost inputs	1. Aust. Wine Assoc. 2. Aust. Wine Assoc. 3. CRC Viticulture 4. Aust. Wine Assoc. 5. CRC Viticulture 6. CRC Viticulture 7. Aust. Wine Assoc.
Irrigated cropping	Irrigated Lucerne	1 Prices 2. Gross Margins 3. Fixed costs 4. Water Use 5. Labour use 6. Land use constraints 7. Variable cost inputs 8. Yield per hectare	NSW Department of Agriculture
Rotational cropping	Irrigated Oats	As Above	As above

3.22 GIS-Generated Economic Datasets for the Agricultural Production System Model Component

Land constraint data sets obtained identify the minimum and likely maximum amount of land required to successfully operate an activity. For intensive activities such as forestry, irrigation and viticulture, the available land required for a viable activity was identified by data sets including soil type, aspect, slope, temperature, rainfall, proximity to the stream and in-stream extraction requirements. Table 3.16 illustrates the physical criteria utilised to calculate the maximum amount of land suitable for viticulture.

Table 3.16: Physical criteria for assessing land suitable for a viticulture enterprise

Soil Type	Aspect	Slope	Proximity to stream	Existing Activity
Loam soil type	North to north-east	<= 15°	Exclude 500m buffer around all streams	Land where Viticulture is already operating

Figure 3.19 illustrates all potential land in Yass catchment suitable for viticultural activities. This includes land containing existing viticulture enterprises. Wine grapes require well-drained soils. For this reason, land containing alluvial soil or poorly drained sites associated with the tributary floodplains were excluded from potential use for viticulture (NSW Department of Agriculture, 2000).

Irrigated agriculture requires access to streamflow. In Yass catchment, it was assumed that the scale of the potential operation was of such small size that pumping from river for storage in farm dams or placement in an irrigation channel would not be economically viable. Instead, it was assumed that irrigation water would be directly applied to the crops from the stream. As a result, irrigated activities were selected by proximity to the stream and alluvial soil type to support intensive crops (Table 3.17).

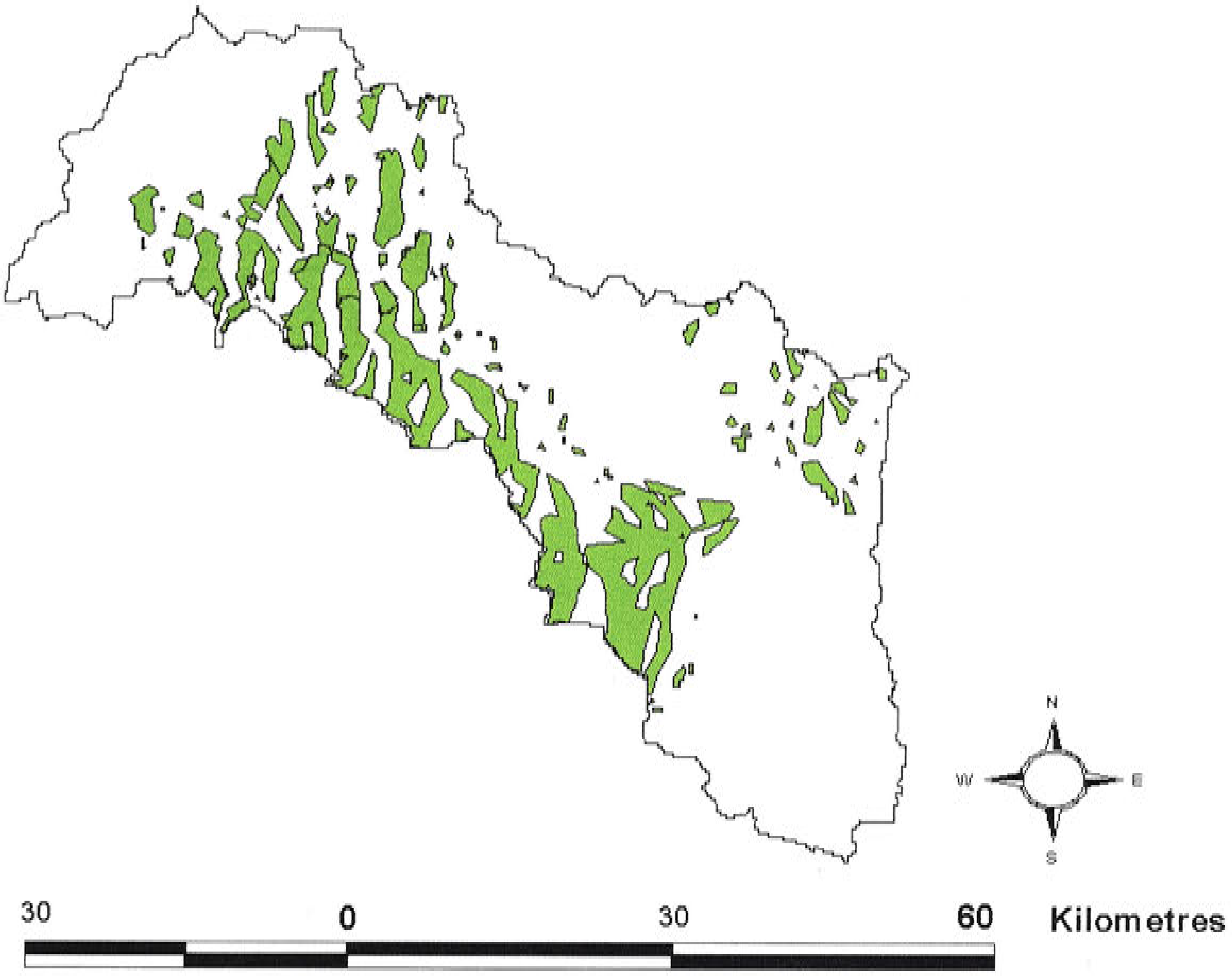

Figure 3.19: Land suitable for a viticulture activity in Yass catchment - for data input into the agricultural production model

Table 3.17: Criteria for selecting land suitable for irrigated crops

Slope	Proximity to streams	Soil type
<= 4°	Within a buffer of 1km from stream (excluding all areas outside of buffer	Alluvial soil or deep loam

Figure 3.20 illustrates the available land as a result of using the criteria to interrogate the GIS data layers. However the shaded areas were excluded. Although satisfying the criteria, these areas represent deeply incised stream channels in the lower part of the catchment. It is not viable economically to extract water for these areas even though the slope of the land adjacent to the streams falls within the criteria.

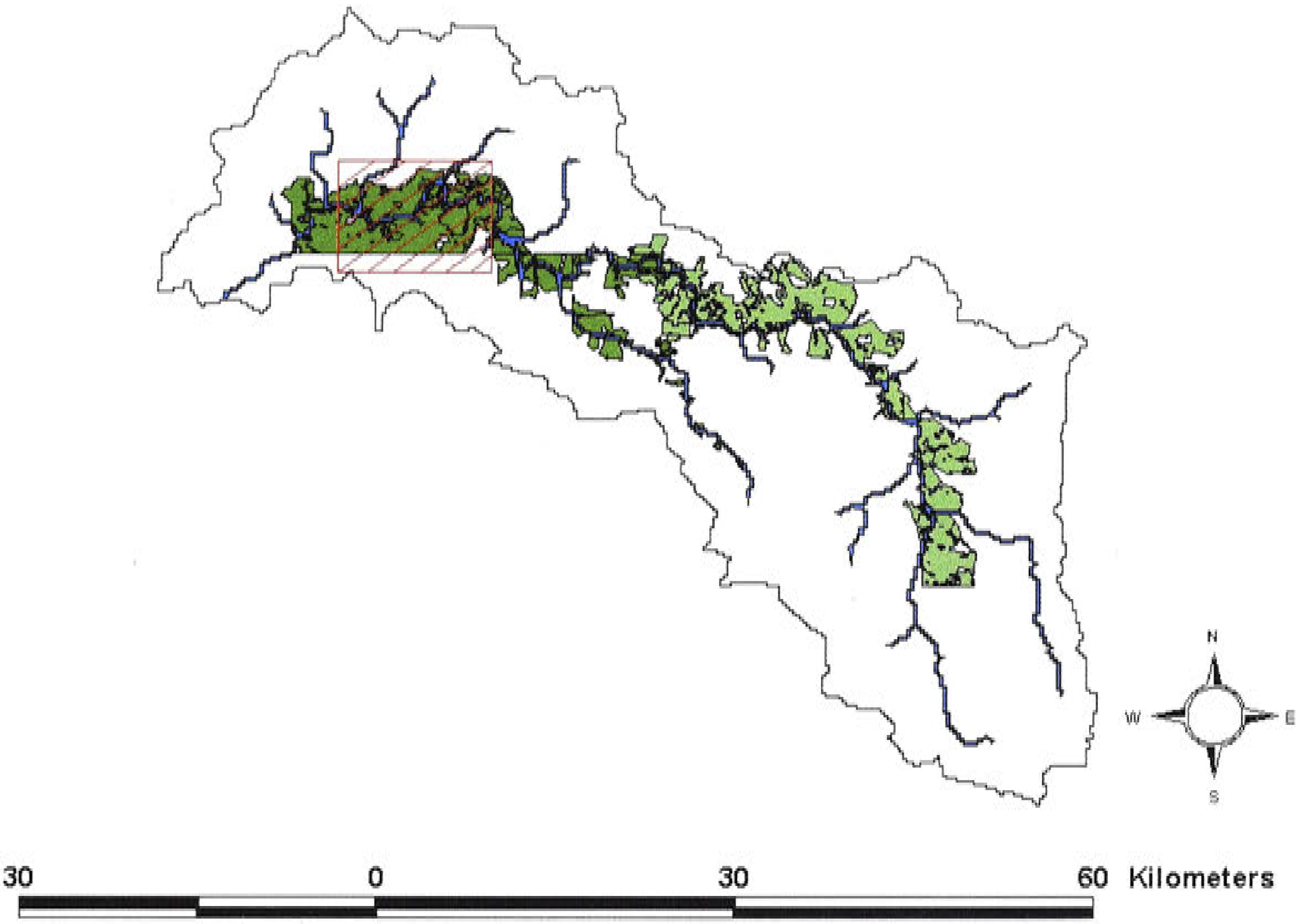

Figure 3.20: Irrigated land constraint determined for Yass catchment

3.23 Conclusions

The chapter has canvassed the type and nature of the biophysical and agricultural production systems in the catchment. It identified the catchment management problems that are current in Yass catchment. Three policy problems were identified. Data set availability and limitations for use in constructing a modelling approach were also identified.

Estimation of daily streamflow requires precipitation and temperature (or some other evapotranspiration surrogate) as inputs and streamflow for model calibration. The review illustrates the spatial and temporal characteristics of temperature, streamflow and precipitation that will require consideration in the model development. In particular, a treatment of the relationship between these climate variables and changes in elevation is required to develop the hydrological network. A networked hydrological system of streamflow is required to identify impacts upon streamflow as a result of implementing a series of changes within the Volumetric Conversions Policy. The hydrological system must be linked to the land use system to also gauge impacts of land use change upon the hydrological system of the catchment.

Secondly, the Chapter illustrates the importance of farm dam development in reducing streamflow as well as the spatial variability in farm dam density. The modelling approach will need to consider movement of water around the catchment and the reduction in streamflow as a result of current farm dam development and the introduction of a Farm Dams Policy. It will also need to consider changes in runoff as a result of plantation forestry establishment given the implementation of a Salinity Management Policy.

The Chapter also identified the heterogeneity of vegetation and soils in the catchment. This will need to be considered in the hydrological component to identify appropriate loss estimates from rainfall as it is partitioned to recharge and runoff. The variation requires a consideration of vegetation characteristics within each subcatchment to appropriately estimate evaporative and recharge loss for the construction of the hydrological network.

In addition, an understanding of land use characteristics is required to construct a modelling system that defines and represents the agricultural production system in its current spatial state. Each land use activity identified should be included in the approach in order to represent the catchment system. This will enable the modelling characteristics, and the spatial and temporal information required, to include land use change in the catchment as a component in the modelling approach.

The Chapter illustrated characteristics of land and water systems in Yass catchment that are of importance for constructing a model representation of the system at the catchment-scale (as shown in Section 3.14 and Table 3.10). In illustrating these features, the review focused upon the identification of catchment-scale processes that may respond to changes in land and water policy options. These are to be considered for inclusion in model construction.

3.23.1 Agricultural Production Systems in Yass catchment

Production systems to be included in the conceptualisation of the model include grazing, lucerne irrigation, and rotational cropping. Activities that have recently been introduced to the catchment and need to be included in the model are forestry and intensive activities such as viticulture.

3.23.2 Catchment Hydrology

As reviewed in Section 3.1 of the Chapter, farm dam development appears to have a significant impact upon the hydrology of the catchment, as do losses to groundwater and surface water extraction at certain points in the catchment. In addition, the catchment consists of several ungauged, ephemeral catchments that will require investigation to build the hydrological network. The conceptual framework and development of the modelling approach will need to incorporate the following catchment biophysical characteristics:

- Development of a catchment system which requires models for predicting ungauged streamflow
- Development of an approach that incorporates the operation of farm dams within the hydrological system
- Incorporation of potential changes in runoff as a result of policy options such as farm forestry or the introduction of other land uses
- Inclusions of the impact upon the hydrological systems of extractions by irrigation enterprises.

3.23.3 Problem statement and Question

Yass catchment and the Upper Murrumbidgee Catchment are undergoing a series of changes to volumetric and environmental flow-based water allocation rules, allowable farm dam capacity and a series of salinity management options. Under the Water Reform Agenda these three changes are the basic land and water policy issues to be addressed in the catchment (and other unregulated catchments within the same region). Given the rate of land use change to 'value-added' industries in the upper catchment, the imposition of these changes to water allocation and access rights by users has the potential to result in adverse consequences upon the catchment. In addition, land use change of this nature requires construction of farm dams, already a problem in reducing run off to streams. There have also been changes to the allowable number and capacity of farm dams under the Farm Dams Policy. Finally, a catchment specific salinity problem has resulted in several initiatives to establish forestry plantations as an economic and environmental solution to salinity management.

The thesis will develop a modelling approach for analysing the impact of Water Reform options under scenario analysis. Questions to be answered are broken into three identifiable types based upon the policy options identified for Yass catchment in the review conducted in this Chapter.

The options to be modelled given the three policy options of current interest in Yass catchment are now outlined.

Farm Dams Policy Options

The model developed will examine the impacts upon farming and land and water systems as a result of introducing a 10% runoff cap. Other options will identify if a larger capture percentage is required for existing and future agricultural production systems. As a result, the modelling approach simulates the following options:

a. A farm dam capture runoff of 10% (the current policy option)
b. A farm dam capture of 20% (suggested as the true runoff capture from recent studies)
c. farm dam capture of 5% as a compromise policy option.

Volumetric Conversions Policy Options

The modelling approach will be used to simulate several volumetric conversion scenarios to examine the impact of imposing the policy on water users within the catchment. This will involve the determination of a bulk extraction limit (BEL) and volumetric entitlements suggested from the literature review options.

Salinity Management (Forestry Plantation) Options

The model presented in this thesis will consider, in aggregated form, the impact of revegetating large parts of the catchment for salinity management upon users within the catchment. The link between salinity management and impacts on other users and runoff to stream will also be identified. The model includes a forestry production component. Studies by Ruprecht and Schofield (1991), Cornish (1989), Cornish and Vertessy (2001) and Smith (1998) show that runoff reduction is not sufficient to affect streamflow volumes where revegetation is carried out on less then 50% of the catchment area. Given the literature concerning impacts of runoff as a result of clearing and vegetation, three broad revegetation policy options will be selected for the modelling approach:

a. Plantation of 20% of the catchment
b. Plantation of 50% of the catchment
c. Plantation of 80% of the catchment

Each policy has the potential to impact on the outcome of any other policy in the catchment. As a result, the modelling approach to be developed must be able to consider direct impact questions upon the catchment of introducing any single policy, as well as a suite of indirect questions focusing on the interaction between policy options. The types of questions that the integrated model should be aimed at addressing, given the issues identified in Chapter 2 as part of the Water Reform Process, and specific land and water issues identified in Chapter 3 for Yass catchment, are of a direct, indirect and trade-off nature.

Direct Impact Questions to be answered

What is the impact on stream flow as a result of farm dam development?

What is the impact on land use change (to viticulture) as a result of changes to the farm dam policy?

What are the impacts on available water to users as a result of imposition of volumetric rules?

What is the effect on runoff and catchment hydrology as a result of vegetation plantation in the catchment to reduce salinity?

Trade-off and Offsite Questions to be answered

What are the off-site trade-offs to volumetric users as a result of viticulture development?

What are the impacts on valued-added industries as a result of volumetric changes and reduced runoff from plantations?

What is the magnitude of environmental trade-off as a result of water policy imposition and land use change by economic units (in this case, agricultural production units)?

Questions of this nature need to be answered to inform the Water Reforms Agenda. It is necessary to consider the spatial impact (of both the hydrological and agricultural production systems) of policies to understand likely trade-offs and impacts between water users given the nature of policy implementation. This is a major goal of decision makers implementing the Water Reform Process.

Chapter 4 The Conceptual Framework

4.1 Introduction

This Chapter provides the conceptual underpinning for the model development in the thesis. It aims to highlight major points of integration between the agricultural production system and hydrological system components.

The first Sections scope out the scale and broad characteristics of the system to be modelled. This Section builds upon the system description contained in Chapter 3 by placing the problem into a modelling context. A broad set of scenarios to be modelled is developed in order to analyse the problem (detailed explanation of scenario development is left until Chapter 7). The nature of the scenarios and land use options to be modelled provides the mechanism for creating modelling units within the catchment.

The subsequent Sections 4.4 to 4.7 focus on describing the system within a modelling framework. Section 4.3 describes the policy integration at the three different levels in the modelling hierarchy. This involves defining production Activities in Section 4.4, Land Management Units (LMU's) in 4.5 and modelling Nodes in Section 4.7. Section 4.6 describes the policy options ascribed to each Land Management Unit.

Having presented the characteristics of the conceptual framework in Chapter 4, a description of specific model equations and variables is left until Chapters 5 and 6. Chapters 7 and 8 provide the results of running and testing the integrated model.

4.2 The Modelling Hierarchy

The integrated modelling approach developed in the thesis operates at three modelling scales. The basic unit of the model hierarchy is the Activity, followed by Land Management Units and finally Nodes. This hierarchy was developed to facilitate integration between different system processes (principally hydrological and agricultural production systems) at each scale. Activities, being the lowest level in the modelling hierarchy, are contained within Land Management Units. Land Management Units are contained within nodal areas, which are the subcatchment areas upstream of Nodes.

At the Activity level, economic return per hectare of each agricultural production activity is calculated. At the Land Management Unit level, this information is used to make decisions as to area devoted to each land use option. At the Node level, system response is calculated as a result of the decisions made at the Land Management Unit level. Integration between agricultural production components and the hydrological system is also undertaken at the nodal scale.

4.3 Policy Integration in the Modelling Hierarchy

The three policy options identified in Chapter 3 are implemented at three different levels in the modelling hierarchy. As discussed in Chapter 3, Yass catchment is a dryland agricultural catchment. There are three main agricultural production activities that impact on streamflow availability in the catchment. One of these is the construction, and use of, farm dams for viticulture. The capture of water in farm dams restricts stream flow. A new policy, the 10% runoff policy will restrict the volume of water that farmers are able to capture in farm dams.

In Yass catchment, there is also a small number of irrigators extracting directly from the stream. Proposed changes to volumetric conversion allocations has the potential to invoke land use change impacting on agricultural production, social and environmental systems in the region.

The third policy involves the introduction of farm forestry options to control dryland salinity. These policy options have the potential to undermine environmental flow policies in the catchment. Given the type of land and water management systems in the catchment, the modelling approach was set up to examine scenarios where the following land and water policy options were introduced in various areas within the catchment:

Farm Dams Policy options
Volumetric Conversion options
Salinity Management option

It is essential to identify the three broad policy options that are the focus of the modelling undertaken in this thesis in order to provide direction for construction of the conceptual framework (for a full description of each policy, see Chapter 3).

A second aspect of policy integration in the thesis is the level in the modelling hierarchy at which the policy options are integrated. Given the type of conceptual integration between the hydrology system and the agricultural production system developed in this thesis, land and water policy options are imposed at three different levels in the hierarchy as Figure 4.1 illustrates. Details of the way in which these policies are implemented are given in this Chapter.

At the Activity level, the Farm Dams Policy is imposed. At this level, the total available farm dam capacity is determined on a per hectare basis given available rainfall. As per hectare variables are calculated at the activity level, the Farm Dam Policy option is required to be imposed at this level. Secondly, the available water per hectare is required before a decision is made as to what land use is potentially sustainable under a policy option.

The Salinity Management Policy is implemented through forestry plantation. The policy option determines what proportion of the catchment is to be planted to forestry to manage salinity. At the LMU level, decisions as to the area of each LMU devoted to individual activities is made. Therefore, at this level, the Salinity Management Policy option is imposed prior to any other decisions being made regarding the allocation of land to activities.

At the Node, the calculation of streamflow occurs, after runoff (as a result of land use change and farm dams) and extractions takes place. Streamflow extraction is the only output at the Node that is passed to downstream Nodes. Therefore, the volumetric policy is implemented at the nodal level.

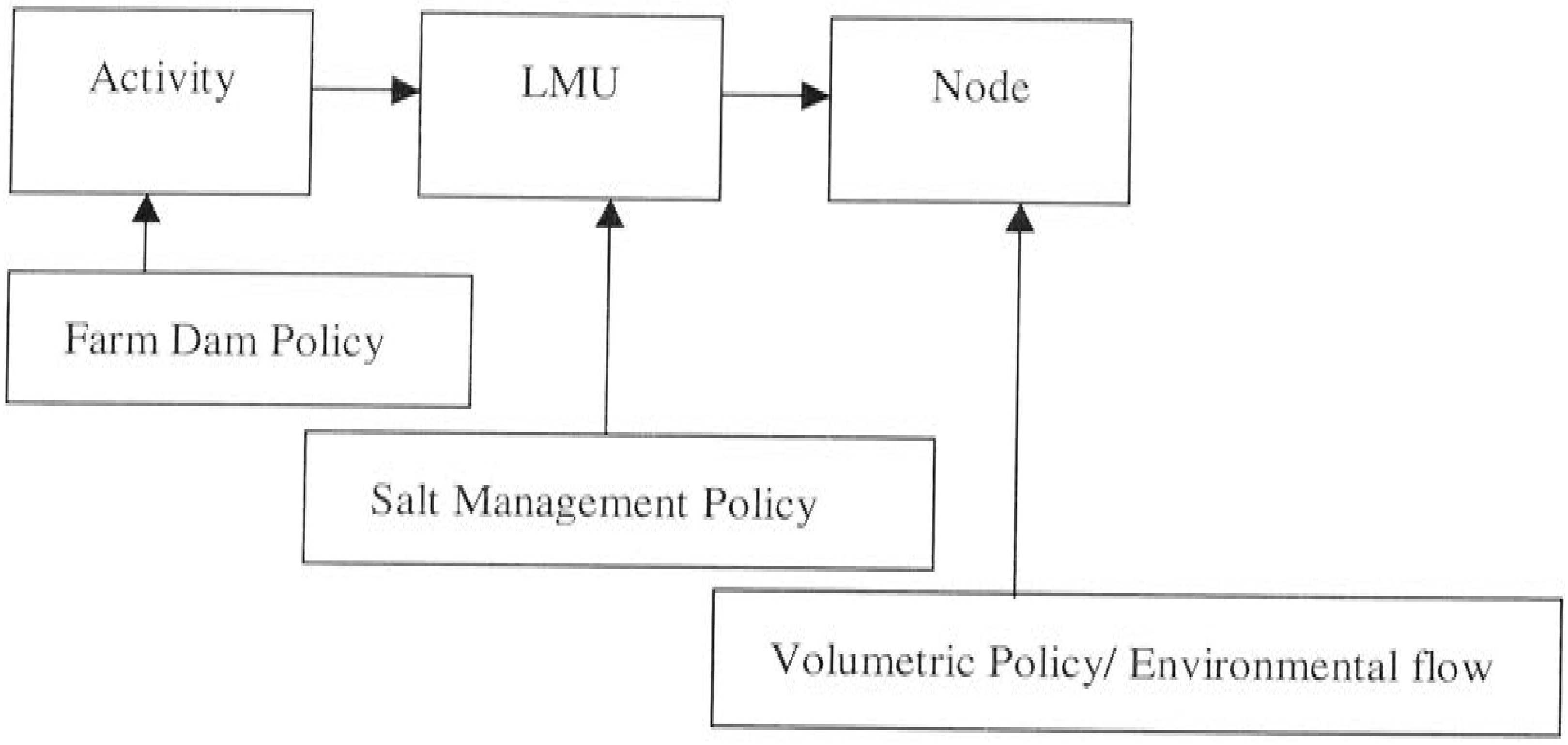

Figure 4.1: Policy integration within the modelling framework

The following sections examine the three levels in the modelling system as well as discussing the way in which each level interacts with others in the hierarchy. Specific processes and variables are left until the model formulation in Chapter 6. Section 4.4 describes the conceptualisation of the Activities. Section 4.5 describes the Land Management Units (LMUs). Section 4.6 presents how and why the policy options are integrated within the three different LMU types and Section 4.7 describes the Nodes.

4.4 Activities

Activities are the lowest level in the modelling hierarchy for the agricultural production system. An activity is distinguished by the property of producing commodities from a single production process, utilising specified resource inputs and technology and interacting with the hydrological system in a defined way. There are six activities represented in the model as indicated by Table 4.1. Four of the six activities produce multiple commodities given resource availability from the hydrological and biophysical systems. Activities are also characterised by a unique set of economic decision rules which define agricultural production on a per hectare basis (see Section 4.6). The total economic return per hectare for each activity is also determined given yield, costs and price inputs. The agricultural production activities and their characteristics are given in Table 4.1. As will be discussed in more detail in Chapter 6, activities consider all variables on a per hectare basis.

Table 4.1: General land and water requirements for the production systems in Yass catchment

Activity	Water Requirement	Land or Soil Requirement
Grazing	Rainfall	Most areas
Viticulture	Farm dam fed irrigation	Well drained soil, sloping areas
Forestry1	Rainfall	Higher fertility soils
Forestry2	Rainfall	Lower fertility soils
Rotational Cropping	In-stream extraction	River flats or alluvial soils
Lucerne Production	In stream extraction	River flats or alluvial soils

The next Section; 4.4.1 to 4.4.4, briefly describe nature of each of these activities.

4.4.1 Grazing Activity

Grazing yields and pasture growth are assumed to be rainfall-dependent. During wetter periods, pasture growth is increased, leading to greater weight gain of cattle and higher yields as a result. During such wet periods, the cattle are sold off after a single year of production. When rainfall is low, during drought periods, pasture growth is reduced and cattle gain less weight. In this case, cattle are grown out to two years. Lower yields are experienced as a result. Costs are also increased due to the requirement that cattle are handfed during dry times. Available rainfall therefore determines the farmers decision making behaviour with regard to the operation of this activity.

4.4.2 Viticulture Activity

The runoff available for viticulture production given a Farm Dams Policy scenario is determined at the Activity level. Rainfall obtained from the hydrological system is used to determine the available farm dam capacity per hectare after the imposition of the Farm Dams Policy. The viticulture production system has a crop conversion rate based upon one of three maturity phases for grape production. In the first phase, between establishment and four years, yield is zero. However, grapes require a higher volume of water per hectare to grow during this period of time compared to subsequent time periods. In the second maturity phase, a grape yield occurs and water required to irrigate the grapes is reduced. In the third phase of maturity, grape yield is highest and water per hectare required to sustain them is the least (see Chapter 6 for details of grape maturity phases and corresponding yields and water use). Economic return per hectare is then determined from calculated yields, costs and price inputs.

4.4.3 Forestry Activities

At the Activity level, yield per hectare and economic return per hectare is determined for two forestry activities. The first activity occurs on fertile soils. Forest growth occurs over three maturity phases. In the first phase, the forest is thinned. In the second maturity phase, seven years later, small sawlogs are produced. In the third phase of maturity, the entire plantation is felled to produce sawlogs. The same production system occurs on low yielding soils with the exception that yield is lower because the product quality on poor soils is lower.

4.4.4 Irrigated Activities

The extractive irrigated activity involves two types of agricultural production. They are rotational cropping and lucerne irrigation. At this level, total economic return per hectare is determined. A crop conversion rate for rotational cropping and lucerne irrigation determined the water required to sustain a crop over the season. The crop is sold at the end of each growing season for both activities. Rotational cropping occurs as a 50% mix with grazing. Lucerne irrigation is planted as a single crop.

4.5 Land Management Units (LMU's)

A Land Management Unit (LMU) is defined as a spatial area of relatively homogenous combinations of land use activity options intersected with subcatchment boundaries. An LMU may contain multiple activities. The LMU Level is the level at which land use decisions are simulated within the modelling hierarchy. Each LMU is assumed to be run by a single, profit maximising farmer with perfect knowledge (see Chapter 6). A decision as to the area devoted to each activity given land and water constraints is simulated.

This is also the level in the modelling hierarchy at which the Salinity Management option through forest plantation occurs. The production decision model involves taking land out of production that would have otherwise been selected for more profitable land uses under normal decisions to maximise profit.

Three generic types of LMUs were identified within the Yass catchment. They are the dryland LMU, supplementary irrigation LMU and extractive irrigation LMU. These LMU types are defined by their links to the hydrological system given the agricultural production activities that may take place within them. The dryland LMU, supplementary irrigation LMU and extractive irrigation LMU each impact on different parts of the hydrological cycle.

4.5.1 The Dryland Land Management Unit

Dryland LMUs are defined as areas that potentially contain only activities which do not require farm dam or extractive irrigation for operation. As such, activities within this LMU integrate with the hydrological cycle only through changes in evapotranspiration and subsequent impact upon the rainfall-runoff relationship. The activities that may be undertaken in a dryland LMU include grazing and forestry. At the Dryland LMU level, a decision is made to determine the area devoted to each activity. Economic return per hectare for both activities contained within the LMU is passed from the activity level. At the LMU level, a decision is made based on economic return to devote a proportion of the LMU to each activity.

Alternatively, where a forestry option is imposed, an area of the catchment devoted to forestry can be input into the model directly. There are two key outputs of the dryland LMU. They are forest area and runoff per hectare as a result of forestry plantation. These are passed to the nodal level.

4.5.2 The Supplementary Irrigation Land Management Unit

Supplementary LMUs are defined as those where viticulture is a possible activity. As described in Section 4.4.2, the activity requires on-farm storage for operation. Other activities able to be selected from the LMU include grazing and forestry production (where there are biophysical constraints as such to allow viticulture production).

This LMU type integrates with the hydrological cycle through both rainfall and impacts of land use decisions on runoff. Rainfall affects yield of all activities considered for this LMU type. Decisions to plant forestry impact upon streamflow through changes in evapotranspiration and runoff. Farm dam capture of rainfall impacts on runoff and hence streamflow.

Five major model inputs from the Activity level are passed to the LMU level. Yield per hectare from each activity, economic return per hectare and the area required to capture one megalitre of water are passed to the LMU level, in addition to the total volume of water available for viticulture production. A decision is made to devote an area to viticulture, grazing or forestry given the availability of water per hectare and profit per hectare.

The forested area and maximum farm dam capacity then is passed to the nodal level to recalculate runoff from rainfall. The dryland and supplementary LMU model are run first to determine changes in runoff and alteration of streamflow. The resultant streamflow is then made available for the third LMU type, extractive irrigation.

4.5.3 The Extractive Irrigation Land Management Unit

Extractive Irrigation LMUs are those which potentially include activities requiring streamflow extraction. Activities that are considered in this LMU type are lucerne and rotational cropping. The LMU interacts with the hydrological system through direct extractions from the stream. Extraction for the purpose of holding in farm dams for irrigation in dry years is not considered by the model.

Economic return per hectare for each activity is passed from the activity level to the LMU. Each irrigated activity has a minimum requirement for water on a per hectare basis (see Chapter 6 for crop conversion rates). Given the availability of water and land to the LMU, the production decision model determines the area to be planted to each activity. After this decision has been made, the annual extraction defined by the land and water use decision is passed to the extraction model at the nodal level. This model determines how much streamflow is actually extracted on a daily basis.

4.5.4 Land Management Units in the Yass Catchment

Characteristics of each LMU in the modelling system are shown in Table 4.2. Twelve modelling LMUs were identified corresponding to the three generic types discussed above. Figure 4.2 illustrates the spatial location of each of these LMUs in the catchment.

Table 4.2: LMU Area and Characteristics

No	LMU Type	Description	Area (Hectares)
1	Dryland	Grazing. Small area in the lower catchment. Isolated from urban areas.	3713
2	Dryland	Grazing and low yielding forestry. Lower catchment, has river access but poor soils.	21792
3	Supplementary Irrigation	Viticulture, grazing and both forestry. Lower catchment downstream of Yass township. Moderately fertile soils with small areas of native vegetation.	10841
3b	Supplementary Irrigation	Viticulture and grazing activities. Large area of native vegetation and sloping areas. Close proximity to Yass township.	11643
4	Supplementary Irrigation	Viticulture, grazing and forestry. Middle catchment. Fertile soils and gentle slopes. Largely cleared.	7126
4b	Extractive Irrigation	Close proximity to Murrumbateman township. High proportion of farm dam development.	2408
5	Supplementary Irrigation	Viticulture, grazing and forestry. Upper catchment hill slopes. Mostly grazing and suitable for a small area of forestry. Small ephemeral tributary.	16762
6	Supplementary Irrigation	Viticulture, grazing and forestry. Upper catchment excluding area around Yass trunk stream. High proportion of farm dam development and grazing activities.	34728
6b	Extractive Irrigation	Irrigation and grazing including Yass main arm downstream of Gundaroo. Rotational cropping and lucerne irrigation.	2609
7	Dryland	Grazing and low yielding forestry. Western ranges of upper catchment. Largely cleared with drained, sandy soils. Steeper slopes.	17603
8	Supplementary Irrigation	Viticulture, grazing and both forestry. Close proximity to Gundaroo township. Higher soil fertility and gentle slopes. Largely cleared.	30211
8b	Extractive Irrigation	Irrigated activities and Grazing. Includes Yass trunk stream in upper catchment. Irrigated and intensive activities. Fertile soils and gentle slopes.	11040

4.6 Policy Options within each LMU Type

Decisions made within Activities, LMUs and nodal areas are influenced by water policy options. Of the three LMU types, each corresponds to a matrix of potential policy options which affect land and water use decisions made at the LMU level. Table 4.3 indicates the policy options available for each of the three LMU types.

Table 4.3: Policy options within a Land Management Unit

Policy	Options	Dryland	Supplementary	Extractive
Salinity Management	20% plantation 50% plantation 80% plantation	Yes	Yes	No
Volumetric Conversions	Single extraction limit above a CTP Multiple extraction limits No restriction on extractions	No	No	Yes
Farm Dams Policy	10% runoff 5% runoff 20% runoff No restriction	No	Yes	No

A policy option pertaining to a change in a volumetric water allocation is restricted to influencing extractive irrigation production activities and their respective LMUs at the node. Similarly, water availability for a viticulture activity is affected by changes to the Farm Dams Policy for the LMU and Node containing it. Thirdly, forestry activities are subject to influence by the Salinity Management Policy, which determines an imposed area planted to forestry. The linking of the policy and LMU type ensures that the policy option selected at the Node impacts upon the appropriate production system.

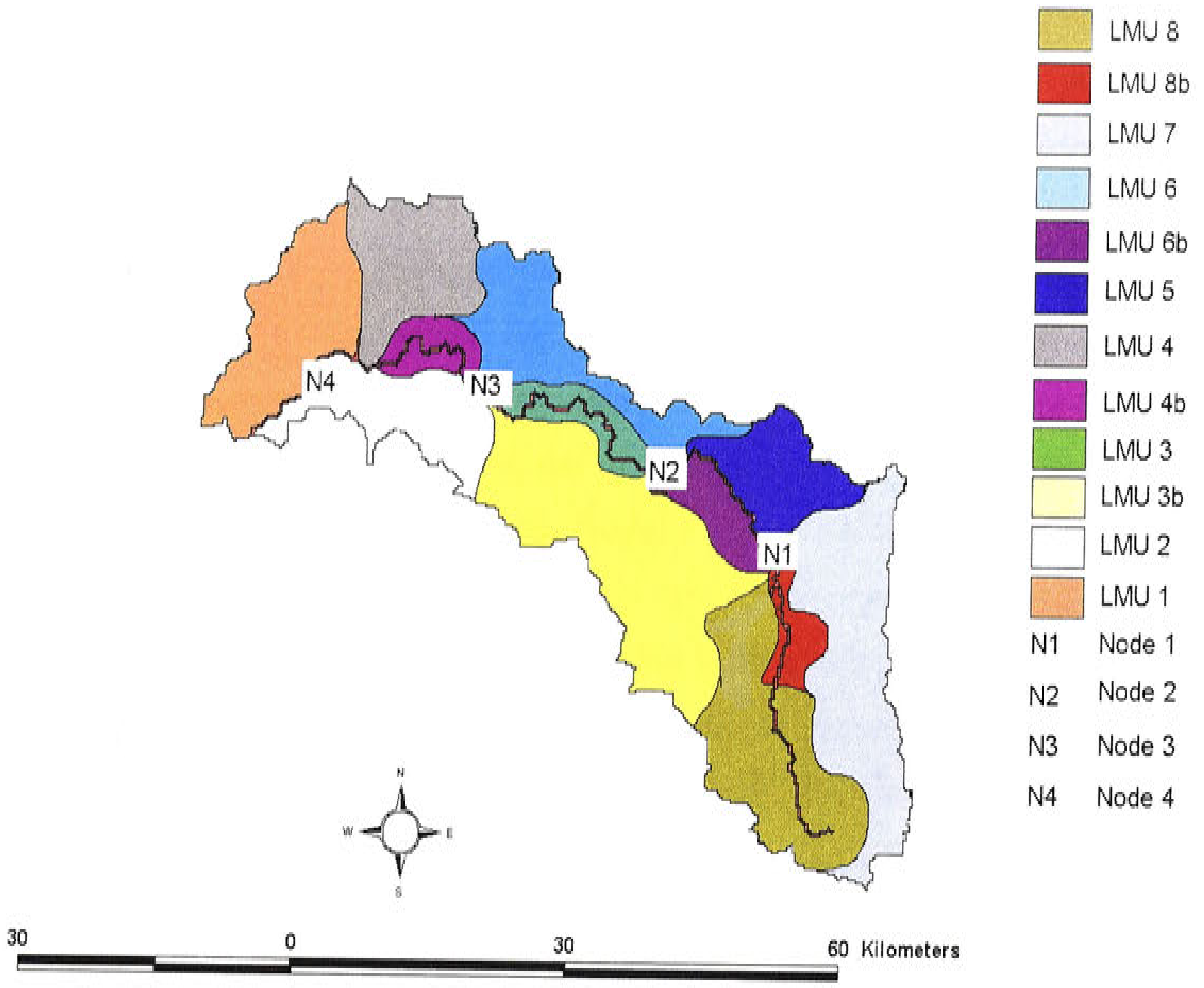

Figure 4.2: Land Management Units and Nodes in Yass catchment

4.7 Nodes

This section discusses operation of the model at individual nodes. Nodes are points of aggregation along the stream network. They are points at which streamflow is modelled and indicators (for residual catchment areas upstream of the node) of agricultural production and hydrological performance are calculated. As Table 4.4 indicates, several LMUs are aggregated at each node. Nodes are also the primary point of integration between the agricultural production and hydrological systems. It was considered that only 4 nodes were required to represent the Yass catchment system. This was done through a process of identifying the point at which several spatially defined LMUs and subcatchment boundaries met. This was refined through several iterations by defining the hydrological boundaries that each LMU type would impact on, and by identifying LMU types able to exist in the spatial area as defined by the biophysical attributes defined in Chapter 3.

Integration at the node can be considered in a generic way by grouping LMUs as pre-extractive and extractive types. Figure 4.3 shows the interaction between pre-extractive and extractive LMUs at the Node level in the model hierarchy. A pre-extractive LMU may be a dryland or supplementary-irrigation LMU. Total forest area and volume of farm dams at the LMU is summed over the pre-extractive LMU at the node. The aggregated information is passed to the hydrology model where the change in runoff and hence streamflow at the Node is calculated for the whole forested area in the LMU. These two variables are then passed to the hydrological model component. This model simulates pre-extraction streamflow at the Node.

A policy model calculates the annual extraction limit given licence volumes and the daily flow extraction rules. Annual extraction limits are passed to the extractive LMU where a land and water use decision is made. This allows the volume of annual extractions to be calculated and passed to the daily extraction model which allocates these extractions over days for the 20-year simulation. Streamflow minus extractions are calculated at the node. A time series of daily extractions is passed to downstream nodes. Forest area and farm dam volumes for these upstream areas are also passed downstream to allow calculations of pre-extraction flows at these nodes.

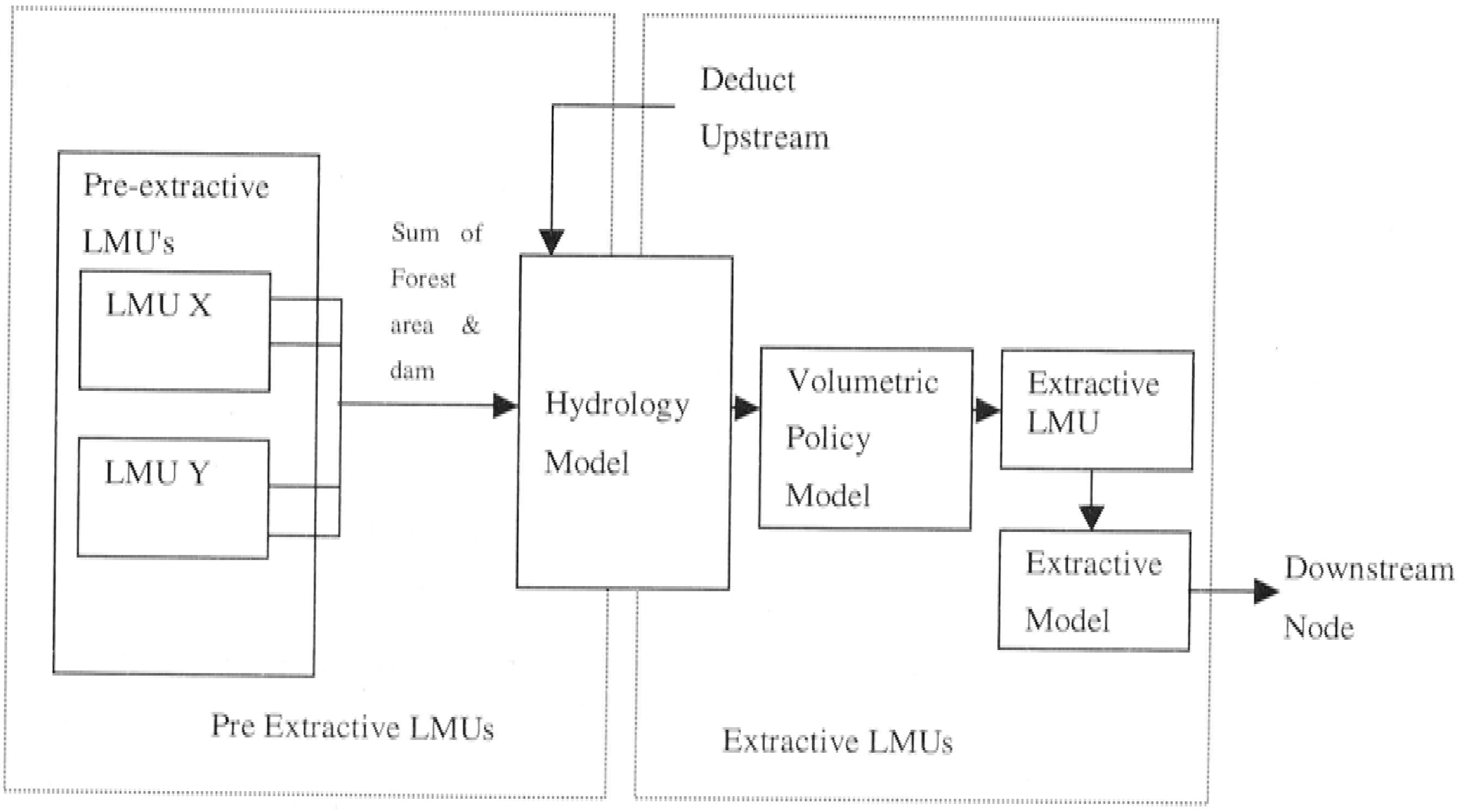

Figure 4.3: Integration at the Node Level in the modelling hierarchy

Figure 4.4 shows the interaction between nodes. Node 1 passes extractions to Node 2. Node 2 deducts these extractions and recalculates streamflow as defined in Figure 4.3. Node 2 passes extractions from both Nodes 1 and 2 to Node 4. There is no irrigated extraction at Node 3. As a result, the node is restricted to pre-extractive LMUs only as defined in Figure 4.9. Node 3 passes streamflow to Node 4. Irrigated extraction does take place at Node 4. Forest area and farm dam volumes are also passed to downstream nodes in all cases.

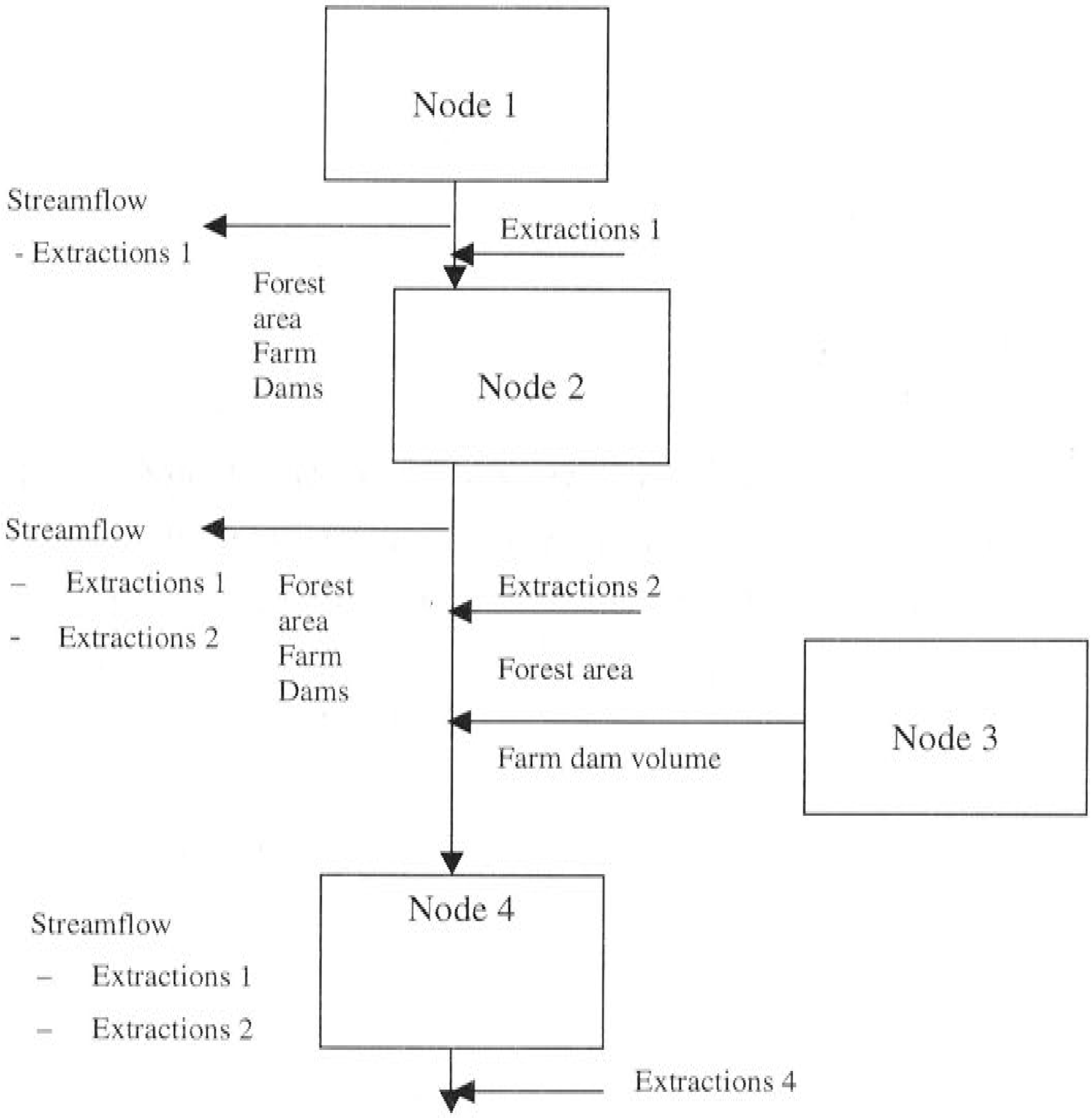

Figure 4.4: Integration of nodes to represent the catchment system

Table 4.4 illustrates the pre-extractive and extractive LMUs at each node, the policy options and hydrological system link. The model can be considered to have a set of pre-optimisation decisions. The optimisation takes place at the LMU level while streamflow changes are calculated at the node. There are three points of integration between the hydrology and the agricultural production systems.

Table 4.4: Spatial and temporal characteristics of Node activities and restrictions

Node	Pre Extractive LMUs	Extractive LMUs	Policy Options	Water System Link
Node 1	LMU 7 LMU8	LMU 8b	Salinity Management Volumetric Conversions Farm Dams	Runoff Rainfall Streamflow
Node 2	LMU 5	LMU 6b	Volumetric Conversions Farm Dams Salinity Management	Runoff Streamflow Rainfall
Node 3	LMU 3 LMU3b LMU6		Salinity Management Farm Dams	Run-off Rainfall
Node 4	LMU1 LMU 2 LMU4	LMU 4b	Salinity Management Farm Dams Volumetric Conversions	Runoff Rainfall Streamflow

4.8 Conclusions

This Chapter has presented the three scales of the modelling approach. It has introduced the concept of Activities, Land Management Units and Nodes as the foundation for model development and integration. The type of interaction between the production system and the hydrology system has also been identified at each level. The activity level is the smallest scale in the system. The agricultural production system is represented by a 'regional' farmer (or LMU) that produces a set of commodities for each activity. Details of commodity production are left until Chapter 6. Importantly, this Chapter shows how the activity level is integrated with the hydrology through changes in runoff or capture of rainfall. At this level, the activity is also integrated with one of three policy options, the Farm Dams Policy. The single most important output at this level is economic return per hectare and the allowable farm dam capture per hectare.

The Land Management Unit (LMU) is the second level in the modelling hierarchy. There are three generic types of LMUs. They are dryland, supplementary-irrigation and extractive LMUs. At this level in the hierarchy, the second policy option is implemented - that of Salinity Management through forestry plantation. At the LMU level, a production decision model determines the area planted to each activity. At this level, the most significant outputs generated are runoff to streamflow from forestry, runoff to streamflow as a result of farm dam development, area devoted to forestry as a proportion of the total LMU area, farm dam volume and area devoted to irrigated activities as a result of streamflow extraction.

The Node is the third level in the modelling hierarchy. At the node level, Volumetric Conversions Policy options are implemented after changes in streamflow associated with dryland and supplementary-irrigation activities are considered. At this level, extractive decisions are made. The volumetric policy model determines the volume of water able to be extracted from the stream for irrigated activities. Annual extractions are then determined by the daily extraction model that disaggregates the extractions to a daily basis. These are sent to the downstream node.

The agricultural production model involves aggregating decisions, temporally from daily to seasonal to annual, and spatially up to the catchment scale. The assumption is made that the regional farmer makes a decision for the entire season based upon knowledge of the hydrological system in the case of the extractive LMU. The decision is then converted to a daily time step to integrate with the hydrological model. Obviously, there are several limitations as to the applicability of the approach given the aggregation of decisions and dissaggregation of model output to facilitate integration between system components. The extent to which individual farmer decisions are able to be represented by regional or LMU decisions is not tested.

The integration of system components also involves aggregation and dissaggregation of biophysical processes. A major spatial assumption is the aggregation of point-wise rainfall to rainfall that is represented at the LMU level. The extent to which rainfall may have local variation at a modelling unit smaller then the LMU level is not tested. Soil type is also aggregated to the LMU level. This is the smallest level at which soil type may vary. The assumption holds in this case given that the data set obtained of soil type was of a low resolution consisting of just four soil types for the entire catchment (see Chapter 3 for the discussion of datasets). In contrast, other biophysical attributes such as farm dam cover, vegetation cover and erosion were more detailed. Thus, the location of LMUs that contain activities such as forestry assumes a broad soil fertility. Were this information more detailed, additional homogenously unique LMUs could be identified given additional biophysical attribute information. The assumption made in the conceptual modelling approach is that there are two broad soil types identifiable at the

LMU level. This is a large scale to be assuming uniformity of biophysical attributes such as soil type.

The Chapter has illustrated the major assumptions in developing the conceptual framework and these are discussed in more detail in Chapter 6. Given that the main aim of the thesis is to produce an integrated modelling capacity, the development of the approach has focused upon ways of integrating the biophysical, production system and policy systems. In doing so, processes from each system have been aggregated and disaggregated at various spatial and temporal scales to facilitate integration. This produces a set of limitations in representing each system component as part of a larger integrated model. The next two chapters contain a detailed description of equations used to model the hydrological, production and policy systems.

Chapter 5 Streamflow Prediction for the Integrated Model

5.1 Introduction

Regionalisation methods in hydrology are used to predict hydrological response properties such as streamflow time series by characterising catchment attributes and relating them to the property of interest. The term regionalisation is broadened here to include not just the prediction of stream discharge properties from landscape attributes, but also from land use and land cover changes. This chapter describes an approach to, and presents results of, predicting streamflow in ungauged subcatchments which may also be subject to land cover changes. A conceptual rainfall-runoff model, IHACRES, was adopted with soil and vegetation information to relate its model parameters to catchment attributes. Daily streamflow estimates were then predicted from the regionalised model for twelve ungauged subcatchments ranging in size from 23 to 388 km². The results are to be utilised in an integrated modelling tool in Chapters 7 and 8 to predict catchment and subcatchment-scale impacts as a result of the imposition of water policy options, climate, commodity price and other external changes. It should be noted that the regionalisation approach should be a general aid in analysing water allocation rules in unregulated river systems, particularly where relevant knowledge of biophysical data and human-induced extractions is sparse as is the case in many unregulated catchment systems.

Section 5.2 provides a concise review of regionalisation while Section 5.3 is an overview of the scope of the hydrological modelling component given the requirements of the integrated model. Further details beyond those in Chapter 3 of the catchment to be modelled is introduced in Section 5.4 and the structure of the rainfall-runoff model used to conduct the hydrological modelling is given in Section 5.5. This Section includes changes made to the model structure required to integrate the hydrology system with the agricultural production system as identified by the system conceptualisation in Chapter 4. Sections 5.6 and 5.7 outline application of the model to the gauged catchments. The remainder of the Chapter is devoted to developing the regionalised model approach on subcatchments within the Yass catchment (Sections 5.8 to 5.10).

Sections 5.11 to 5.13 present the application of the regionalisation method on gauged catchments in the Macquarie catchment.

5.2 Recent Regionalisation Approaches

Regionalisation can be defined as using hydrologicaly homogenous areas and driving variables to predict streamflow on data sparse areas (such as ungauged subcatchments) of a similar homogeneity (Bates, 1994). A literature review revealed a number of techniques dependent upon the component of the hydrological cycle being investigated. A classification into four main groups was elicited.

Regionalisation techniques have been applied widely to hydrological estimation on ungauged subcatchments. Mosley (1980) goes so far as to describe regionalisation as a standard technique, yet one that has no standard methodology attached to it. He argues, in order for regionalisation to be applied successfully, a degree of confidence in driving hydrological variables and system scale boundaries should be known in addition to the objectives of the study having been identified. The objectives relate to what part of the hydrological response is to be modelled ie. peak flows, base flows, recession or runoff parameters, or other hydrological system components. The main objective of the hydrological component of this thesis is to predict streamflow for ungauged subcatchments. Given the three policy options identified for analysis, the approach must be capable of characterising in-stream extractions and farm dam capture from runoff and is also sensitive to land cover changes. The regionalisation approach used must therefore give an estimation of peak flow and runoff components of the system and their volumes

Studies by Avissar (1991), Becker and Numec (1987), Becker (1995), Becker and Braun (1999); Braun *et al.*, (1997) and Ewen *et al.*, (1998) have suggested that recognising changes in heterogeneity with scale is the key to identifying hydrological similarity and hence application to ungauged subcatchments. Pilgrim (1983) recognised the importance of scale. He examined the problem in transferring hydrological relationships between small and large subcatchments for regionalisation purposes. His studies show the importance of conducting regionalisation at the appropriate scale of homogenous classification. Studies by Baron *et al.*, (1980), McDermott and Pilgrim (1982), Pilgrim *et al.*, (1979), Yu (1989) and Burn (1988) suggest that catchment area or basin size should be considered in the transferring of hydrological information for regionalisation purposes.

Other approaches move away from the characterisation of catchment or basin approaches, arguing that parameter estimation at ungauged sites should focus upon variables contained in the hydrological cycle. This is particularly attractive where conceptual rainfall-runoff models are utilised, owing to their ability to handle climate-related parameter variability (Servat and Dezetter, 1993). Servatt and Dezetter (1993) used land use fraction and potential evapotranspiration to produce model parameters. The study concluded that inclusion of vegetation and land use characteristics significantly improves estimation of model parameters in ungauged subcatchments.

Nathan and McMahon (1990) investigated the prediction of ungauged flow by basin characteristics alone. They conclude that climate characteristics should be considered as potential driving variables in catchment response. Peel *et al.*, (2000) examined relationships between catchment attributes and model parameters from the conceptual model, SIMHYD (Chiew *et al.*, 1996). Climate was identified as the driving factor in distinguishing parameter values, with three of seven model parameters yielding statistically significant relationships to climate and only one to a catchment attribute, soil type (Chiew and McMahon, 1994).

This review identified several important factors in selecting an appropriate regionalisation method. These can be summarised as:

- Parameter sensitivity varies with spatial and temporal scale, and hence consistent application between ungauged and gauged areas is required with respect to scale.
- Driving variables for the purpose of transfer to ungauged subcatchments should not be limited to basin characteristics, but extend to climate variables. This is particularly advantageous when using a conceptual model to predict ungauged parameter values.
- The use of conceptual hydrological models to estimate parameters relating to baseflow, peak flow and runoff is attractive owing to their structural ability to handle climate variability, especially where a multiple store model is selected. In this case, model parameters may have some physical meaning in terms of catchment attributes.

The regionalisation approach used in this thesis adopts a conceptual rainfall-runoff model to relate catchment attributes to hydrological model parameters. In view of the literature review, an approach was developed to relate catchment attributes such as area, land cover characteristics (in this case, vegetation cover and soil type) as well as climate attributes (in this case effective rainfall and evapotranspiration) to hydrological model parameters in the IHACRES rainfall-runoff model. Post and Jakeman (1999) and Post and Jakeman (1996) have enjoyed some success with the IHACRES model in regionalising its parameters for small, mountain ash catchments in Australia. Kokkonen *et al.*, (in press) have had similar success with this model in small, forested catchments of the Coweeta hydrological laboratory. Section 5.4 lists the considerations in selecting a model and Section 5.9 details the regionalisation approach developed for ungauged subcatchments in Yass given the modelling objectives of the thesis.

5.3 Predicting Streamflow for Use in an Integrated Modelling Approach

It is of little benefit to represent an agricultural production system component in great detail if the hydrological modelling does not utilise the detail, and vice versa. Thus, the prediction of streamflow upon ungauged subcatchments did not warrant a complex approach. Indeed the utility of the integrated model is to be able to assess the socio-economic and hydrological outcomes of policy and other issues in a relative sense (see also Section 2.10 for a discussion of model complexity considered useful for informing policy makers). Therefore, the aim is to be able to discriminate confidently between the outcome sets of any two scenarios driving the integrated model. Such an aim is consistent with the inherent difficulties in modelling any catchment system, especially, as is often the case, where the data available to parameterise it are scant and/or have not been collected with the aim of performing integrated modelling.

Streamflow predicted for 12 ungauged subcatchments (Figure 5.1) was needed as input data into the integrated model. As the predictive capacity of the hydrological component need be of no greater detail than necessary for the integrated model, detailed routing of discharge along the stream, was unnecessary given the small scale of Yass catchment (1700 km^2) and the limited gauged data available to calibrate a routing model. Rather, streamflow within the networked system was simply advected downstream within the same time step, daily in this case. Other considerations for the rainfall-runoff model development are presented in Section 5.4.

The model parameters identified for each subcatchment in Yass could not be subject to rigorous validation and testing in the traditional sense due to a lack of gauged sites. Subsequently, the approach is tested on the Macquarie Catchment (see Section 5.12). A detailed account of the performance of the ungauged model on other catchments, as part of the validation of the approach in the Upper Murrumbidgee and Macquarie systems, is found in Letcher (2002) and Newham (2002).

In addition, model parameters deemed important to evaluate the performance of the ungauged approach were subject to sensitivity testing in Chapter 8. Using this approach, the impact of varying model parameters upon the integrated model results was investigated to identify if detailed parameter estimation is required in future work for developing an integrated model.

5.4 Study Catchment and Model Purpose

As presented in Chapter 3, the Yass catchment is an unregulated river system located in the Upper Murrumbidgee. The catchment suffers from water quantity problems as a result of the over-extraction of its water resources, and water quality problems as indicated by the presence of highly salinised land and water systems. The hydrological network of the integrated model and tributaries requiring estimation of streamflow for the integrated model are depicted in Figure 5.1. Nodes requiring use of the rainfall-runoff model are designated differently (as circles) to those requiring in-stream advection (as triangles). Filled in circles denote an ungauged site. The open circles denote gauged sites, only one of which is used as being gauged. The triangles denote that a simple advection model was used between nodes on the Yass trunk stream. The approach taken for predicting streamflow within the ungauged system was to relate the parameters of a rainfall-runoff model to landscape attributes. A review of rainfall-runoff models is found in Appendix A. The review revealed several critical considerations in selecting an appropriate hydrological model. These were as follows:

- Allow for the application over a small range of spatial scales (in this case, the catchment scale of the Yass catchment tributaries)
- Minimise the number of hydrological model parameters to facilitate ease of transfer of relationships between catchments

- Allow model parameters to be related to catchment attributes for ungauged sites i.e a parametric regionalisation approach.
- Be of sufficient complexity to ensure the uniqueness of Australian catchments is considered ie. the effect of antecedent soil conditions and partitioning between recharge and runoff
- Permit annual, monthly and daily estimation for the purpose of obtaining crude streamflow estimates for use in answering a series of water policy questions over short and long-run time spans (in this case, up to a 20-year time span).

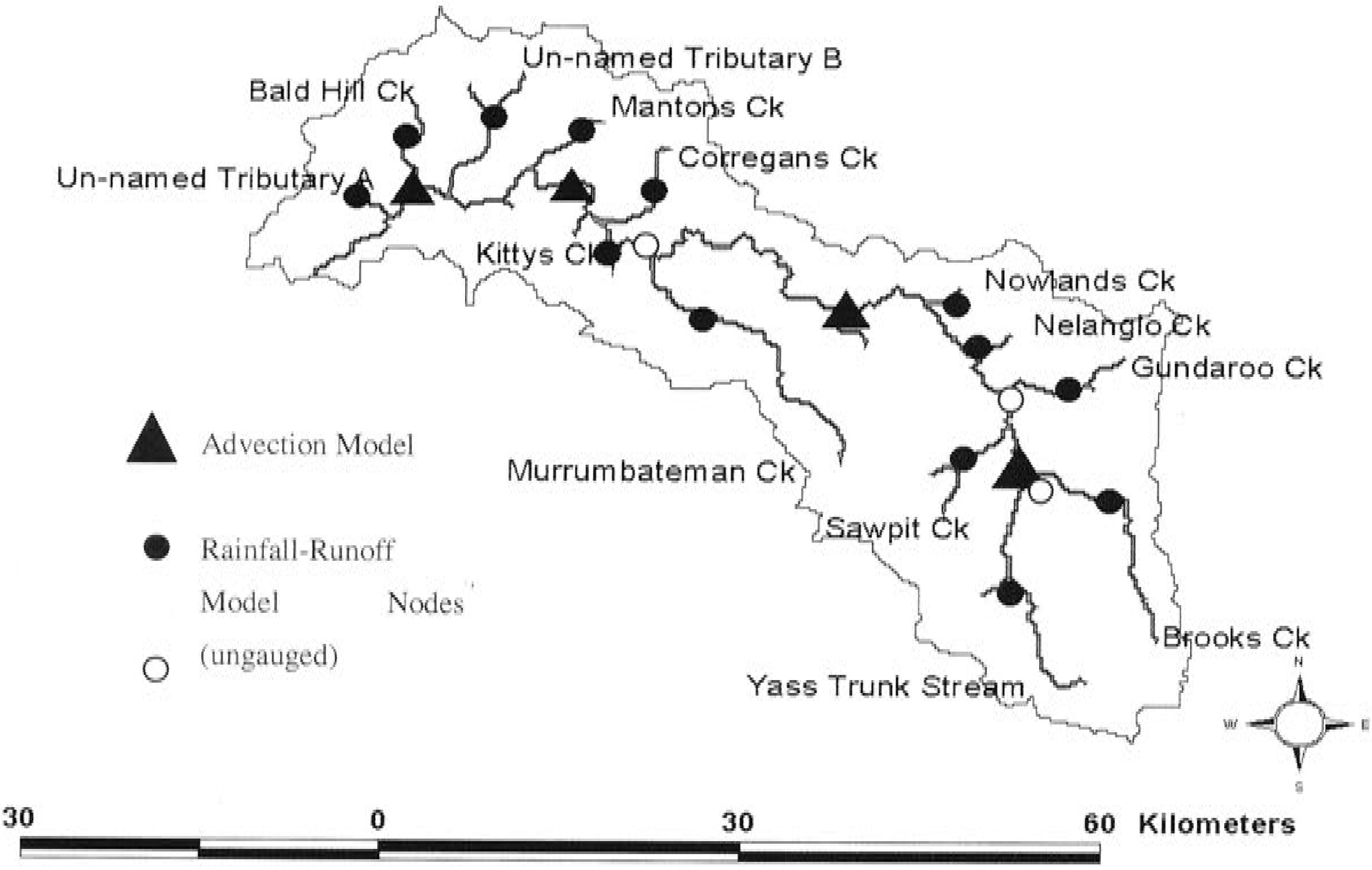

Figure 5.1: Yass Catchment tributaries and nodes in the hydrological network requiring streamflow prediction (Yass trunk stream included as advection node and therefore not modelled as an ungauged site, hence 12 ungauged subcatchments are modelled only)

According to the review of hydrological models, it was deemed that a conceptually based model would best fit the above criteria for the modelling application. The IHACRES model is one such model that has been successfully applied at various scales. Its widely successful application is partly due to the relatively small number of parameters required for calibration. Despite this parametric efficiency, the structure of the model can be sufficiently complex in representing essential catchment processes such as subsurface flow and evapotranspiration as well as baseflow separation. The IHACRES model has provided more than reasonable predictions of stream discharge across a wide range of climatic environments, although Jakeman and Hornberger (1993) suggest that it should not be utilised where annual precipitation is less than 300 mm per annum. It has been utilised in catchment-scale land use change analysis and as a tool in answering hydrologicaly-focused water management questions. In addition, the model has also been utilised in regionalisation studies relating its parameter values to landscape attributes (e.g. Post and Jakeman, 1996; Post and Jakeman, 1999; Kokkonen *et al.*, in press). For a description of its areas of application see for example Jakeman *et al.,* (1990), Jakeman *et al.,* (1993), Jakeman and Hornberger (1993), Ye *et al.,* (1997) and Schreider *et al.,* (1996).

5.5 IHACRES Model Structure

The IHACRES conceptual rainfall-runoff model contains a linear transfer function module and a non-linear loss module (Jakeman *et al.*, 1990). The non-linear loss module contains several algorithms for converting rainfall, r_k at time step k (areal catchment rainfall derived from gauged rainfall sites), to effective rainfall, u_k (rainfall that is available for transport as runoff or subsurface throughflow). The linear module converts the effective rainfall to streamflow, x_k. Figure 5.2 illustrates the fundamental structure of the model.

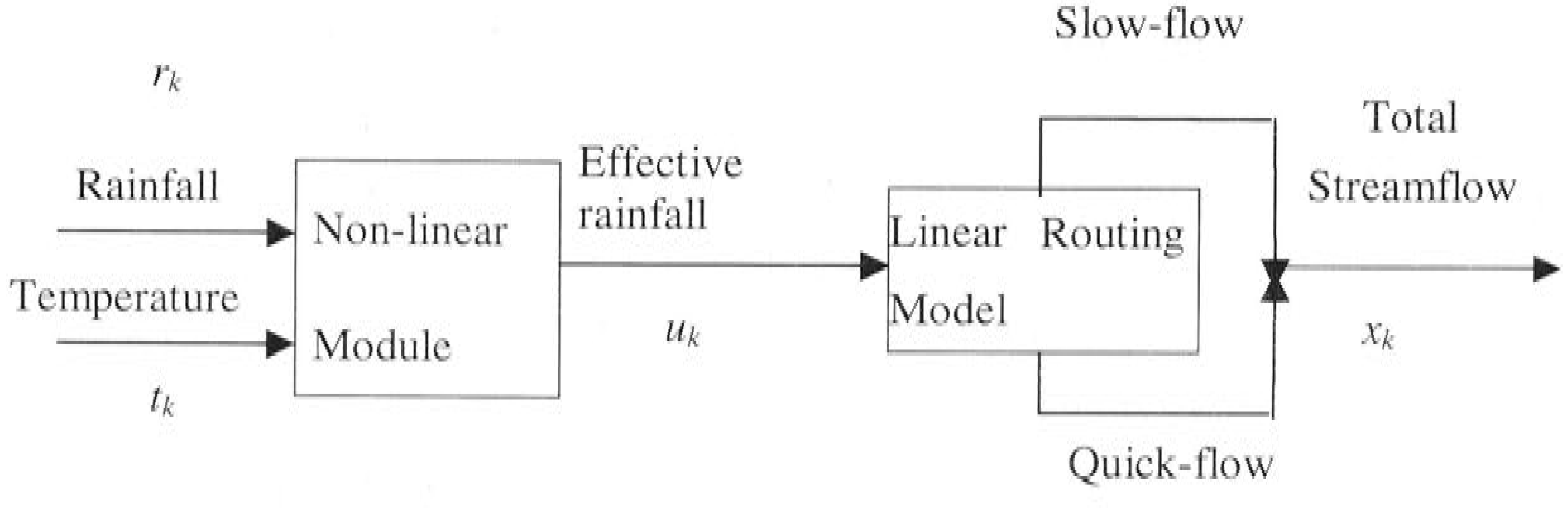

Figure 5.2: Structure of the IHACRES rainfall-runoff model

The non-linear component contains a store representing the catchment's wetness condition. Loss to evapotranspiration is a function of climatic inputs, in the simplest case just temperature, as well as the catchment antecedent conditions. As Figure 5.2 illustrates, routing of the remaining (effective) rainfall takes place through a slow and quickflow component that relate to baseflow and more direct runoff respectively.

5.5.1 The Standard Linear Loss Module

In the linear module, the unit hydrograph is calculated by the routing of effective rainfall through a configuration of storages, usually two storages in parallel whose inputs are designated as quickflow and slowflow.

Jakeman *et al.* (1990) utilised an SRIV (simple refined instrumental variable) technique to estimate the hydrograph parameters. Modelled streamflow is a combination of quick (denoted by the q subscript) and slow flow (denoted by the s subscript) component given by (Jakeman and Hornberger, 1993):

$$x_k = -a_1 x_{k-1} - a_2 x_{k-2} + b_o u_k + b_1 u_{k-1} \tag{5.1}$$

The decomposition of this into quick and slowflow is represented as:

$$q_k = -\alpha_q q_{k-1} + \beta_q u_k \tag{5.2}$$

$$s_k = \alpha_s s_{k-1} + \beta_s u_k \tag{5.3}$$

$$x_k = q_k + s_k \tag{5.4}$$

Equations 5.1 to 5.4 indicate how α_q, β_q and α_s, β_s can be calculated from a_1, a_2, b_0 and b_1. Variations in the model structure have resulted in additional parameters such as the seven parameter model used by Post and Jakeman (1996). Croke and Jakeman (2001) used a nine parameter model as a result of including a farm dam interception of storage module in addition to the two store component. The model has been utilised in consideration of the impact of farms dams on streamflow delivery.

5.5.2 Changes to the Model Structure

The most used version of the model is described in detail in Jakeman and Hornberger (1993). Examples of studies which have used this version of IHACRES can be found in

Schreider *et al.*, (1996), Post and Jakeman (1996), Ye *et al.*, (1997), Hansen *et al.*, (1996), Evans and Jakeman (1998), Jakeman *et al.*, (1992) and Schreider *et al.*, (2002).

A modified version of IHACRES (Croke and Jakeman, 2001) was invoked to construct the rainfall-runoff models required for the hydrological network in this thesis. The model uses a catchment moisture deficit (CMD) accounting scheme that allows calculation of the evapotranspiration on the same time step at which rainfall and energy variables are available. It involves two modifications made to the parameterisation of the non-linear loss module as first described by Evans and Jakeman (1998). Firstly, the equation relating evapotranspiration (ET) to the catchment moisture deficit (CMD) has been altered to give a constant ET (the potential ET, denoted as PET) for CMD less than a threshold value. When CMD is greater than the threshold, the ET is assumed to decrease exponentially with rising CMD according to the following equation:

$$ET=PET\ exp(2(1-CMD/f)) \tag{5.5}$$

where f is the threshold of plant stress. PET can be estimated from the daily maximum air temperature using:

$$PET = eT \tag{5.6}$$

for some constant, e (Chapman, 2001). The second change involves the drainage equation. Instead of the two-parameter relationship between rainfall excess (u), rainfall (r) and CMD adopted by Evans and Jakeman (1998), a simplified one-parameter relationship has been developed. This relationship is based on the assumption that the amount of effective rainfall produced by a small amount of rainfall depends only on the CMD value (CMD). The form adopted is:

$$\begin{aligned} \frac{du}{dr} &= 1-\left(\frac{CMD}{d}\right) && \text{for CMD} < \text{d} \\ \frac{du}{dr} &= 0 && \text{for CMD} \geq \text{d} \end{aligned} \tag{5.7}$$

The d parameter sets the threshold for producing flow. If CMD>d there is no effective rainfall. However, when this is convolved with an exponential unit hydrograph there is always continuous minimal streamflow after the first rainfall event. Using the fact that $du = dp + dCMD$, then integration gives:

$$u_k = \begin{cases} 0 & CMD_{k-1} - r_k \geq d \\ r_k - CMD_{k-1} + d\exp\left(1 + \dfrac{CMD_{k-1} - r_k}{d}\right) & \begin{cases} CMD_{k-1} > d \\ CMD_{k-1} - r_k < d \end{cases} \\ r_k - CMD_{k-1}\left[1 - \exp(r_k / d)\right] & CMD_{k-1} < d \end{cases} \tag{5.8}$$

This change to the non-linear loss module results in a decrease in the number of parameters needed from four to three (Croke, 2001 and Croke and Jakeman, 2001). These parameters are denoted by d, e and f in Equations 5.5 to 5.7. The linear module structure was also modified. A power law function was used to define recession characteristics and timing of events pertaining to the unit hydrograph (Croke, 2001). The two-parameter function used to fit the observed hydrograph was:

$$y=1/(1+(x/a)^{b}) \tag{5.9}$$

Parameter a is the time taken for the flow to fall to half the peak flow, and therefore gives a measure of the width of the recession curve. Parameter b sets the decay for the tail or longer response of the unit hydrograph. The variable x is the time after peak and y is the fraction of peak height. In order to derive the observed unit hydrograph, events were selected from the stream discharge history. A description of the procedure is given in the next section but more details can be found in Croke (2001).

5.6 Construction of the Unit Hydrograph on Gauged Catchments

Three streamflow gauges are located in Yass catchment (see Figure 3.10 for gauge locations in the catchment). Gauge 90 is located in the Upper catchment on the junction of Brooks Ck and Yass main trunk stream and drains an area of 388 km². Gauge 60 drains an area of 26 km² from Sawpit Ck. Gauge 26 is located between Corregans Ck and Kittys Ck junction with Yass River. It is affected by extractions from Yass weir for the town water supply. These three gauges were used to identify model parameters for application to the ungauged subcatchments (see Section 5.7).

In order to fit the power law function to hydrographs, several steps were taken to identify hydrograph peaks from the flow record. Firstly, a minimum threshold volume for peak selection was defined for the hydrograph peaks. The derived unit hydrograph is likely to be affected by subsequent flow peaks, resulting in deviations from the true unit hydrograph, particularly at longer times from the peak. This could potentially result in an underestimation of the decay rate. This was overcome by selecting peaks with a 10-day separation to minimise the impact of lower flow contamination on larger peaks. Figure 5.3 illustrates the peaks selected for Gauge 90, given a threshold of 10 cumecs and a separation of 10 days. Each ordinate value of the final selected peaks were then summed to give the mean event profile, which was then scaled to a peak value of one. The power law function was then fitted to the mean event profile.

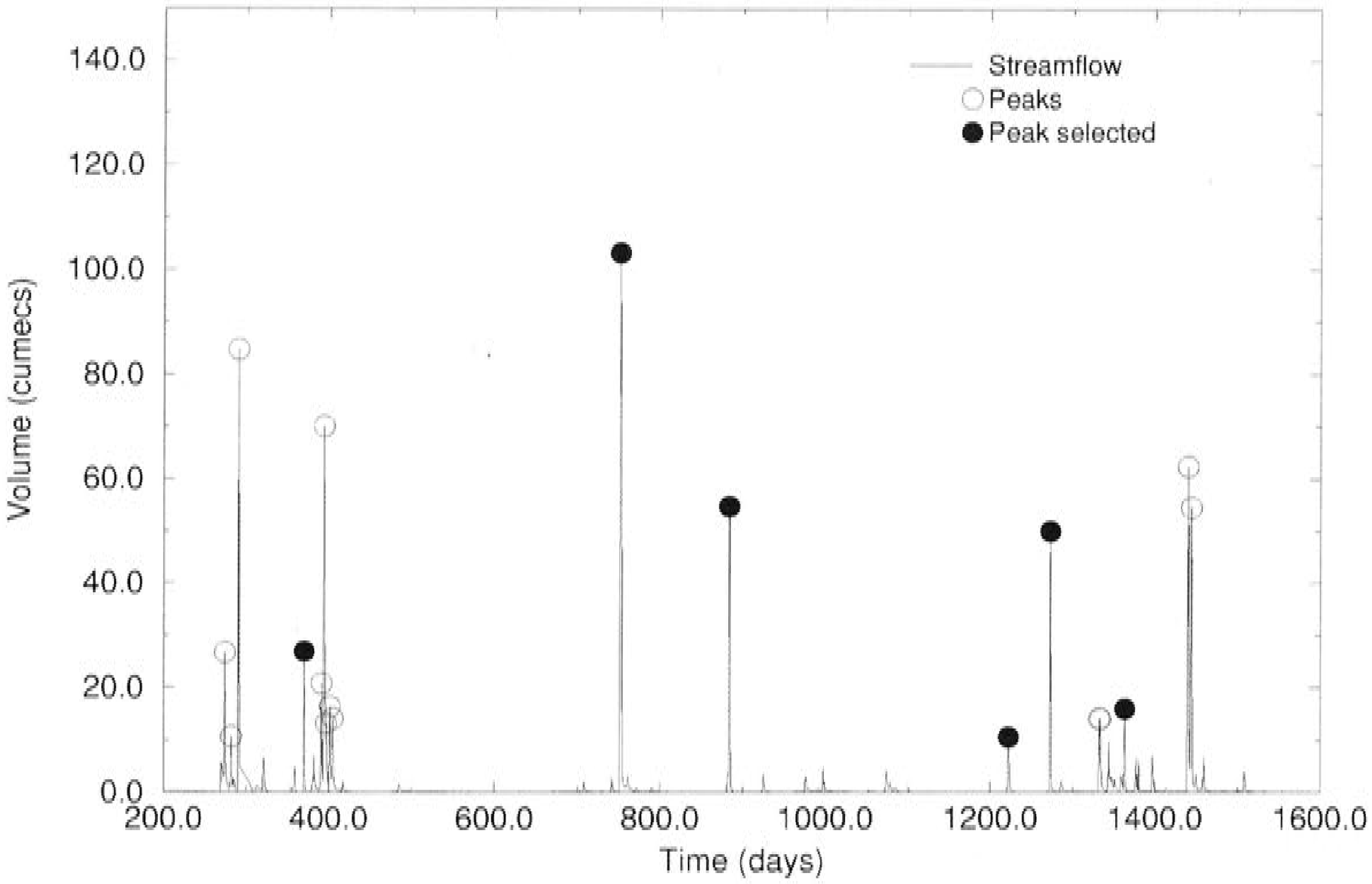

Figure 5.3: Selection of unit hydrograph peaks obtained from a minimum threshold of 10 cumecs and a peak separation of 10 days for Gauge 90 in Yass catchment (Period of record from 14/4/1975-12/2/1975)

The parameter values for the power law function were then derived from manually fitting the mean unit hydrograph response curve. This was achieved by determining the asymptote of the unit hydrograph, with the slope corresponding to the *b* parameter, and the intercept of the asymptote and the line $y=1$ defining the *a* parameter. For computational efficiency, the power law was converted into a series of exponential terms. Results computed for two different sets of selected peaks are given in Table 5.1. Note that the *b* parameter defined in the exponential function is approximately 2.0 for all gauges.

Table 5.1: Estimation of unit hydrograph using two sets of peaks and the fitting technique for gauged catchments in Yass

Number of peaks identified	Parameter a	Parameter b
Gauge 90 using daily data		
73	0.45	2.00
29	0.31	2.00
Gauge 60 using daily data		
116	0.24	1.98
120	0.54	1.98
Gauge 26 using hourly data		
14	0.14	2.00
11	0.41	2.00

Table 5.1 illustrates that for the three gauges in Yass, estimation of model parameters was most consistent for Gauge 90 and less so for Gauge 60. The *a* parameter at Gauge 26 was the most variable. Due to the influence of extractions at Yass Weir, Gauge 26 was excluded from the analysis in obtaining appropriate model parameters for use in predicting streamflow for the ungauged subcatchments. Gauge 60 was also excluded due to the short period of recorded streamflow. The derived unit hydrograph and fitted power law for Gauge 90 are shown in Figure 5.4 (where $a = 0.45$ and $b = 2.00$) using observed hydrographs from the flow record.

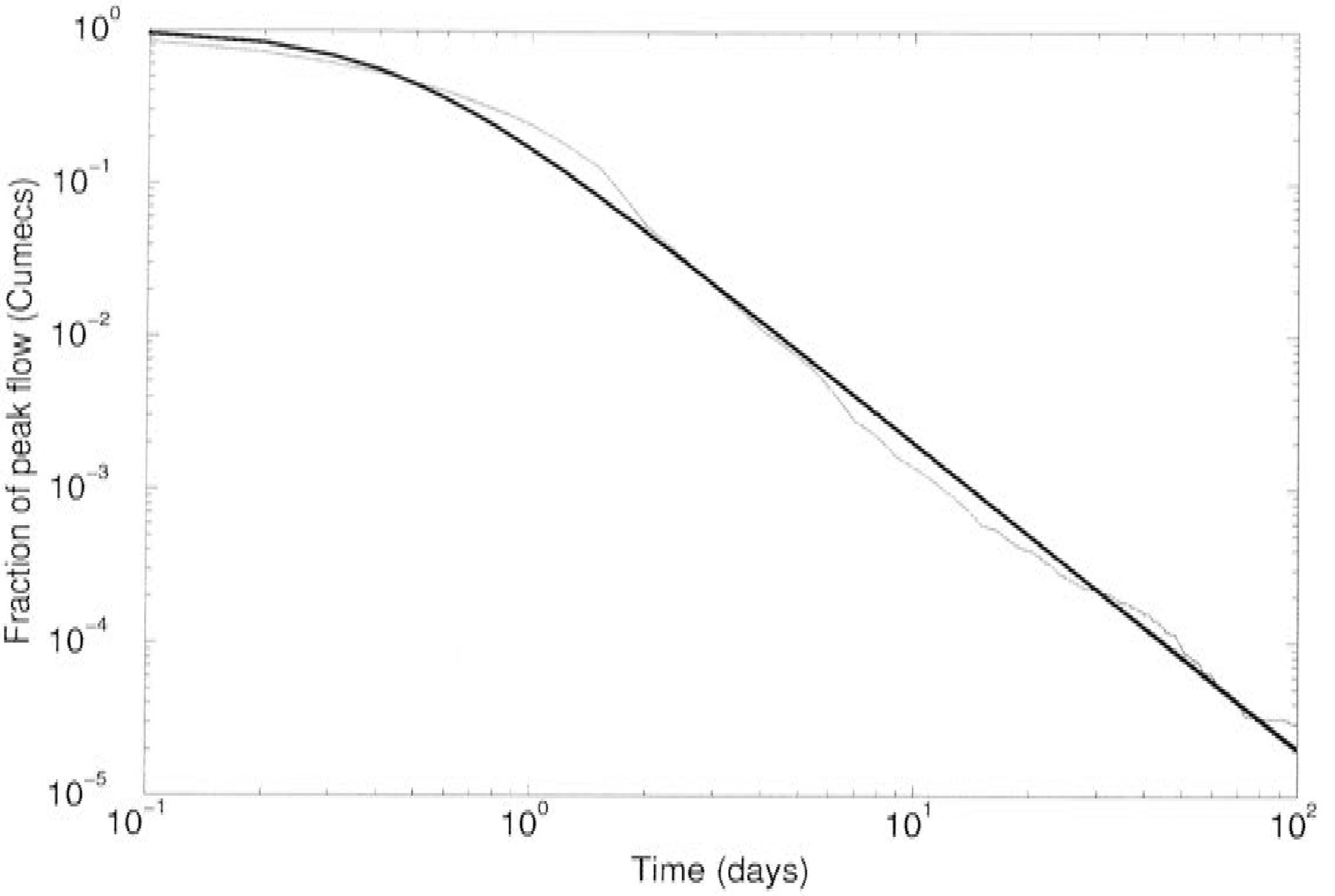

Figure 5.4: A two-parameter power law fit (bold line) to streamflow data for Gauge 90 in Yass catchment

5.7 IHACRES Model Development on Gauged Catchments

The modified version of the IHACRES rainfall-runoff model was used to predict flow at Gauges 90 and 60. In order to assess the related model performance, several statistics were computed. These include three quantities that capture the relative fit of the model to the observed flow with n daily time series values. These are R^2, O_1 and O_2 and are given by:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Q_o - Q_m)^2}{\sum_{i=1}^{n} (Q_o - \overline{Q}_o)^2} \tag{5.10}$$

$$O_1 = 1 - \frac{\sum_{i=1}^{n} \left(\sqrt{Q_o} - \sqrt{Q_m}\right)^2}{\sum_{i=1}^{n} \left(\sqrt{Q_o} - \sqrt{\overline{Q}_o}\right)^2} \tag{5.11}$$

$$O_2 = 1 - \frac{\sum_{i=1}^{n}\left(\frac{1}{1+Q_o} - \frac{1}{1+Q_m}\right)^2}{\sum_{i=1}^{n}\left(\frac{1}{1+Q_o} - \frac{1}{1+\overline{Q}_o}\right)^2} \tag{5.12}$$

where Q_o is the observed flow, and Q_m is the modelled flow. The performance function, R^2, also known as model efficiency, indicates goodness of model fit to peak flows while O_2 indicates the fit for low flows. The O_1 is a measure of overall fit between the observed flow and modelled flow, the square root function decreases the significance of high flows. The R^2 statistic is given for a 10-day calibration and 1-day calibration. The 10-day calibration statistic was considered a useful indicator of performance as the integrated model requires simulated streamflow that predicts the pattern of streamflow well over the irrigation season while not necessarily placing large emphasis on predicting the timing of streamflow at the daily time step. The results in Table 5.2 show that for the upper catchment the efficiency of the model fit, being 0.81 for a 10-day average is reasonable. The result for Sawpit Ck is not quite as good due to the small size of the catchment and resulting problems of rainfall estimation and the affect of modelling at the daily time step.

Table 5.2: Calibration results for Yass catchment gauge using the modified IHACRES model

Gauge and period of model fit	**Model efficiency (R^2) at 10 day time step**	**Model efficiency (R^2) at a 1 day time step**	**O_1 at a 1-day time step**	**O_2 at a 1-day time step**
90 Upper catchment (28/5/1965 to 19/6/1985)	0.81	0.65	0.56	0.23
60 Sawpit Ck (3/2/1989 to 7/4/1998)	0.65	0.57	0.66	0.57

Figure 5.5 shows the cross-correlation between rainfall and streamflow at Gauge 90, where the larger peak is the autocorrelation of rainfall and the smaller peak is the cross correlation of rainfall and streamflow. The peak of the cross-correlation function is greater than 0.4. This indicates a good correlation between rainfall and streamflow. However, the peak is offset by 1-day, indicating a delay of approximately 24 hours.

This is primarily due to the sampling of streamflow and rainfall data at the daily time step, where streamflow is re-sampled from midnight, to midnight of the next day, and daily rainfall is available for the period from 9am of the previous day to 9am of the current day. For this reason, a 1-day delay was added to the model. In addition, the cross correlation function shows a persistence of streamflow following the peak with a significant correlation 3 days after the peak. Figure 5.6 show the subsequent calibration result for Gauge 90 and Figure 5.7 shows the model error.

Several calibrations were carried out on the rainfall-runoff data for Gauge 26. It represents the node of a lower catchment, downstream of Yass weir. The model was able to fit peak flows but the base flow component did not fit as well. This could be expected given the gauge is below a weir that extracts the Yass township water supply. Successive attempts to restore natural flow conditions yielded marginal improvements in the model fit to observed data. However, information pertaining to the distribution of extractions was not available on a daily basis. The calibration fit and model error for Gauge 26 are shown in Figures 5.8 and 5.9 respectively. Figure 5.10 and 5.11 illustrate the model fit for Gauge 60. Model efficiency, R^2 for this catchment was 0.65 at the 10-day time step while the other objective function values were of a similar order to those of the upper catchment at Gauge 90.

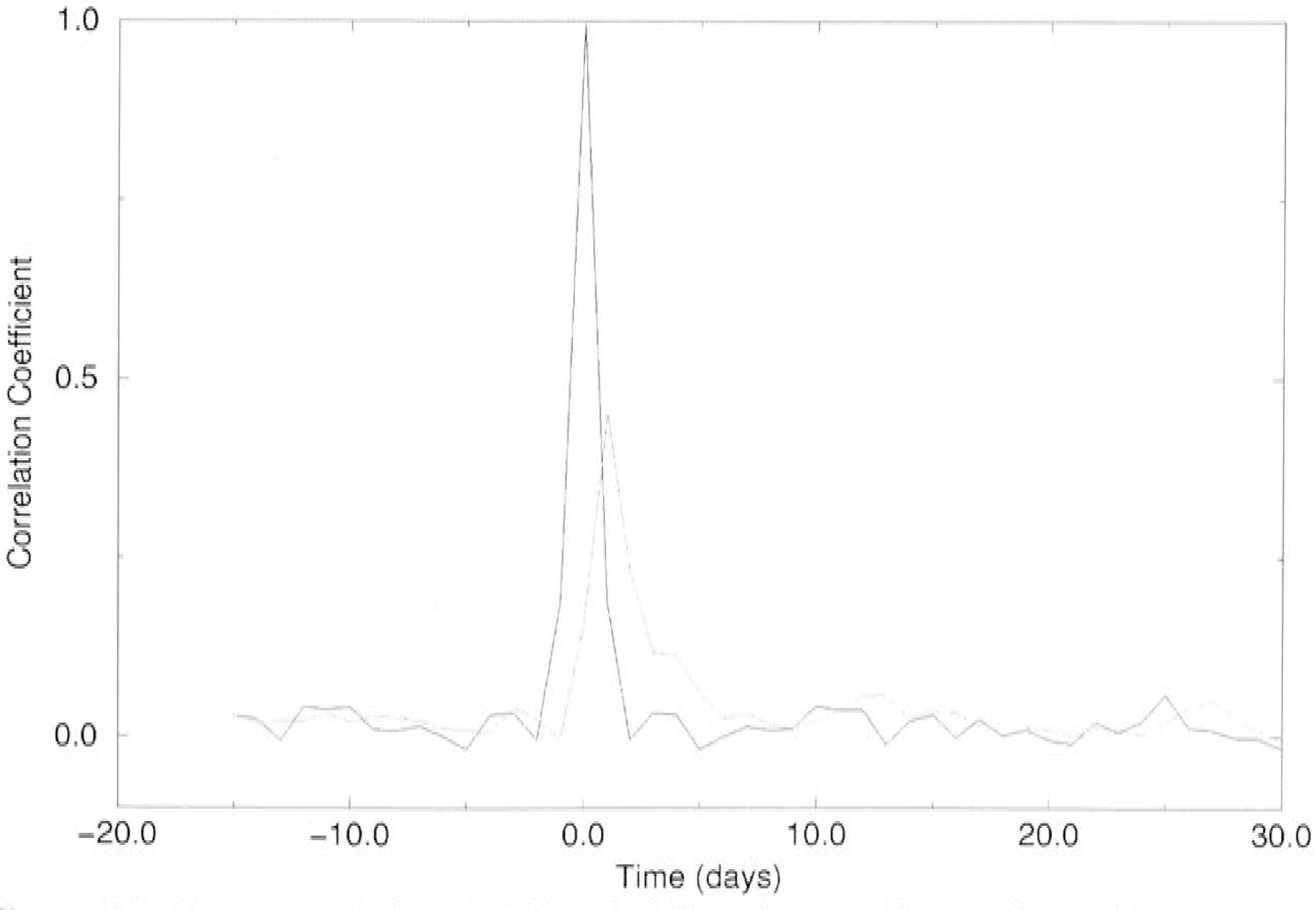

Figure 5.5: Cross correlation of daily rainfall and streamflow at Gauge 90

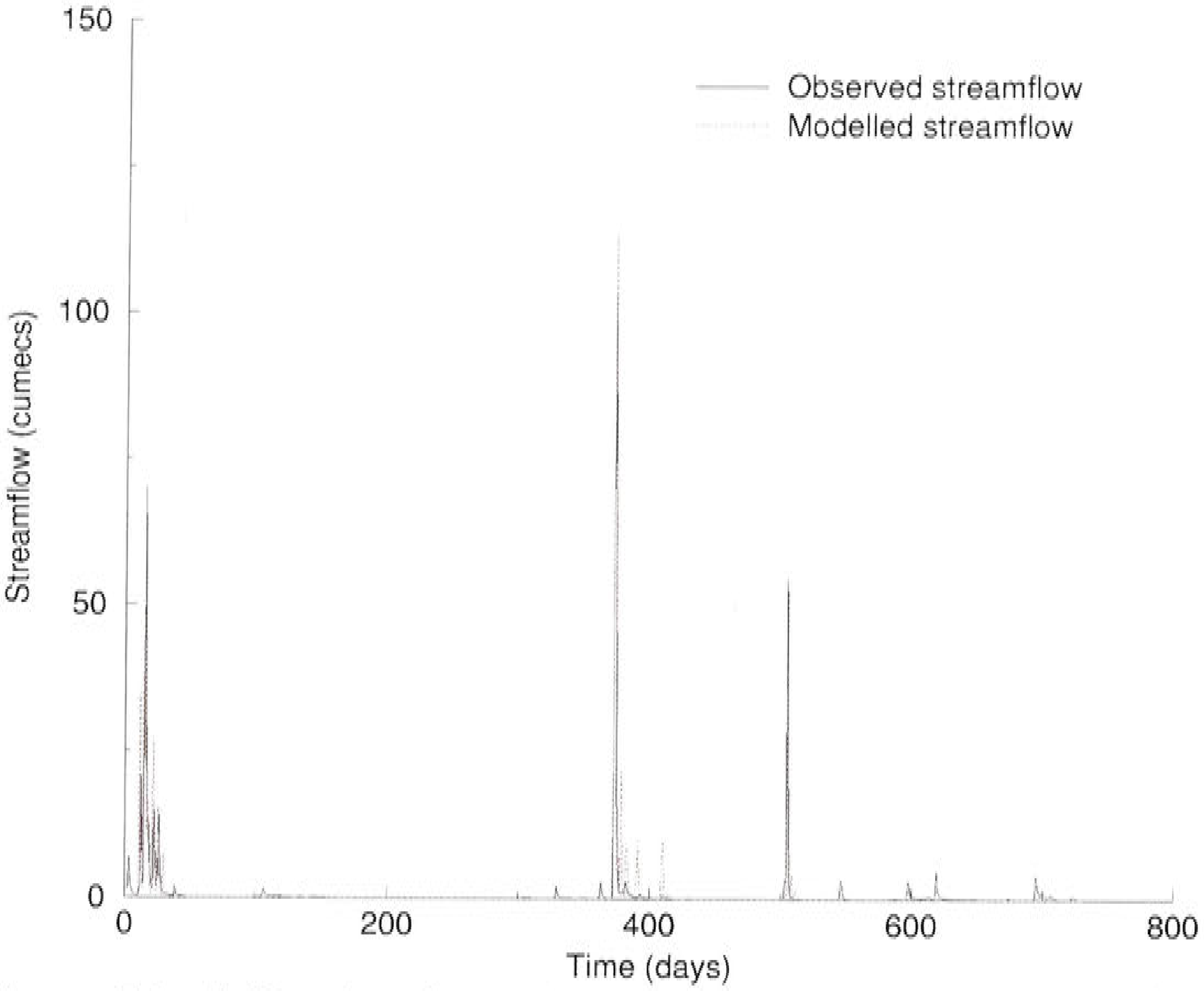

Figure 5.6: Calibration fit to daily streamflow for Gauge 90 in upper Yass catchment. (Period of record: 11/10/1975-10/10/1975)

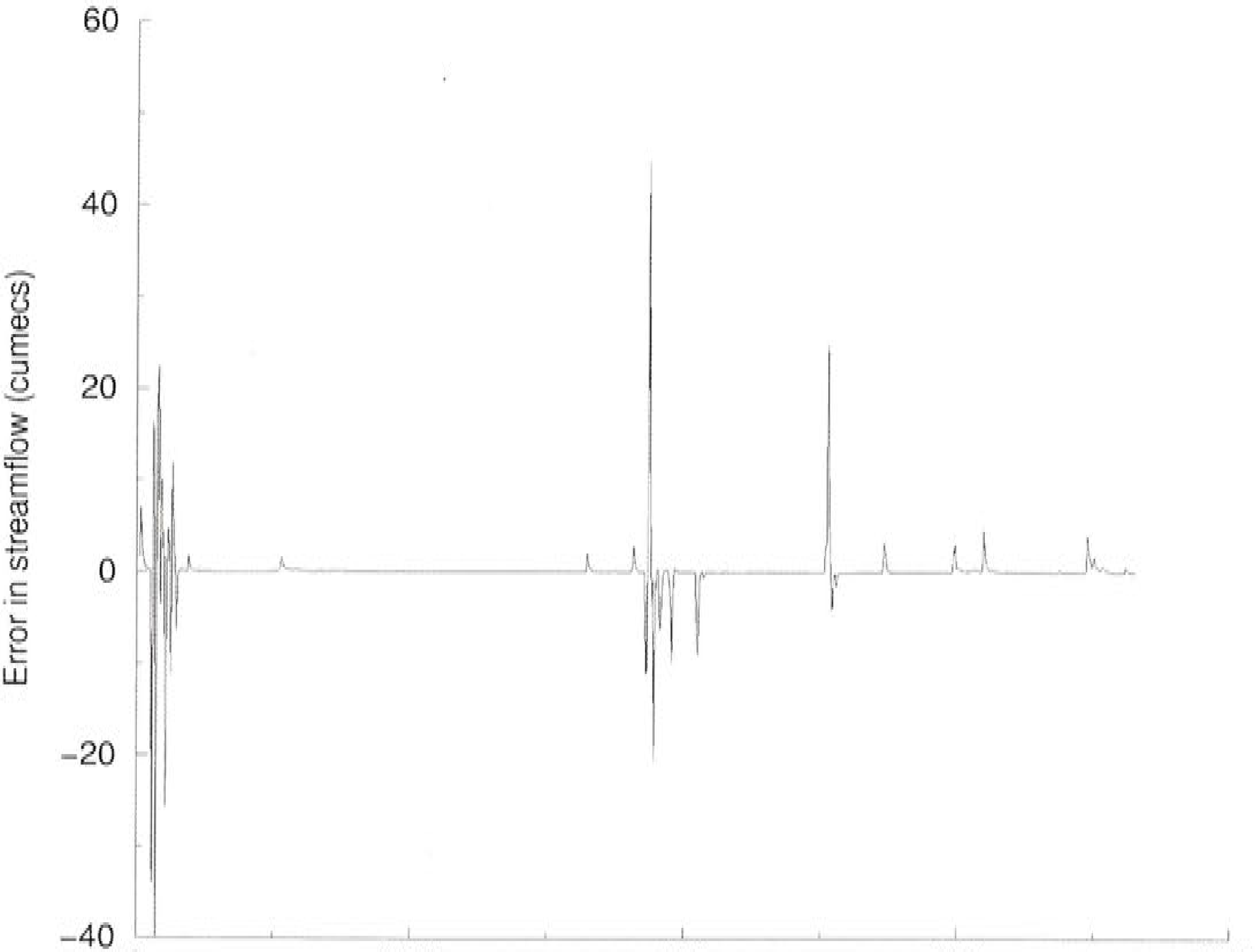

Figure 5.7: Calibration error for Gauge 90 daily streamflow model. (Period of record: 11/10/1975-10/10/1975)

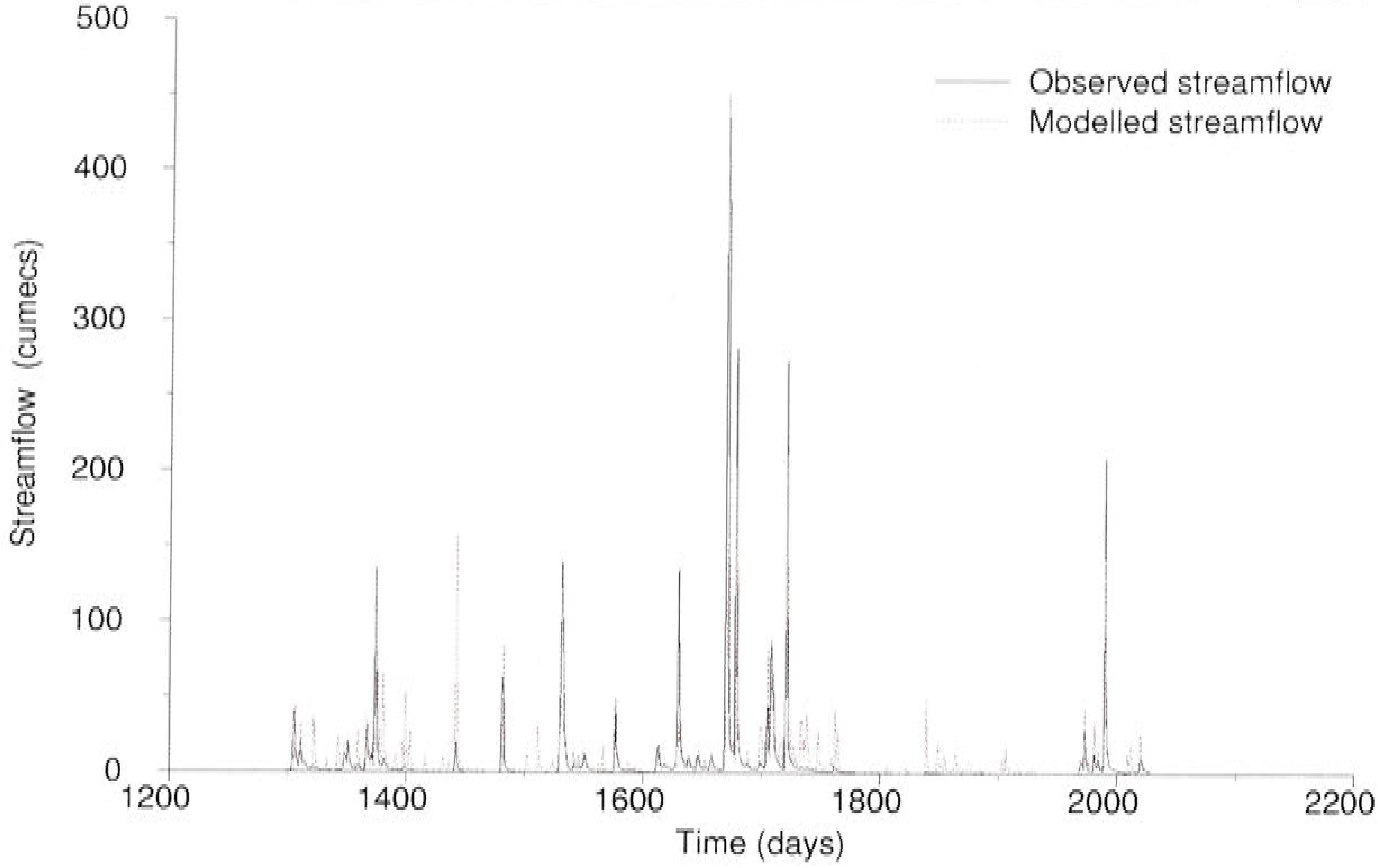

Figure 5.8: Poor calibration fit to daily streamflow Gauge 26 owing to a town water supply weir upstream of the gauge. (Period of record: 23/8/1973-22/8/1975)

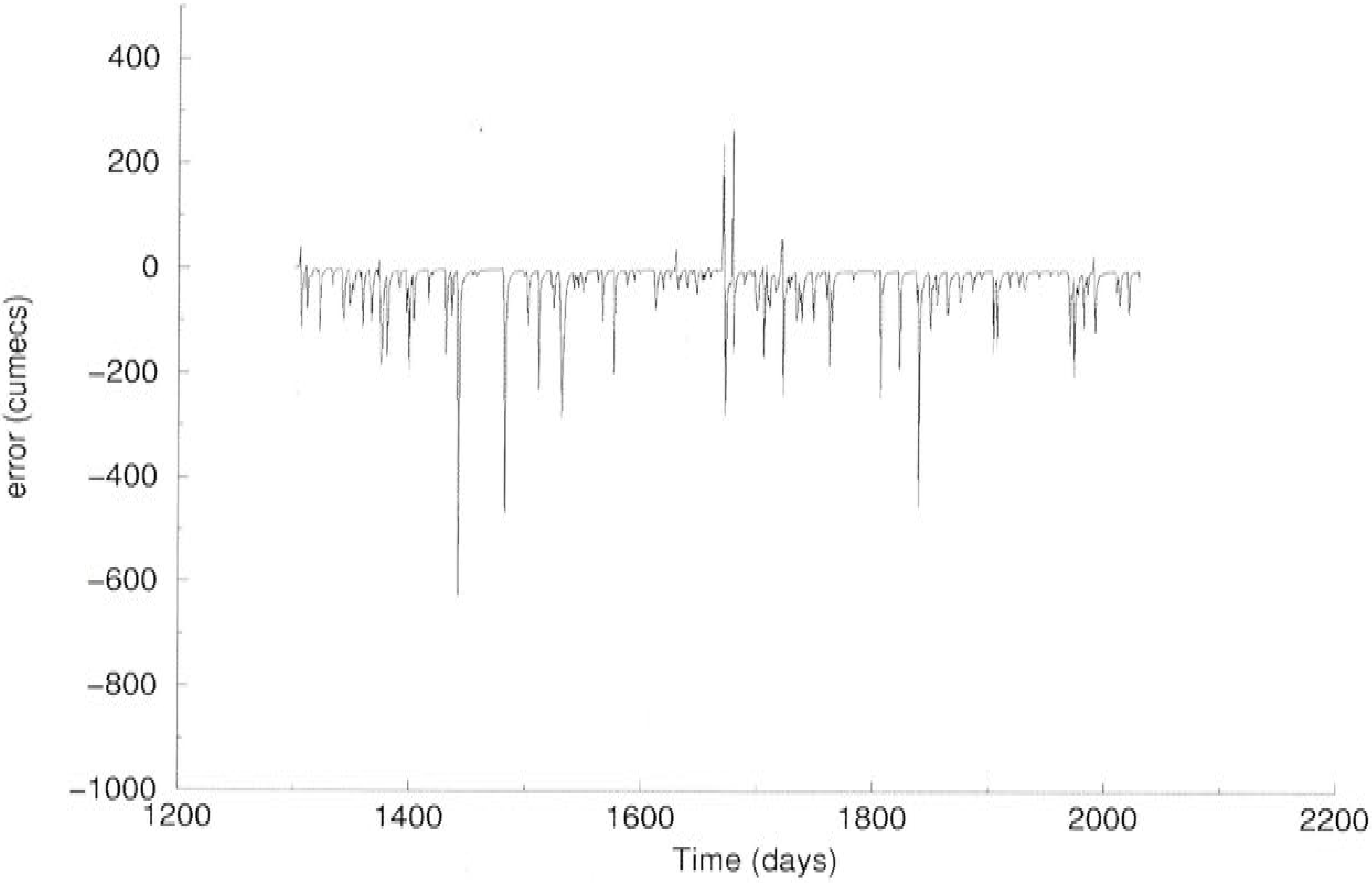

Figure 5.9: Calibration error for Gauge 26 daily streamflow model. (Period of record: 23/8/1973-22/8/1975)

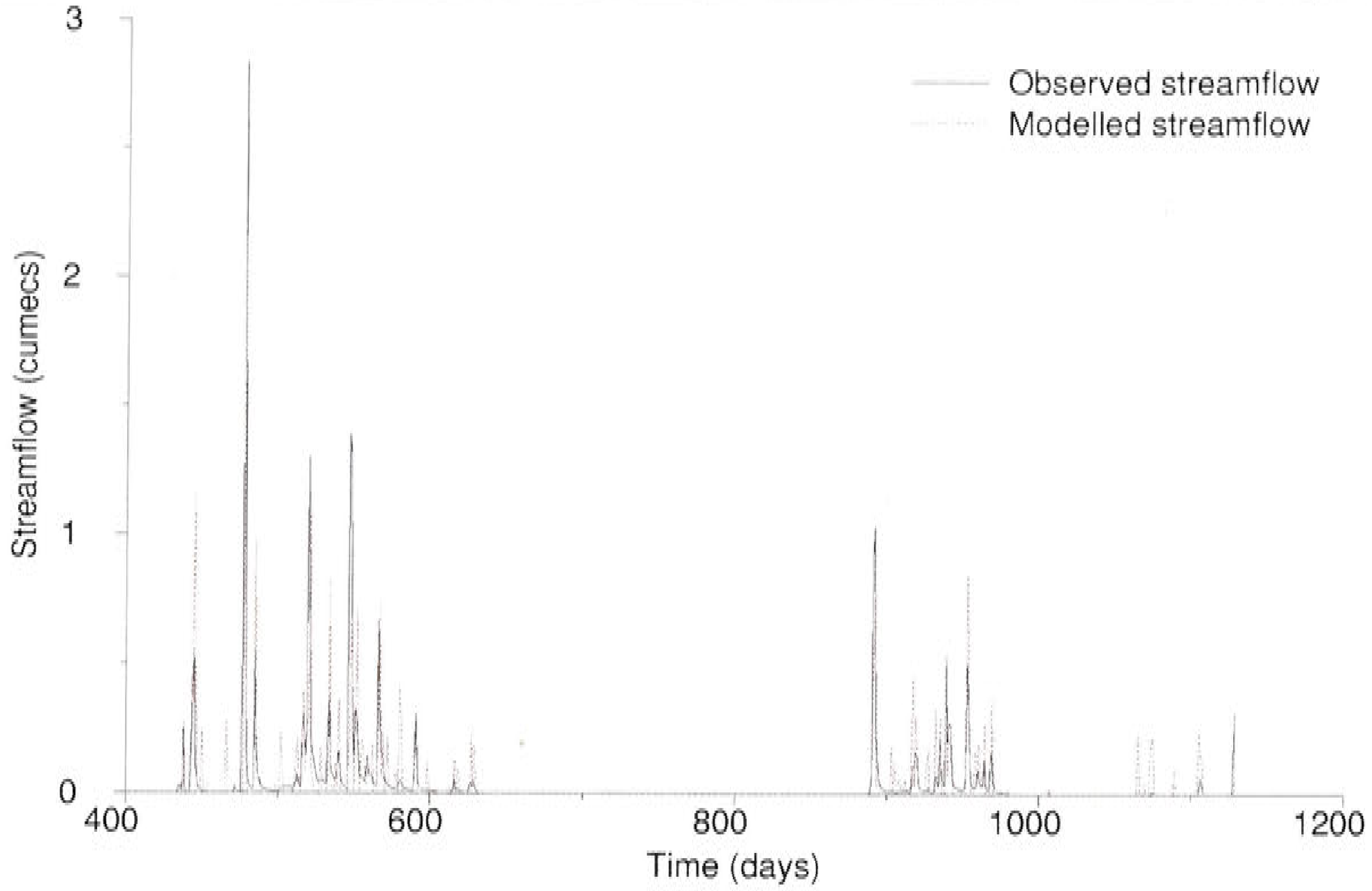

Figure 5.10: Calibration fit to daily streamflow for Gauge 60. (Period of record: 18/4/1990-17/4/1992)

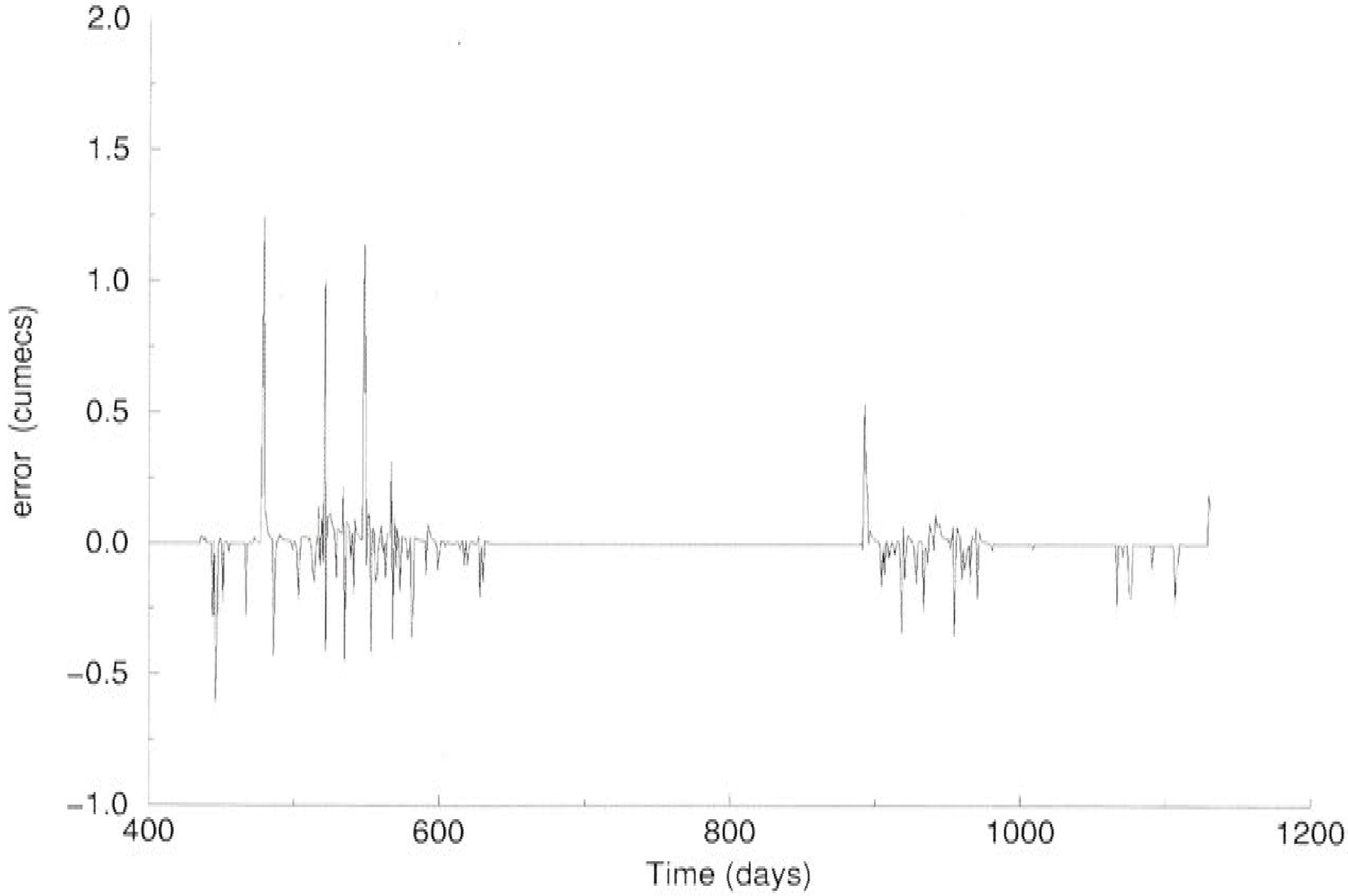

Figure 5.11: Calibration error for Gauge 60 daily streamflow model. (Period of record: 18/4/1990-17/4/1992)

5.8 Rainfall Estimation Using Thin Plate Smoothing Splines

Along with temperature and streamflow information, daily rainfall for each of the subcatchments was required as one of the three data inputs to the rainfall-runoff model. The estimation of daily rainfall on each ungauged subcatchment was the first step in the ungauged model development. Areal rainfall for each subcatchment was estimated using a two-step procedure.

In the first step, smoothing splines were used to generate monthly rainfall surfaces for the catchment from time series of rainfall data at individual rainfall gauges. The spline model assumes that rainfall is spatially correlated with latitude, longitude and elevation. A comprehensive description of the ANUSPLIN procedure used here for producing monthly to annual rainfall surfaces can be found in Hutchinson (1995). The ANUSPLIN software package was utilised to develop a set of twelve long-term mean monthly rainfall surfaces. Continuous daily rainfall data for the time period (in this case, monthly) was required as well as elevation data. The surfaces were constructed for an area containing the Upper Murrumbidgee catchment (see Chapter 3 and Figure 3.11).

In the second step, the rainfall surface was used to scale the daily data from each rain gauge to give an areal estimate for each subcatchment. Eighteen gauges in or near the Yass catchment were available for this purpose. An average rainfall surface was used to give an areal estimate of daily rainfall using:

$$P_{c,g,i} = P_{g,i}\frac{S_c}{S_g} \tag{5.13}$$

where, at time i, $P_{c,g,i}$ is the areal precipitation estimated for the subcatchment area c for the gauge g. S_c is the mean surface precipitation value for the subcatchment, and S_g is the value of the rainfall surface at the gauge. The estimated daily catchment precipitation is then computed as:

$$P_{c,i} = \frac{\sum_{g=1}^{m} P_{c,g,i}}{m} \tag{5.14}$$

where m is the number of rain gauges used to give an estimate of areal daily rainfall. The method gives a weighted average of the daily rainfall from all gauges used, with the weight set from the rainfall surface. Daily areal rainfall was estimated on each of the twelve subcatchments.

5.9 Parameterisation and Streamflow Estimation Procedure for Ungauged subcatchments

One of the aims of the thesis was to model the impacts of land use change on the hydrological network. An approach that related changes in land use to hydrological model parameters was therefore necessary. As already stated in the modelling objectives the approach also required some estimate of runoff and recharge (baseflow) conditions to be estimated as a prerequisite for predicting impacts as a result of farm dam and forestry plantation interceptions (see Chapter 3 Conclusions). Finally, the literature review of regionalisation illustrated the importance of applying a consistent scale for the purpose of regionalisation. The approach used in this thesis needs to predict broad changes in the hydrological response at the catchment scale given this is the scale at which the policy options were to be modelled as part of the integrated model.

Given that the two driving variables of the hydrological cycle in Australian dryland catchments are rainfall and evapotranspiration, an approach that related these catchment variables to the conceptual model parameters was deemed suitable for ungauged streamflow estimation.

Section 5.5 outlined the rainfall runoff model used in the thesis and the necessary changes made to its structure as part of the integration process. Section 5.7 showed how the model was used to parameterise and estimate streamflow on gauged catchments. This section will explore the application of the model to ungauged subcatchments. In order to estimate the mean annual streamflow in ungauged subcatchments the mean annual rainfall was partitioned between the significant components of the water balance: evaporation, recharge and runoff.

5.9.1 Partitioning of Rainfall

A general water balance for a catchment can be found by examining the proportion of rainfall that is left as runoff after evapotranspiration and recharge are accounted for, assuming all other terms are negligible. Rainfall is then partitioned according to:

$$\overline{P} = \overline{E}_t + \overline{Q_R} + \overline{Q_{ro}} \tag{5.15}$$

where P is precipitation, $\overline{E}_t$ is evapotranspiration, Q_R is recharge to soil and Q_{ro} is runoff. The approach used in this thesis uses this relationship to estimate streamflow on ungauged subcatchments in Yass catchment. The following sections detail how this equation was used to partition rainfall for parameter estimation on ungauged subcatchments in Yass. The basic data required were areal rainfall, land use and soil types for the ungauged subcatchments. Evapotranspiration was then estimated from vegetation attributes. Following this, runoff and recharge were estimated by partitioning the remaining water according to soil attributes.

5.9.2 Evapotranspiration Estimation

For a dryland catchment such as Yass catchment, the most important water balance term is evapotranspiration (after precipitation). Zhang *et al.*, (2001) investigated driving variables affecting evapotranspiration, including dryland catchments in Australia. Theoretical and empirical results showed that, at the catchment scale, the main driving variable for evapotranspiration was changes in vegetation or land use cover. Zhang *et al.*, (2001) developed a two-parameter model that relates land cover (grass and forest) to evapotranspiration (known as Zhang curves). This was applied to each subcatchment by converting each land use type to an estimated effective forest cover. The catchment effective forest fraction was then calculated using;

$$\delta = \sum_{lu} \delta_{lu} \frac{A_{lu}}{A} \tag{5.16}$$

where δ_{lu} is the effective forest fraction attributable to a particular land use, *lu* (Dawes *et al.*, 2001), A_{lu} is the area with a given the land use type, and *A* is the total subcatchment area.

The derived empirical relationship was successful in predicting catchment-scale changes in evapotranspiration and hence runoff for 93% of forested catchments and 90% of grassed catchments. These results were consistent for 96 Australian dryland catchments studied. The relationship is given by

$$E = P\left(\frac{1 + wEo/P}{1 + wEo/P + P/Eo}\right) \qquad (5.17)$$

where

$E_0 = 1410\ mm,\ w = 2.0$ for forested catchments

$E_0 = 1100\ mm,\ w = 0.5$ for grassed catchments

The variable *E* denotes actual annual evapotranspiration, *P* is annual rainfall, *Eo* is a rainfall scaling factor and *w* is the available water to the vegetation. Where the vegetation is mixed, a proportion of effective forest fraction for a catchment can be obtained using effective forest cover estimates for different land uses (e.g cropping, grazing, native grasses and native forest). The effective forest cover was then used to find the actual evapotranspiration using:

$$ET = \delta E_f + (1 - \delta)E_g \qquad (5.18)$$

where *ET* is the estimated evapotranspiration, δ is the fraction of effective forest cover, E_f is the estimated evapotranspiration from a forested catchment and E_g is the estimated evapotranspiration from a grassed catchment (Zhang *et al.*, 2001).

5.9.3 Runoff estimation using soil type catchment attributes

Petheram *et al.*, (2000) used the relationship to relate soil type to runoff and recharge in dryland catchments. At the catchment scale, it was found that a soil recharge fraction could satisfactorily partition the water balance between quickflow and slow flow components. See Petheram *et al.*, (2000) for a detailed description of the approach. As stated in Section 5.3, the objectives of the study require that a partitioning into these components is necessary for integration of the hydrological and economic models. With the aid of the conceptual rainfall-runoff model, runoff may be partitioned into quickflow (runoff) and slowflow (recharge) components at the catchment scale.

A GIS layer of broad soil types was obtained from the NSW Department of Agriculture. Each soil type was converted into a recharge fraction using the broad categories shown in Table 5.3 (Zhang *et al.*, 2001 and Petheram *et al.*, 2000). The recharge fractions were then averaged across each subcatchment.

Table 5.3: Recharge fraction of excess water for generic soil type descriptors (Source: Dawes *et al.*, 2001)

Soil Type or Texture	Recharge Fraction
Sand	0.90
Sandy-Loam	0.75
Loam	0.50
Clay-Loam	0.25
Heavy Clay or Duplex soil	0.10

Effective rainfall, according to soil type, was partitioned between runoff and recharge by:

$$Q_{recharge}=(P\text{-}ET_{actual})Soil_f \tag{5.19}$$

$$Q_{runoff}=(P\text{-}ET_{actual})(1\text{-}Soil_f) \tag{5.20}$$

where P is an annual rainfall estimate, ET_{actual} is estimated evapotranspiration, $Soil_f$ is the estimated fraction of effective rainfall that becomes recharge (based upon Petheram curves) and Q_{runoff} is the volume of flow to runoff and $Q_{recharge}$ is volume of flow to recharge. The runoff coefficient for the ungauged subcatchments is then given by:

$$R_{coeff} = \frac{Q_{recharge} + Q_{runoff}}{P} \tag{5.21}$$

where R is runoff and P is precipitation.

5.9.4 Parameter Estimation

To estimate streamflow on all 12 ungauged subcatchments, a modified version of the IHACRES model was developed to incorporate the evapotranspiration versus rainfall relationships developed by Zhang *et al.*, (2001). For a full description of the model, see Croke and Jakeman (2001). The approach relies upon identifying evapotranspiration from mean annual rainfall and adjusting the IHACRES model parameters to obtain the closest estimate of the evapotranspiration. The IHACRES model then generates streamflow, using the adjusted parameter values. The IHACRES model inputs for the ungauged subcatchments were temperature and rainfall time series, the effective forest cover, a recharge coefficient and catchment area.

5.9.5 Modifying the IHACRES model parameters

The use of catchment attribute relationships identified in Section 5.9.1 within the conceptual model required the additional input of a land cover fraction. The model was run in simulation mode to produce estimates of the time series streamflow for the ungauged subcatchments. Where a streamflow and rainfall record is normally required for calibration or simulation, the twenty-year daily rainfall record for each subcatchment was used as input into the simulation. Streamflow was generated using the relationships defined by Zhang *et al.*, (2001) to partition rainfall into recharge and runoff components, in addition to utilising the model conceptual framework to produce a unit hydrograph for each subcatchment using the parameter values defined for the unit hydrograph on gauged catchments in Yass.

The parameter *a* in the linear routing module was scaled by catchment area based on a relationship derived for gauged catchments in the Upper Murrumbidgee (Newham, 2002), and *b* was fixed at the value derived for the gauged catchments (see section 5.6). This regionalisation is assumed to hold for Yass catchment given the proximity of the gauges used to derive the relationship. This is different to the *a* parameter in the non linear module that is used to define the power law fit. The parameter *e* in the non-linear module scales daily temperature to daily potential evaporation, and was fixed at 0.3 mm/^{0}C for all subcatchments. The non-linear module parameter *d* was also fixed at 190 mm as the model is relatively insensitive to this parameter. The *f* parameter was optimised to reproduce the evapotranspiration estimate derived using Equation 5.17. This is different to the hydrology model parameter identified in equation 5.5. Effectively, the model was reduced to a two-parameter model (*a* and *f*). These two-parameters were optimised on the gauged catchments within Yass to estimate potential pairs of parameter values that could be applied to the ungauged subcatchments. Each gauged catchment was calibrated across wet and dry periods in addition to varying the land use fraction to characterise variation in evapotranspiration.

The model optimised the parameter to the evapotranspiration estimate, *f*, as identified by the Zhang *et al.*, (2001) estimate. The model was therefore optimised to minimise the bias between mean and actual evapotranspiration.

5.10 Results

The previous section described the methods utilised to estimate driving hydrological variables for Yass catchment. Following the review of catchment physical characteristics in Chapter 3, catchment area, land use and soil type were utilised to partition rainfall into evapotranspiration and runoff. Table 5.4 and 5.5 show the estimates obtained from using the approach for each ungauged subcatchment within Yass catchment. The period of rainfall used to generate the evapotranspiration estimates were for the period 1890 to 1999.

Table 5.4: Estimation of annual hydrological variables using area, landuse, soil and climate parameters in conjunction with Zhang *et al.*, (2001) and Petheram et *al.*, (2000) curves for Yass subcatchments

Catchment	Annual Precipitation	ET Forest	ET Grass
cat500 (Kittys Ck)	743	651	388
cat504 (Corregans Ck)	745	652	383
cat514 (Murrumbateman Ck)	729	387	641
Catem (Un-named tributary)	803	690	388
Catcm (Un-named tributary)	753	659	389
Catbm (Bald Hill Ck)	766	667	389
cat579 (Brooks Ck)	714	632	387
cat568 (Spring Ck)	691	617	386
cat559 (Gundaroo Ck)	724	640	388
cat529 (Nelanglo Ck)	714	632	387
cat465 (Mantons Ck)	744	652	388
cat538 (Nowlands Ck)	715	633	387

Table 5.5: Estimation of partition states of annual hydrological variables using area, landuse, soil and climate parameters in conjunction with Zhang *et al.*, (2001) and Petheram *et al.*, (2000) curves for Yass subcatchments

Catchment	Land use fraction	Et Actual	Qr (runoff)	R (baseflow)	Runoff coeff	Soil fraction
Cat500	0.87	616	63	63	0.16	0.50
Cat504	0.78	592	72	79	0.20	0.52
Cat514	0.63	480	93	155	0.34	0.62
Catem	0.90	659	29	113	0.17	0.79
Catcm	0.90	632	60	60	0.16	0.50
Catbm	0.97	658	53	53	0.14	0.50
Cat579	0.85	595	48	70	0.16	0.59
Cat568	0.76	561	38	90	0.18	0.70
Cat559	0.79	587	52	84	0.18	0.61
Cat529	0.77	575	51	86	0.19	0.62
Cat465	0.89	622	60	60	0.16	0.50
Cat538	0.95	620	28	66	0.13	0.70

The estimated values of evapotranspiration were used as input into the IHACRES model. The model was run in simulation mode given that the parameters, land cover and area were fixed. In addition, a 1-day delay was added to the model to allow for the delay between rainfall and catchment response as streamflow (see Figure 5.7).

This section is also concerned with using those catchment variables to identify relationships between conceptual model parameters and driving catchment variables (ie evapotranspiration and runoff). Derivation of such relationships allows an estimation of the distribution of streamflow temporally in addition to estimating the shape and distribution of the unit hydrograph on ungauged subcatchments.

The sensitivity of the model parameters to the land use fraction was examined with three simple tests. The first test identifies the change in model parameters where the land use fraction is changed. The second test considered the stability of the relationship between the land use fraction and model parameters by varying calibration lengths while the third test examined the parameter stability over dry and wet calibration periods. These simple tests were able to confirm (or otherwise) that the change in model parameters was due to changes in the land use fraction, an important relationship to ensuring the ungauged regionalisation performed adequately by incorporation of the Zhang *et al.*, (2001) relationships.

Table 5.6 shows the results for the first test. The table illustrates the optimised parameter values, bias (difference between optimised value and actual evapotranspiration) used to optimise model parameters within the ungauged subcatchments. The number of days for model calibration is held constant. The model is also started on the same day given that calibration results can change dependent upon the model being started in a wet or dry period. Therefore, the sample size and start date were held constant to investigate the impacts upon the model parameters as a result of varying the land use fraction. At least 40 calibrations were carried out to select the pair of model parameters suitable for use on ungauged subcatchments. The start time indicates the day the model was run on, and the sample size indicates the number of days the model was run over. As indicated, the parameter *f* varies in accordance with variation in the land use fraction. The *f* parameter increases as the land use fraction increases.

Table 5.6: Testing the variation in the *f* parameter identified for Gauge 90 by varying the land use fraction

Land Use Fraction	**Start time (sample size)**	**d mm**	***f* %**	**Et mm/yr**
0.9	1 (730)	190	97	623
0.8	1 (730)	190	92	611
0.6	1 (730)	190	87	587
0.4	1 (730)	190	83	563

Table 5.7 indicates the variation in model parameters as a result of starting the calibration period at the same time but varying the time period over which the model was run. The results indicate that over varying calibration lengths the model parameter, *f* for a given land use fraction does not vary significantly. This is informative as the integrated model is required to be run over short and longer time periods to obtain the appropriate results.

Table 5.7: Testing the variation in the *f* parameter for Gauge 90 given the varying the calibration period from starting in wet and dry years

Land Use Fraction	**Start time (sample size)**	*d mm*	*f %*	*Et mm/yr*
0.77	400 (730)	190	92	608
0.77	400 (1500)	190	91	617
0.77	400 (1000)	190	90	640
0.77	400 (900)	190	88	639
0.77	400 (1000)	190	90	640

Table 5.8 illustrates the parameter values by starting the model at different time steps corresponding to wet dry periods. The period over which the model is run is kept constant at 730 days. The *d* parameter does not vary. The *e* parameter was fixed to the gauged calibration results. The result indicates that the *f* parameter is stable.

Table 5.8: Testing the *f* parameter for Gauge 90 varying the start period of calibration from wet to dry for a calibration period of 730 days

Land Use Fraction	Start period (sample size)	*d* *mm*	*f* %	*Et* *mm/yr*
0.77	1000 (730) wet	190	90	640
0.77	3200 (730) wet	190	91	640
0.77	400 (730) wet	190	92	640
0.77	1800 (730) dry	190	92	640
0.77	2000 (730) dry	190	90	640

The identification of model parameters for application to each ungauged subcatchments is given in Table 5.9. In using the streamflow and rainfall records from gauged catchments, parameter estimation considered the distribution of events in time on a daily basis. Hence, the parameter values were identified from variations in climate over a 20-year period. The catchments described as cat514 and cat504 are the largest subcatchments in the system. This could explain the slight variation in the *f* parameter. As the result in Table 5.6 and model changes in Section 5.9.6, the parameter is optimised for a given evapotranspiration estimate and catchment area.

Table 5.9: Estimated ungauged parameter values using the IHACRES model and Zhang *et al.*, (2001) relationships to scale parameter values to land cover fraction and catchment area

	Parameter	
Catchment	d	*f*
cat500	190	126
cat504	190	114
cat514	190	79
catem	190	85
catcm	190	83
catbm	190	82
cat579	190	92
cat568	190	94
cat559	190	89
cat529	190	85
cat465	190	83
cat538	190	97

5.11 Testing of the Gauged Approach: Streamflow Estimation Results

Figure 5.12 illustrates the result obtained from testing the regionalisation approach on the gauged catchment 90 for the period from 18/5/1976 to 4/12/1976. The approach predicts the streamflow well, with a small negative bias as indicated by the error. The approach slightly overestimates streamflow for large rainfall events as Figure 5.12 illustrates. This is expected given the ephemeral nature of the tributaries and its loss to groundwater. The loss to groundwater is not included in the modelling approach. This could be the reason for the overestimation of streamflow by the ungauged model. The evapotranspiration estimate given by the Zhang relationships and the IHACRES model obtained were 557mm and 569mm respectively.

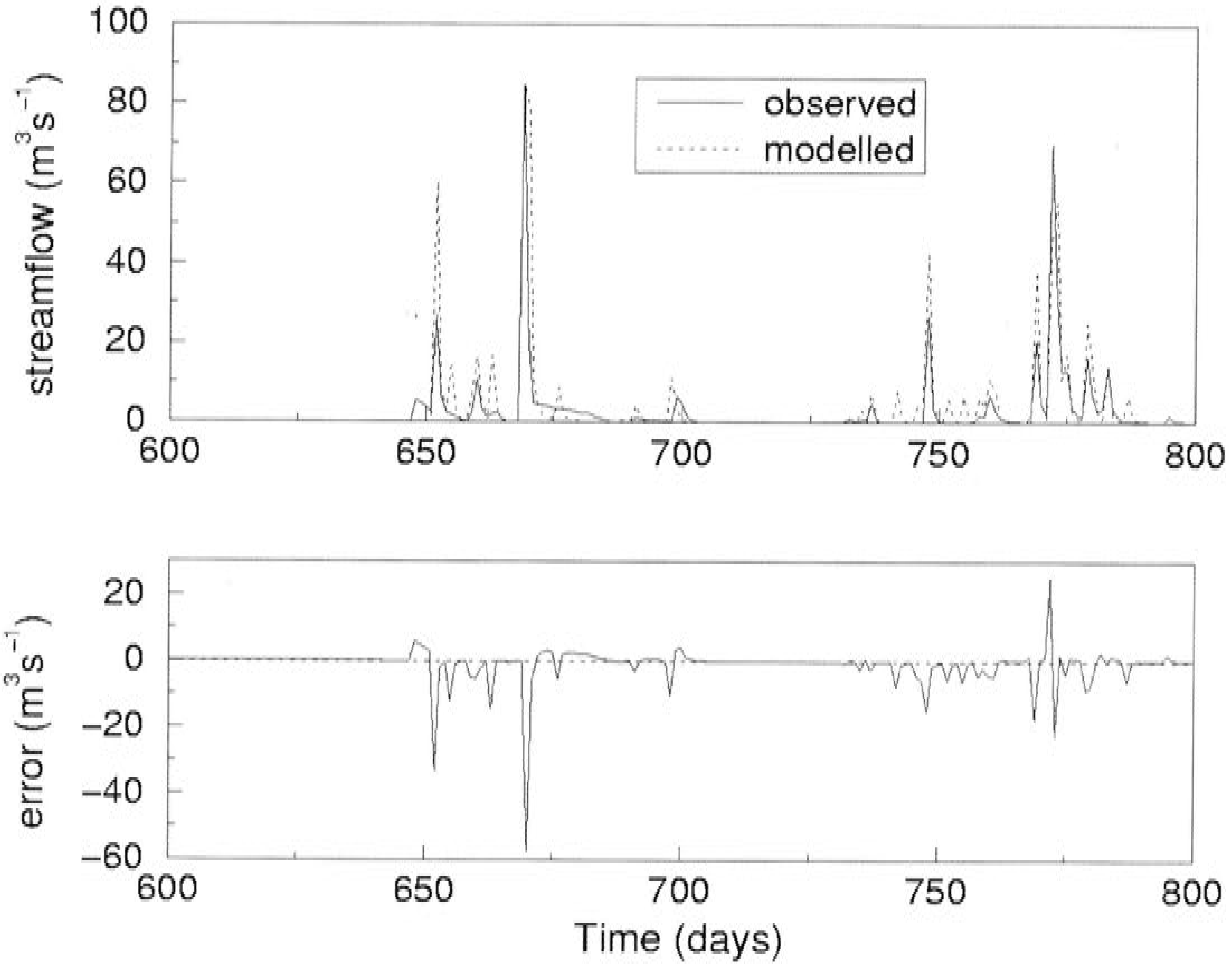

Figure 5.12: A comparison of daily observed and predicted streamflow for Gauge 90 in Yass catchment (Period of record: 18/5/1976-4/12/1976)

In the next section the regionalisation approach will be tested more comprehensively in gauged catchments in the Macquarie.

5.12 Testing the Regionalisation Method: Case Study of Macquarie Catchment

The Yass catchment has only a single suitable gauge for testing (Gauge 90). For this reason, testing of the approach required the selection of a catchment system with adequate streamflow time series data and land use cover. It should also be in close spatial proximity to Yass catchment and preferably, contain unregulated subcatchments to test the approach. The Macquarie catchment was selected for this reason. The method is tested by applying the modified version of IHACRES to selected gauged subcatchments. Generated streamflow is compared with the actual streamflow at each gauge in order to assess the predictive capacity of the regionalisation method.

5.12.1 Catchment Overview

The Macquarie catchment is located in central western New South Wales. The catchment is a regulated system containing three dams in the Upper Catchment: Ben Chifley, Burrendong and Windamere Dams. The network branches out to form the Macquarie marshes west of Dubbo and flows into the Barwon Darling River. Figure 5.13 illustrates the catchment and subcatchment systems with major landmarks.

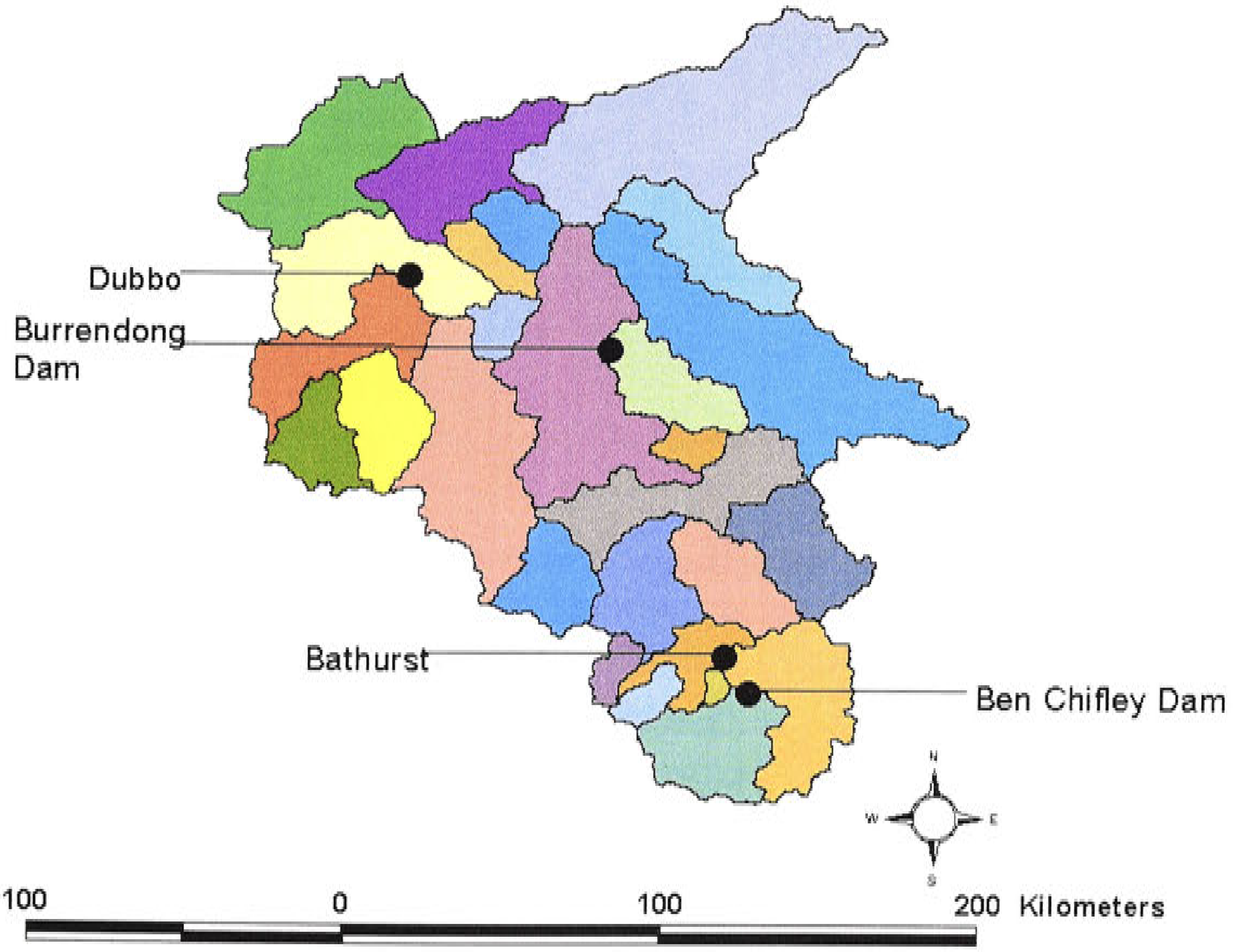

Figure 5.13: The Macquarie catchment and subcatchments with major landmarks

The lower catchment contains the Macquarie Marshes. The presence of braided and anastomising river network within the Marshes could make hydrological estimation problematic. This is the reason for selecting the middle and upper subcatchments for testing of the ungauged streamflow approach. All gauges selected for analysis were above Narromine in the upper catchment area. The upper catchment area was also selected due to the occurrence of land use activities similar to the dryland and extractive systems in Yass catchment. Upper subcatchments are also unregulated in that there are no upstream regulation to impact upon them. Figure 5.14 illustrates the hydrological network constructed for analysis and the gauges selected to test the approach.

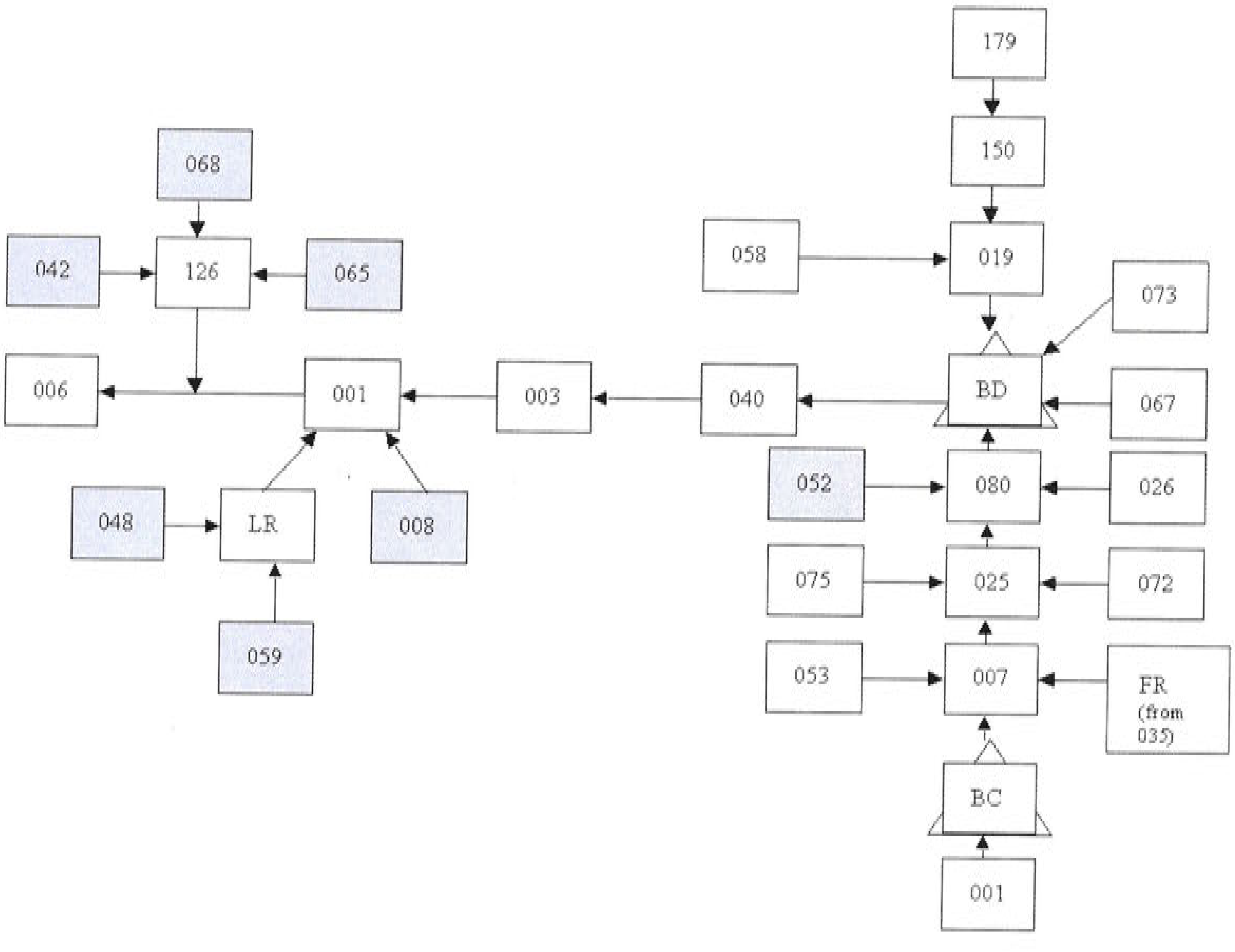

Figure 5.14: Hydrological network constructed for testing the ungauged streamflow predictive methodology showing gauges tested in bold

Upper subcatchment tributaries are less likely to be contaminated by extractive water use and are not affected by the regularly impact of a major dam. Stream gauge data free of extractions or regulation are more likely to produce a better relationship between rainfall and streamflow, essential for testing the regionalisation method. Secondly, in testing the approach, catchments of similar characteristics to Yass catchment were selected. These included a smaller catchment area on the unregulated section of the Macquarie network. For these reasons, gauges 065, 052, 048, 058 and 068 were selected. Two other gauges (042 and 008) within the unregulated river system were selected in order to provide variation in catchment size for testing of the methodology. Table 5.10 shows the catchment areas and the two-parameter power law fits for unit hydrograph estimation on each of these subcatchment using the relationship as per Yass catchment (see Section 5.6). Figure 5.15 is an example of the unit hydrograph fit for a gauge within the network.

The first step in testing the approach was to derive *a* and *b* parameters for the linear module of the IHACRES model. This was done by fitting the power law function (see Equation 5.9 in Section 5.5.2) to actual streamflow data for all 7 gauges as shown in Table 5.10. Figure 5.15 is an example of the unit hydrograph estimation using the two-parameter fit. The heavier shaded line shows the model fit.

Table 5.10: Subcatchments from the Macquarie catchment selected for analysis with size and unit hydrograph parameters

Catchment Gauge and Site Name	Size (km²)	Parameter *a*	Parameter *b*
042 (Talbragar River at Elong Elong)	3049	0.56	1.63
048 (Little River at Obley)	611	0.56	1.51
059 (Buckinbah Ck at Yeoval)	708	0.77	1.54
008 (Bell River at Wellington)	1864	0.54	1.37
065 (Mitchell Ck at Westella)	281	0.84	1.45
052 (Lewis Ponds Ck at Ophir)	620	0.37	1.70
068 (Spicers Ck at Saxers Crossing)	376	0.30	1.99

Figure 5.15 shows the power fits the peak event between 3 and 10 days. Any period after 10 days is of such a time after peak as to expect the introduction of significant contamination from neighbouring events.

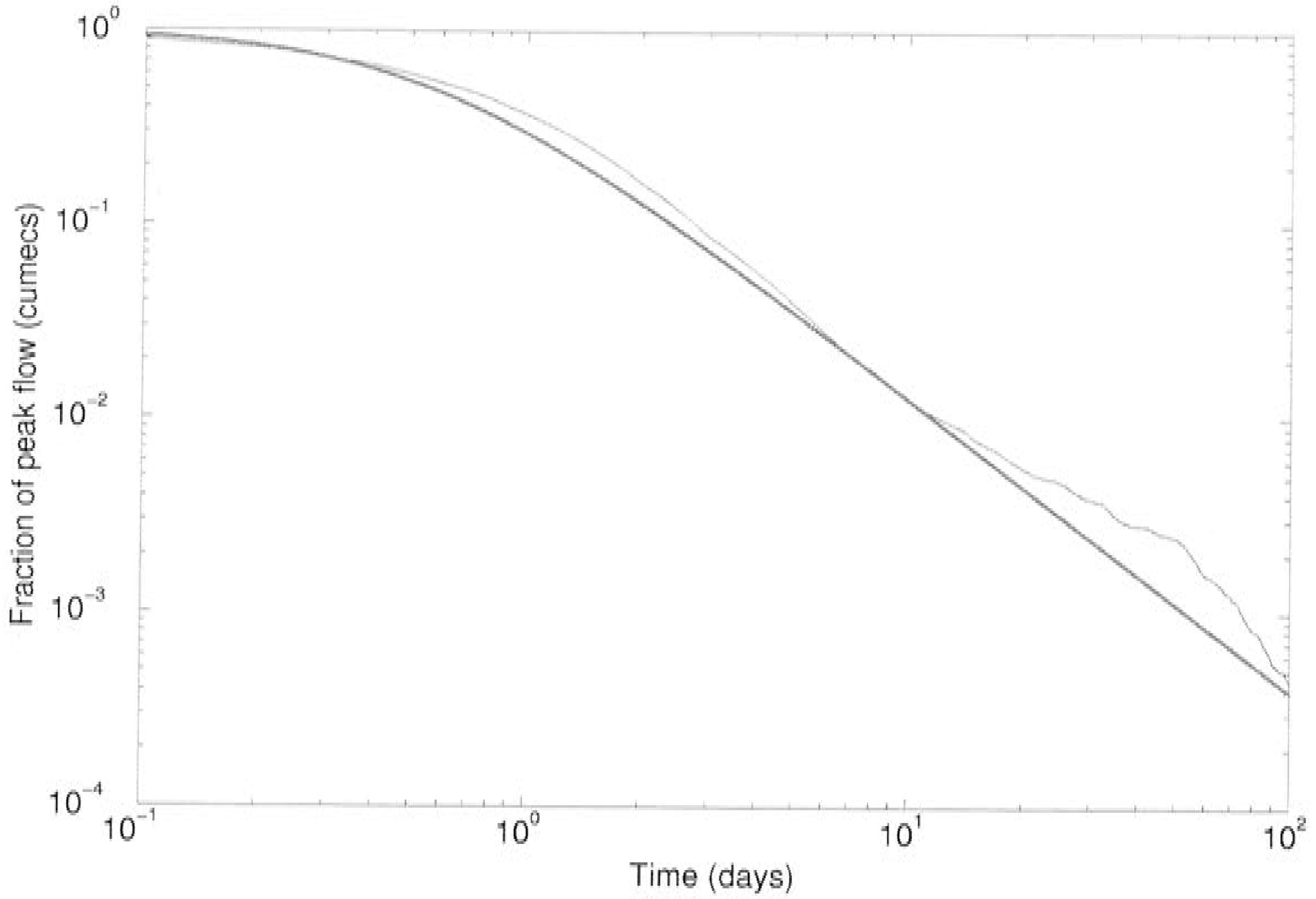

Figure 5.15: Two-parameter power law fit for an unregulated catchment containing Gauge 048 in the Macquarie catchment

5.12.2 Rainfall and Vegetation catchment attributes

The next step in testing the ungauged approach was to derive the effective forest cover from land use information and the soil fraction from soil information in the catchment as described in Sections 5.9.2 and 5.9.3. The Macquarie subcatchments were classified according to the land use classification convention developed by Zhang *et al.*, (2001). The actual evapotranspiration rate (E_t) was calculated using E_f, E_g and the land use fraction to identify E_t from the linear relationship as outlined in Section 5.9.3. The evapotranspiration estimate and land use fraction for each of the test catchments as given in Table 5.11.

Table 5.11: Calculated land use fraction, evapotranspiration (Et), evapotranspiration under forestry (Ef), evapotranspiration under grasslands (Eg) and annual average rainfall for each test gauge

Catchment Gauge Number	Annual Average Rainfall (mm)	Land use fraction	*Et*	*Eg*	*Ef*
042	651	0.91	589	493	599
048	648	0.92	588	491	596
008	697	0.57	583	515	634
059	643	0.99	592	489	592
052	697	0.90	704	564	719
065	629	0.61	542	482	581
068	611	0.59	529	473	567

5.13 Ungauged Calibration Results

The catchment area, the effective forest cover, daily rainfall and daily temperature were inputs to the modified IHACRES model. The linear model *b* parameters was obtained from the gauged catchment calibration and the *a* parameter was scaled to catchment area. The parameter *f* was optimised for the evapotranspiration estimate given in Table 5.11. The parameters *e* and *d* were optimised from the gauged calibration for each of the selected subcatchments in the Macquarie.

Table 5.12 compares the actual streamflow with the result obtained from the regionalisation procedure. The result compares the actual streamflow volume and runoff coefficient for each gauge compared with the values obtained from using the regionalised model.

Table 5.12: Predicted and gauged flow statistics for selected gauges in the Macquarie catchment

Gauge	Mean Annual Volume (cumecs)		Runoff Coefficient	
	Predicted	Actual	Predicted	Actual
008	11.08	7.10	0.22	0.14
048	2.84	1.12	0.18	0.07
052	2.64	1.97	0.16	0.12
065	0.96	0.17	0.16	0.03
042	4.38	1.20	0.07	0.02
059	1.50	0.72	0.12	0.06
068	0.76	0.125	0.10	0.02

The results from each gauge show that predicted natural flow is consistently higher than the observed streamflow. A number of factors could account for this over-estimation. Extractions by irrigators in the catchment could result in the model over estimating streamflow. A second reason is that recharge to the aquifer is assumed to returned to the stream within the catchment, that is, there is negligible subsurface flow out of the catchment. A third reason is the interception of runoff by farm dams. This is considered in the integrated model but is not considered in the regionalisation approach. The integrated model takes into account the affect of land use change and associated farm dam development. Expressing the result as a runoff coefficient removes the influence of area, giving a smaller range of values as shown in Table 5.12. The catchments with very low runoff coefficients (~0.02) are likely to be significantly influenced by extractions; hence the over estimation of the model may not be unreasonable at this gauge when compared to observed streamflow. All catchments show evidence of extractions.

The distribution of streamflow is also important given that the results are to be used to investigate the three policy options that are the subject of the thesis. The time series of streamflow for both gauged and predicted streamflow at Gauge 008 and 052 are shown in Figures 5.16 and 5.17. The results from the regionalised model reproduce the distribution of flows, allowing for the slight overestimation of total flow volume for these catchments. In comparison, data errors or irrigation extraction may be the cause of the erroneous result for Gauge 048 (Figure 5.18) and 065 (Figure 5.19).

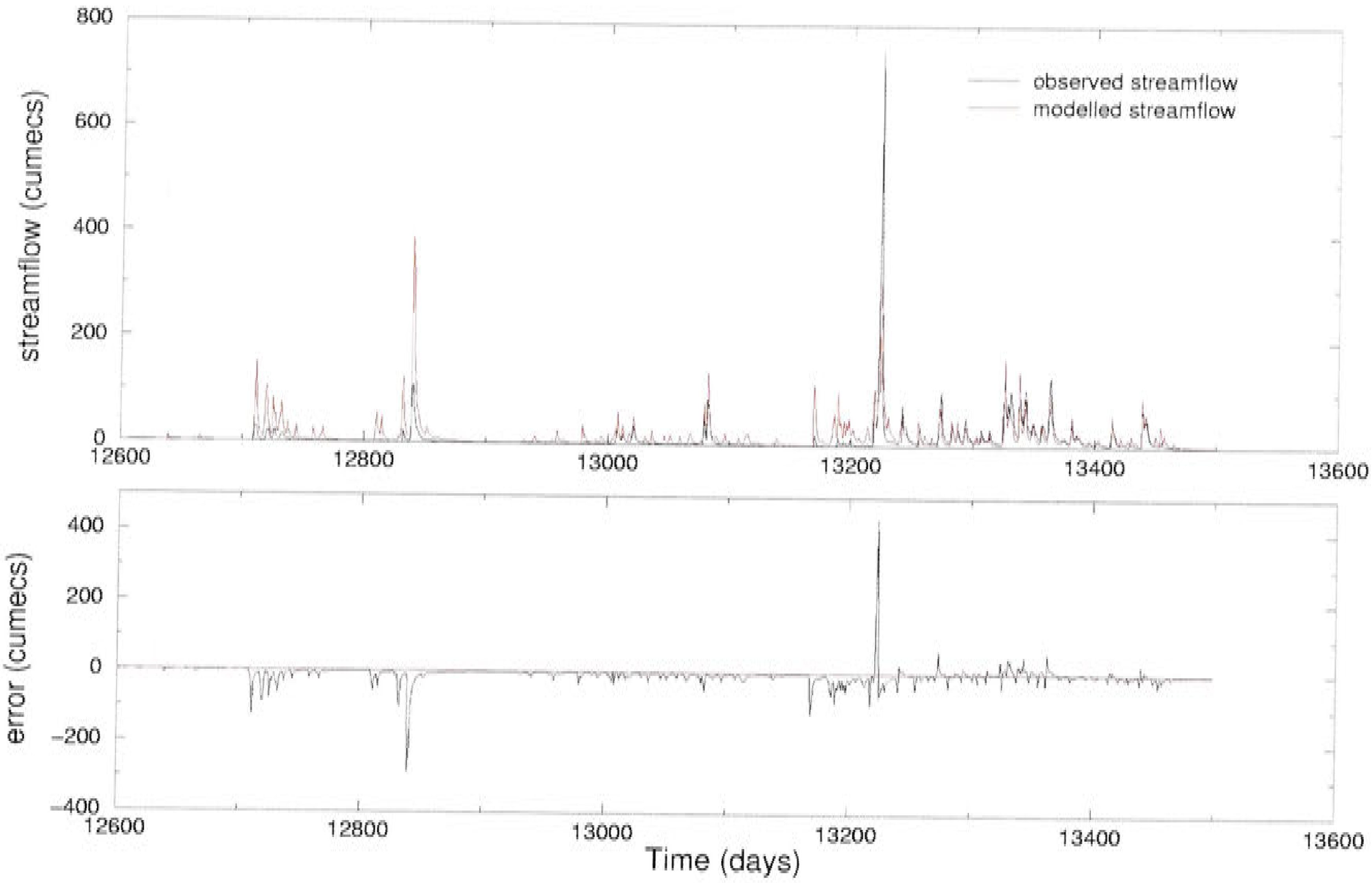

Figure 5:16: A comparison of observed streamflow and predicted streamflow using the ungauged IHACRES model at Gauge 008. (Period of record: 1/7/1954-27/3/1957)

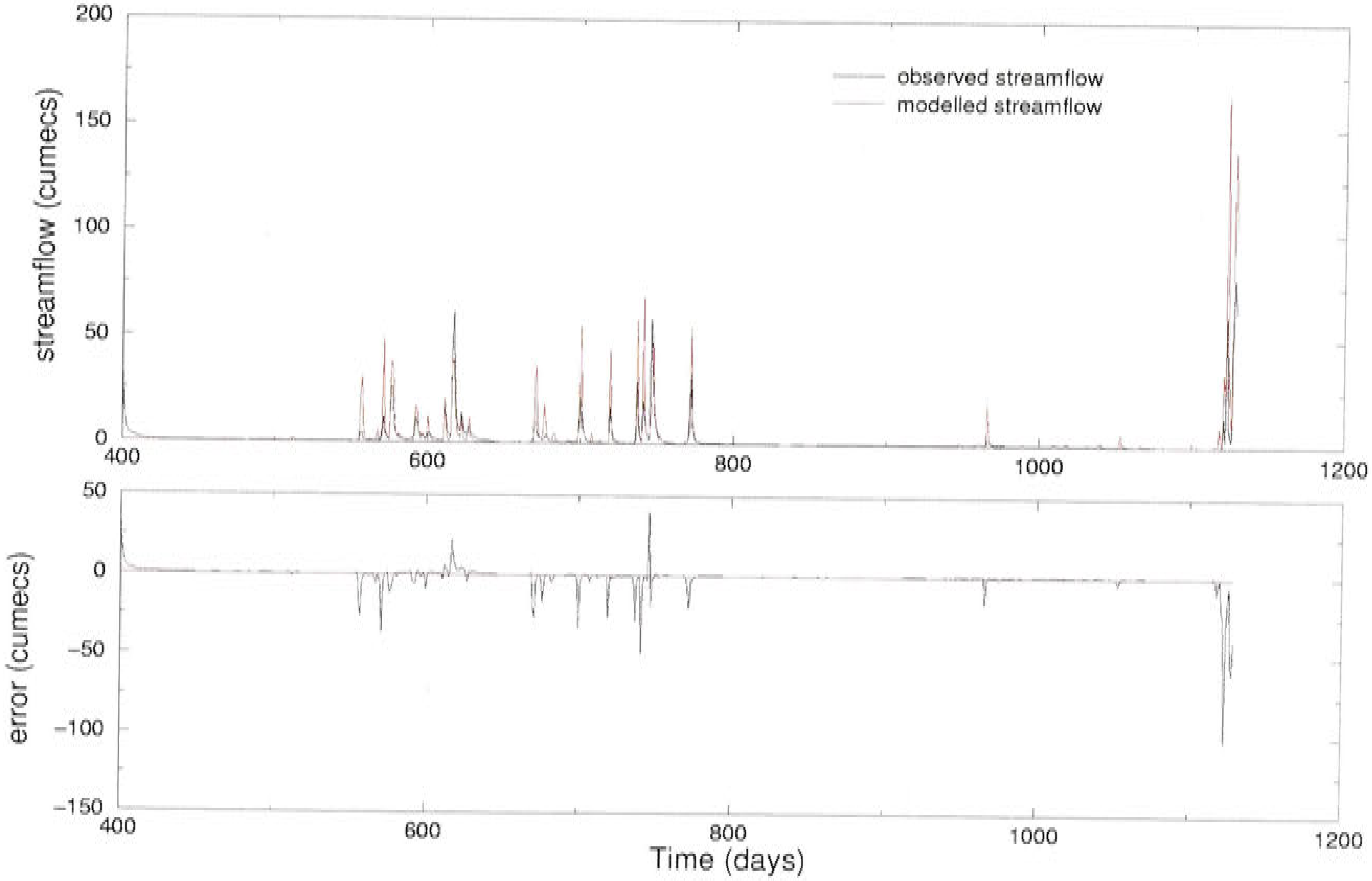

Figure 5:17: A comparison of observed streamflow and predicted streamflow using the ungauged IHACRES model at Gauge 052. (Period of record: 16/3/1972-25/5/1974)

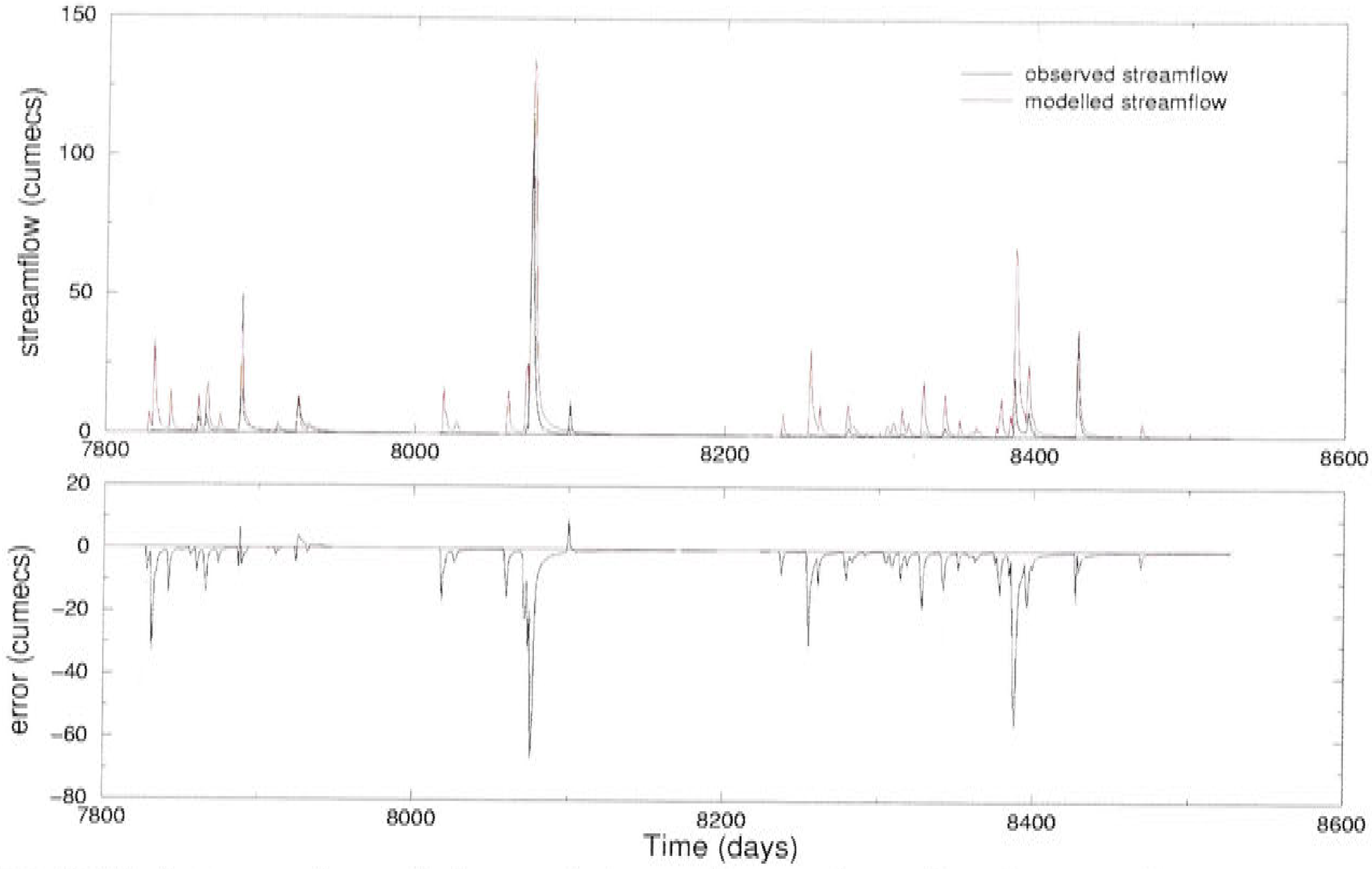

Figure 5:18: A comparison of observed streamflow and predicted streamflow using the ungauged IHACRES model at Gauge 048. (Period of record: 11/5/1991-19/7/1993)

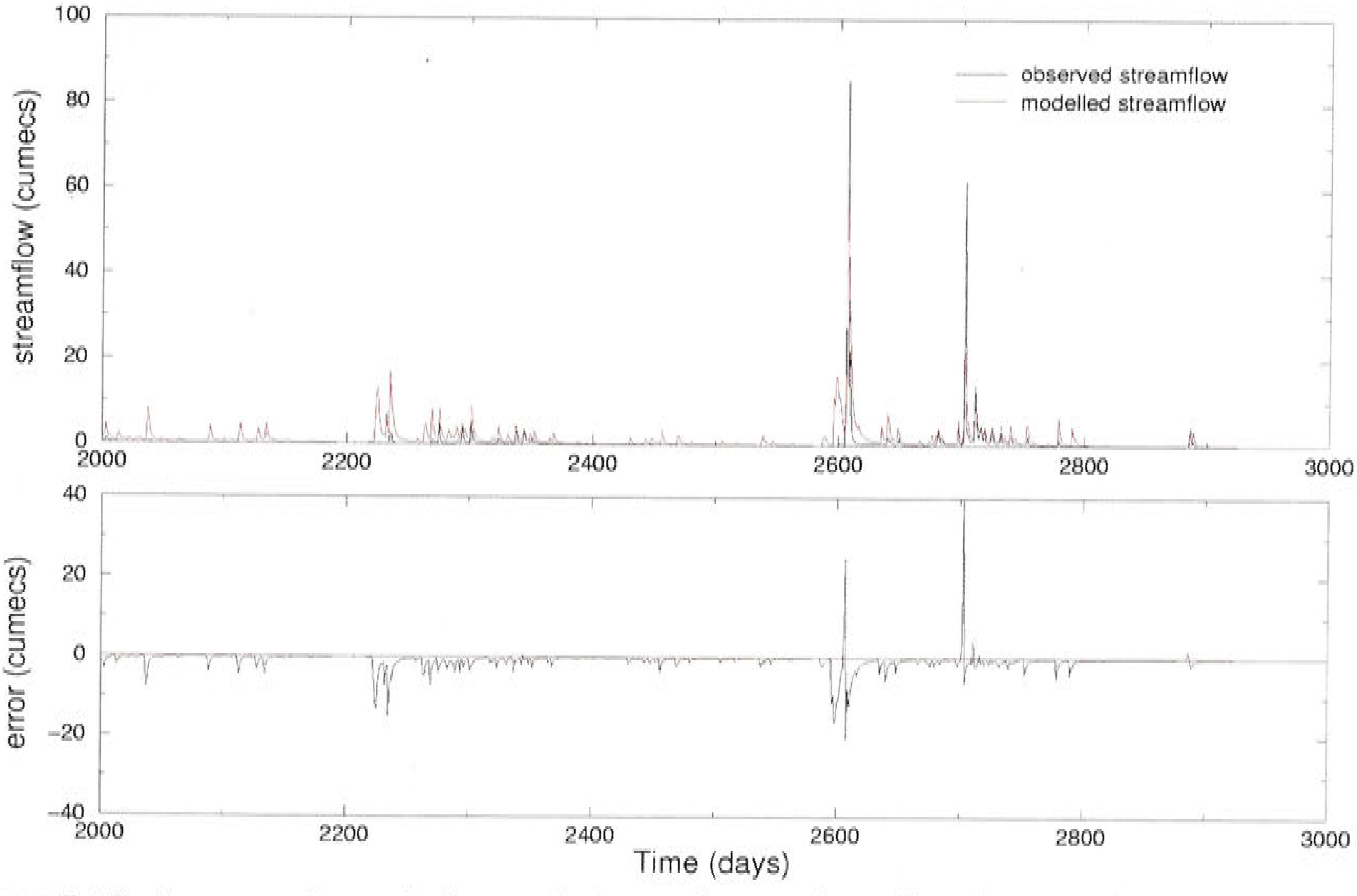

Figure 5:19: A comparison of observed streamflow and predicted streamflow using the ungauged IHACRES model at Gauge 065 indicating a poor result. (Period of record: 3/12/1991-29/8/1994)

5.14 Conclusions

The Chapter has presented a procedure for estimating streamflow for ungauged subcatchments, and in particular, unregulated river systems. The results are to be utilised in the integrated model in Chapter 7, designed to analyse the impacts of policy questions upon land and water systems. The hydrological network for Yass catchment that has been described here forms the foundation of the integrated model.

Rainfall-runoff models require good quality gauged data to derive the appropriate parameters for use in streamflow estimation. Gauged data should be obtained from areas of similar land use and catchment attributes but not necessarily from the same geographic location. The gauges contained within Yass catchment varied in data quality. As a result, each gauge varied in suitability for use in the regionalisation. Gauge 26 could not be used because of timing errors and extractions from Yass weir. Of the two remaining gauges, Gauge 60 was also rejected due to a short period of recorded flow. As a result, the estimation of flow at the nodes required for the integrated model was carried out using the regionalisation approach, based largely on the results for Gauge 90. Baseflow and groundwater recharge modelling did not take place as part of the modelling approach in this Chapter. This is a considerable limitation in the hydrology network.

The regionalisation approach related climate and catchment attributes to the hydrological model parameters as suggested by the literature review in Section 5.2. These relationships were used to develop a regionalisation approach for ungauged subcatchments in Yass as given in Section 5.9. Preliminary testing of the streamflow estimation procedure in the Macquarie catchment (Section 5.10 and Section 5.11) revealed that the regionalised approach provides a good approximation of natural streamflow for the purpose required by the integrated model. The results suggest that the distribution of streamflow and total volume is predicted well. However, the method does over-estimate streamflow on some unregulated catchments. This could be due to extractions from the stream or errors in rainfall and streamflow. The overestimation is smaller than might be expected given the reliance on land use and catchment vegetation cover to derive model parameters.

Chapter 6 Agricultural Production Model

6.1 Introduction

This Chapter provides a detailed account of the equations used to describe the agricultural production systems outlined in Chapter 4. The Chapter first describes the model formulation for Activities, before moving onto that of Land Management Units (LMUs), and finally modelling Nodes. This allows for a clear demonstration of the ways in which these components are integrated. At each level in the modelling hierarchy, a short description and justification of the formulation developed is given.

Section 6.2 provides a brief review of agricultural production systems modelling. This review demonstrates the contribution of the model formulation in this thesis in the context of recent approaches to integrated modelling using production systems models. In doing so, it also highlights the limitations and issues not to be addressed by the model formulation. Section 6.3 is devoted to describing the model formulation for Activities. At the activity level, a description of the input parameters and variables used for the agricultural production model is given. This includes prices, yields, costs and the assumptions that are attached to their use in the integrated model where appropriate.

Section 6.4 describes the optimisation procedure used to allocate land to various agricultural activities at the Land Management Units. Section 6.5 describes the model formulation at the Node. This also contains the formulation for the in-stream policy model in Section 6.5.1 and the daily flow extraction model in Section 6.5.3, which are used to integrate extractive LMUs with the hydrological system at the Node level.

6.2 Recent Approaches in Agricultural Production Systems Modelling

Agricultural production models range from computationally simple, regression based or empirical models to models using optimisation algorithms to solve large scale land and water allocation problems. Earlier approaches focused on simply estimating supply and demand curves for production systems. More recent approaches integrate hydrology and production systems at various scales, from farm level to regional and sector level. The most common of these integrated studies simply use output from a hydrological model as an input into a production model (see for example Dimitrios and Lakakis, 1997; Rogers *et al.*, 1993). An analysis of the strengths and shortcomings of these approaches was undertaken for the thesis. The main findings of the review are summarised in the remainder of this section (see Appendix B for the literature review).

- Linear programming (LP) formulations have been widely applied to agricultural production systems modelling, and more recently have been used in conjunction with hydrological models to build integrated assessment models (IAMs). The use of linear programming in IAMs has primarily been to construct systems to inform decision makers with regard to policy options. More recent frameworks have tended to move away from data intensive and computationaly demanding models by aggregating processes. The major assessment and strengths of mathematical programming formulations for integrated land and water systems identified by the literature review are sumarrised below.
- The ability to aggregate processes to the spatial and temporal scale at which the policy question is imposed
- The ability to system represent spatial and temporal processes at various scales integration
- The ability to integrate models with geographic information systems to build model hierarchies and hence produce inter-scale applications
- the ability to identify and define of key processes that are system driving variables within the modelling framework
- validation of agricultural models (often against a base case model) using a linear programming formulation
- recent and evolving application advances in programming techniques to model non-linear and dynamic agricultural production processes (ie use of dynamic programming).

The major weaknesses in using agricultural production models to answer water policy questions were found to be:

- a lack of integration between hydrological and agricultural production systems in most applications, often resulting in a bias toward more detailed representation of the agricultural production system without commensurate levels of detail for the biophysical system

- in most cases there is a lack of integration between the hydrological cycle and the agricultural production system, with the result that the hydrological model (where used) is reduced to a set of inputs that are able to be modelled independently of the agricultural production system (ie determined exogenously before the agricultural production model is run)
- poor conceptualisation and modelling of socio-economic processes with the result that integration between land and water systems is often biased by the influence of biophysical factors upon farmer decision making (as opposed to other social factors that determine economic decisions)
- poor linking of the hydrological and agricultural production systems in a spatial sense. This has limited the number of studies capable of performing both upstream-downstream and temporal trade-offs within a single modelling framework
- lack of integration between agricultural production systems contained within the modelling framework (decisions made within a land unit at a spatially defined point within the catchment are not linked nor expected to affect the resource use, and hence decision of other agricultural production units within the spatial area)
- lack of representation of processes within the hydrological cycle such as runoff, recharge partitioning and groundwater loss.

This review describes the current state of the art in integrated agricultural production systems modelling. This serves the purpose of highlighting the contribution of the model formulation in this thesis as well as eliciting its limitations. Each aspect is discussed in Section 6.6.1 and 6.6.2.

6.3 Model Formulation for Activities

The term 'activities' within the case study catchment refers to agricultural production systems or land uses that are carried out in the catchment. A detailed description of the activities considered by the model was given in Section 4.4. The model is run over a 20-year period, calculating returns and yields for various enterprises given land and water resource constraints and farmer decision making in response to changes in policy imposition. This section describes the way in which economic return and yield per hectare are calculated. The Farm Dams Policy is imposed at this level of the model. This section also describes the way in which this policy is integrated with the production and hydrological modelling systems.

6.3.1 Treatment of Capital Investment

The model considers only short-run production decisions. The costs of capital investment are considered as a one-off fixed cost at the beginning of the 20-year simulation period. These costs are considered to be avoidable once the decision is made to devote an area to an activity. Costs of technological change and potential increases in profit resulting from technological change and investment are not treated in the model.

6.3.2 Profit Calculation at the Activity Level

Profit is calculated on a short-run basis for each activity over 20-years. The net present value (NPV) of profit is calculated for each activity over this time period. The discount rate used for the NPV calculation is 10%. Short run costs for each activity have been identified from gross margin estimates obtained from the NSW Department of Agriculture. Details of the costs included are found in Section 6.3.3. The NPV of profit over the 20-year simulation period for a specified activity is given by:

$$\Pi_i = \sum_{t=1}^{20} (P_{i,t} y_{i,t} - C_{i,t}) \frac{1}{(1+r)^{t-1}} \tag{6.1}$$

where Π_i is profit for activity i, $P_{i,t}$ is the price of the commodity for activity i in year t, $y_{i,t}$ is the yield per hectare for the commodity for activity i in year t, r is the discount rate and $C_{i,t}$ are the costs per hectare of production for activity i at time t. The costs of production include fixed costs that are incurred in the first time period and variable costs that are calculated for each year in the simulated period. Both fixed and variable costs are used on a per hectare basis.

The following section provides the equations for individual agricultural production activities in the catchment. In profiling each production system in Chapter 4, the purpose was to identify links between Activities, Land Management Units and Nodes. Each decision available in the agricultural production system not only defines the characteristics of production system operation, but also determines the point of integration with the hydrological system. As identified in Chapters 3 and 4, there are six activities in the catchment that are considered in the model formulation. They are 1) grazing, 2) forestry for high-yielding hardwood production, 3) forestry for low-yielding softwood, 4) viticulture, 5) lucerne irrigation, and 6) rotational cropping.

6.3.3 Grazing Activity

The formulation for the grazing activity shows the dependence of yield on rainfall (the point of integration between the grazing production system and the hydrological system). The grazing activity consists of two potential cattle production options. Rainfall strongly influences pasture growth. Where a minimum rainfall is not received over the season, pasture growth decreases. Where rainfall over the season is greater than a predetermined threshold, the yield is sufficient to enable sale to market and hence end the production cycle at 12 months. Where this is not the case, the cattle are grown out to 24 months before the production cycle ends. The requirement of feeding cattle in drought-prone years for 24 months results in a lower yield per hectare for the grazing activity.

Pasture growth is determined by a series of rainfall thresholds that correspond to a given yield (see Table 6.1). Each year is divided into four seasons. Total yield is the sum of these seasonal yields. Annual yield per hectare is thus given by:

$$y_t = \begin{cases} 0 & \text{if } \min\limits_{j=[1,2,3,4]} (R_{j,t}) < \bar{r} \text{ and } \min\limits_{j=[1,2,3,4]} (R_{j,t-1}) \geq \bar{r} \\ \sum\limits_{j=1}^{4} \alpha_{j,t} & \text{if } \min\limits_{j=[1,2,3,4]} (R_{j,t}) \geq \bar{r} \text{ and } \min\limits_{j=[1,2,3,4]} (R_{j,t-1}) \geq \bar{r} \\ \sum\limits_{j=1}^{4} \alpha_{j,t} + \alpha_{j,t-1} & \text{if } \min\limits_{j=[1,2,3,4]} (R_{j,t-1}) < \bar{r} \end{cases} \tag{6.2}$$

where

$$\alpha_{j,t} = \begin{cases} \beta_1 & \text{if } 0 \leq R_{j,t} < \mu_1 \\ \beta_2 & \text{if } \mu_1 \leq R_{j,t} < \mu_2 \\ \beta_3 & \text{if } \mu_2 \leq R_{j,t} < \mu_3 \\ \beta_4 & \text{if } \mathrm{R}_{j,t} \geq \mu_3 \end{cases} \tag{6.3}$$

and $R_{j,t}$ is the sum of the daily rainfall over season j in year t, μ_k is the rainfall threshold and β_k is the seasonal yield for the kth threshold, $\bar{r}$ is the rainfall threshold below which cattle are grown out for 24 months, and y_t is the yield (weight of cattle) for year t. Table 6.1 gives the values for yield given each rainfall threshold. The start and end dates of the four seasons are given in Table 6.2.

Table 6.1: Grazing model variables for yield and rainfall

Yield parameter(weight (kg)/Ha sold)	Value
β_1	15
β_2	21
β_3	25
β_4	20
Rainfall threshold Parameter values (mm)	
μ_1	4
μ_2	8
μ_3	15

Table 6.2: Growing season for cattle production defined at the Activity level in the modelling hierarchy

Season	Start Date	End Date
Winter	June 1st	August 31st
Spring	September 1st	November 30th
Summer	December 1st	February 28th
Autumn	March 1st	May 31st

Table 6.3 shows the values for price and cost of cattle production used in the model. These values were obtained from farm budgets provided by the NSW Department of Agriculture. A stocking rate of 20 cows per hectare was assumed (NSW Department of Agriculture, 2001a).

Table 6.3: Price and cost values used as model input for a grazing activity

	Price ($/head)	Cost ($/Ha)
Yearling (12 months)	810	15362
Young cattle (15-24 months)	702	10914

The simplifying assumption was made that 100% of the cattle were sold at either 12 months or 24 months. According to the New South Wales Department of Agriculture, a percentage of cows are retained for future stocking. However, the gross margin estimates used for model input do assume a mortality rate (NSW Department of Agriculture, 2001b; McDonald, 1998).

6.3.4 Forestry Production Activities

Forestry has been modelled as two separate activities, depending on soil type and geology. These activities differ by the yields achieved due to these biophysical differences. Yield of forest products per hectare is also rainfall dependent in time. Harvesting of forest products is assumed to occur in the 7th, 14th and 20th year of the production cycle. However, the equations used to describe the two activities are the same.

At the end of the first 7 years, forest growth given annual average available rainfall is determined and the first commodity harvest is assumed, that being forest thinnings. The activity on low yielding soils is assumed not to produce a high enough yield to obtain a commodity at 7 years.

At 14 years a second harvest is made, producing sawlogs. In this case, the yield of sawlog production is dependent on the average annual rainfall received for forest growth over all 14 years. Where rainfall is sufficient to obtain a yield high enough to obtain an economic return given the costs of production, both forestry activities have the potential to produce sawlogs of varying yields.

The third harvest is made at 20 years. Forestry areas are clearfelled, ending the production cycle. Yield for clear felled logs is also dependent upon the annual average rainfall received for years 15 to 20.

Forestry yield per hectare, y_t for year t, is given as

$$y_t = \begin{cases} 7p_7 \ \textit{if}\ t = 7 \\ 7p_7 + 7p_{14} \ \textit{if}\ t = 14 \\ 7p_7 + 7p_{14} + 6p_{20} \ \textit{if}\ t = 20 \\ 0 \quad \text{otherwise} \end{cases} \tag{6.4}$$

where rainfall dependent, annual forest growth, p_k for k=*7, 14, 20*, is given by:

$$p_k = \begin{cases} \alpha_{1,k} & \text{if} \quad R_k \le \bar{r}_1 \\ \alpha_{2,k} & \text{if} \quad \bar{r}_1 < R_k \le \bar{r}_2 \\ \alpha_{3,k} & \text{if} \quad \bar{r}_2 < R_k \le \bar{r}_3 \\ \alpha_{4,k} & \text{if} \quad R_k > \bar{r}_3 \end{cases} \tag{6.5}$$

where p_k is the annual growth of forest maturity in phase k, $\alpha_{i,k}$ are the rainfall dependent growth values for maturity phase k and between rainfall thresholds i and $i+1$. and R_k is the average annual rainfall over the maturity phase k, and r_i are the rainfall thresholds. Table 6.4 shows the parameter values used for rainfall dependent yield given maturity phases. These values were obtained from the Rural Industry Resarch and Development Council and the Rural Industries Research and Development Council joint venture agroforestry program (Zorzetto and Chudleigh, 1999; DPIE, 2000; Lamb and Borschmann, 1998; McCormack *et al.*, 2000; and Stanton, 2001). The parameter values obtained were from literature concerning commercial forestry in low rainfall areas (being less then 650 mm per annum). For a good overview of typical farm forestry agricultural production practices in Australia, see Harper *et al.*, (2000) and Landsberg (1999).

Table 6.4 illustrates that the greatest growth per hectare per year is obtained in the first 7 years. Total yield per hectare is an aggregate of these values and so is maximised at 20-years.

Table 6.4: Rainfall dependent growth for high yielding forestry (tonnes /Ha)

	t=7	t=14	t=20
$\alpha_{1,t}$	52	14	15
$\alpha_{2,t}$	55	20	25
$\alpha_{3,t}$	65	25	45
$\alpha_{4,t}$	70	35	60

Table 6.5 shows the equivalent growth per hectare for farm forestry carried out on low yielding soils. Where rainfall is particularly low, it is not economically viable to thin the trees at the first stage of maturity (7 years). In this case yield is zero and the trees grow out to the next maturity phase, at 14 years.

Table 6.5: Rainfall dependent growth for low yielding forestry

	T=7	t=14	t=20
$A_{1,t}$	0	50	50
$A_{2,t}$	15	110	100
$A_{3,t}$	80	180	150
$A_{4,t}$	100	200	200

Table 6.6 shows the rainfall thresholds, $\bar{r}_n$, selected for each forestry activity on higher yielding soils, denoted as F_1 and low yielding soils, denoted as F_2. The parameter values are for a standard logging operation in eastern Australia. According to Zorzetto and Chudleigh, (1999) low rainfall values for forestry are between 400 mm to 600 mm per annum. Above this threshold is considered the point at which a higher yielding activity may operate. This sets the thresholds for rainfall dependent yield for the forestry activity. Table 6.6 indicates that, for forestry activities on low yielding soils, a slightly higher volume of rainfall is required to obtain the same growth as a forestry activity on good quality soils. This is the reason for the difference between rainfall dependent growth for these activities.

Table 6.6: Forestry rainfall thresholds (mm/year) for forestry on high yielding soils (F_1) and forestry on low yielding soils (F_2)

	F_1	F_2
$\bar{r}_1$	150	201
$\bar{r}_2$	400	500
$\bar{r}_3$	650	650

Table 6.7 shows the values for price and cost used for both forestry activities given the three different commodities produced in time

Price and cost parameters for both high and low yielding forestry activities	**Cost ($/Ha)**	**Price ($/tonne)**
Low yielding forestry	1840	602 (thinnings) 1074 (small sawlogs) 3164 (sawlogs)
High yielding forestry	2100	990 (thinnings) 4660 (small sawlogs) 6413 (sawlogs)

6.3.5 Viticulture Activities

The Farm Dams Policy is implemented at the viticulture activity level. As with grazing and forestry, viticulture yields are rainfall dependent. Rainfall is captured in farm dams for use as dryland supplementary irrigation for the growing of grapes. The available water for farm dam establishment and grape irrigation is given by

$$V = p_{fd} E \tag{6.6}$$

where V is the volume of water available for farm dam capture per hectare (mm/Ha), p_{fd} is the farm dam policy option (given as a proportion of available rainfall) and E is the average annual effective rainfall potentially available for capture. The variable, p_{fd}, varies with the policy option selected.

With regard to the Farm Dams Policy, it is assumed that the activity area is determined after the available water per hectare has been detemined. This ensures that farmers do not plant more grapes then they could potentially irrigate. The number of hectares required to drain one megalitre of water for grapevine estbalishment is given as

$$k_d = \frac{1}{100 r_c R_t} \tag{6.7}$$

where the runoff coefficient for the catchment is given by r_c , and R_t is the annual rainfall in year t. The model assumes that the grape vines will not be planted unless there is sufficient water in every year to irrigate them. A minimum water volume is predefined for the activity over the 20-year simulation period. The farm dam capture volume is used as a constraint in the LMU supplementary level and is given by

$$\bar{f}_t = \min\left(\sum_{t=1}^{365} r_{i,t}, V\right) \tag{6.8}$$

where $\bar{f}_t$ is the volume of water available to be captured per hectare for a viticulture activity in year t, $r_{i,t}$ is the effective rainfall on day i for year t, and V is as defined in Equation 6.6. This value, $\bar{f}_t$ is passed to the LMU level of the model (see Section 6.4.2).

Water use, costs and yield are time-dependent. There are 3 maturity phases for grape production. In the first 4 years, there is zero yield from the grapes but a high water use given grape vine establishment. During this time in the production cycle, costs are incurred for establishment including the costs of water use per hectare of vines planted to allow grapes to grow to full size. During this period, the economic return is calculated but is always negative given that costs are incurred due to vine establishment but yield is zero. At four years, the first yield occurs and water use per hectare increases due to given the near full maturity of the grape vines. At 7 years, the grape vines are considered fully matured. From 8 to 20 years, the maximum yield per hectare occurs. The yield of grape vine production is given by

$$y_t = \begin{cases} \alpha_1 \text{ for } 1 \leq t \leq 4 \\ \alpha_2 \text{ for } 5 \leq t \leq 8 \\ \alpha_3 \text{ for } 9 \leq \mathrm{t} \leq 20 \end{cases} \tag{6.9}$$

where y_t is the yield per hectare in year t, α_1 is the annual yield of grapes per hectare up until 4 years, α_2 is the annual yield of grapes per hectare from years 5 to 7 years and α_3 is the yield per hectare for grapes at full maturity, from years 8 to 20. The costs of establishing a viticulture enterprise are also time dependent, given by

$$C_t = \begin{cases} k_1 \text{ for } 1 \leq t \leq 4 \\ k_2 \text{ for } 5 \leq t \leq 8 \\ k_3 \text{ for } 9 \leq \mathrm{t} \leq 20 \end{cases} \tag{6.10}$$

where C_t is the cost of grapevine production per hectare for year t, k_1 is the cost of grapes up until 4 years, k_2 is the annual cost of grapes per hectare from years 5 to 8 and k_3 is the annual cost for grapes per hectare at full maturity from years 9 to 20. Water use is also time dependent given by

$$W_t = \begin{cases} \Omega_1 \text{ for } & 1 \leq t \leq 4 \\ \Omega_2 \text{ for } & 5 \leq t \leq 8 \\ \Omega_3 \text{ for } & 9 \leq t \leq 20 \end{cases} \tag{6.11}$$

where W_t is the total wateruse per hectare for grapevine production per hectare in year t, Ω_1 is the annual water use per hectare of grapes up until 4 years, Ω_2 is the annual wateruse of grapes from years 5 to 8 years, and Ω_3 is the annual water use per hectare for grapes at full maturity, from years 9 to 20. Table 6.8 shows the parameter values for water use per hectare, cost and yield for a viticulture enterprise at the three stages of maturity. Other input variables include a runoff-coefficient that was estmated as 0.21 using rainfall and streamflow data in Yass catchment, and a price received for grape production, given as \$760/tonne (Department of Natural Resources and Environment, 2000).

Table 6.8: Values for Yield (tonnes/Ha), Wateruse (ML/Ha) and Costs (\$/Ha) used as model input for a viticulture activity

j	α	Ω	K
1	0	5	4840
2	18	6	4221
3	24	4	610

Values were obtained from the Australian Bureau of Agricultural and Resource Economics and the Grape and Wine Research and Development Corporation (Shepherd, 1999; and Shepherd, 2000). This data covered New South Wales and the Australian Captial Territory region which contains the Murrumbidgee Irrigation Area grape data. Various biophysical and economic factors influence the profitability and viable size of a viticulture enterprise from catchment to catchment. Typically, the enterprise occurs on subdivided plots of land. This precludes large-scale viticulture operations such as those found in the Hunter Valley.

Table 6.9 gives the industry benchmark profitability of a viticulture enterprise for wine production. Profitability is divided into Low, Industry Standard and High profitability. Given the low annual rainfall in Yass catchment, the relatively poor soil quality and inability to pump water from the stream for supplementary irrigation, the assumption was made that the activity in Yass catchment was within the lowest category for grape production. This was compared with the more favourable profitability factors in the

Murrumbidgee Irrigation Area. Table 6.9 shows the break down of fixed and variable costs used as model input varables. The shaded area numbers have been used as input parameters for the Yass catchment model.

Table 6.9: Profitability factors for the Wine Grape Industry in the Murrumbidgee Irrigation and Griffith areas. Shaded numbers are used for Yass catchment integrated model

	Low (bottom 25% of all growers)	**Industry standard**	**High (top 25% of all growers)**
Size (Ha)	33	28	32
Price ($/tonne)	731	760	912
Yield (tonnes/Ha)	14	24	29
Income ($/Ha)	10426	17759	26598
Costs			
Overhead Costs ($/Ha)	240	345	321
Capital Costs ($/Ha)	4557	4503	4555
Variable Costs ($/Ha)	500	610	293
Profit ($/Ha)	428	8081	17879

According to Shepherd (2000), the minumum size for a viable operation in a catchment such as Yass is approximately 33 Ha. This was used as a constraint on the minumum area selected under the optimisation. Where an area less then 33 Ha was selected, the area was given to the next most viable land use activity given by the optimisation procedure.

6.3.6 Lucerne and Rotational Cropping Irrigation Activities

Lucerne irrigation and rotational cropping have a similar production cycle, with the exception that the rotational cropping activity is planted as a fixed proportion of the total irrigable area available given its requirement to be carried out in conjunction with grazing. Given all other decision rules occur at the same time, the two activities are treated in a similar manner, as irrigation activities.

At the Activity level, yield, price and costs are constant in time and space for these irrigated activities. Unlike the viticulture activity, it is assumed that the volume of water required per hectare to sustain lucerne and rotational cropping does not vary over time.

Yield per hectare is also a constant for the entire simulation period. Table 6.10 shows variable values used as model inputs at the Activity level for lucerne and rotational cropping activities (NSW Department of Agriculture, 2001d).

Table 6.10: Values used as model input at the activity level for irrigated activities

	Yield (tonnes/Ha)	Costs ($/Ha)	Price ($/tonne)	Wateruse (ML/Ha)
Lucerne	8	938	200	6
Rotational Cropping	6	298	100	4

Values were obtained from the New South Wales Department of Agriculture Farm Budgets (NSW Department of Agriculture, 2001a; NSW Department of Agriculture, 2001c; NSW Department of Agriculture 2001e). Information regarding operation of an agricultural production system for pasture and rotational cropping was also obtained from The NSW Department of Agriculture.

6.4 Land Management Units

As discussed in Section 4.5, Land Management Units (LMUs) are the second level in the modelling heirachy. There are 12 LMUs representing the Yass catchment system. The Salinity Management Policy (through forestry plantation) is imposed at the LMU level. Production decisions are simulated at the LMU level, given constraints on land and water. It is assumed that the LMUs are each operated by a single, profit maximising farmer with perfect knowledge. Profit maximisation is carried out by a linear programming formulation using a simplex algorithm. Details of the algorithm can be found in Strayer, (1989). The next section identifies the model formulation for each generic LMU type.

6.4.1 Dryland Land Management Unit

Dryland Land Management Units potentially contain three activities: grazing, forestry located on poor yielding soils and forestry located on high yielding soils. This LMU type is the simplest in that it has one point of integration with the hydrological system. Two policy options may be pursued: to impose or not to impose a Salinity Management Policy by forestry plantation.

Dryland Option 1: Salinity Management Policy is Imposed

Where salinity management through forestry plantation is imposed on the Land Management Unit by, then forest area is given by,

$$F_j = A_j P \tag{6.12}$$

where F_j is the area planted to the *jth* soil type, j=1,2 is the forestry activity on the *jth* soil type, P is the percentage of forest as specified by the salinity management policy option and A_j is the area of land within the LMU of soil type *j*. A Salinity Management policy option is given as a proportion of the catchment area. It has a single value ranging from 0 to 1. The remaining area of the catchment is available, for the grazing activity given by:

$$G = \sum_{j=1}^{2} A_j - F_j \tag{6.13}$$

where G is the catchment area planted to grazing, A_j is the area of the LMU after the imposition of the Salinity Management Policy option by forestry plantation, given in Equation 6.12.

Dryland Option 2: Land use Choice by Simulation

The second option available within the LMU is to refrain from imposing a plantation forestry option, in which case the selection of areas for activity establishment is determined by simulated farmer decision making. This component of the integrated model simulates decision making behaviour for the LMU assuming the LMU is controlled by a single, profit maximising farmer with perfect knowledge. Thus, behaviour is simulated as the solution to the following optimisation problem:

$$\left.\begin{aligned}&Max(d_1F_1 + d_2F_2 + d_3G)\\[1em]&\text{subject to the constraints :}\\[1em]&F_1 + F_2 + G \le A_1 + A_2\\&\qquad F_1 \le A_1\\&\qquad F_2 \le A_2\end{aligned}\right\}\tag{6.14}$$

where d_1 is the per hectare economic return from a forestry activity on high yielding soils, F_1 is the area selected for forestry on high yielding soils, d_2 is the per hectare economic return from a forestry activity on low yielding soils, F_2 is the area selected for forestry on low yielding soils, d_3 is the economic return per hectare for a grazing activity and G is the area selected for grazing. As previously defined, A_1 is the area within the LMU available for a forestry activity on high yielding soils and A_2 is the area within the LMU available for forestry on low yielding soils.

6.4.2 Supplementary-Irrigation LMU

The supplementary-irrigation LMUs contain up to four activities, being viticulture, grazing, forestry on high yielding soils, and forestry on low yielding soils. Within this LMU type, water and area constraints are determined for the viticulture activity. All activities are constrained by available land. At this level, a choice between two policy options can be made. In the first case, a Salinity Management Policy option is imposed. In this case, a pre-determined proportion of land is devoted to forestry. Consequently, land is taken out of production from other activities under this policy option. The remaining land available is devoted viticulture or grazing activities by solution of an optimisation problem. The second option is where a Salinity Management Policy option is not imposed. This involves a choice between the all land use activities.

Supplementary-Irrigation Option 1: Salinity Management Option is Imposed

The Farm Dams Policy is implemented at the activity level. At the LMU level, the water constraint is calculated for each phase of grape vine maturity. Three land and water constraints are then used in the optimisation to determine area devoted to viticulture. As in the case of the dryland LMU type

$$F_j = A_j P \tag{6.15}$$

The area remaining (not under forestry) in the LMU on which a farmer makes a decision with regard to land use is given as

$$B = \sum_{j=1}^{2} A_j - F_j \tag{6.16}$$

where B is the area of the LMU available for other land uses after an area of the catchment has been planted to forestry under the salinity management policy. Let

$$\begin{aligned} \phi_1 &= \max_{1 \le t \le 4} (W_t . e) \\ \phi_2 &= \max_{5 \le t \le 8} (W_t . e) \\ \phi_3 &= \max_{9 \le t \le 20} (W_t . e) \end{aligned} \tag{6.17}$$

where W_t is the water use per hectare in year t (given by Equation 6.11) and e is the irrigation efficiency from farm dams. This has been estimated as 0.65 for this thesis. The available water that is used as a constraint for each maturity phase is then given by

$$\begin{aligned} \overline{w}_1 &= \min_{1 \le t \le 4} (\frac{f_t}{100}).A_v \\ \overline{w}_2 &= \min_{5 \le t \le 8} (\frac{f_t}{100}).A_v \\ \overline{w}_3 &= \min_{9 \le t \le 20} (\frac{f_t}{100}).A_v \end{aligned} \tag{6.18}$$

where f_t was calculated in Equation 6.8. Division by 100 converts rainfall capture by farm dams to megalitres per hectare. The total area available for capture is then equal to the area available for viticulture excluding forestry.

The remaining area, B, now becomes a constraint on decision making, defined in Equation 6.20. The area planted to either grazing or viticulture is given by the solution of a problem of the following form

$$\left.\begin{aligned} & Max(d_3G + d_4H_a) \\ & \text{subject to the constraints :} \\ & G + H_a \le B \\ & \quad H_a \le A_v \\ & \phi_1 H_a \le \overline{w}_1 \\ & \phi_2 H_a \le \overline{w}_2 \\ & \phi_3 H_a \le \overline{w}_3 \end{aligned}\right\} \qquad (6.19)$$

where d_3 is the total economic return for a grazing activity per hectare, and G is the area planted to grazing given the solution to the optimisation procedure. The total economic return for a viticulture activity per hectare is given by d_4 and H_a is the area planted to a viticulture activity, A_v is the LMU area that is able to be planted to viticulture given its biophysical attributes of slope, aspect, soil type and land capability being, deemed suitable for the establishment of a viticulture activity (see Section 3.22). Decisions are also constrained on viticulture establishment by the total area (B) available at the LMU after the imposition of the salinity management option. Grazing is only constrained by this area (B).

Supplementary Irrigation Option 2: Land use choice by simulation

The second option within this LMU type uses a linear programming formulation to identify land use given four potential land use options. The following linear programming formulation is used where a Salinity Management Policy option is not imposed:

$$\left.\begin{array}{l} Max(d_1 G + d_2 F_1 + d_3 F_2 + d_4 H_a) \\ \\ \text{subject to the constraints:} \\ \\ G + F_1 + F_2 + H_a \leq A_1 + A_2 \\ \\ \quad F_1 \leq A_1 \\ \quad F_2 \leq A_2 \\ \quad \mathrm{H_a} \leq A_v \\ \phi_1 H_a \leq \overline{w}_1 \\ \phi_2 H_a \leq \overline{w}_2 \\ \phi_3 H_a \leq \overline{w}_3 \end{array}\right\} \qquad (6.20)$$

All other terms and constraints are as previously defined under supplementary-irrigation Option 1.

Within this LMU type, two additional calculations are made with respect to viticulture and forestry. After the area devoted to each activity has been determined by the optimisation, two variables are required as input into the hydrology model at the Node. These are the fraction of forested area, and the catchment area draining to farm dams. Each is used in the hydrological model to simulate the impact of farm dams and runoff and associated farm dam capture as a result of viticulture establishment and forest plantation respectively.

Having determined the total area of the catchment planted to the viticulture activity by either Option 1 or Option 2, the total volume of dams contained within each LMU is calculated as

$$D_{\mathrm{lim}} = \frac{Ha.\max\limits_{i=1,2,3}(\phi_i)}{e} \qquad (6.21)$$

where D_{lim} is the total volume of farm dams summed over a single LMU area. All other variables are as previously defined.

The maximum volume of water required in any year is used in this calculation because it was assumed that the farm dam is constructed to hold the maximum amount of water required by the vine grapes at any point in the production cycle. i.e. a farmer will not build a smaller dam than is required to keep the vine grapes from wilting. One could assume a larger volume in reality for contingency purposes in dry years. For the purpose of the modelling approach, it is assumed that the size of the farm dam constructed and volume of water captured by the dam is sufficient to satisfy vine grape requirements during the irrigation season and average evaporative losses and no more. This calculation also used the assumption that famers have perfect knowledge. Hence, no additional volume was assumed to be necessary to manage the risk of dry years. This is one assumption of the model that could be tested if required.

The total area draining the catchment is required to ensure that an overestimate of water captured by dams is not applied to the model. For this reason, the variable k_d was estimated at the activity level and defines the area of the LMU catchment required to drain 1 ML of water. At the LMU level, k_d is used in conjuntion with the solution from the linear programming formulation to identify the farm dam area in hectares draining the catchment , given as

$$\lambda_{den} = \frac{D_{\lim}}{k_d} \tag{6.22}$$

where all terms are as previously defined. This variable is passed to the hydrological model at this Node (see Section 6.5)

6.4.3 Irrigation LMUs

An irrigation LMU potentially contains two activities: lucerne irrigation and rotational cropping. Dryland activities and supplementary irrigation activities do not have the option of operating within irrigable land areas and vice versa. The total area of potential irrigable land defines the boundaries of the irrigation LMUs. Given the separation of the LMU irrigation type, the formulation of the model is restricted to a linear programming problem to determine the optimal area of land laid to lucerne and rotational cropping activities. A water constraint is determined by the volume of streamflow able to be pumped given climate and Volumetric Conversions Policy options. The area constraint is simply the total area of land within the irrigation LMU. The land use decision made by farmers is given as the solution to the following linear programming formulation

$$\left.\begin{array}{l} Max(d_5 L + d_6 R) \\ \text{subject to the following constraints:} \\ L + R \leq A \\ W_L\ L + W_R\ R \leq U \end{array}\right\} \qquad (6.23)$$

where d_5 and d_6 are the total economic return obtained from lucerne and rotational cropping irrigation activities respectively. The area devoted to lucerne and rotational cropping is given by L and R respectively. The total area of the irrigation LMU is given by A. The variable, W_L, is the water required per hectare to sustain a lucerne production activity (crop conversion rate) W_R defines the crop conversion rate for a rotational cropping activity and U is the available water for irrigators to extract from the stream given environmental and volumetric flow policies (see Section 6.5.1 for its derivation).

6.5 Node Model Formulation

At the Node level, the third policy option pertaining to Volumetric Conversions is implemented. Nodes utilise several variables generated at the LMU and Activity level to integrate agricultural production systems with the catchment hydrological systems. There are 4 Nodes that represent the Yass system (see Section 4.7).

The Node formulation is the point of integration between spatial units: LMUs, and the hydrological system. Three key interactions resulting from farm dam capture, forest cover changes and in-stream extraction occur at the Node. The first involves a calculation of streamflow given changes in runoff. This is a result of dryland and supplementary irrigation operation in the form of forestry plantation and viticulture operation-induced changes to runoff. The second option involves using the recalculated runoff to determine water available from streamflow using a policy model (see Section 6.5.1) for irrigation activities. The third interaction calculates the impact of irrigation extraction on daily streamflow using a daily extraction model (see Section 6.5.3).

Note that within irrigation LMUs, the required water has been calculated to satisfy the crop area but it is at the Node level that water is extracted from the stream. Daily extractions and changes in runoff are used as inputs to downstream Nodes. This reflects the impact of irrigation extraction, forestry and farm dam on the hydrological system at each Node.

The first calculation carried out at the Node is to sum the forested areas acros all LMUs at the Node. This is then divided by the total nodal area. That is

$$F_f = \sum_{m=1}^{k} \frac{F_1(m) + F_2(m)}{A_n} \tag{6.24}$$

where F_1 and F_2 are the areas of each forestry activity within each LMU region, denoted by m, A_n is the total catchment area for the Node, and k is the total number of LMUs at the Node. This forest fraction (F_f) is then passed to the hydrological model at the Node.

Two other points of integration occur between LMU and Node level in linking the hydrological and agricultural production systems. The variable defining the volume of farm dams in the mth LMU region, $D_{\lim}(m)$, is aggregated and used at the Node level as an input to the hydrological model. Similarly, $\lambda_{den}(m)$ is the area draining the catchment to farm dams in the mth LMU region. Both are summed across the LMU to give a total farm dam density and farm dam volume at the Node. This is given by

$$\Gamma_{den} = \frac{\sum_{m=1}^{k} A(m)\lambda_{den}(m)}{A_n} \tag{6.25}$$

where Γ_{den} is the density of farm dams at the Node, $A(m)$ is the area of the mth LMU, and all other terms are as previously defined.

The values for the farm dam density, farm dam volume and forest fraction are calculated at the Node level before being used as inputs to the hydrological model to determine streamflow at the Node after the impact of farm dams and forestry plantation on runoff.

6.5.1 Policy Model for the Irrigation LMUs: Volumetric Conversions

The second key interaction carried out at the Node involves the determination of the allowable streamflow extraction for activities for the irrigated LMUs. The available water for extraction each year after the imposition of volumetric limits (see Section 3.13.1 for an explanation of volumetric rule limits) is calculated by Equations 6.26 to 6.29 as follows:

$$\psi_t = \begin{cases} 0 & if \quad q_1 < L_1 \\ M_1 & if \quad L_1 \le q_t < L_2 \\ M_2 & if \quad L_2 \le q_t < L_3 \\ M_3 & if \quad q_t \ge L_3 \end{cases} \tag{6.26}$$

$$D_t = \min(q_t, \psi_t) \tag{6.27}$$

$$F = \sum_{t=1}^{365} D_t \tag{6.28}$$

$$U = \min(F, W) \tag{6.29}$$

where q_t is simulated daily flow obtained from the IHACRES daily rainfall-runoff model (see Chapter 5), L_1, L_2 and L_3 are flow pump limits and M_1, M_2 and M_3 are bulk extraction limits, W is the licensed allocation, U is the streamflow available after the volumetric policy options has been implemented and t is time in days over a year. The methods by which volumetric pump rules and bulk extraction limits are calculated are described in the next section.

6.5.2 Calculation of the BEL and CTP limits at the Node

The calculated peak demand for daily water in the catchment (the maximum daily demand to meet production requirements) is 28 ML per day (DLWC, 1998d). It is suggested that the BEL (bulk extraction limit) should be current peak daily demand less

10%, as identified in the review of current policy options in Section 3.13. As Table 6.10 illustrates, the gauged flow in Yass catchment has a long term annual average of 22 527 ML. The annual entitlement is set at 4 270 ML with the BEL set at 25.2 ML/day. The CTP rules also provide for protection of low flows specifically by restricting pumping to above 0.34 ML per day.

As Table 6.11 indicates, the 80th percentile calculated for 20 years of streamflow data was 0.34 ML while the 50th percentile was calculated as 2.85 ML. Given an off-season demand of 13 ML and an irrigation season demand of 28 ML for the catchment, it is obvious that the original volumetric rules are unworkable in the catchment. For this reason, and because of the ephemeral nature of the catchment, The Department of Land and Water Conservation (DLWC) has recommended that only the C class licence allocation should be implemented (DLWC, 1999c). Recent documents suggest the 50th percentile as the C class license allocation while other documents suggest the 80th percentile (model sensitivity to both is tested in Chapter 8). To overcome the problem of volume calculation, zero flows were removed from the streamflow record. Table 6.12 gives the resultant 50th and 80th percentile flows that were trialled as scenarios in the integrated model (see Section 7.7).

Table 6.11: CTP rules where the whole streamflow record is utilised with gauged data

Protection of Low Flows: Option 1	
Total Annual Average long term gauged flow (ML)	22527
BEL (bulk extraction limit)	25.2
Average Daily Percentile Flow Bands	
80th percentile (ML)	0.34
50th percentile (ML)	2.85
30th percentile (ML)	8.92
20th percentile (ML)	18.35
Flow Rules (Commence/Cease To Pump Rules)	
A class	0
B class	0
C class	Remaining flow to 0.34 ML

Table 6.12: CTP rules where zeros flows are removed from the streamflow record with a BEL of 25.2 and a CTP of 21.6 with gauged data

Protection of Low Flows: Option 1	
Total Annual Average long term gauged flow (ML)	22527
BEL (bulk extraction limit)	25.2
Average Daily Percentile flow bands	
80th percentile (ML)	21.60
50th percentile (ML)	10.63
30th percentile (ML)	3.62
20th percentile (ML)	0.51
Flow Rules (Commence/Cease To Pump Rules)	
A class	0
B class	0
C class	Remaining flow above 21.6

6.5.3 Daily Flow Extraction Model

Having determined the annual water use of irrigated activities and available streamflow, daily water extraction is simulated. Total annual water use at each Node is distributed across each day of the streamflow simulation by the daily flow extraction model. The model assumes that extraction during the irrigation season is proportional, for each day, to the total volume that is able to be extracted given the daily flow extraction rules. This is given by

$$d_t = D_t . \frac{Y}{F} \tag{6.30}$$

$$y_t = q_t - d_t \tag{6.31}$$

where d_t is the daily extraction limit, Y is the total volume of water used by the irrigated activity, F and D_t are as defined previously, q_t is the simulated daily flow and y_t is the daily streamflow after extractions have been deducted. Daily extractions are passed to the next Node to be deducted from streamflow before the irrigated production model is run at the Node. This ensures that the effect of irrigation extraction on water available at downstream Nodes is taken into account. Extraction from the stream is the only time series variable passed between Nodes. It also ensures that spatial trade-offs as a result of Volumetric Conversion Policy imposition can be estimated, which was one of the objectives of the integrated model (see Chapter 4).

6.6 Conclusions

This Chapter has presented the model formulation developed to construct the agricultural production models and integrate them with the hydrological models. Operation of the agricultural production systems is defined by the availability of water. This is seen in the model formulation for LMUs in Section 6.4. All decisions carried out in the formulation are as a result of availability of water or changes in water from the hydrological system.

Section 6.3.2 showed the simple annuitised economic return per hectare equation used for each activity. A consistent discount factor is used for all activities. This section also showed how yield for dryland and supplementary irrigation activities are rainfall dependent. At the LMU level, the model formulation shows how biophysical factors such as soil type, catchment runoff coefficients, evapotranspiration and available daily rainfall are integrated with the production model formulation. At the Node level, available daily streamflow is integrated with the production models

6.6.1 Contribution of the Model Formulation

The modelling conceptual framework defined in Chapter 4 and the model formulation in Chapter 6 make the following contribution to modelling agricultural production systems:

- Hydrological processes such as recharge, runoff and streamflow responses to rainfall are represented and modelled by a daily rainfall runoff model. Integration of the hydrology model with the linear programming formulation occurs through interactions with these three parts of the hydrological cycle with the agricultural production system.
- The hydrological model is used at several points for integration between systems. Inputs from the model are used to inform the agricultural model. The response of the hydrological model is then fed back into the hydrological model. The integration is tight to the point that the hydrological model is run to determine economic decisions, which in turn are required for changes to the hydrological system. Thus, unlike the majority of studies, identified in the literature review, the point of integration between systems occurs at more then one junction per model run.

- Multiple policy options are modelled within the system. The approach is particularly useful for policy makers in that the conceptual framework is flexible enough to conduct an analysis of multiple policy options, which can be demand or supply side oriented.
- Modules developed in the conceptual framework and the processes represented are generic and could be scaled to allow potential application of the approach outside of the case study catchment to which it is applied in the thesis.
- Also the integrated modelling is undertaken in a comprehensive way, such that the hydrological and agricultural production models are of equal detail. In doing so, the aim has been to present an integrated study while minimising disciplinary bias (discussed in Section 2.11 and Appendix B). The result is a much more robust integrated model in that impacts on either the hydrological or agricultural production system are equally useful in scenario analysis

6.6.2 Potential Modelling Contribution not to be Addressed

The literature review found in Appendix B revealed several evolving areas in modelling integrated agricultural production systems. The modelling approach developed in the thesis has several areas which are outside the scope of the approach or which represent a weakness in the conceptual approach. The major limitations are summarised below:

- There is a lack of representation of social factors that influence the decisions made by farming units. All points of integration and decisions are determined by the conditions contained within the biophysical system of the catchment. The economic system (including such factors as interest rate changes and access to technology) is assumed static.
- The agricultural production model is short-run in that farmers cannot respond to policy changes by capital investment. Rather, a profit maximising farmer only has the choice of land use change given that technological change is not possible.

This Chapter has served to identify the contribution of the integrated modelling formulation developed in this thesis. More importantly, it highlights what is not included, and therefore what are the limitations of the conceptualisation and model formulation used in this thesis. Chapter 7 outlines the results for various policy scenario runs and base case model run the integrated model.

Chapter 7 The Base Case and Policy Scenario Simulation

7.1 Introduction

Chapters 7 and 8 are devoted to evaluation of the integrated model. The purpose of this Chapter is to demonstrate how model outputs and indicators change in response to selecting and running scenarios changing the three land and water policies. Indicators used to assess model output are given in Section 7.2. This analysis of model output is aimed at identifying the plausibility of the model results, and therefore, how well the model conceptualises the links between the agricultural production, hydrological and policy systems.

The Base Case model conditions are given in Section 7.3. A Base Case model run serves to provide a useful tool for evaluating the extent to which the model is capable of representing the system described in Chapter 3. It also illustrates the major assumptions made in conceptualising the agricultural production system. This has implications for assessing the model limitations later in Section 7.9. The Base Case model runs are used as a benchmark against which to evaluate impacts of running policy scenarios. Sections 7.5 to 7.8 contain the results of running the integrated model. A discussion of results from the integrated model, its usefulness and limitations is given in Section 7.9. Conclusions of the Chapter are given in Section 7.10. This provides the basis for sensitivity testing of the model in Chapter 8.

7.2 Model Output Interpretation and Indicators

In developing the integrated model in this thesis, emphasis has been placed on conceptualising the system links correctly rather than on using absolute output as exact numbers to inform the policy environment. Given this emphasis, the direction and relative magnitude of change in model output to a policy option is considered of the utmost importance in model evaluation. Indicators provide a way to assess the direction and relative magnitude of changes in model output. Three main indicators were selected to analyse model results from each policy scenario. They were area of an Activity in hectares, streamflow in megalitres per day and regional profit in dollars. It is the variation in these quantities from the Base Case or other cases that is considered when interpreting the model results.

The plausibility of the model outputs is often difficult to compare on a regional basis due to the limited observed data available for the catchment. For this reason, and, where appropriate, regional profit is converted to dollars per hectare and streamflow is indicated by the number of zero flow days and/or the median of non-zero flows. All model outputs are compared with the Base Case model run for analysis.

7.3 The Base Case Model Simulations

The following sections outline the major assumptions used in developing the Base Case model. It shows the adequacy of the model in representing the system as well as identifying the major limitations of the model conceptualisation in developing the integrated model. Base Case modelling inputs were obtained from Australian Bureau of Agriculture and Resources Economics (ABARE), The NSW Department of Agriculture and the Australian Bureau of Statistics (ABS). Yass catchment is considered to be a sub-region within the Upper Murrumbidgee for the ABS data and most ABARE data sets. For this reason, a comparison with actual data for the Yass catchment was problematic. This problem was partially overcome by comparing the regional farm budgets with the Base Case model output on a per hectare and annual basis for each activity where possible.

7.3.1 Total Area: Agricultural Activities

Figure 7.1 illustrates the area devoted to various agricultural activities under the Base Case scenario. Grazing is the main activity in the catchment, covering approximately 75% of the total catchment area (as identified in Chapter 3). The Base Case area is therefore indicative of the current grazing land use. There is very little forestry activity in the catchment (less than 20 hectares according to the digital land use map); hence the value of zero hectares planted to forestry is a reasonable assumption. The Base Case model also allocates a very small area to irrigated activities. This is consistent with the land uses identified in Chapter 3.

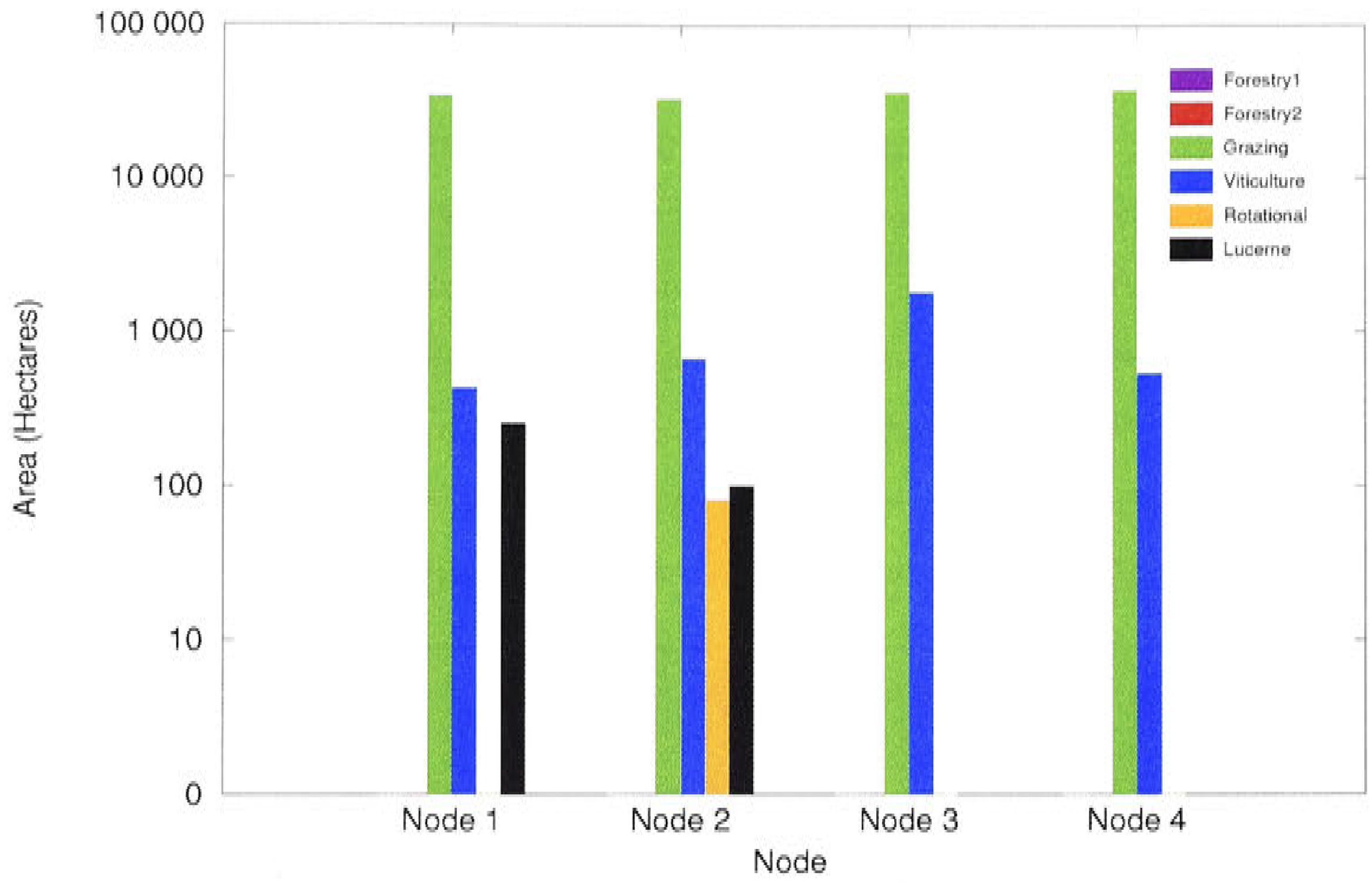

Figure 7.1: The Base Case area (Ha) by Node for agricultural production activities in Yass catchment. Areas shown as logarithmic values

The Base Case model makes the assumption that areas where irrigated lucerne and rotational cropping activities are limited to areas in the upper and middle catchment where water and fertile river flats are available. These activites are not found in the lower catchment due to poor soil fertility and lack of water caused by upstream extraction for the town water supply. As can be seen in Figure 7.1, irrigated activities are excluded from Nodes 3

The Base Case model overestimates the current area planted to viticulture. This is due to the nature of the model structure and constraints set. The model structure uses a linear programming formulation to select an activity by profit maximisation based upon land, water and labour constraints. As viticulture is the only 'value-added' intensive activity in the model, it could be expected that the model formulation would overestimate the current area laid to viticulture. Secondly, the viticulture activity is constrained by land capability classes, of which a high proportion of the total catchment area was deemed suitable for viticulture according to the biophysical constraints. This is an example of how the modelling system is limited due to the simple input assumptions generated in the conceptualisation.

7.3.2 Total Profit in the Yass Catchment

Figure 7.2 illustrates the profit by node of agricultural activities within the catchment under the Base Case. Forestry activities yield zero economic return given that no land is allocated to forestry under the current situation. This is expected given the low economic return for forestry production and the assumption of profit maximisation in the model. Therefore, the modelling assumption in the Base Case serves two purposes: a) it represents the current level of forestry in the catchment well; and b) it allows the cost of forestry to be ascertained in policy option scenarios where forestry is imposed as a land use.

Rotational cropping and lucerne irrigation activities receive a higher economic return per hectare than grazing. This is represented well by the Base Case model as indicated by its comparable profit to grazing at Nodes 1 and 2 given their significantly smaller areas.

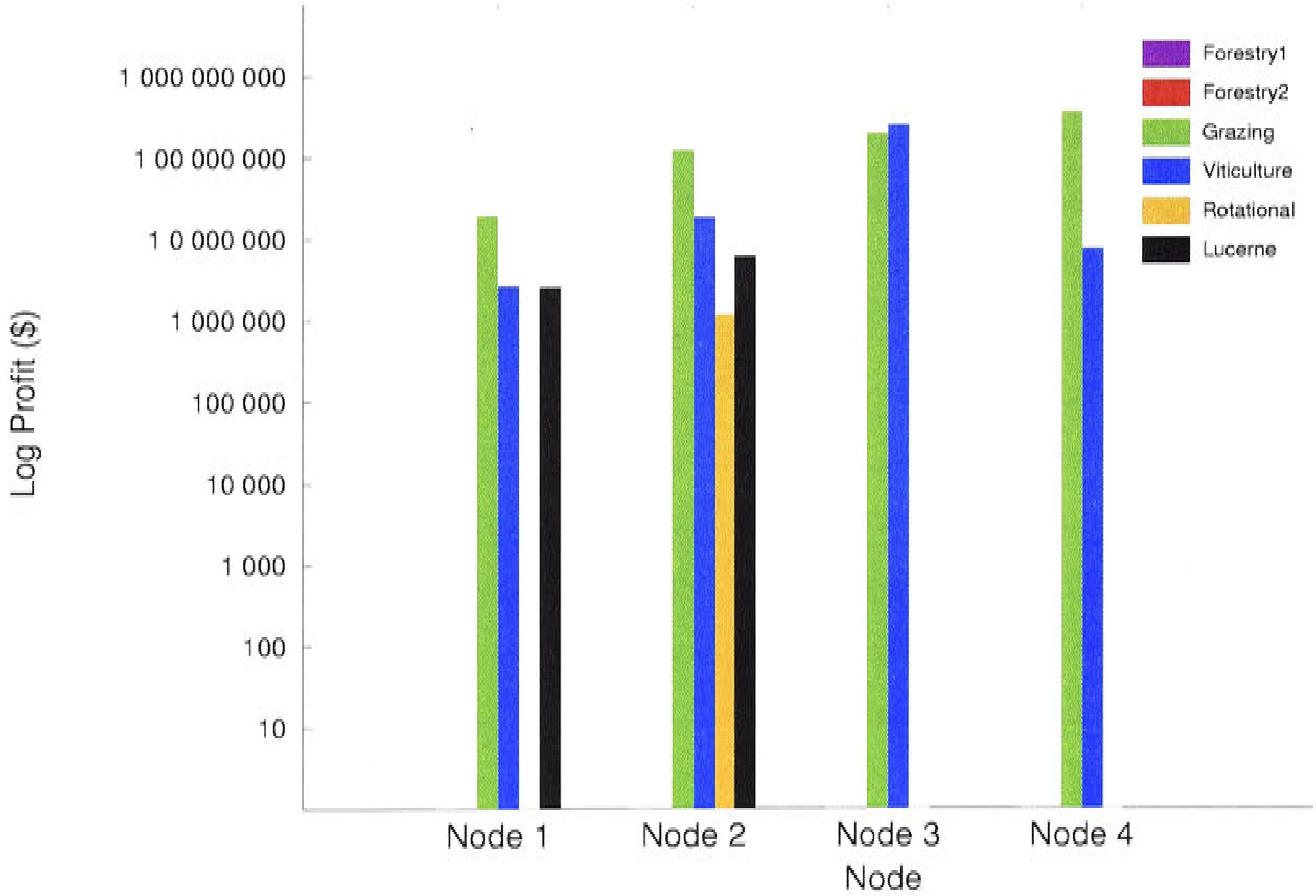

Figure 7.2: Total profit over simulation period of agricultural activities ($) by Node for the Base Case in theYass Catchment. Profit shown as logarithmic values

7.4 The Base Case and Modelling Assumptions for Agricultural Production Activities

This Section outlines the major modelling assumptions used in the Base Case with regard to agricultural production activities.

7.4.1 Viticulture

Of the three production modules, the viticultural production system had the most complex interaction with the hydrology, through the use of farm dams. Several assumptions were made regarding the capture and use of water in the production system.

The model limits the area planted to the activity by imposing a land constraint. This constraint value is set as the maximum area suitbale for viticulture at the Node given soils and topography. Rainfall is also used as a constraint in the linear programming formulation. This constraint restricts the activity by rainfall available for capture, and subsequent irrigation, to 10% under the current Farm Dams Policy. The model also calculates the area required to drain 1 ML of water. It is assumed that a viticulture enterprise requires 4 ML of water per hectare. The constraint operates under the assumption that the average farm dam size in the catchment is 6 ML (the most common estimated by Scown, 2000). An evaporative loss from the dams of 65% was also assumed. In addition, the rainfall available for capture was restricted to a runoff coefficient of 0.21, calculated by available streamflow and rainfall records in the catchment. Given the hydrology of the catchment and the water required for the activity, most dams were emptied every 12-18 months. Hence, if a wet year occurred, excess runoff above the farm dam capacity in megalitres per hectare was not captured, but allowed to runoff as streamflow. This ensures that the model only allocates to viticulture what is physically possible given current agricultural production technology.

It would not be unreasonable to expect farmers to buy up land for the purpose of water capture while only setting a small portion of land aside for grape production. This would involve allowing the model to collect water potentially from the entire catchment area and using excess land for grazing. An alternative is to assume that the production system can only capture water from the area given over to grape production. Although each are equally feasible and possible, it was decided to select the former assumption for model operation. The reason is that grape growers in theYass catchment are located on small plots of land that have been subdivided from grazing activities. The production system is smaller in that it consists of intensive hobby farms for production or boutique wineries. This is unlike the larger commercial operations in other regions, that could potentially buy up land solely for the prupose of capturing water. As a result, water became the limiting resource for viticulture activities in the model. This assumption also has the advantage of capturing the sensitivities of the production system to water policy related changes, a key aim of the conceptualisation. An additional modelling assumption that was made, given the characteristics of grape production in the Yass was the restriction of rainfall-runoff capture to fill farm dams only. In other production areas, extraction from the river could take place as part of the supplementary irrigation activity. In the Yass catchment there are currently no viticulture activities that pump water from the stream.

Figure 7.3 shows the annual per hectare economic return from the operation of a viticulture enterprise, consistent with the NSW Department of Agriculture farm budget. It illustrates the type of assumptions made for the operation of a viticulture activity. A viticulture activity requires a high level of initial investment costs. In the first four years grape yield is also zero owing to the time required for grapevine maturity. According to the production system assumptions, the activity experiences a loss for the first four years followed by a steady increase as yield becomes positive.

Table 7.1 illustrates a comparison between the economic return per hectare per year obtained from the model and the NSW Department of Agriculture Farm Budgets and information from the CRC for Viticulture. The Base Case model output suggests an annuitised return per hectare over 20-years of $13 538. This is slightly higher than the industry average shown in Table 7.1. A gross margin of this magnitude was considered reasonable when compared with highly profitable areas such as Sunraysia in Victoria and the Hunter Valley in NSW. This was also considered reasonable given the 'boutique' wineries within the area that concentrate on producing low volume, high quality wines.

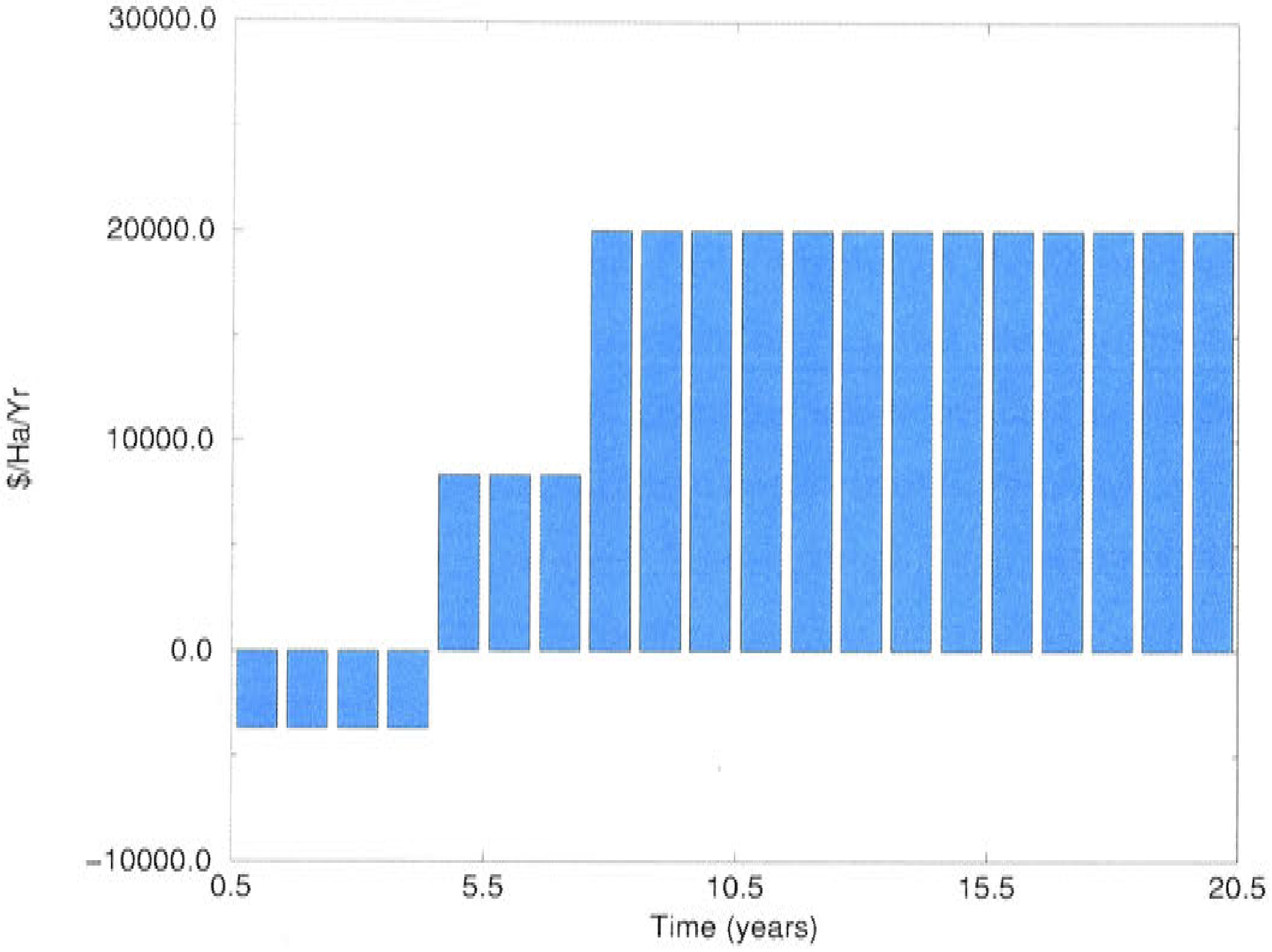

Figure 7.3: Model representation of gross margin ($/Ha/Yr) for a viticulture enterprise in the Yass catchment for the Base Case

Table 7.1: A comparison of actual and Base Case values for the economic return from viticulture in Yass catchment

Viticulture Enterprise Profit Factors	Low 25% Profit	Industry	High 25% Profit	Model Gross Margin
Gross Margin ($/Ha/Yr)	428	8 081	17 879	13 538

In order to determine the area laid to viticulture under a supplementary irrigation scheme through runoff capture, the total area required to drain 1 ML of water sets a contraint on the minimum area required for successful establishment of the enterprise given its water requirement. A second assumption in the Base Case is that viticulture uses approximately 4 ML of water per hectare (see Chapter 6). A further assumption was also made that a viticulture activity has a minimum area for which it is economically viable. According to ABARE, this minimum area is 33 Hectares. This was included in the modelling approach to prevent unrealistically small areas from being planted to the activity.

7.4.2 Cattle Grazing

The model conceptualisation has assumed that a grazing activity does not rely on any form of irrigation for operation. The enterprise is integrated with the hydrological cycle by rain-dependent yield only. A simplifying assumption was made that ties profit to just two rainfall thresholds (see Section 4.4.1). Figure 7.4 shows the fluctuation in profit given this assumption. The assumption reveals that during times of drought the enterprise makes an economic loss given the additional cost in supplementary fodder and the requirement to grow the cattle to two-year olds, resulting in a lower yield than grass-fed cattle sold as yearlings. These simplifying assumptions made in the conceptualisation have several implications for the interpretation of the model results. In reality, the relationship between climate and cattle production is more complex than conceptualised for the purpose of developing the integrated model in this thesis.

The economic return, therefore, could be expected to be higher in areas where factors other than climate, such as soil fertility, are directly related to economic return per hectare. These differences are shown in Table 7.2.2.

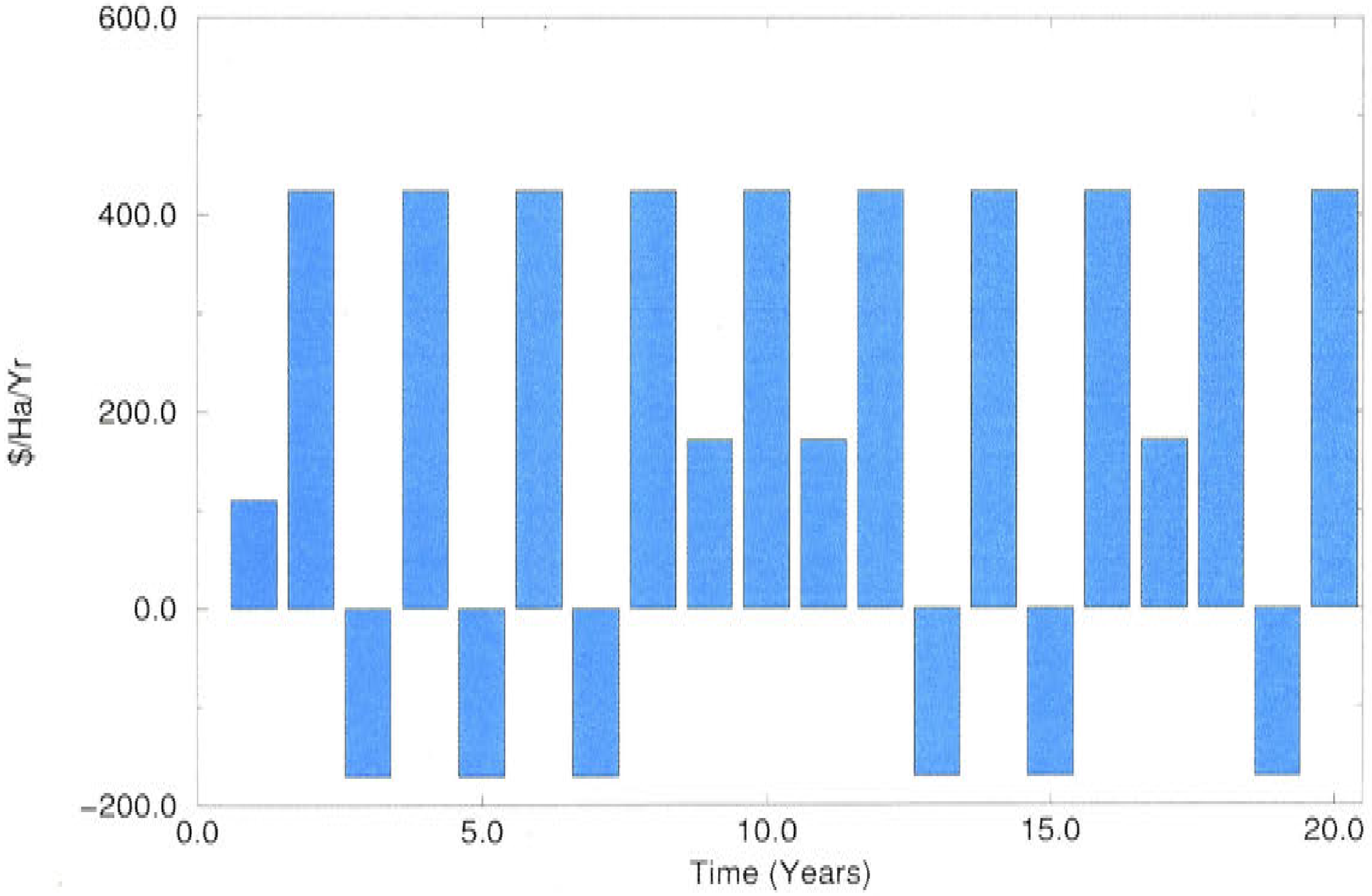

Figure 7.4: Gross margin ($/Ha/yr) for the Base Case for a grazing activity in Yass catchment

Table 7.2: Gross margins for the Base Case ($/Ha/yr) for cattle grazing in Yass catchment

	Gross Margin $/Ha
Farm Gross Margin Estimate	210
Model Gross Margin Estimate	
Node 1	410
Node 2	280
Node 3	220
Node 4	220

7.4.3 Lucerne Irrigation and Rotational Cropping

Lucerne irrigation and rotational cropping activities occupy the river flats in the middle and upper catchment. These activities are not an option at Node 3 so have not been selected at this Node. This assumption prevents irrigated activities from operating on steeply incised river channels where pumping from the river is not economically viable (see Section 3.22). These activities were also not chosen at Node 4 even though they were potentially able to be undertaken. This was due to the limited water availability caused by upstream extractions. The total economic return is shown in Table 7.3 for lucerne production activities and Table 7.4 for rotational cropping activities. The return is comparable to the regional budget (ABS, 1999) (for the Upper Murrumbidgee, which includes Yass catchment).

Table 7.3: Farm budget gross margin ($/Ha) and area (Ha) versus model values for lucerne irrigation in Yass catchment for the Base Case

	Area	Total Return ($/yr)
Regional Budget	287	2 274 600
Node 1	255	2 614 241
Node 2	100	638 754
Node 3	0	0
Node 4	0	0

Table 7.4: Farm budget gross margins ($/Ha) and area (Ha) versus values for rotational cropping in Yass catchment for the Base Case

	Area	Total Return ($/yr)
Regional Budget	180	486 220
Node 1	60	90 090
Node 2	80.5	120 120
Node 3	0	0
Node 4	0	0

7.4.4 Stream Flow

Streamflow was simulated for each Node using the regionalisation method and parameter values identified in Chapter 5. Figures 7.5 and 7.6 illustrate simulated streamflow for just 2 years (1989 to 1991) at Nodes 1 and 2 for the Base Case model runs. The hydrology model does not explicitly consider loss of water due to the town water supply at Node 3 (see Chapter 5 for assumptions). However, for the purpose of the integrated modelling approach the assumption is considered valid for the following reasons. The majority of irrigated agricultural activities relying on in-stream extraction do not occur downstream of Yass weir. Hence any change to streamflow downstream of the Yass weir due to town water extraction has a relatively small impact on agricultural production systems. This assumption would tend to lead to an over-estimate of irrigated areas at Node 4. However, under the Base Case these areas are simulated to be zero anyway, illustrating that this assumption has no effect on the Base Case. While this result does not imply the assumption has no impact on the model results for any scenario, it does indicate that the impacts is likely to be minimal around the Base Case value.

A second point to note is that there are no days where simulated streamflow is zero, although there are periods where streamflow is extremely low. This is due to the use of exponential decay functions to represent the unit hydrograph in the rainfall-runoff model (see Chapter 5). Additionally, Figure 7.5 and 7.6 simulate streamflow for a wetter than average year. The streamflow is modelled at the outlet (Node) of each subcatchment and the model represents an averaged extraction over the subcatchment area. The model does not consider the variation in access to water within a subcatchment and therefore may tend to underestimate the impact on low flows. An alternative approach would be to include a loss mechanism such as evaporation and infiltration.

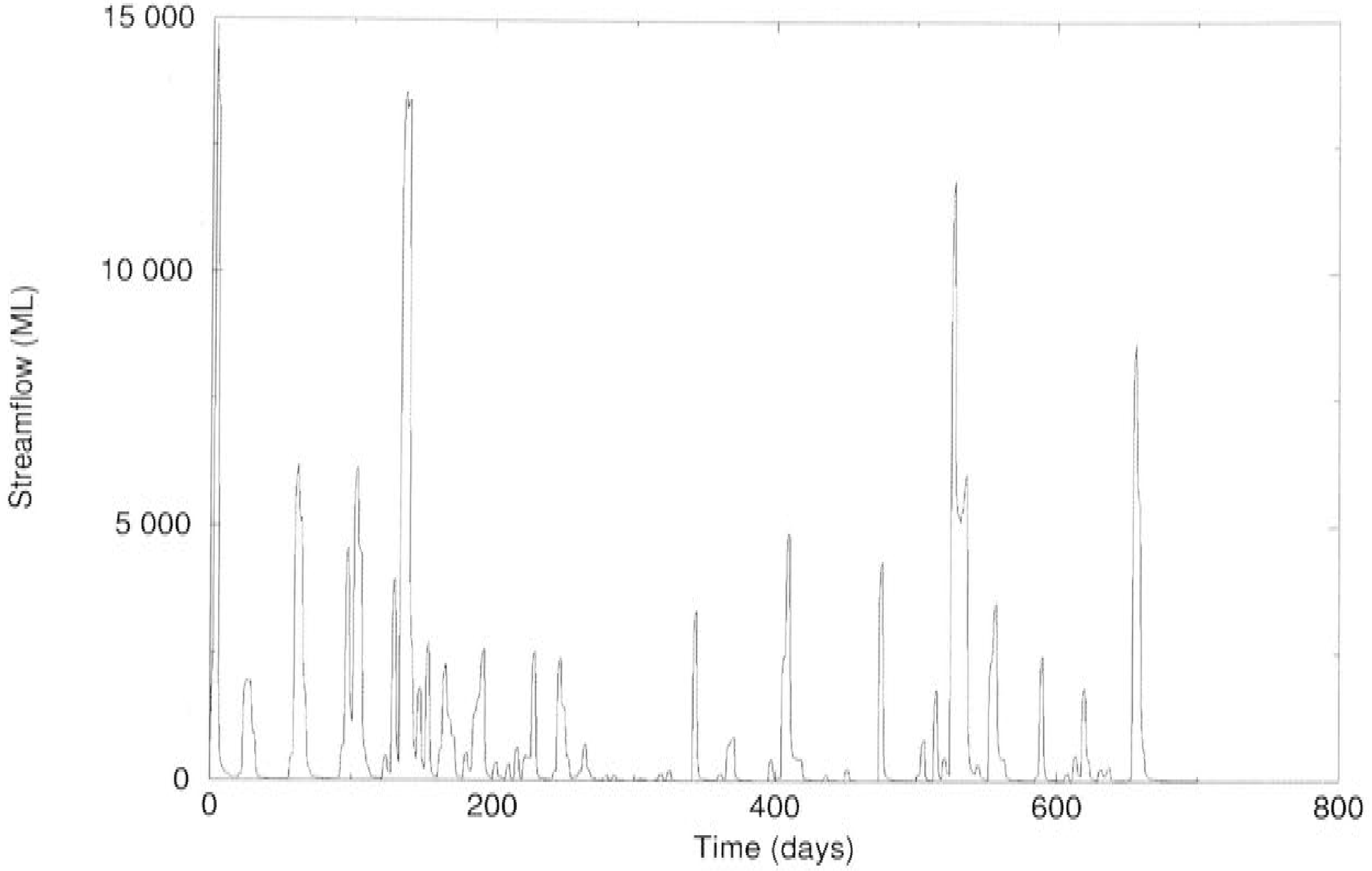

Figure 7.5: Node 1 simulated streamflow for the Base Case in Yass catchment. Period of record: 1/3/1989 to 8/5/1991

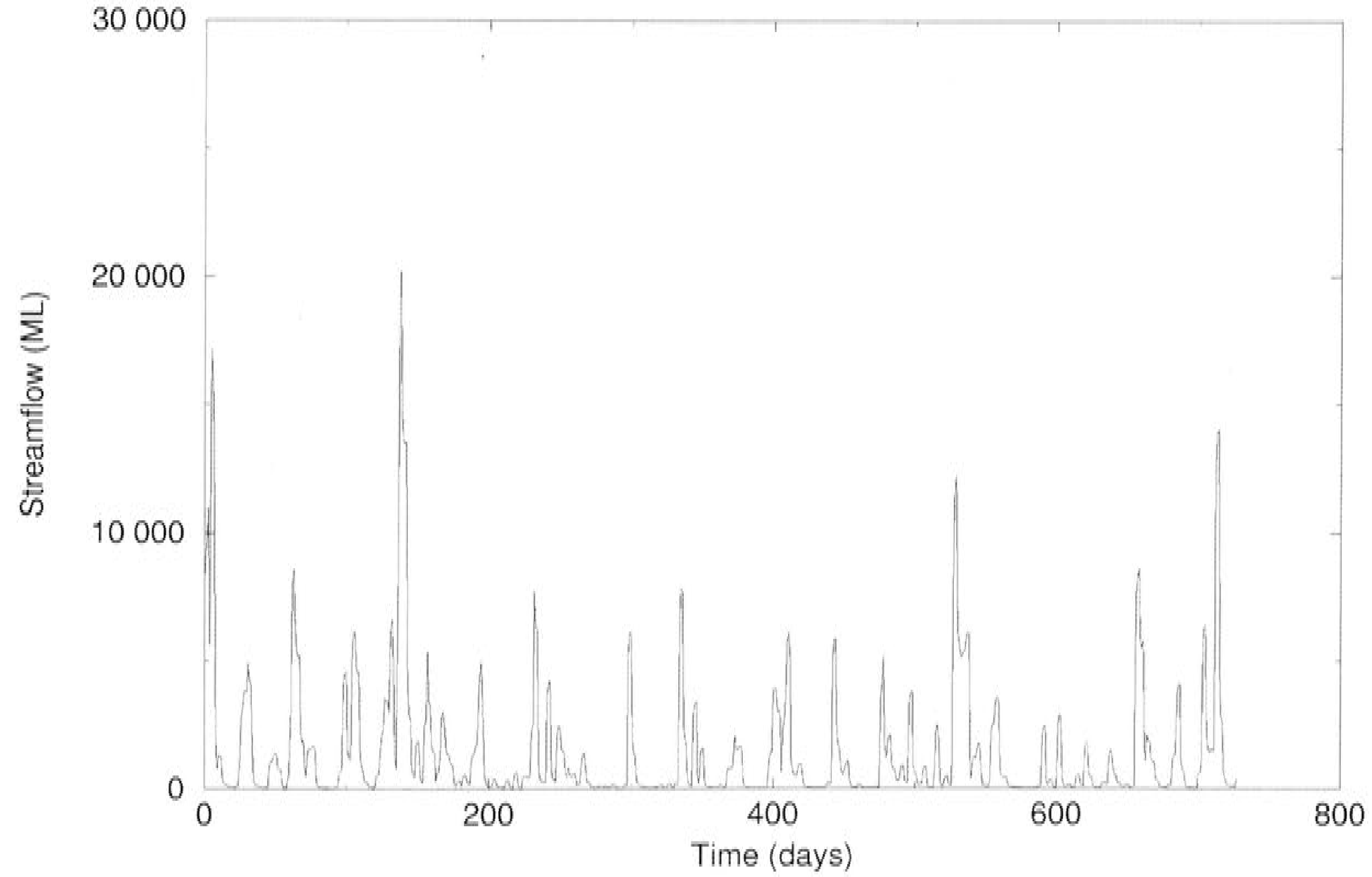

Figure 7.6: Node 2 simulated streamflow for the Base Case in Yass catchment. Period of record: 1/3/1989 to 8/5/1991

7.4.5 Water Allocation and Extractions

An assumption underlying the Base Case for the unregulated tributary system is one of no Commence to Pump or Cease to Pump (CTP) limits on the level of water extracted from the river. Table 7.5 compares the actual area and volume of water extraction attributable to irrigation activities in the catchment with the Base Case model estimate given the area laid to irrigation under the Base Case. A breakdown of extraction by rotational cropping and lucerne irrigation could not be obtained from actual data. Therefore, they are both referred to as 'irrigated activities'. The model estimate of extractions is averaged over 20-years in order to compare the Base Case estimate with the actual annual estimates. The Base Case over-estimates extraction from the stream. The result should be interpreted with caution as information obtained from the Department of Land and Water Conservation were estimates only. Data on actual extractions is not kept for unregulated rivers.

Table 7.5: A comparison of actual licensed extractions from Yass River and the Base Case estimates (Source: DLWC, 2000c)

	Activity	Area (Ha)	Extraction (ML)
Base Case	Node 1	356	691
	Node 2	81	7702
Actual	Irrigated Activities	570	3417

Figure 7.7 illustrates the maximum daily extraction level during the irrigation season given by the Base Case model for Node 1. At the Node, the extraction limit is set at 1 578 ML per annum with a maximum capacity of 28 ML per day. These estimates were for Yass catchment, and obtained from the Department of Land and Water Conservation. The Cap on extraction is considered to be the physical pump capacity for irrigation activities in the catchment. Therefore, the Base Case has an estimated licensed pump capacity of approximately 3400 ML per annum (DLWC, 2001a).

Figure 7.8 illustrates the volume of extractions at Node 2 for the Base Case. On low flow days, less than the maximum 28 ML is available to pump, indicating that a significant volume of low flow compromises events that are lost to irrigation. These events occur from day 300 which also coincides with the beginning of the 121-day intensive irrigation season. A higher volume of flow is extracted during these times as the standard practice is to pump directly from the stream, as opposed to pumping during periods of flow abundance for storage in farm dams (a standard practice in flood-irrigated areas).

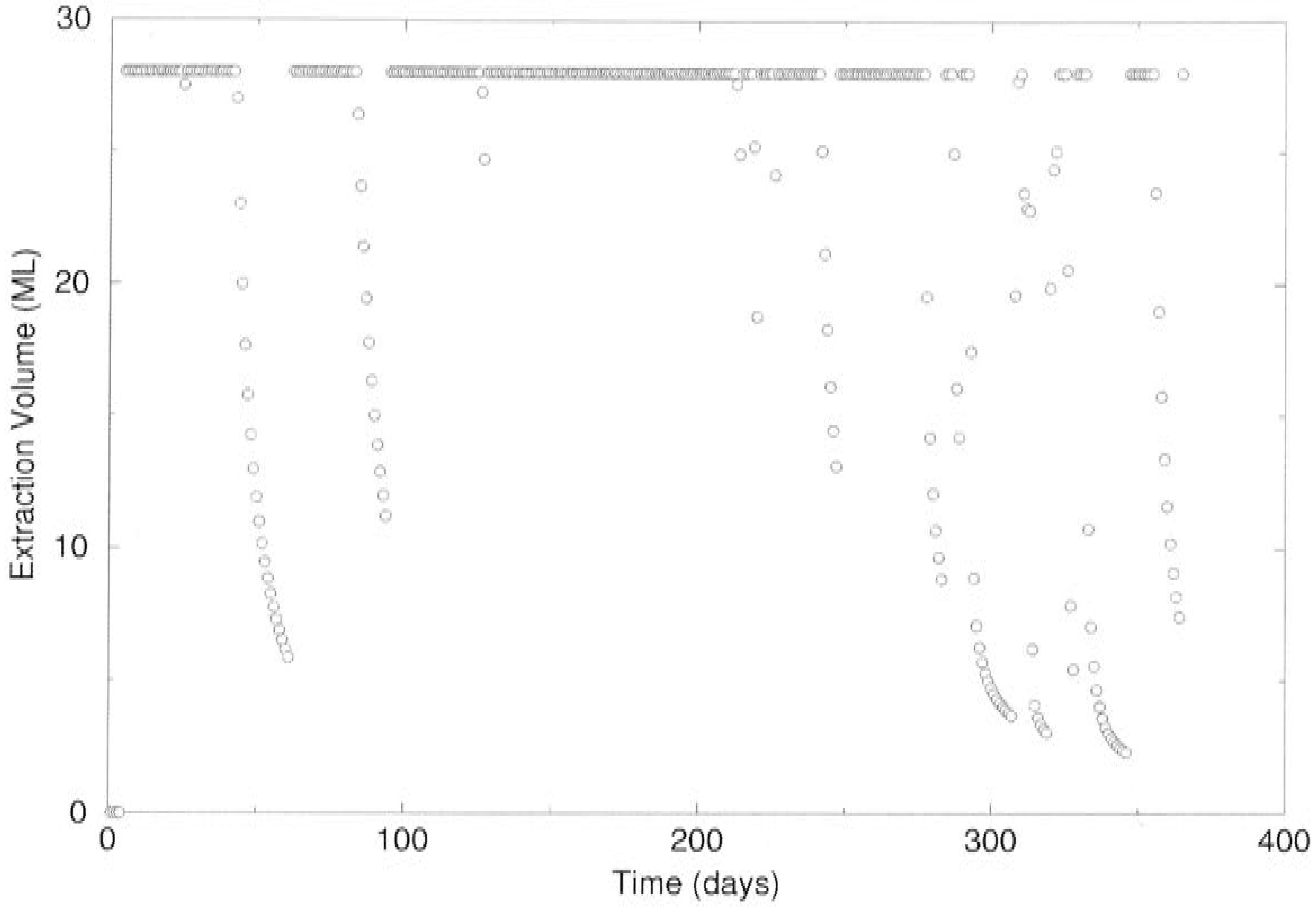

Figure 7.7: Daily allowable extractions (ML) at Node 1 under the Base Case water policy situation over a single annual period beginning with the irrigation season

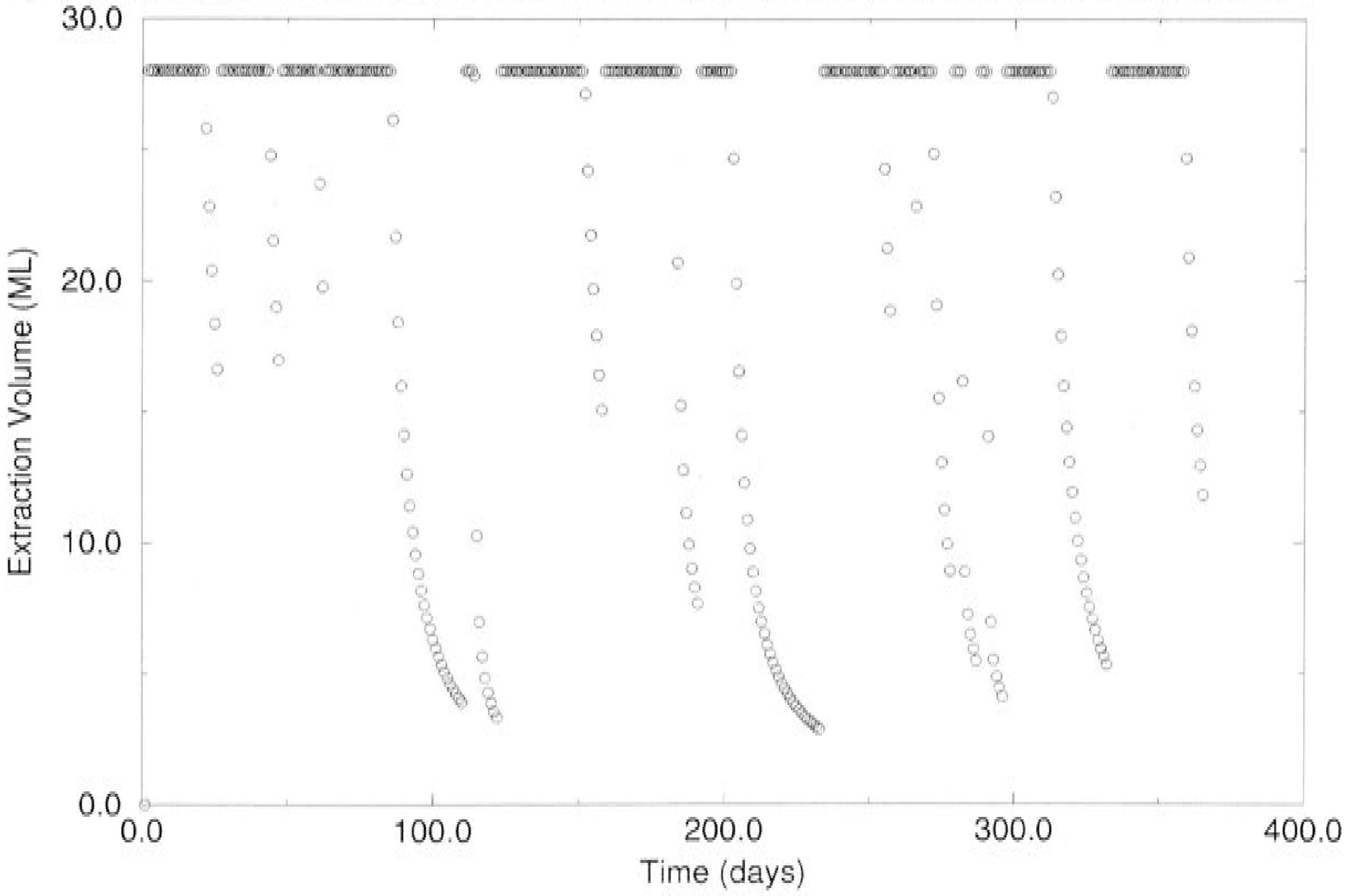

Figure 7.8: Daily allowable extractions (ML) at Node 2 under the Base Case water policy situation over a single annual period beginning with the irrigation season

Table 7.6 reports the cumulative frequency of days where streamflow was fully allocated under the Base Case given a physical pump capacity of 28 ML per day per hectare and an annual cap of 1578 ML given by the Department of Land and Water Conservation. Table 7.6 illustrates that, under the Base Case situation, 46.5% of streamflow is available for extraction for irrigation purposes.

Table 7.6: Number of days available for streamflow extraction under the Base Case rules and the percentage of total streamflow available for extraction (given as a cumulative frequency of streamflow extracted over a 20-year simulation at Node 1)

Flow Range	No. of days	Cumulative Frequency %
0 to 28 ML	3 393	47
28 to 100 ML	1 932	73
100 to 300 ML	1 118	88
Above 300 ML	853	100

Table 7.7 reports the total number of days where streamflow was fully allocated under the Base Case given the physical constraint on pump capacity. The table shows that over a 20-year simulation under the current licence arrangements, 37% of total flow was committed to irrigated activities in the catchment. The majority of streamflow, 70%, occurred above the licence range representing medium flows.

Table 7.7: Number of days available for streamflow extraction under the Base Case rules and the percentage of total streamflow available for extraction (given as a cumulative frequency of streamflow extracted over a 20-year simulation at Node 2)

Flow Range	No. of days	Cumulative Frequency %
0 to 28 ML	2 671	37
28 to 100 ML	2 458	70
100 to 300 ML	1 257	88
Above 300 ML	910	100

This section has examined the major assumptions made in developing the Base Case model for irrigated activities. In particular, a physical pump capacity limit and licence limit has been assumed to prevent the model from overestimating the area available to irrigated activities. These two assumptions were not only necessary in the conceptualisation to prevent the profit maximising optimisation from devoting all areas to irrigated activities given their high economic viability, but also neccesary for the imposition of water policy options. One set of water policy options is imposed by varying the volume of water available for pumping (see Section 3.13.1). These assumptions in the conceptualisation are essential in tying extractive water policy options to the area devoted to irrigated activities.

7.5 Scenarios for the Integrated Model

Scenarios run for each policy option are given in Table 7.8. These scenarios are selected based on the policy issues determined in Chapter 3 to be the subject of the thesis.

Table 7.8: Scenario options selected for model runs in Chapter 7 for the Yass Catchment

Policy	Scenario Options
Salinity Management Policy	Plantation of 20% of catchment to softwood production Plantation of 50% of catchment to softwood production Plantation of 80% of catchment to softwood production
Volumetric Conversions Policy	Commence to pump set at the 80th percentile Commence to pump set at the 50th percentile
Farm Dams Policy	5% runoff rule 10% runoff rule 20% runoff rule

Each scenario has been selected from the relevant policy literature that was considered current at the time of model development (see Chapter 3). For each policy scenario, the remaining two policy options were set as per the Base Case model. Hence, changes to the three policy options were not run in parallel (although this is possible given the model structure) to keep the interpretation and presentation of results as simple as possible and to allow for the assessment of the impacts of each policy scenario separately.

7.6 Salinity Management Policy by Forestry Plantation Scenarios

Each scenario involves taking current agricultural land out of production to establish softwood plantations. This is the only scenario option contained in the model that is not subject to an optimisation. Rather, a proportion of the catchment is left to farm forestry, with the remaining land use area being determined by the linear programming optimisation (see Chapter 6 for justification). The policy options for the salinity management scenarios are the plantation of 20%, 50% and 80% of the total Land Management Unit (LMU) area belonging to each node.

7.6.1 Forestry Plantation: 20% of potentially forested area of the catchment

Figure 7.9 shows the land use decision modelled as a result of imposing a 20% forestry plantation option. The model allocates an area to forestry dependent upon soil type. The change to activity areas is seen by the increase in area planted to forestry on poor and good quality soil types when compared to the base case (no forestry planted). The area devoted to the higher yielding softwood plantation is considerably less at Node 4 than Node 1.

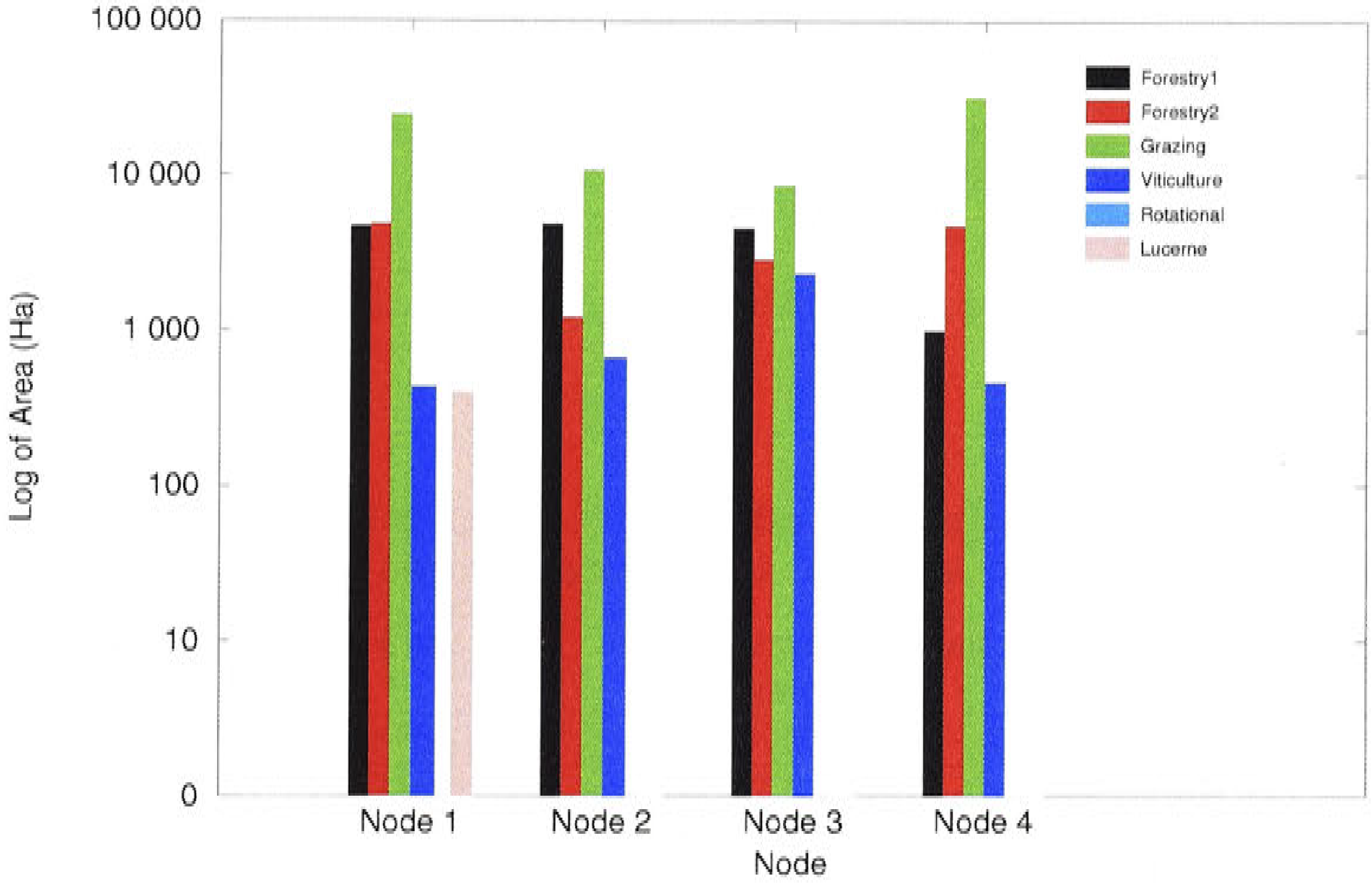

Figure 7.9: Total area (Ha) of agricultural production activities by Node given a policy option of 20% forestry plantation cover

The most significant change in production activity areas is the reduction in irrigated activities that rely on streamflow. Rotational cropping is reduced by 80 Ha at Node 2 while lucerne production is reduced by 100 Ha at Node 2 compared to the Base Case (Figure 7.1). Lucerne production at Node 1 is reduced by 20 Ha. Given that forestry and viticulture activities are excluded from irrigated areas, a reduction in irrigated activities can only be caused by changes in streamflow as a result of land use change to forestry upstream. At the downstream node, Node 2, irrigated activities are reduced with rotational cropping being taken out of production entirely. The available streamflow for the purpose of extractive activities is reduced from a 20-year total of 7 701 ML to 7 589 ML at the Node when compared with the Base Case model.

Table 7.9 shows the reduction in profit at each Node compared to the Base Case given a policy option of 20% forestry plantation. The Salinity Management Policy option has a significant effect on the profitability of production systems in the catchment. However, the result needs to be interpreted with caution. At Nodes 1, 2, 3 and 4 land was taken out of grazing production to be replaced with forestry. Value added activities such as the area devoted to viticulture did not change as the lower valued activity (grazing) was taken out of production.

Node 2 experienced a decrease in profit given that land was taken out of irrigation production in this spatial area. At Node 1, the plantation to forestry also resulted in a smaller reduction in profit than Node 3 and 4 for the reason that biophysical constraints allowed high yielding forestry to be planted, resulting in a higher profit than low yielding forestry. The loss in profit at all Nodes could be interpreted as the subsidy required to encourage farmers to take land out of grazing production to plant forestry for salinity management.

Table 7.9: Profit and % Change in Profit for a Salinity Management Policy: 20 % forestry plantation option compared to the Base Case model in Yass catchment

	Base Case ($)	20% Forestry Plantation Option ($)	% Change
Node 1	690876338	559609833	-19
Node 2	133216981	97248396	-27
Node 3	478246564	392162182	-18
Node 4	702520073	533915255	-19

7.6.2 Forestry Plantation: 50% of the potentially forested area of catchment

Figure 7.10 shows the areas estimated by the model to be planted to agricultural production activities at each node given the selection of the policy option that devotes 50% of agricultural production land to forestry. Once again, forestry plantations on high and low yielding soil types are allocated to 50% of the total area at Node 1, with all other nodes having a plantation area of less than 50% for high yielding forestry given the soil type. This is most obvious at Node 4 where the lower quality soils prevent the plantation of 50% of the area to high yielding softwoods. The largest change in area is to the grazing activity at all nodes. Given the increase in total forest area, the model takes land out of grazing production to allocate to forestry. The area devoted to lucerne irrigation at Node 2 is reduced from 394 Ha to 320 Ha compared to the Base Case model.

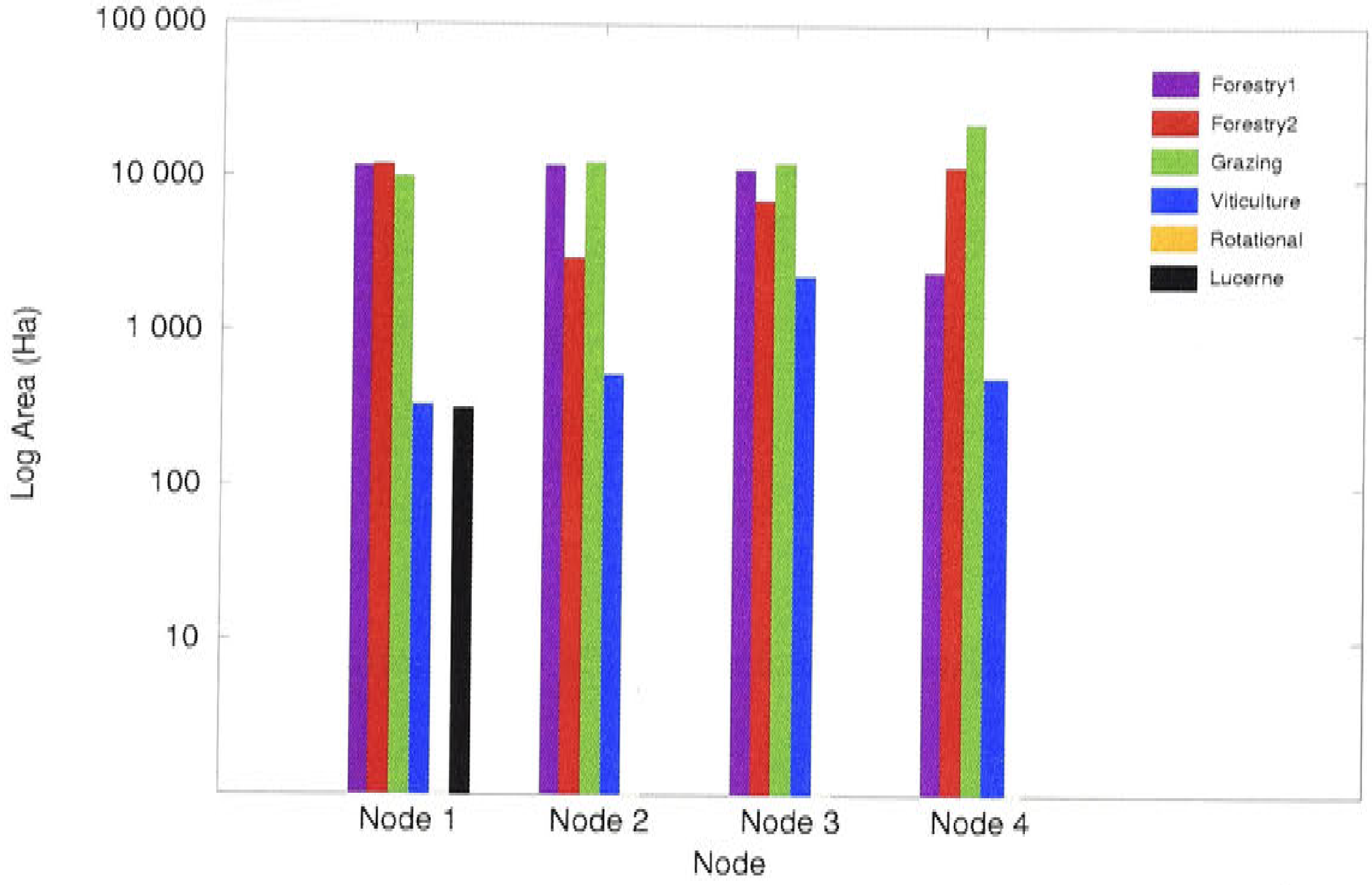

Figure 7.10: Area (Ha) of agricultural production activities by Node given a policy option of 50% forestry plantation cover

The 50% change to land cover results in a larger reduction in profit across all Nodes as could be expected. This can be compared to the 20% policy option where the average reduction across Nodes 1 to 4 was between 18% and 27%. This is a result of the relatively large catchment area taken out of grazing production for forestry activities. The remaining small amount of land is then allocated to viticulture rather than grazing given the decrease in total land available for all activities. In the Base Case model run, the total land area constraint did not affect the area available to viticulture given the abundance of land under this policy option and the constraints upon viticulture (being confined to a smaller spatial area given biophysical constraints) than grazing. The area devoted to viticiculture remains unaffacted. The total land constraint is not activated for either the 20% or thr 50% policy options.

The cost to the catchment agricultural production systems as a result of imposing a forest policy option of 50% plantation, where applicable, is given in Table 7.10. The largest impact is at Node 2. The lower quality soils (compared to Node 1) mean that land is taken out of production from grazing for forestry. However, the remaining land is not entirely allocated to the higher-valued viticulture activity given the biophysical constraints on its potential location at the Node. At this Node, the policy option impacts on the spatial location of grazing activities.

Table 7.10: Profit and % Change in Profit for the Salinity Management Policy: 50% forestry plantation option compared to the Base Case model in Yass catchment

	Base Case	50% Forestry Plantation Option	% Change
Node 1	690876338	276350535	-60
Node 2	133216981	50622452	-62
Node 3	478246564	210428488	-56
Node 4	702520073	323159233	-54

7.6.3 Forestry Plantation: 80% of the potentially forested area of the catchment

Under this option, the total estimated area available to forestry and other land use activities is shown in Figure 7.11. Interestingly, an increase in forestry does not result in any significant decrease in land made available for lucerne irrigated production, resulting in a reduction of just 10 Ha. The largest change in land use is to the area made available for grazing activities. This is also the first Salinity Management Policy option that results in a large change to the area of land devoted to viticulture. This is due to the area constraint being activated given that the majority of land is being planted to forestry under this scenario. Unlike the 50% policy option, that only impacts upon grazing, the 80% option now has a significant impact on the area of land laid to viticulture activities, as Figure 7.11 shows. Compared with the Base Case model, the area devoted to viticulture is reduced by 1478 Ha.

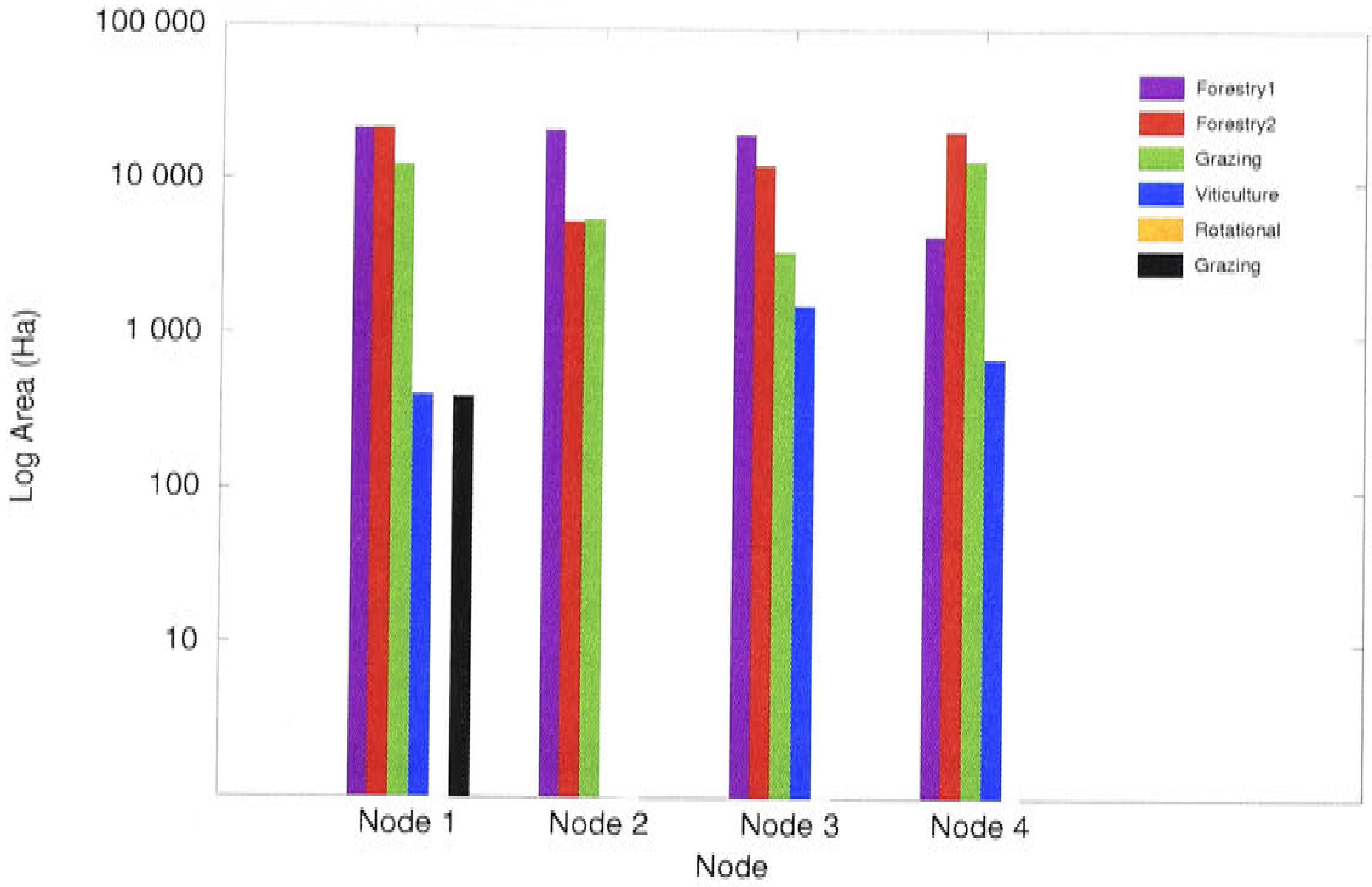

Figure 7.11: Area (Ha) of agricultural production activities by Node given a policy option of 80% forestry plantation cover

The largest change to profit by node compared to the Base Case is at Node 4 as Table 7.11 indicates. The 96% reduction in profit compared to the Base Case is explained by the fact that the value-added land use, viticulture, is taken out of production only at the 80% policy option. In contrast, the profit at Node 4 is reduced by a relatively small amount that for other Nodes under the 20% policy option. Consequently, the greatest spatial impact on agricultural production activities as a result of imposing the 80% option is at Nodes 3 and 4 because viticulture is reduced. However, under the 20% option the greatest spatial impact is felt at Node 2 where higher-valued activities are less viable. The impact is exceptionally high for Node 4 given that forestry is not an economically viable activity. Forestry profit is approximately one twentieth of that of grazing over the 20-year simulation after a discount rate is considered.

Table 7.11: Profit and % Change in Profit for the Salinity Management Policy: 80% forest cover option compared to the Base Case model in theYass catchment

	Base Case	80% Forestry Plantation	% Change
Node 1	690876338	13266504	-81
Node 2	133216981	23979056	-82
Node 3	478246564	28694793	-94
Node 4	702520073	28100802	-96

7.6.4 Streamflow Impacts under the 20%, 50% and 80% Policy Options

Table 7.12 illustrates the streamflow as a total volume and on a per hectare basis per annum for each node. Streamflow decreases at all nodes as forest cover increases. The average annual reduction in streamflow (per hectare) over the entire catchment is 482.8 ML/Yr when forest cover is increased to 80% land cover. The results show that a change in 20% forest cover does not have a significant impact on streamflow compared to the Base Case. The model may not be senstive to this scenario. However it is more sensitive to larger changes in forest cover as Table 7.12 indicates.

Table 7.12: Available streamflow (over 20-year simulation) (ML) after the imposition of Salinity Management Policy options in Yass catchment by forestry plantation

	20% Option	50% Option	80% Option	Base Case
Node 1	4 079 145	4 079 484	4 078 346	4 079 145
Node 2	5 319 230	5 317 110	5 312 640	5 320 106
Node 3	5 370 085	5 369 574	5 369 384	5 370 085
Node 4	4 239 855	4 250 303	4 239 165	4 239 855
Difference between Scenario and Base Case	0	5 000	9 656	0

Figure 7.12 illustrates the annual impacts on streamflow available for extraction in the catchment as a result of imposing a salinity management option through forestry plantation of 80% of the catchment. It shows streamflow extracted on a daily timestep for the first year of model simulation at Node 1 only. The policy option does not impact on the maximum allowable extraction limit under the current situation, that being an extraction of a daily maximum of 28 ML. However, the policy option does impact on the lower flows available for extraction on a daily basis. The 20% policy option does result in a change to streamflow but the change is to lower flow events. This has little impact on the water available for irrigators to pump. This could explain the small impact that the 20% option has on the catchment hydrology and viability of catchment land use activities. A policy option of 50% impacts on streamflow. This results in a reduction in water available to irrigators. However, further increases in forestry do not significantly alter the viability of irrigated activities. This is due the fact that irrigators are only impacted at low flows. Increases in forestry to the 80% option from 50% appear to impact primarliy on the low flow events.

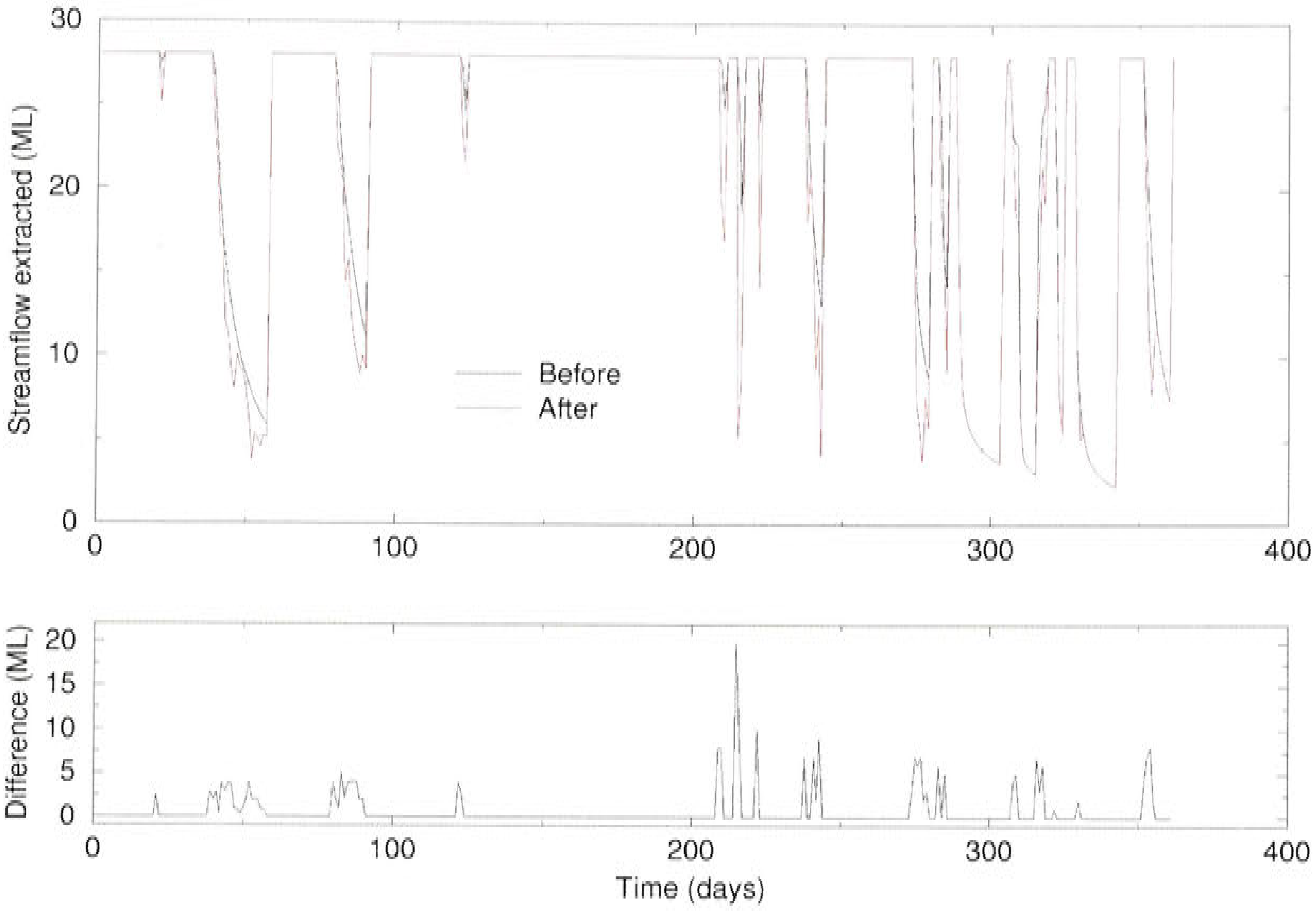

Figure 7.12: Predicted impact on available water for extraction by irrigated agricultural activities as a result of imposing Salinity Management Policy: 80% plantation option

7.7 Volumetric Conversions Policy Option Scenarios

The flow regime of the Yass catchment is typical of Australian dryland ephemeral streams in that it is highly variable with long periods of low flow. Typically, over-extraction during dry years has resulted in inadequate low flows for survival of the aquatic ecosystem. The policy of volumetric conversions in Yass seeks to identify a volume of water available for irrigators that does not compromise the number of low and moderate flow events in the catchment. For this reason, the number of zero and low flow days is an important indicator as to the most appropriate volumetric rule. The aim of this set of scenarios is to trial various volumetric rules within the catchment and examine the resultant impacts on streamflow (particularly low flows) and water users (by area and economic return of each irrigated activity). The model is run by changing the daily flow extraction rules.

The allocation of an environmental share of water is a major aim of the Volumetric Conversion Policy. The current suggested environmental option is to protect 10% of all flows where the conservation of flows above the 95th percentile should be used as a starting point. In Yass catchment, the protection of low flows entails no pumping when flows are at or above the 80th percentile in the scenario runs. Commence to pump (CTP), cease to pump and bulk extraction limits (BEL) were calculated for each node (see Chapter 6). Table 7.13 shows the calculated extraction rules for each Node. The BEL determined from peak daily demand was assumed to be constant over the entire catchment as subcatchment demand data was not available.

Table 7.13: Calculated commence to pump (CTP) and bulk extraction limits (BEL) in ML for each Node in Yass catchment for the CTP scenario

Node Number	CTP (C class license limit)	BEL
Node 1	29.6	25.2
Node 2	32.3	25.2
Node 3	71.6	25.2
Node 4	80.5	25.2

7.7.1 Volumetric Policy Option Scenarios

Two types of scenarios were run in addition to the Base Case. The first set of scenarios involved varying the Commence to Pump (CTP) rules. The Catchment Management Board is to decide the CTP limit. The current policy suggests several options including setting the CTP at the 50th percentile or the 80th percentile. Two model runs were carried out to examine the impact on the catchment of implementing both options currently under consideration. A second scenario involved varying the Bulk Extraction Limit (BEL) in the catchment. It has been suggested that a higher BEL can be allocated to take into consideration future water demand. The BEL was varied to examine the impact of increasing water use given the potential of future developments such as viticulture and farmers capacity to pump from the stream (even though the current physical limit is estimated at 1 578 ML per annum). Table 7.14 shows the model scenarios which were run.

Table 7.14: Volumetric Conversions Policy options trialed as scenarios in Yass catchment

Scenario	Commence to pump (CTP) variable limits	Bulk extraction limit (BEL) Allocation
Base Case	No imit	No limit
Variation in CTP rule	Set at the 50th percentile	1 578
	Set at the 80th percentile	1 578
Bulk Extraction Limit (BEL)	Set at the 80th percentile	4 500
	Set at the 80th percentile	4 500

7.7.2 Varying the Commence to Pump Rule

Table 7.15 shows the change in area planted to irrigated activities estimated by the integrated model as a result of implementing both the 50th and 80th percentile rules, where the BEL was set at 4 500. This is the annual BEL calculated given the current policy on water extraction in the catchment. The second set of model runs altered the annual entitlement from 4 500 ML to 1 578 ML. This is the annual allocation considered operational by the current production system. Table 7.15 indicates that the area devoted to both irrigated activities would increase by 400 Ha where the proposed allocation was implemented. This assumes that the pump capacity of each activity could be increased by technological change. The result indicates that the daily extraction limit would not impact adversely on irrigated activities. However, where the BEL is set at the operation level (1 578 ML), the imposition of the 50th percentile policy option would result in a reduction of the total irrigated area of 310 Ha.

Table 7.15: Agricultural production area (Ha) in Yass catchment for Volumetric Conversion Policy Scenarios

	Rotational Cropping (area in Ha)	Irrigated Lucerne (area in Ha)
Base Case: unrestricted pumping up to pump capacity of 28ML per day with an annual allocation of 1 578	140	355
CTP at the 50th percentile with an annual allocation of 1 578	0	185
CTP at the 80th percentile with an annual allocation of 1 578	140	394
CTP at the 80th percentile with an annual allocation of 4 500	213	727
CTP at the 50th percentile with an annual allocation of 4 500	133	648

Table 7.16 indicates the change in profit as a result of policy imposition at each Node. Under this policy option, a 100% reduction in profit for rotational cropping and a 47% reduction in profit for irrigated lucerne occurs over the 20-year simulation when compared to the Base Case.

The total volume available for pumping from the stream before the implementation of the policy option is given in Table 7.17. The daily streamflow available for extraction is estimated at 53 ML while the daily streamflow available for extraction at the 50th percentile is 17 ML. Given that the crop conversion rate for lucerne and rotational cropping is 4 ML and 6 ML respectively, it would appear that there is sufficient volume of water to support irrigated activities. However, as Figure 7.13 and Figure 7.14 illustrates, it is the number of zero consecutive pumping days that has the greatest impact upon irrigated activities for Nodes 1 and 2 respectively. During the 121 days of the irrigation season, the number of zero flows is up to 60 days. Given the model assumption that irrigators do not store water in farm dams but pump directly from the stream, the result indicates that the number of consecutive zero pumping days under the policy option will have an adverse impact upon irrigators. The distribution of zero pumping days could be problematic for irrigators in the catchment even though the average daily water available over the entire irrigation season meets demand, being 17 ML.

Table 7.16: Impact upon agricultural production profit ($) in the catchment as a result of unrestricted pumping

	Rotational Cropping ($)	Irrigated Lucerne ($)
Base Case: unrestricted pumping up to pump capacity of 28 ML per day with an annual allocation of 1 578 ML	3 252 996	4 035 190
CTP at the 50th percentile with an annual allocation of 1578 ML	0	2 102 710
CTP at the 80th percentile with an annual allocation of 1578 ML	3 252 900	4 478 204
CTP at the 80th percentile with an annual allocation of 4 500 ML	4 949 055	8 263 082
CTP at the 50th percentile with an annual allocation of 4 500 ML	3 090255	7 365168

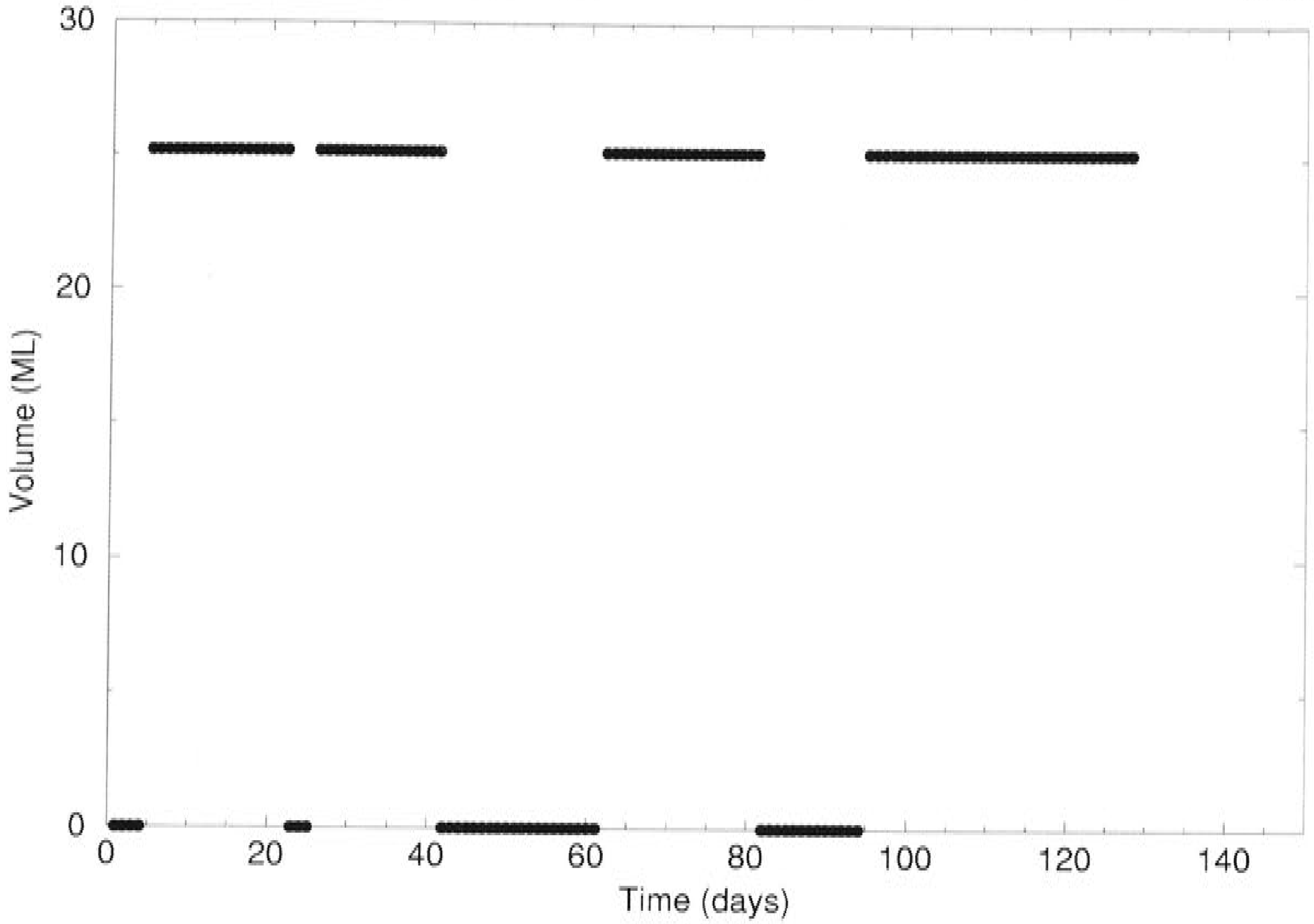

Figure 7.13: Available pumping volume by day in Yass catchment during the 121 day irrigation season. Example from Node 1. Scenario: 80th percentile rule for the CTP

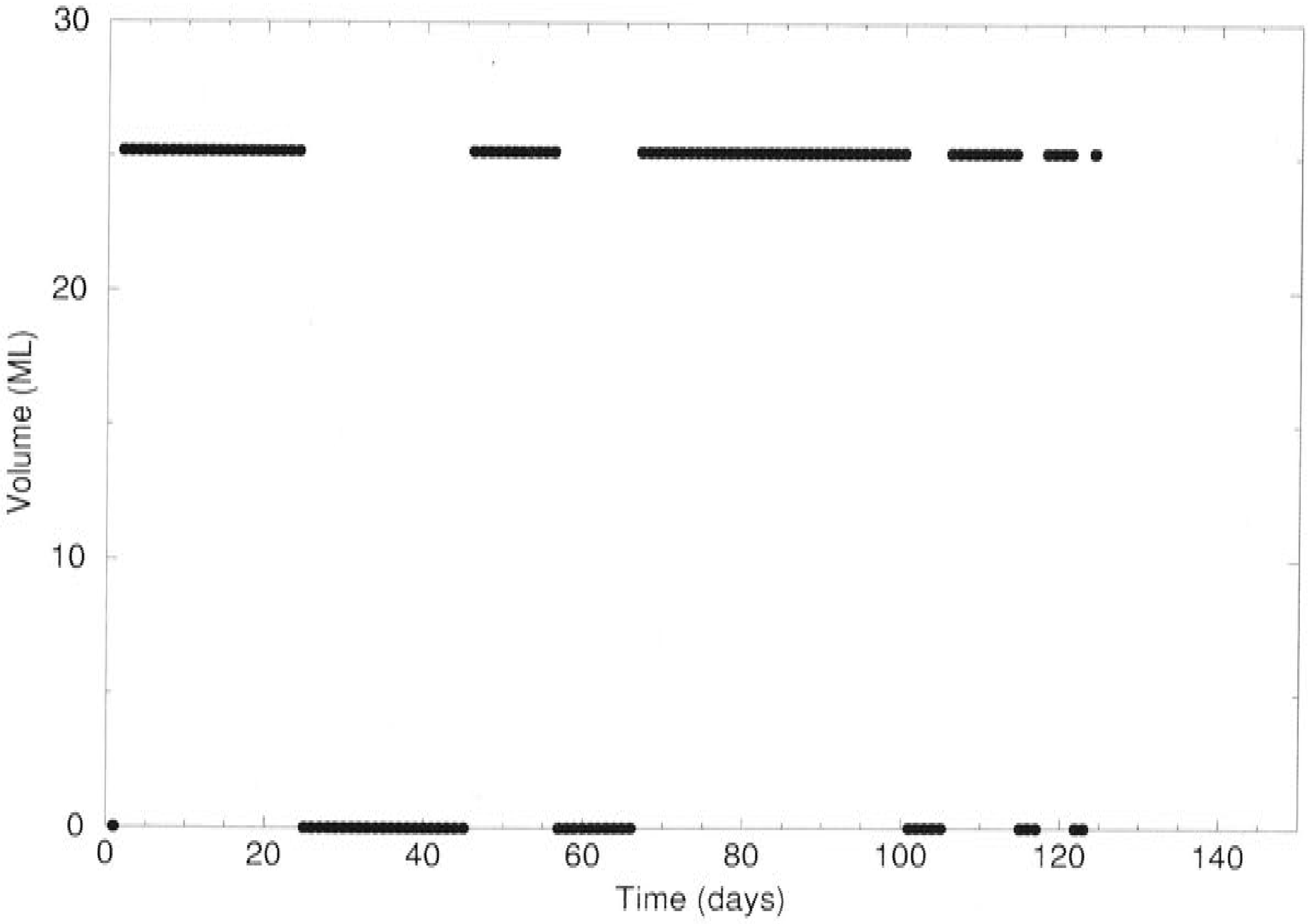

Figure 7.14: Available pumping volume by day in Yass catchment during the 121 day irrigation season. Example from Node 2. Scenario: 80th percentile rule for the CTP

Table 7.17 indicates the number of zero flow days by node over the 20-year simulation. The number of days unavailable to irrigators to pump from the stream increases with the implementation of the Volumetric Conversion Policy. This is primarily due to the large number of low flow events that do not exceed the Commence to Pump Limit of 21.6 ML per day for the 80th percentile policy option and 36.6 ML per day for the 50th percentile policy option.

Table 7.17: Impact of Volumetric Conversions Policy Options on the total number of pumping days over the 20-year simulation. Shows the number of days not available for pumping due to either zero streamflow or as a result of the CTP minimum threshold for pumping

	Total number non pumping days: The Base Case	Total number of non pumping days after implementation of the 80th percentile	Total number of non pumping days after implementation of the 50th percentile
Node 1	2 920	3 429	3 649
Node 2	2 440	3 049	3 221
Node 3	1 900	2 084	3 036
Node 4	2 800	3 040	3 612

7.8 Farm Dams Policy Scenarios

Intensive agricultural activities often rely on supplementary irrigation by the capture of water in farm dams. In Yass catchment, viticulture relies on the capture of water by farm dams to operate a viable enterprise. However, the recent introduction of the Farm Dams Policy has placed a restriction on the capture of runoff to 10% of all rainfall falling on the catchment (see Chapter 3). The aim of this scenario was to examine the potential impact that the continued expansion of the viticulture industry might have on the catchment hydrology given policy imposition and vice versa.

The current policy requires that the Farm Dam Policy (like the Volumetric Conversions Policy) be implemented uniformly across the catchment i.e. the catchment scale is the smallest spatial unit for policy implementation. This is unlike the forestry scenario that can be implemented at the Land Management Unit (LMU) level or subcatchment scale. For this reason, the scenarios have the same policy option in each LMU across the entire catchment system.

Sections 7.8.1, 7.8.2 and 7.8.3 provide results from the integrated model illustrating the impact on area, profit and catchment hydrology respectively as a result of imposing Farm Dam Policy options. The current policy 10% restriction for capture is simulated, as well as 5% and 20% proportions of rainfall. The Base Case allows farmers to capture up to 30% of runoff after evaporative losses and a runoff coeffiecient have been deducted.

7.8.1 Total Area

The land area devoted to viticulture production under policy options of 5%, 10% and 20% is shown by Figure 7.15. The imposition of the current policy option of 10% has the greatest impact on Nodes 1 and 3 where production is reduced by 250 Ha and 1 145 Ha compared to the Base Case model result. The result indicates that farmers at Node 1 would benefit more from a change in policy from 10% to 20% than from 5% to 10%. The total area changes by 14 Ha in the first instance and 29 Ha in the second. However, as a proportion of total area devoted to viticulture under the Base Case, a change in policy from 10% to 20% results in a relatively small increase in land devoted to the activity - just 9% of the current production system. In changing the policy option from 20% to 10%, the total area of land in production is halved at Nodes 1, 3 and 4. The result also indicates the large difference in land made available to viticulture between the Base Case area and policy options. Node 3 has the greatest impact (given it contains the Land Management Unit corresponding to Murrumbateman). The result indicates that imposing a 10% policy option has the potential to reduce land available to viticulture by approximately one third.

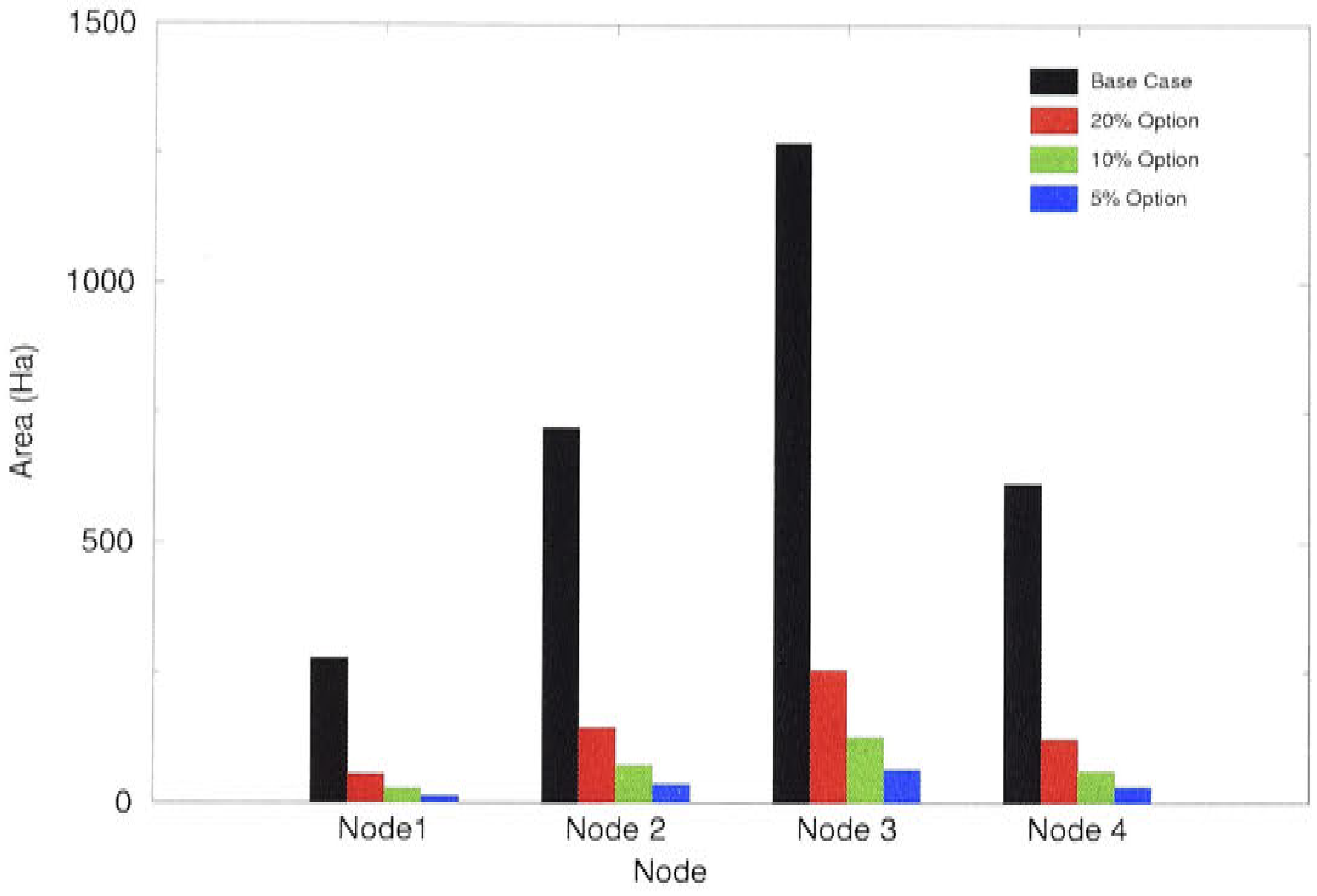

Figure 7.15: Areas (Ha) for a viticulture activity by Node compared to the Base Case (current viticulture land use) for each Farm Dams Policy option simulated

7.8.2 Total Profit

The percentage change in profit under each policy option is shown in Table 7.18. The model results show that at each node, imposition of the 10% Farm Dams Policy rule results in a reduction of profit by about 95% for the viticulture activity. Doubling the allowable limit does not result in a significant change to farm profits. Imposing a 20% option results in a profit reduction of approximately 80% for the viticulture production systems at each node. The result indicates that allowing production systems to double the runoff captured from 10% to 20% does not result in a significant positive impact upon the profitablility of the production system while increasing the negative impacts upon the environment.

Table 7.18: Reduction in profit compared to the Base Case as a result of imposing policy options

	% Change in profit by Node under the 20% option	% Change in profit by Node under 10% option	% Change in profit by Node under 5% option
Node 1	83	91	94
Node 2	80	90	95
Node 3	85	92	96
Node 4	80	90	95

Figure 7.16 illustrates the nature of impacts spatially across the catchment by identifying the reduction in profit per hectare per year under the 20-year simulation. Node 3 experiences the greatest reduction in profit given the imposition of the 10% and 5% Farm Dams Policy rule. Node 3 experiences the greatest reduction in profit under the 20% rule of all nodes. Profit is reduced by up to 96% given the imposition of a 5% policy at Node 3. Note that Node 3 represents the spatial area of Murrumbatemen, a local wine growing area in the Yass catchment.Node 3.

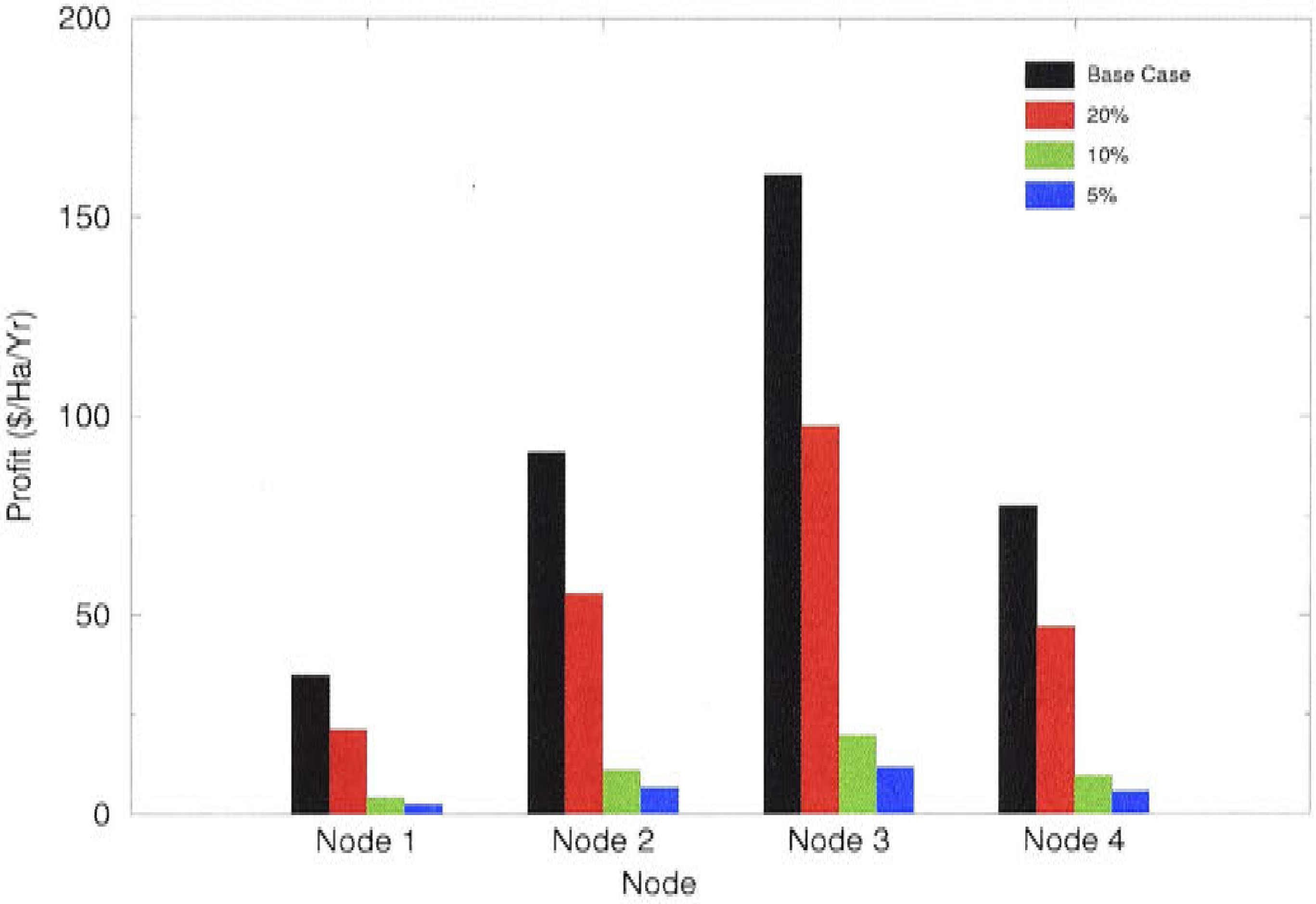

Figure 7.16: Profit ($) per hectare per year calculated by nodal area under the Farm Dams Policy options

7.8.3 Impacts upon Catchment Hydrology

The smallest volume (ML) of water available to grape growers over the growing season was used to examine impacts on the hydrology indicators. The assumption was made to capture the smallest volumes of water available rather than the maximum for the following reason pertaining to the operation of the production system. The grape production system must always have a level of water available to prevent the grapes from wilting during a given season. As the model formulation did not explicitly consider the relationship between available water at a given timestep and time to wilt for the grapes, it was assumed that the farmer would not plant grapes unless there was sufficient water available to sustain them for the entire production season (and 20-year simulation).

An alternative would be to consider in the model formulation a relationship between available water and time to wilt or die for the grapes. The production model assumption would then be that the farmer could plant out a larger area to grapes and accept a loss of production in drier years or reduction in grape yield due to wilting. However, given that the relationships between water, yield and wilting point were not available or deemed consistent with the modelling scale and objectives, the model formulation assumed that the grape grower would only plant an area that could be satisfied by the minimum available volume of water. Hence grape yield is 100% per hectare planted. Figure 7.17 illustrates the minimum water available to farmers by season given this assumption for each policy option at Node 1.

Given that the current policy option is to reduce runoff captured to 10% of effective rainfall, the difference between 10% of the Base Case volume and the actual volume available (smallest volume of water available for farm dam capture) is shown on the second axis. This is the smallest amount of volume available to farmers to sustain production. The result shows that for 10 of the 20-years, there is not enough rainfall to prevent grape wilting and sustain the 10% rule at Node 1. A lesser yet significant impact at Node 4 is also shown by Figure 7.18. The result implies that viticulture production needs more than 10% runoff to sustain production in a given land area.

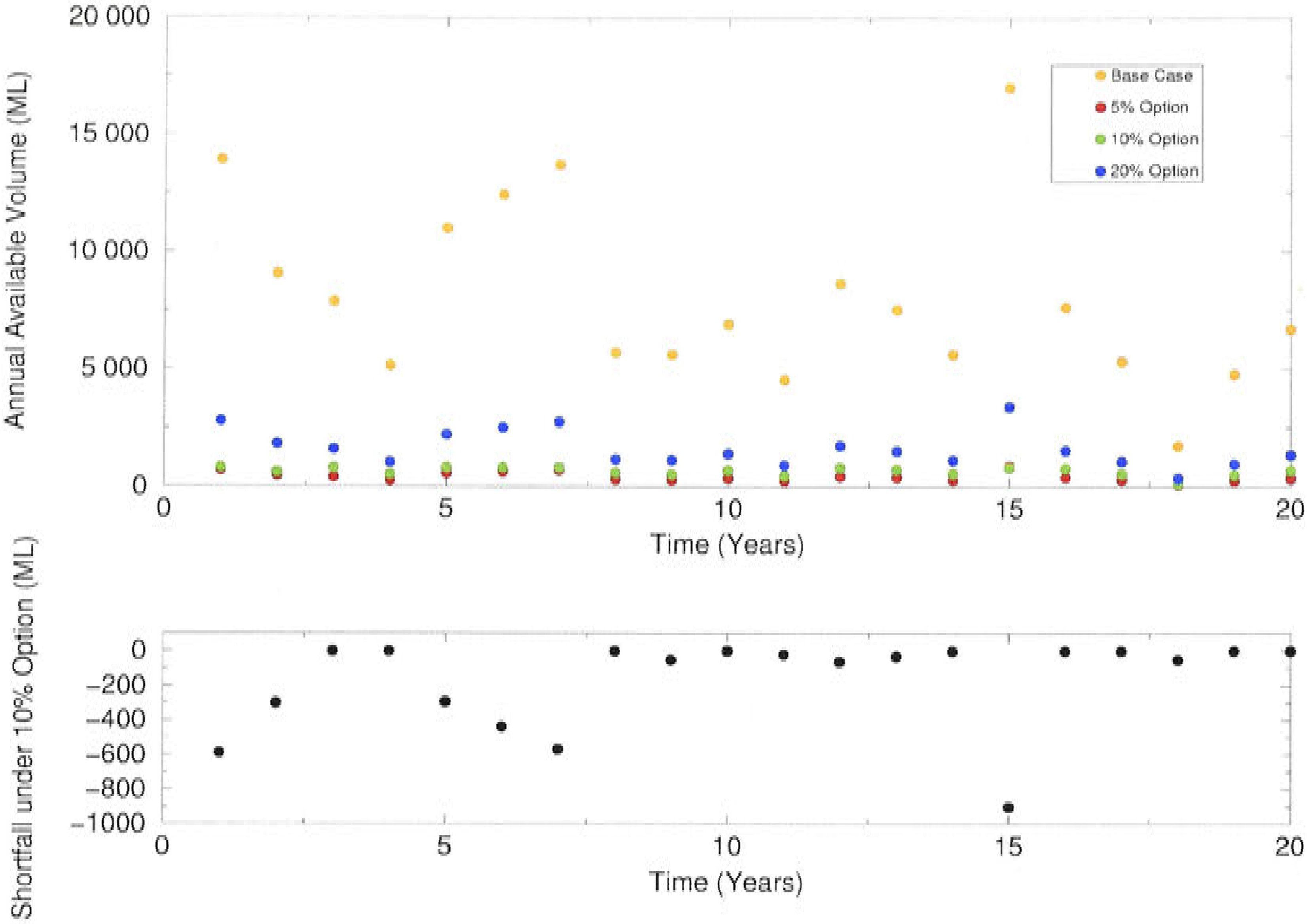

Figure 7.17: Available water volume under various Farm Dams Policy options at Node 1 (above) and shortfall (below)

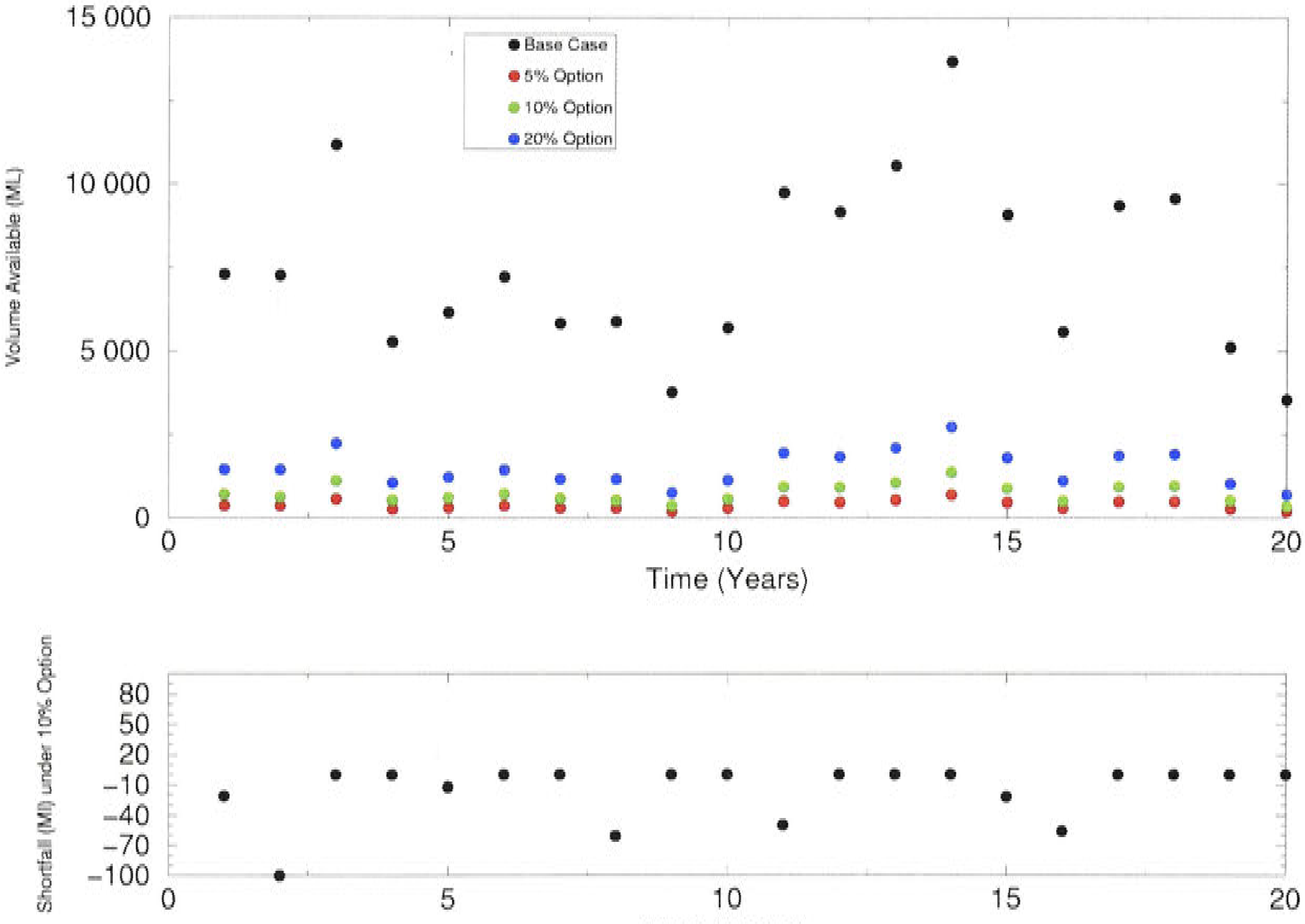

Figure 7.18: Available water volume under various Farm Dams Policy options at Node 4 (above) and shortfall (below)

The model formulation specified three growing periods or maturity phases for grape production. Within each period, the model varies the total volume of water required per hectare to establish or maintain grape growth (given as waterperiod). Tables 7.19 and 7.20 illustrate the results for two Land Management Units located within Nodes 1 and 2 respectively.

Table 7.19 shows the model result for LMU 8 at Node 1 under various Farm Dams Policy options where waterperiod 1, 2 and 3 are the maximum amounts of water available for farm dam capture under the three different phases of maturity. These three variables constitute the water constraint determined by the model and are determined by assuming a dam capture efficiency of 65% at each node (see Chapter 6 for variable definition). The results show two interesting features of the model. Firstly, the water constraint tightens (the volume of water available decreases) as the farm dam capture limit is reduced under a Farm Dam Policy option. The water constraint also shows the non linear response of the integrated model to imposition of the Farm Dams Policy options in terms of water availability under each option. Secondly, as the shaded area in Table 7.20 indicates, the constraint on production occurs in the second and third growing phases for Node 2 in contrast to Node 1 (see shaded area in Table 7.19) where the constraint does not occur until full grape maturity. The model is capable of identifying at what point in the production cycle water will become a constraint on production under each policy option. This type of model response is useful for identifying at what point in time water will be scarce under each policy option. As the results indicate, choice of policy option could bring forward or delay a shortage of water for grape growers. This is shown by Node 2 (Table 7.20), where imposition of the 10% Farm Dam Policy Option results in a shortage of water sooner.

Table 7.19: Water used by area planted to grapes and available water at each growing phase planted under various policy options (Node 1:LMU 8)

LMU8	**Water Constraint**	**Water constraint: Maturity Phase 1**	**Water constraint: Maturity Phase 2**	**Water constraint: Maturity Phase 3**
Base Case	1111	5113	7143	1111
5%	55	255	357	55
10%	111	334	522	111
20%	222	1022	1428	222

Table 7.20: Water used by area planted to grapes and available water at each growing phase planted under various policy options (Node 2: LMU 5)

LMU 5	Water constraint	Water constraint: Maturity Phase 1	Water constraint: Maturity Phase 2	Water constraint: Maturity Phase 3
Base Case	2888	7099	5136	2888
5%	55	255	357	55
10%	233	609	233	288
20%	577	1419	1027	577

Given the available water at each node, the results from trialling various Farm Dams Policy options suggest that Nodes 2 may not be the ideal areas for growing grapes under the 10% policy options. However, the result should be interpreted with caution as each constraint is an average calculated over the maturity phase. Individual years experiencing drier conditions may still limit the ability to implement the a policy option.

The results are consistent with Figure 7.17 that illustrates a large deficit in available water at Node 1 where the 10% Farm Dams Policy is implemented. This can be compared with Figure 7.18 where the difference between available water and that required under the 10% rule per annum is substantially less for Node 4.

The impact on streamflow under each policy is shown by Table 7.21. The model result indicates the reduction in streamflow over the 20-year simulation run as a result of allowing viticulture production systems in the catchment to capture 10%, 20%, and 5% of rainfall. The change in streamflow is deduced by comparison to the Base Case streamflow. The largest change in streamflow is at Nodes 1 and 2. Within these nodes, the model devotes a greater area to viticulture given the more favourable land constraints compared to Nodes 3 and 4 that represent the spatial area with poorer biophysical attributes favourable to viticulture establishment. Hence, this is why the change in streamflow is less at these nodes.

Table 7.21: Reduction in streamflow (ML) as a result of allowing production systems to capture various runoff options. The result is the difference in streamflow between the policy option compared to the Base Case streamflow calibrated at the node over the 20-year simulation

	10% Capture (ML)	20% Capture (ML)	5% Capture (ML)
Node 1	173	194	201
Node 2	192	170	202
Node 3	87	65	124
Node 4	124	156	149

7.9 Discussion of Results and Modelling Assumptions

This section contains a discussion of the usefulness of the integrated model. It also examines the plausibility of the integrated model results in identifying trade-offs and impacts with reference to the three land and water policy scenarios selected for analysis. The third sub section discusses the major modelling assumptions utilised in scenario analysis. Model limitations as a result of the assumptions are also discussed. In view of the large amount of results that were presented in this chapter, the synthesis of results uses examples to relate key points.

7.9.1 Synthesis of Model Output for Model Scenarios

This section identifies the major outcomes and usefulness of using the integrated model to assess the land and water policy options considered in this thesis. These can be summarised by the following three major outcomes:

Trade-offs: The results from running the integrated model illustrate several trade-offs specific to each policy option that could not be ascertained easily without running an integrated model. In Section 7.6, three scenarios were run to examine the impact of planting forestry as a Salinity Management Policy. Plantation of 50% and 80% of the potentially forested catchment area to forestry not only resulted in the impact upon profit for those activities that must take land out of production, but more importantly, the scenario highlighted the trade-off for irrigated activities that would occur as a result of policy imposition. This caused a reduction in irrigated areas as a result of reducing runoff and hence streamflow available for in-stream extraction by lucerne and rotational cropping activities. This illustrates the usefulness of the integrated model in identifying impacts on land use systems that are not targeted by the policy option. Thus, the integrated model identified the effects on irrigated land use systems as a result of imposing dryland policy options.

System Interactions: The results from the integrated model illustrate the non-linear system interactions that can not be considered easily in partial system studies. Section 7.6.1 to 7.6.3 presented results from running three forestry options resulting in the plantation of 20%, 50% and 80% of the catchment to forestry. The model showed that imposing a 20% plantation gave a proportional (i.e approximately 20%) change in profit of the agricultural production systems for the catchment (given by all four nodes) as a whole. The 20% scenario showed how forestry could be planted without compromising economic viability by taking land out of grazing production (that has a lower per hectare economic return) and leaving 'value-added' activities such as viticulture. This was shown by the fact that when 80% of the catchment was planted to forestry, the impact was greater than just the proportional change indicated for the 20% option. This shows the potential for land use change to mediate some of the impacts of imposing policy options within the catchment. Studies that do not include integration of land, water and agricultural decision making behaviour may over-estimate these types of impacts. The integrated model allows assessment of the impact of changed agricultural production behaviour in response to policy imposition rather than assuming no adjustment in response. An integrated model overcomes the problems in assuming a linear relationship between land taken out of production and profitability. Thus, the integrated model is useful in presenting land use solutions not previously thought of, in an effort to reduce direct impacts (upon farm profit in this case) as a result of imposing a policy that takes land out of production.

Thresholds for Change: The results from the integrated model presented in this Chapter illustrate the usefulness of the integrated model in identifying thresholds of change. Where a policy option is selected, the impact may not be linear. This is illustrated by the results from Section 7.6.4 which shows the impact on streamflow as a result of imposing salinity management strategies through farm forestry plantation. The result shows that there is a relatively small impact on streamflow for a plantation of 20%. It is not until the 50% and 80% policy option imposition that the impacts upon the hydrology become significantly large. However, the adjustment and impact on the agricultural production system begins with an adjustment by land use change at 20% plantation cover, and changes in profit at just 50% plantation cover. While the validity of the actual result should be interpreted with extreme caution, the result indicates that an integrated model of this nature can be useful in identifying thresholds for impact.

These results are informative, especially where, as is the case with the integrated model, policy option selection can be trialed to identify the option that has the least impact on the system while still satisfying the policy goal of managing salinity levels for instance. In this example, the integrated model shows that preserving the economic viability of production systems in the catchment could be obtained by land use change rather than a subsidy where a 20% option is selected. The remaining two policy options would require farmer subsidy to preserve economic viability.

Relative and Marginal Impacts: The results from the integrated model are useful in identifying relative change, and therefore ascertainng the marginal impact (adverse or otherwise) of imposing policy options. Section 7.8 shows the impact on agricultural production system viability as a result of imposing a Farm Dams Policy. The results show that the marginal impact is greatest between 5% and 10% imposition. However, the impact arising from changing the policy from 10% to 20% is much less on farm profit. The integrated model is useful in identifying where in the system the marginal impact will be greatest.

Spatially Defined Impacts: A benefit of conceptualising an integrated model of the catchment system is the ability to consider spatially-defined impacts and trade-offs simultaneously. The results from the integrated model have demonstrated this with regard to all three policy options selected for analysis. In Section 7.6, the imposition of the Salinity Management Policy by forestry plantation resulted in an increase in profit at Nodes 1, 3 and 4 given that land use change took place to compensate for the imposition of the policy. However, at Node 2 profit decreased because value-added activity (irrigated lucerne) was taken out of production. In Section 7.8, economic and hydrological impacts on spatially-defined areas are identified in reponse to the imposition of the Farm Dams Policy. The results show that a larger reduction in profit occurs in the spatial area of Node 3 compared to other areas in the catchment.

These results demonstrate how a policy option can be imposed uniformly across the entire catchment yet the impacts vary spatially. The integrated model is thus able to isolate spatial areas by magnitude of impact or trade-off in response to a policy option. This outcome can only be obtained by the unique conceptualisation of the system, being a hierarchy defining various Land Management Units and activities within them. Each Land Management Unit varies in spatial scale, potential scale and responsiveness to specific policy options. The hierarchy-based conceptualisation is crucial for the integrated model to spatially isolate impacts as a result of policy imposition.

7.9.2 Plausibility of Scenario Results

The plausibility of model results can be assessed by several methods. In this thesis, this was done in three ways:

a) examining the magnitude of change in response to policy options;
b) Examining the direction of change in response to policy impositions
c) Considering the type of response from imposing a policy option in order to identify if the conceptualisation of the system and its links were consistent with what could be expected. Examples are used from the model results to explore each method.

Magnitude and Direction of Change: Base Case model results, although within the same order of magnitude for actual land use estimates, overestimated the current extent of value- added and intensive activities such as viticulture. At the Activity level, the results show that the model estimate of viticulture profit was $13 538 per hectare. This is acceptable given that the industry profit varies from $428 per hectare to $17 870 per hectare. The problem in overestimation of the land use occurs at the next level up in the modelling level - the Land Management Unit (LMU). Within the LMU, the model uses a linear programming formulation and optimisation algorithm that maximises profit only. The result is that value-added activities are more likely to be selected over activities that are located in the majority of the catchment such as grazing. The over estimation of some of these land uses in the Base Case could be overcome by tightening the constraint on the available land to such activities, or by including other factors which currently constrain this area.

The Base Case model also results in an overestimation of streamflow in the hydrological system at Nodes 3 and 4. This corresponds to the physical location in the catchment of Yass weir. This was not included in streamflow estimation at the node. Rather, streamflow was added downstream rather than routed under the assumptions generated in Chapter 5 (see Chapter 5 conclusions for details). However, the overestimation was not problematic in generating appropriate outputs for the integrated model scenarios for the reason that extraction from the stream only occured at Nodes 1 and 2 in the upper catchment. Activities downstream altered streamflow but did not effect extractions as was the case for the larger areas at Nodes 1 and 2. The applicability of the assumption is shown by the Base Case result where extraction from the river is estimated at 6 911 ML/Year at Node 1 and 7 701 ML/Year at Node 2. This is comparable with the actual rate of extraction that has been estimated by using licence numbers and crop conversion rates, that is, 3 417 ML /per annum.

The salinity management scenario resulted in a large change to profit given that land was taken out of production for forestry activities. The model output was consistent with the production system, having the greatest impact where valued-added activities were taken out of production. Model output of this nature as a result of salinity management scenarios was therefore successful in identifying within-node impacts and spatial trade-offs as a result of changes between nodes.

However, the impact on the hydrological systems was of less magnitude than that on profit, resulting in a small decrease in streamflow. As the results in Section 7.6 show, imposing plantations of 20% of the catchment area did not have a significant impact on runoff and hence streamflow. Streamflow impact did occur however at the 50% and 80% plantation policy options. The insensitivity of the integrated model at 20% to changes in streamflow was not expected. The plausibility of this result requires further testing and, in particular, sensitivity analysis to ascertain if the result is plausible or if the model conceptualisation requires further work.

System Links and Conceptualisation: Section 7.7 presented the results for running a volumetric conversions scenario. This is a useful example of selecting the appropriate modelling assumptions with which to investigate a particular policy option. In this case, the assumptions made in the extractive model result in the true economic impact on irrigator profit being underestimated. Given the distribution of flows in Yass catchment, the model overestimates the economic viability and area planted to irrigated activities under water policy options. This is due to the nature of the extractive policy model in the integrated model. Within the model, streamflow from the hydrology module is aggregated to a seasonal volume to be passed to the production system model. The production system model assesses water demand and supply for the entire season and allocates land accordingly, given the water constraint in the optimisation. Hence the irrigated production module does not consider the number of consecutive days of no flows. Rather the total volume over the season is used to make decisions regarding the production of irrigated activities As a result, according to the model, it is possible to conduct an economically viable irrigated activitiy if the season's streamflow falls within a short period of time, given that a system assumption is that water is not held in farm dams for dry periods. An alternative would be to assume a carryover or dam holding capacity in the model formulation.

In summary, the results of the scenario analysis appear largely consistent with what could be expected given it was designed as a tool for catchment-scale analysis of land and water policy issues of interest in the thesis. However, there is room for improvements, as well as further testing of the model response to changes in policy imposition.

7.9.3 Major Modelling Assumptions and Limitations

The major modelling assumptions are given in Table 7.22. It outlines the assumptions made in the agricultural production system and the hydrological systems. A brief discussion of the assumptions and the implications for the usefulness of the integrated model are given in this section.

A major limitation in the integrated model is the system assumption that the regional farmer makes production decisions based on changes in the biophysical system only. In this case, dryland farmers make a decision based on available rainfall, irrigators make production decisions based on daily streamflow, and viticulture farmers make production decisions based on runoff and farm dam capacity. In addition, the farmer is assumed to have perfect knowledge ragarding the next 20-years of climate data including rainfall and steamflow. However, this assumption could easily be relaxed by incorporating other socio-economic factors that influence farmer decision making.

Table 7.22: Major Modelling Assumptions used in the integrated modelling approach

Economic (Agricultural Production System)	**Hydrology (climate and streamflow system)**
No change in price	Lack of groundwater model to estimate recharge and discharge to streams
No Change in Yield	Lack of model to estimation extractions for town water supply
Yield not rainfall dependent for viticulture production	The runoff coefficient is assumed by analysis of streamflow and rainfall time series. It is constant over the entire catchment
Yield not rainfall dependent for irrigated activities	Evaporative loss from dams is assumed constant over the entire system and is obtained from the literature
Land use change does not incur exit costs	Streamflow is advected downstream
External factors contributing to profit are static: i.e. inflation and interest rates	
There is no investment in new technologies to improve viability of current land use	
Farmers only plant out an area that is able to be supported by the available water	
Decision making is based on profit maximisation only (not other important socio-economic factors)	
Irrigation farmers do not hold water in farm dams for a carry-over. All water is pumped directly from the stream for immediate use on the crop.	
Rotational cropping always assumes a 50/50 mix of rotational cropping and area that is fallow for grazing	
Model is a regional model so a single farmer makes a decision for the entire region	
Grazing yield is tied to a limited number of climate thresholds only	
Farmers have perfect knowledge with regard to climate and streamflow	

Although the viticulture production system does vary in yield with maturity of the grape vines, yield is not dependent on rainfall. Rather the assumption has been made that farmers do not plant any more grapes than they have water to irrigate. This assumption was crucial to avoid the model planting a large area of grapes in one year and then having no water in the following year to sustain the grapes, but then replanting again in the following year and obtaining high yields. Given that grapes take at least 5 years to mature, the assumption was made that the farmer calculates the volume of water available over all irrigation seasons for the 20-year simulation, and plants only enough grapes to avoid wilting or death of the crop given a crop conversion rate that varies only over three maturity phases.

The assumption for water use of irrigated crop activities was simpler again; assuming a single crop conversion rate and perfect knowledge of farmers with regard to the area of irrigated crop able to be sustained over the 20-year simulation. A valid assumption in Yass catchment given the nature of current land use practices is that irrigators do not extract from the stream for the purpose of holding water in farm dams or using the water for carryover. All water that is extracted from the stream is applied directly to the crop at that point in time. A major assumption of irrigated activities is that rotational cropping only occurs in a 50/50 ratio with grazing. Obviously, this could be varied in the model if required.

The point of integration between dryland production systems and the biophysical system was through rainfall. The assumption was different to irrigated and supplementary irrigated systems in that yield was rainfall-dependent at two thresholds only. In particular, the responsivenss of the grazing dryland system to changes in the biohysical system could be improved by modelling the relationship between yield and rainfall in a more detailed way. A second option could be to integrate the dryland grazing module with a more sophisticated existing model such as dryland cattle production.

Where land use change occurs, a simplifying assumption is made that the farmer does not incur any exit costs of production. Hence, a farmer could make a land use change from grazing to viticulture given land and water availability, without incurring exit costs other than the capital required to start a viticulture activity.

The agricultural production system is also a partial equilibrium system in that the impacts of wider macroeconomic policy changes do not affect farmer decision making with regard to crop plantation or land use change. Therefore, economic factors such as inflation and interest rates are assumed static. Furthermore, prices received for production are assumed static for a given yield. Clearly, this could be varied if desired. In addition, the regional or catchment-scale focus of the model entails assumptions about household farmer behaviour. At the Land Management Unit (LMU) level, the assumption is made that there is a single farmer who acts as a decision maker for the LMU and household. The LMU is assumed to be representative of household's behaviour in the region. Past modelling approaches have used household data aggregated to the regional level as a process of identifying the exact nature of the regional farmer. In this case, a profile of the regions and their production systems is assumed sufficient in detail to construct a regional model.

A major limitation of the biophysical model applied to Yass catchment is the lack of any groundwater model or means to integrate surface water and groundwater interactions. Given that the current irrigated land use does not rely upon conjunctive use, a decision was made to model only surface water. However, groundwater recharge and the interaction between groundwater and surface water is a significant process in the catchment with seven recharge areas identified (see Chapter 3 and Scown and Nicoll, 1993).

A final assumption made within the hydrology model component is the static nature spatially and temporally of both the runoff coefficient and the evaporative loss from farm dams. The latter was obtained from literature on farm dams. Any improvements to these assumptions could be incorporated into the model.

7.10 Conclusions

The results presented in Chapter 7 show that the modelling approach is capable of representing and analysing catchment-scale land and water policy issues. The model results show that catchment-scale trade-offs and impacts are able to be ascertained. The results for scenario analysis are supported by the Base Case model run that predicts many of the facets of the current land and water situation to be the same order of magnitude as observations. The results indicate that the approach has a firm conceptual and modelling basis for further work to overcome the limitations of the model presented in Section 7.9.2.

Although the modelling approach results indicate that the framework developed in the thesis approach is suitable for Volumetric Conversions, Salinity Management and the Farm Dams Policies, the model has many limitations that prevent it from being used in its current form to fully investigate specific policy options. The largest limiting assumptions with respect to the biophysical system is the lack of a groundwater model. This is particularly important in Yass catchment given the nature of its hydrogeology and aquifer system connection to surface water flow. One of the largest assumptions in the agricultural production system model is that farmers make decisions based on profit maximisation only. Traditional activities such as grazing may well have other factors that influence farmer behaviour.

Refinement of benefit to the model would therefore involve the development of a groundwater model component. Furthermore, the incorporation of other socio-economic factors such as behavioural interactions with farmer decision making would yield greater benefits to analysing land and water policy options of the type investigated in the thesis.

The discussion of the plausibility of model results and the limitations of the conceptualisation raises the issue of model testing to validate the approach. A specific example is the small change in hydrological indicators given the imposition of a salinity management option where the forestry option imposed was the plantation of 20% of the total catchment area. Yet a significant change in the hydrology indicator occurred at 50% and 80% forestry plantation options. Clearly, more sensitivity testing of the model to changes in policy parameters would be of benefit in further characterising the bahaviour of the model and the structure of the conceptualisation. This is the subject of Chapter 8.

Chapter 8 Sensitivity Analysis and Model Limitations

8.1 Introduction

Chapter 8 is concerned with sensitivity testing of the model output identified in Chapter 7. It elaborates on the major system assumptions used to construct the integrated model. In applying sensitivity analysis to the integrated model, the validity and importance of the assumptions can be identified. Sensitivity analysis assists in identifying to what extent an integrated model of the type developed in this thesis is useful for analysing the three land and water policy issues used for scenario runs. In this respect, Chapter 8 has the following components:

- Sensitivity testing of the hydrological component of the integrated model
- Sensitivity testing of the agricultural production component of the integrated model
- Sensitivity testing of other major system assumptions in the integrated model
- Identification and discussion of the limitations of the modelling approach used in the thesis

8.2 Testing of Model Variables

Table 8.1 shows the model variables that could be subject to sensitivity testing given the modelling assumptions and issues raised with regard to specific model variables in Chapter 7. The second column identifies which of these variables are tested, giving the section of the chapter in which the testing is to be found, and the variables that are not tested.

The agricultural production modelling component tests the maximum area devoted to each activity. Calculation of the total area available to each activity was identified by available GIS data (see Section 3.15). In particular, the land made available to viticulture activities was the result of using land use maps and slope to identify areas. The sensitivity analysis varies the potential land available to viticulture and examines the effects on the results at each node. Similarly, area devoted to irrigation is also tested given that the same land use data was utilised to identify all areas of potential for irrigable activities.

Sensitivity testing is carried out on all three policy options to ascertain how appropriate the integrated modelling approach was for examining scenarios specifically aimed at the Farm Dams Policy, Volumetric Conversions Policy and Salinity Management Policy options.

The hydrology component was not exhaustively tested in Chapter 5. Those selected variables of the hydrological modelling component deemed important for the performance of the integrated model are subject to sensitivity testing in this chapter.

Table 8.1: Variables used for sensitivity testing in Chapter 8

Variable Value	Chapter Section if test performed
Agricultural Production Model Component	
Area devoted to forestry production	8.3
Maximum area of viticulture	8.11
Maximum area of irrigable land	8.6
Yield for viticulture	no
Yield for irrigable activities	no
Yield for forestry	no
Grazing yield variability with rainfall	no
Prices for crop yields	no
Water use of viticulture and irrigable crops	no
Hydrological Model Component	
Threshold for the catchment moisture deficit	no
Available daily rainfall	8.8
Evaporative loss from farm dams	8.12
Area required to drain 1 ML of water	no
Runoff coefficient	8.9
Integrated model (Policy Scenarios)	
Maximum allowable volume of farm dams	8.10
Commence to pump rules	8.7
Maximum pump capacity of irrigators	no
Daily Extraction entitlement	8.5
Annual Licence Allocation	8.4
Area of land devoted to farm forestry	8.3

For each of the variables identified in Table 8.1, a percentage variation from the Base Case was applied. The sensitivity analysis was carried out by changing the value of the variable over several (up to ten) increments. The change occurred in increments, usually both above and below the variable identified in the Base Case. The measure of sensitivity is:

$$\%\ \text{change} = \frac{\text{scenario indicator value - base case indicator value}}{\text{base case indicator value}} \bullet 100$$

All other model variables remained as per the Base Case model, that is, only one variable at a time was changed to examine the effect on the outputs. The simulations are carried out over 20 years on a daily time step.

In order to apply consistency in testing both the production model and the hydrology variables, the following three indicators were selected to test the model at each node:

- Total nodal profit ($)
- Median of non zero flows (Megalitres)
- Number of zero flow days

Finally, the indicator results were represented as a percentage change. This ensured a consistent scale to compare variable sensitivity across both agricultural production and hydrological variables. This also serves the purpose of identifying the direction and magnitude of variable change in evaluating the integrated model. The second indicator takes the median value of all stream flow but excludes zero flow days since streams in this area are often ephemeral so that median of all flows is not a good estimator of flow magnitude. The number of days where flow does not occur is also an important indicator of the hydrological system. When used in combination with the median of non-zero flows, this indicates the extent to which the catchment is 'dried out'. Table 8.2 shows the interaction between the flow indicators. It shows the possible explanation of model behaviour with changes in the indicators.

Table 8.2: Interaction of hydrology indicators

	Median non-zero flow		
		Increase	Decrease
Number of Zero Flow Days	Increase	Low flows are being dried out. Other flows may be increasing or decreasing	Catchment is drier overall
	Decrease	Catchment is wetter overall	Increases number of low flow events (by increasing flows on previously dry days)

The following Sections 8.2.1 to 8.2.10 show how each variable was tested and any assumptions made underlying the testing.

8.2.1 Area of Farm Forestry

To test the variable responsible for implementation of the Salinity Management Policy Option through forestry plantation in the integrated model, the area of farm forestry was changed by 10% increments. Normally the percentage change would be measured from the Base Case for consistency in testing. Given that there was no forestry planted under the Base Case model, it was decided to vary the area of the catchment planted to forestry from 10% of the total catchment area (available for forestry given restrictions placed upon it by soil type) to 80% of the catchment area available for forestry plantation.

8.2.2 Annual Licence Allocation

The annual licence allocation is the annual limit on pumping for irrigators in the catchment. The Base Case allocation was set at 1578 ML per annum for the Yass catchment, which is the current volume. The allocation was increased and decreased by 10% increments from this value. Five of these percentage change values were above the Base Case model value and four were below.

8.2.3 Daily Extraction Volume

The daily extraction volume has a Base Case value of 28 ML per day per node. This is the maximum value that can be pumped from the river given the physical limitation of the pumps in the catchment. The variable was tested by changing the daily extraction volume from 8 ML to 53 ML, in 5 ML increments.

8.2.4 Land Available for Irrigated Activities

Irrigated activities include lucerne irrigation and rotational cropping. As both of these activities exist within the same Land Management Unit, the total area available for both activities was tested. The Base Case model area at each node was changed in 10% increments. Where these activities are possible (Nodes 1, 2 and 4) five increments were above and four were below the Base Case value. As the model results show in Chapter 7, irrigated activities are not an option at Node 3 under the Base Case.

8.2.5 Commence to Pump Rules

The Base Case value for the commence to pump (CTP) rule was zero megalitres (ML) per day. The CTP rule was varied over increments of 5 ML each, ranging from 0 to 40 ML per day.

8.2.6 Rainfall Variation

Daily rainfall for the Base Case model was taken from areal catchment estimates as developed in Chapter 5. As the interest in managing water for drought scenarios is more important than flood scenarios in a dryland catchment such as Yass, it was decided to test the sensitivity of the model by reducing rainfall only. Daily rainfall was varied over four increments. Rainfall was reduced by 5%, 10%, 15% and 20% of its original daily volume (the Base Case value) for the 20-year simulation period. Each value in the daily time series was adjusted by these proportions.

8.2.7 Runoff Coefficient

The runoff coefficient was estimated from the ratio of total discharge to total rainfall as 0.21 for Yass catchment for the Base Case model. The value was varied in increments of 0.05 from 0.1 to 0.55, where 0.1 represents 10% of rainfall running off the catchment to form streamflow.

8.2.8 Runoff Captured by Farm Dams

This variable represents allowable runoff capture under the Farm Dams Policy. The runoff captured by farm dams was assumed as 30% for the Base Case value as indicated by Schreider *et al.*, (2002). The variable was tested by making percentage changes above and below the Base Case. The model sensitivity was tested at 10% increments between 10% and 90% (of runoff captured by farm dams).

8.2.9 Land Available for Viticulture

Given that the model overestimated the area devoted to viticulture activities (see Chapter 7 for details) it was decided to test the viticulture land constraint ranging in increments of 10% of the Base Case value at each node. The variable was tested in three 10% increments below the base case and six 10% increments above the base case.

8.2.10 Changes in Evaporative Loss from Farm Dams

The Base Case value for the efficiency of farm dams was 65%. Sensitivity testing of this variable occurred in increments of 10% from 0% to 90%, where 90% represents the evaporation of 90% of water stored in farm dams.

8.3 Land Use Change: Farm Forestry

Sensitivity of the three indicators to the area devoted to farm forestry was tested with respect to the area belonging to each node. The hydrology indicator, number of zero flow days, did not change. However, the hydrology indicator, the median of non zero flows, was sensitive to changes in forestry scenarios as was the profit indicator.

Table 8.3 shows the change in the median of non zero flows given an incremental change in forest area. The scenarios show that a threshold occurs for Nodes 1 to 3 at 40% to 50%, corresponding with the plantation of the catchment from 40% to 50% of the total nodal area. Node 4 is less sensitive. The model is less sensitive to further changes in forestry plantation. The result indicates that even where 80% of the catchment area is devoted to forestry, the impact upon the median of non zero flows is less than a 6% change compared to the Base Case at any node.

Table 8.3 Percentage change (compared to the Base Case) of the median of non zero flows given plantation of the nodal area as a percentage of the catchment area

	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**
Node 1	0	0	0	0	-2.6	-3.5	-3.7	-4.1
Node 2	0	0	0	0	-2.8	-4.2	-3.4	-4.8
Node 3	0	0	0	0	-2.3	-2.6	-3.4	-3.8
Node 4	0	0	0	0	0	0	-2.3	-5.3

The number of zero flow days did not change. This could be expected as changes in runoff as a result of plantation establishment were not significant. The number of zero flows could be expected to increase if the total change in runoff was larger. As Table 8.3 indicates, the modelled runoff is not highly sensitive to changes in plantation cover. At most, a 5.3% change in the median of non zero flow occurs. This is probably not enough to reduce small streamflow events to zero streamflow events in the integrated model.

Figure 8.1 shows the change in total nodal profit as a result of implementing a salinity management option, ranging from taking land out of production for the plantation of softwood from 10% of the catchment to 80% of the catchment. The Base Case value corresponds to zero on the horizontal axis. The greatest economic impact occurs for the area belonging to Node 4. There is a 92% reduction in profit where the area devoted to forestry is 80% of the catchment area. Node 3 has the second largest impact because viticulture is taken out of production and replaced with forestry. Viticulture is a 'value added' agricultural activity with a high per hectare economic return relative to other activities. It could be expected that replacing this activity with forestry would result in a larger reduction in profit compared to other nodes that do not contain the activity. Nodes 1 and 2 also experience a decrease in profit up to 60% when the land use change to forestry occurs.

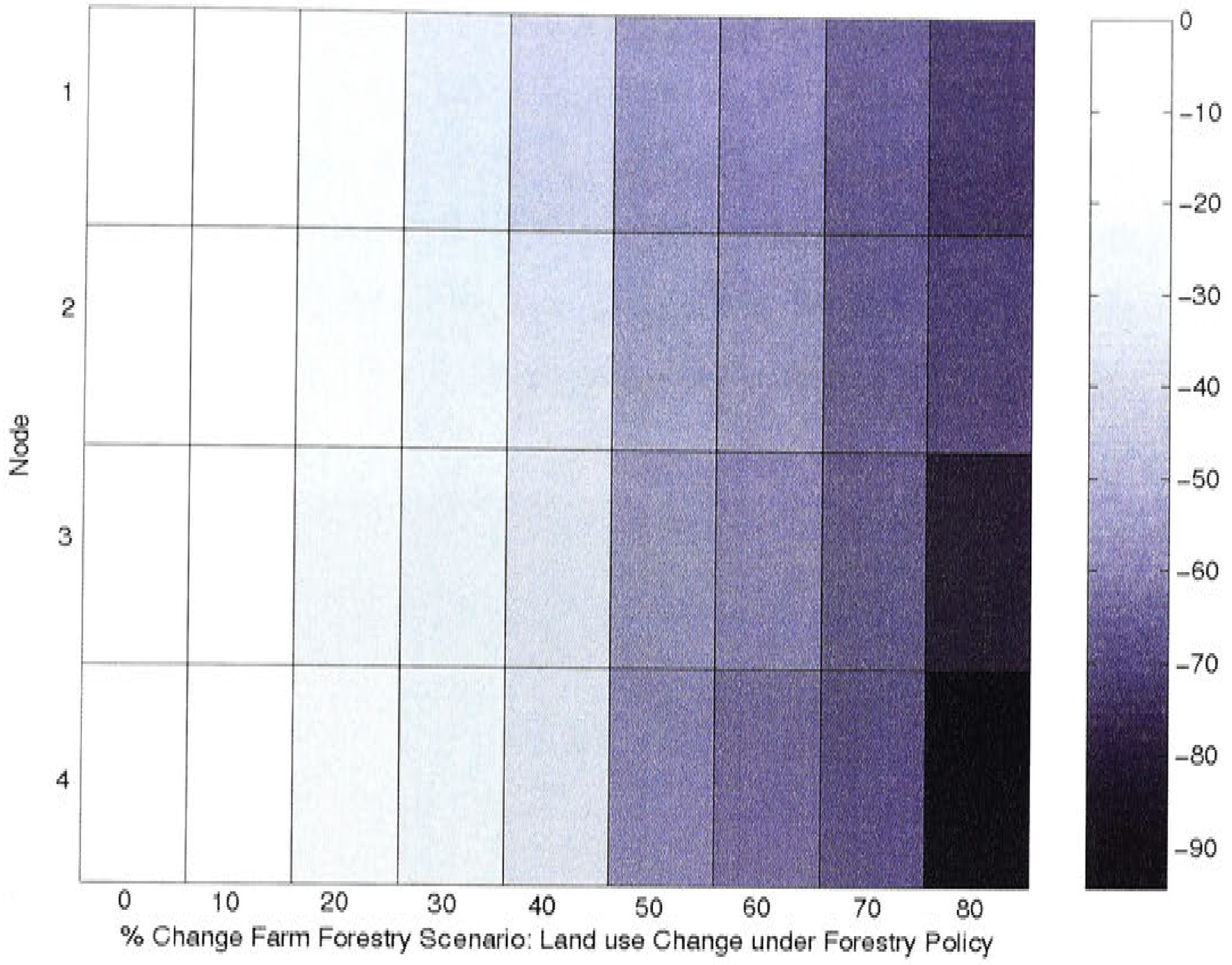

Figure 8.1: Model sensitivity of nodal profit to percentage of catchment under forest cover. Base Case value is shown at 0 on the horizontal axis

8.4 Annual Licence Allocation

The bulk extraction limit is the annual streamflow volume available for irrigation under the volumetric rule. The scenario was only activated at nodes where extractive irrigation LMUs were present (ie Nodes 1, 2 and 4). Profit was most sensitive to changes in the annual licensed allocation. The hydrological indicator, median of non zero flows, was also sensitive whereas the number of zero flow days did not change over the 10 scenario options. Figure 8.2 illustrates the change in profit as a result of varying the annual allocation. There is no change to total profit at any nodes other than at Node 1. A 10% increase in the allocation from the current limit on pumping capacity of 1578 ML/Yr results in a 0.44% increase in profit. The maximum increase in profit occurs when the allocation is increased to 2367 ML. This allocation is a recently suggested limit in unregulated catchment systems including Yass catchment (DLWC, 2001a).

Profit is linearly sensitive to changes in the annual allocation, with a change of 0.44% for each 10% increase in annual allocation. There are no changes in profit at other nodes as smaller areas of land are available for in-stream activities due to biophysical constraints in the lower catchment. The area devoted to rotational and lucerne activities requires less than the 1578 ML allocated under the Base Case model. Hence increasing the annual allocation does not result in an increase in the area devoted to irrigated activities because that annual allocation at Nodes 2 and 4 is never a binding constraint in the optimisation. Land constraints on production and the daily extraction limits at these nodes constrain irrigation production before the annual allocation does.

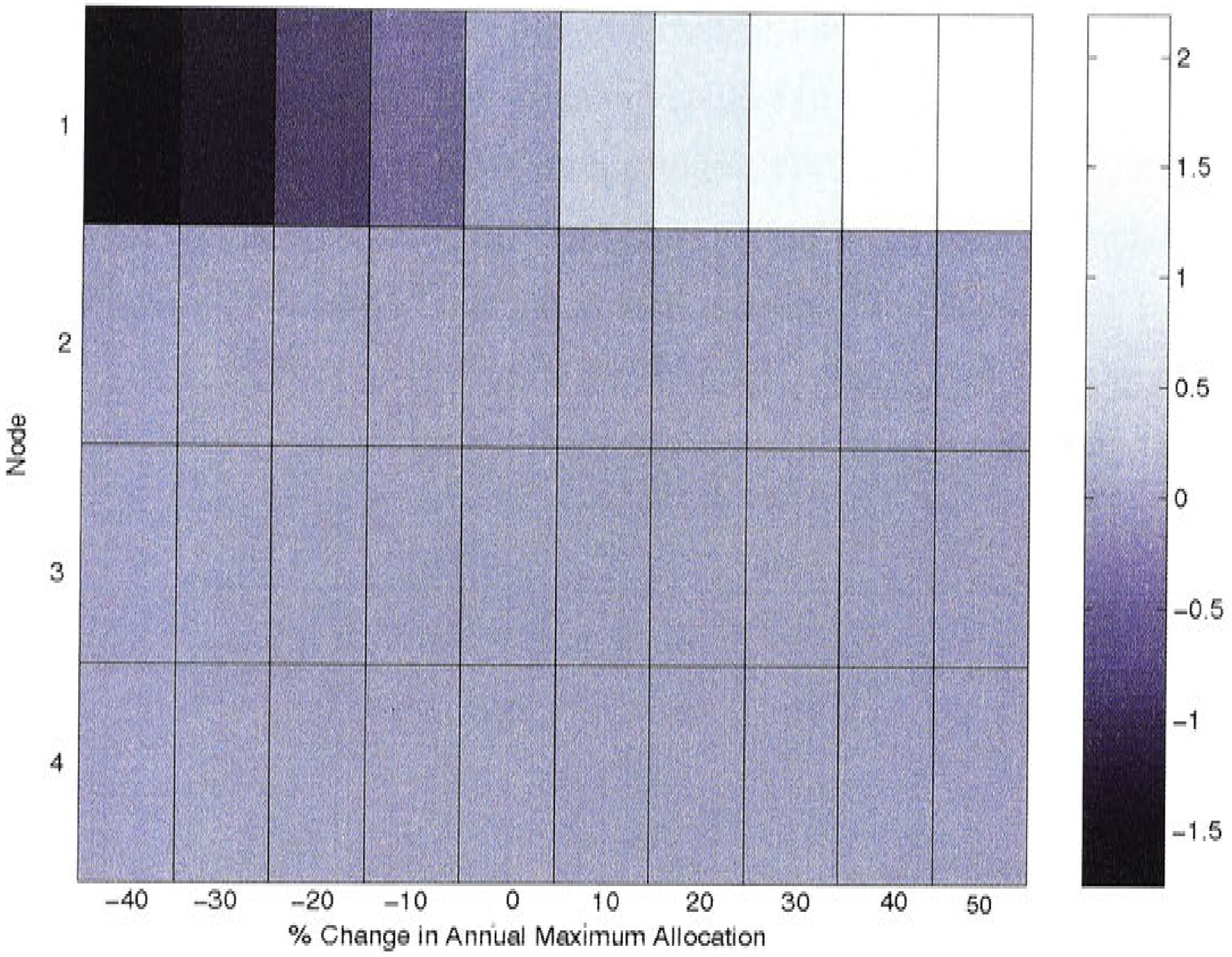

Figure 8.2: Model sensitivity of profit to percentage changes in the annual allocation volume. The Base Case value of 1578 ML is located at 0 on the horizontal axis

Figure 8.3 illustrates the sensitivity of the median of non zero flows for each scenario representing the annual bulk extraction limit. The greatest impacts are at Nodes 2, 3 and 4, where each node experiences a reduction in the median of non zero flows of 22% if all of the available allocation were taken up by farmers. Note that even though no extraction is undertaken at Node 3, a significant impact on streamflow still occurs at this node. Node 1 experiences a reduction up to 19%, slightly less than the other nodes.

The number of zero flow days does not change at any of the four nodes. This is due the operation and assumptions underlying the policy option model (see Chapter 7 conclusions).

The result indicates that although the distribution of streamflow events is shifted with an increase in the annual allocation, the number of zero flow days and low flow events is not affected. Hence there is no trade-off between increasing the annual bulk extraction limit for irrigation and the protection of low flow events for environmental purposes. This assumes that there is no technological change introduced to increase the daily pump capacity of irrigators. Rather, irrigators could extract the same volume of water over different days and increase profit by approximately 2% as Figure 8.2 indicates for Node 1. This is consistent with what could be expected given the conceptualisation of the model. However, it is also a potential limitation as shown in Section 7.9.3.

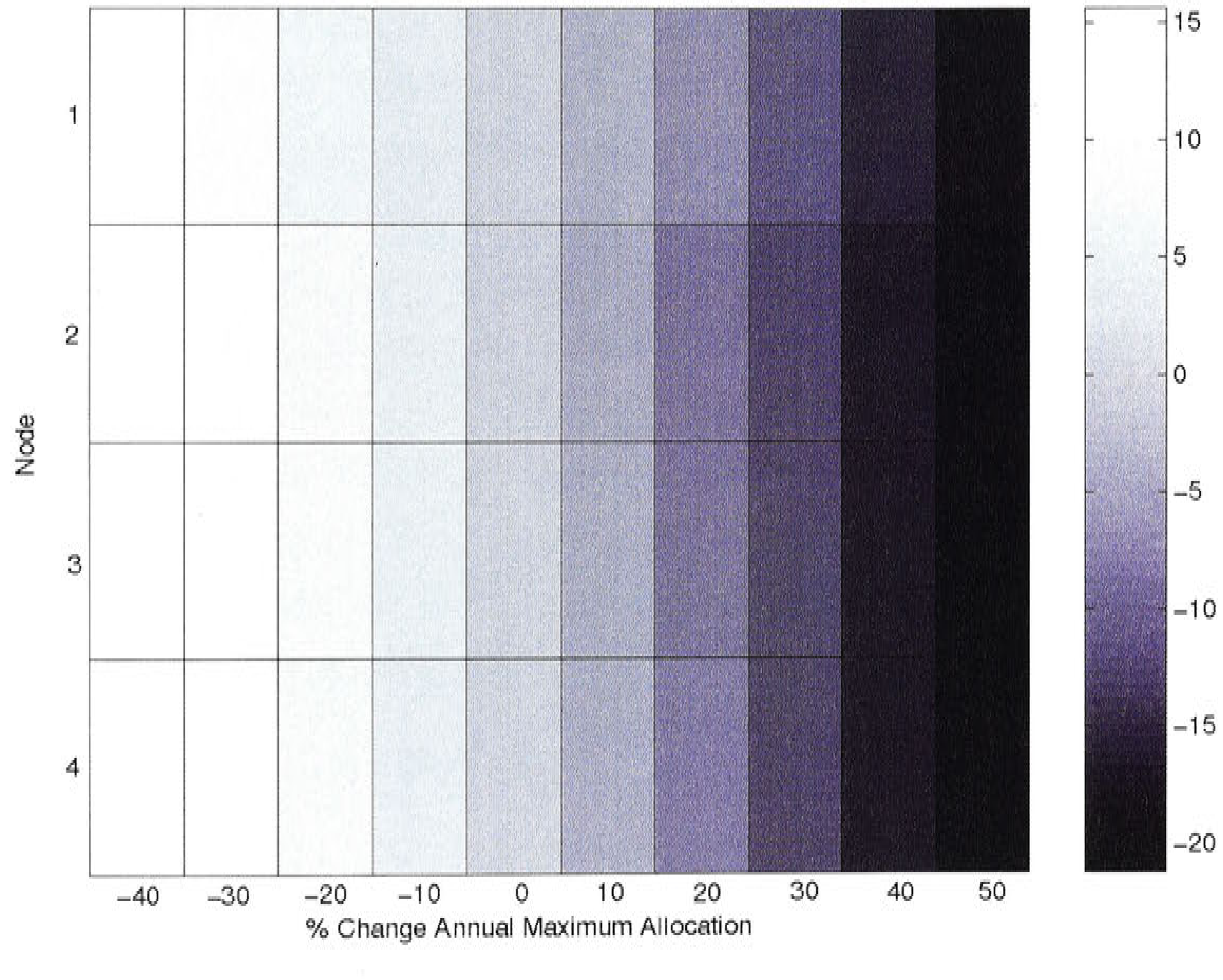

Figure 8.3: Model sensitivity of median of non zero flows to percentage changes in the annual allocation volume. Base Case value of 1578 ML is shown at 0 on the horizontal axis

8.5 Daily Extraction Volume

All three indicators were sensitive to the scenario runs involving changing the daily extraction volume. In this exercise, the annual allocation and commence to pump (CTP) thresholds were fixed at 1578 ML and 0 ML respectively. This scenario therefore allowed irrigators to start pumping from the stream at any river height. However, the total volume they were allowed to extract on a daily basis was capped. Variations in this cap formed the scenarios. The Base Case daily extraction limit was 28ML/day. Note this scenario is only activated at Nodes 1, 2 and 4 where irrigation production is present.

Figure 8.4 shows the change in profit as a result of incremental changes of 5 ML for the daily extraction limit. The results shows that profit is linearly sensitive to changes in the daily extraction limit at Node 1. Raising the daily extraction limit further results in an increase in profit at Node 1. For example, a change from 48 ML per day to 53 ML per day results in a 5.3% change in profit for the area belonging to Node 1. The result indicates that the greatest impact upon irrigator profit is from changes to the daily extraction limit rather than the annual allocation.

For Nodes 2 and 4, varying the allowable daily extraction limit does not have an impact upon profit. At Node 2, the land constraint prevents additional extraction. However, increasing the daily extraction volume allows irrigators to redistribute the days on which extraction does take place. This is seen in the change in the number of zero flow days and the increase in the median of non zero flows in Figures 8.5 and 8.6 respectively for these nodes. Note that this change in flows is also seen at Node 3 even though no irrigated activity is undertaken at this node.

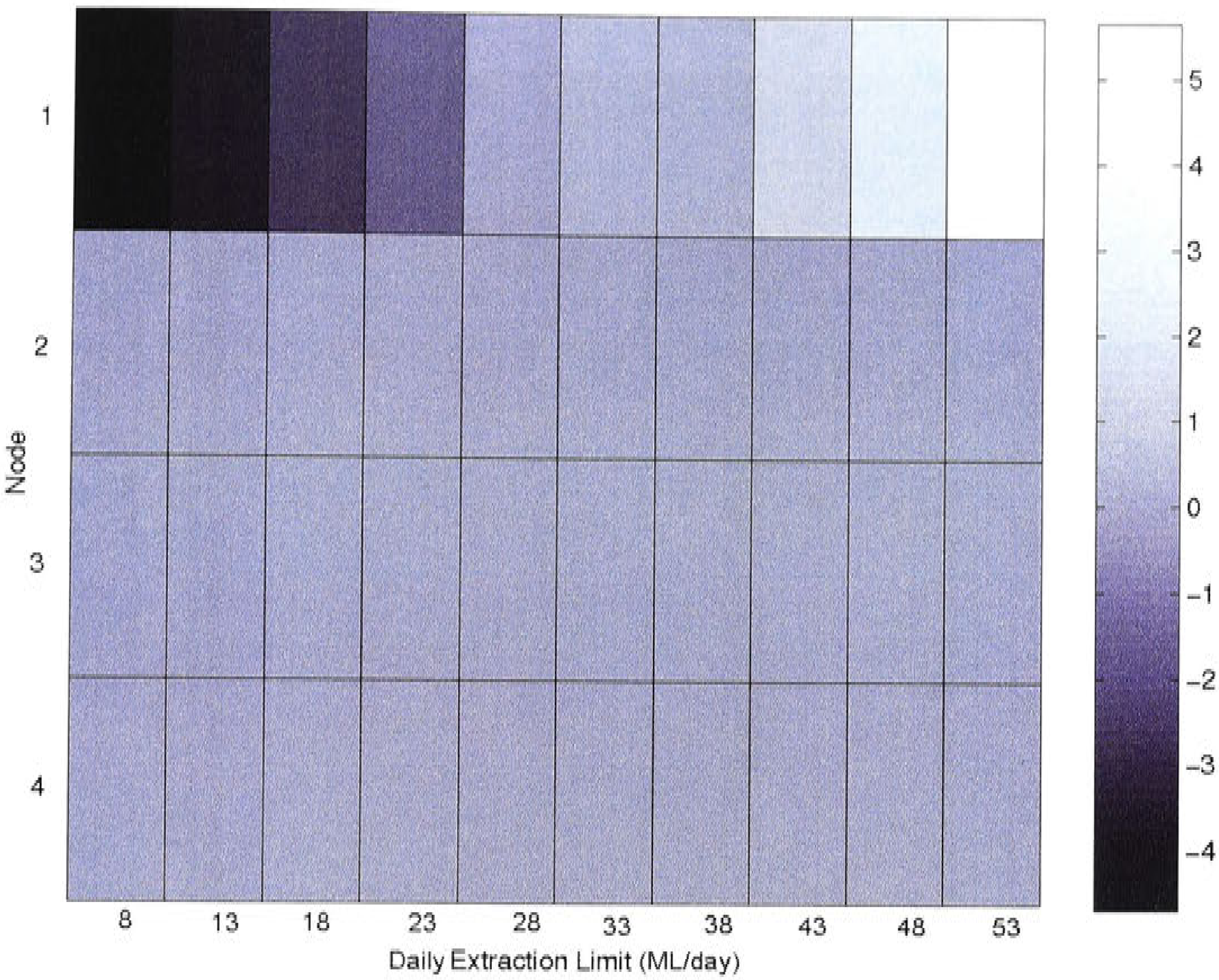

Figure 8.4: Model sensitivity of profit to changes in the daily extraction limit. The Base Case value of 28 ML is shown on the horizontal axis

For any node the number of zero flow days does not change significantly between a daily extraction limit of 8 ML per day and 28 ML per day as indicated by Figure 8.5. A threshold occurs between 33 ML and 38 ML per day from where the proportional increases begin to occur. The reason for the threshold is that at low flows, irrigators extract just part of the hydrograph peak. However, as the allowable limit increases, irrigators may extract the entire hydrograph peak, resulting in the increase in zero flow days at the particular extractive volume. Between 38 ML and 43 ML per day the number of zero flow days over the simuation period increases by approximately 30% at Nodes 1 and 3, and approximately 40% at Nodes 2 and 4. Between 48 ML per day and 53 ML per day the number of zero flow days increases by approximatley 55% across the nodal network.

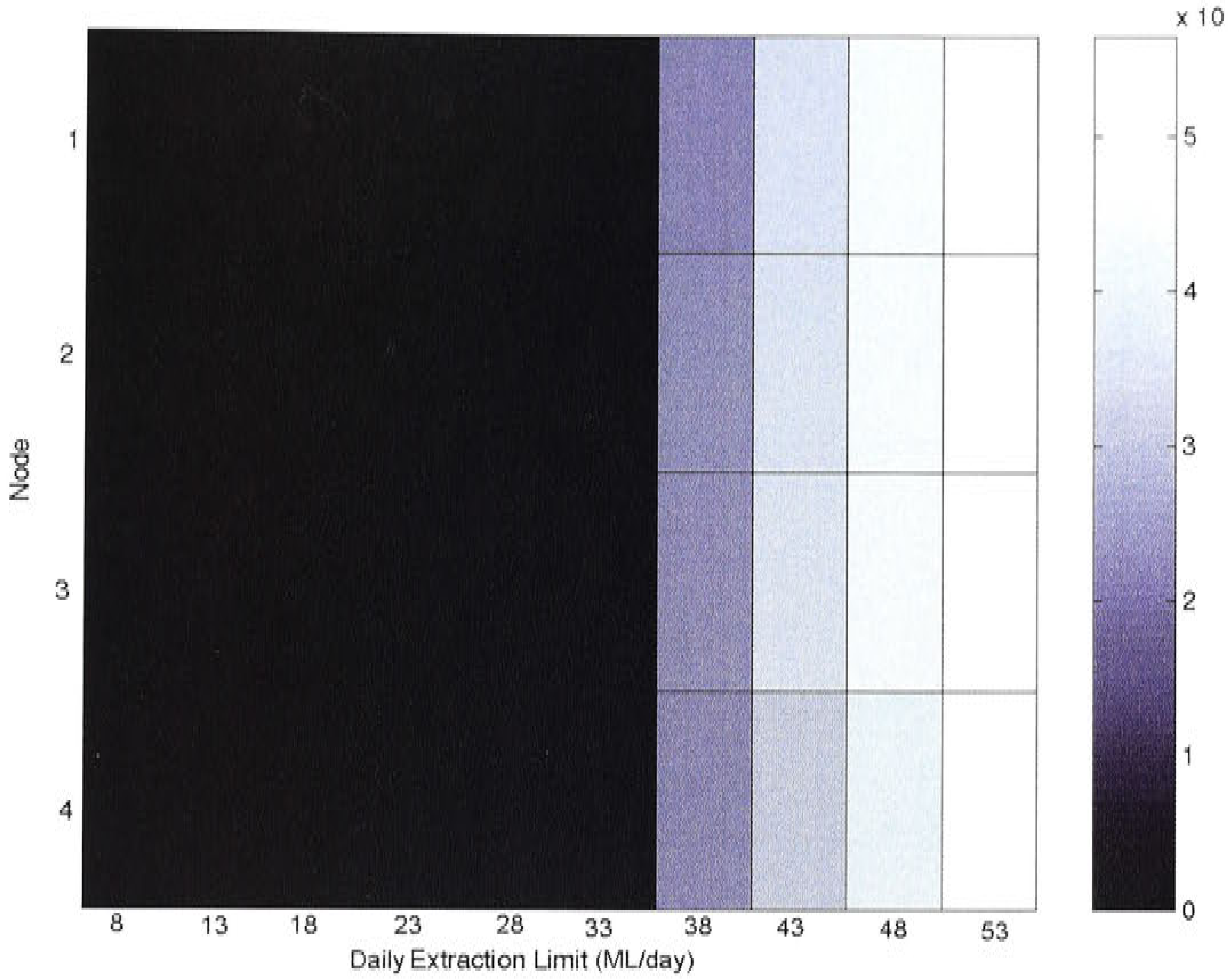

Figure 8.5: Model sensitivity of the number of zero flow days to changes in the daily extraction limit. Base Case value of 28 ML is located on the horizontal axis

Changes to the median of non zero flows as a result of varying the daily extraction volume are shown in Figure 8.6. The results show that the median of non zero flows decreases when extraction is increased above the Base Case value across the nodal network. This is to be expected. As extraction increases the median value of flows will decrease as more water is pumped from the stream. The maximum decrease in the indicator is approximately 27% across the nodal network. Similarly, and as Figure 8.6 shows, when extraction decreases, median flows increase as less water is taken from the stream. Even though Node 3 does not support irrigated agricultural activities, Figure 8.6 shows a change in the indicator, consistent with the direction and magnitude of change for the other nodes that do support irrigation production systems. The result shows the downstream impact on the flow indicator as a result of upstream extractions at Node 1. At Nodes 1 and 2, a change in indicator direction occurs at 13 ML per day. This can be expected. The median of non zero flows can shift in either direction given the change in volume extracted and peak height of streamflow at a given point.

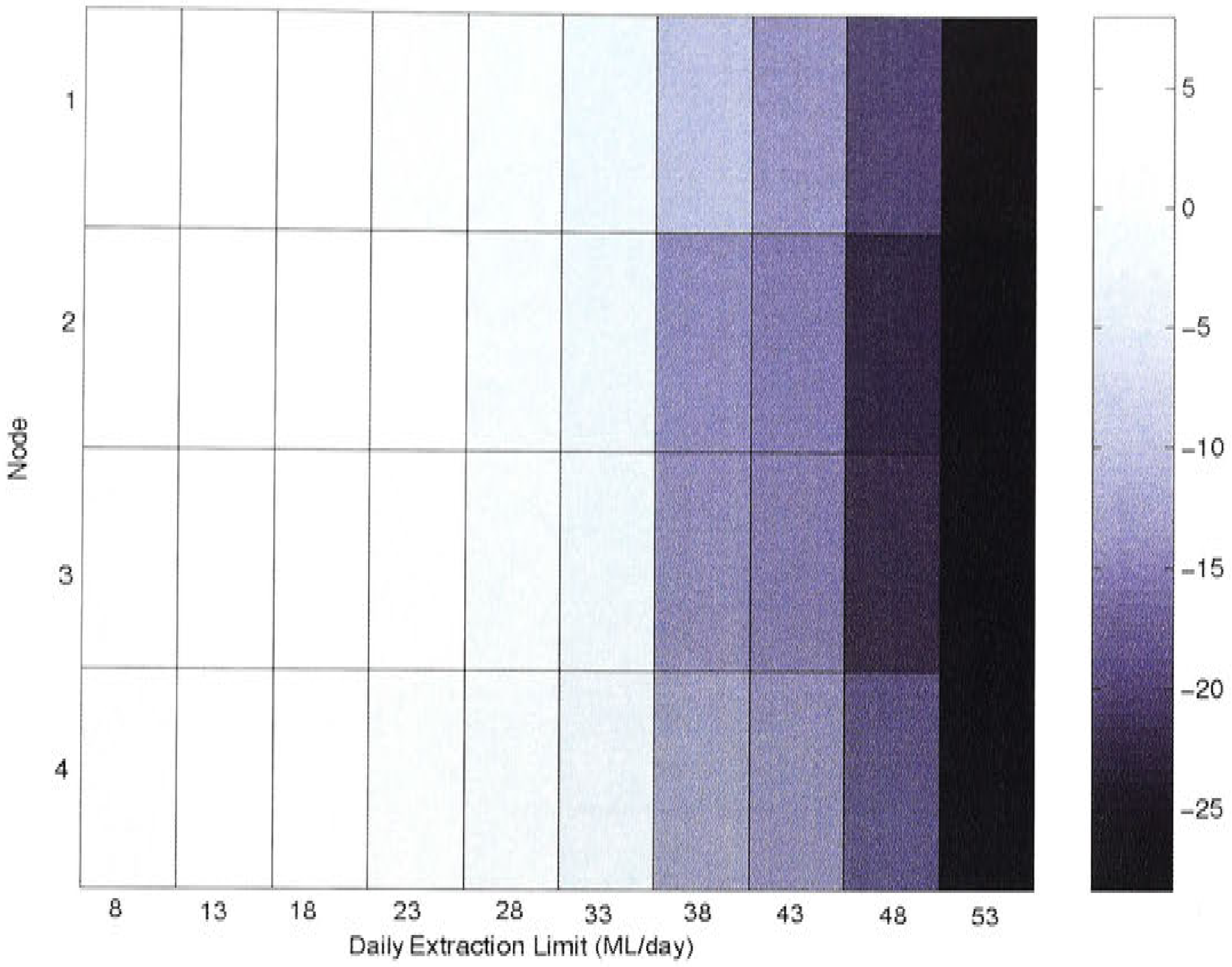

Figure 8.6: Model sensitivity of median of non zero flows to changes in the daily extraction limit. Base Case value of 28 ML is located on the horizontal axis

Figure 8.7 shows the change in the number of zero flow days for each scenario. The greatest increase in the hydrology indicator is shown at Node 4 in Figure 8.7, where the number of zero flow days corresponding to the daily extraction volume between 28 ML and 48 ML. Node 4 corresponds to the spatial area downstream of all other nodes. As the change in the daily extraction volume was imposed on the upstream nodes where irrigation takes place, it is not unreasonable to expect the greatest impact on streamflow to be downstream of these nodes. As the results in Chapter 7 showed, in-stream extraction does not take place at Node 3, while extraction is greatest at Nodes 1 and 2. The conceptualisation of the model in Chapter 4 shows that extractions are passed to the downstream node to be deducted from streamflow at that node. Another interesting feature of Figure 8.7 is that the number of zero flow days decreases between 48 ML and 53ML. Irrigators stop pumping at this point due to either a land constraint or a constraint placed upon them by the other volumetric conversion rules.

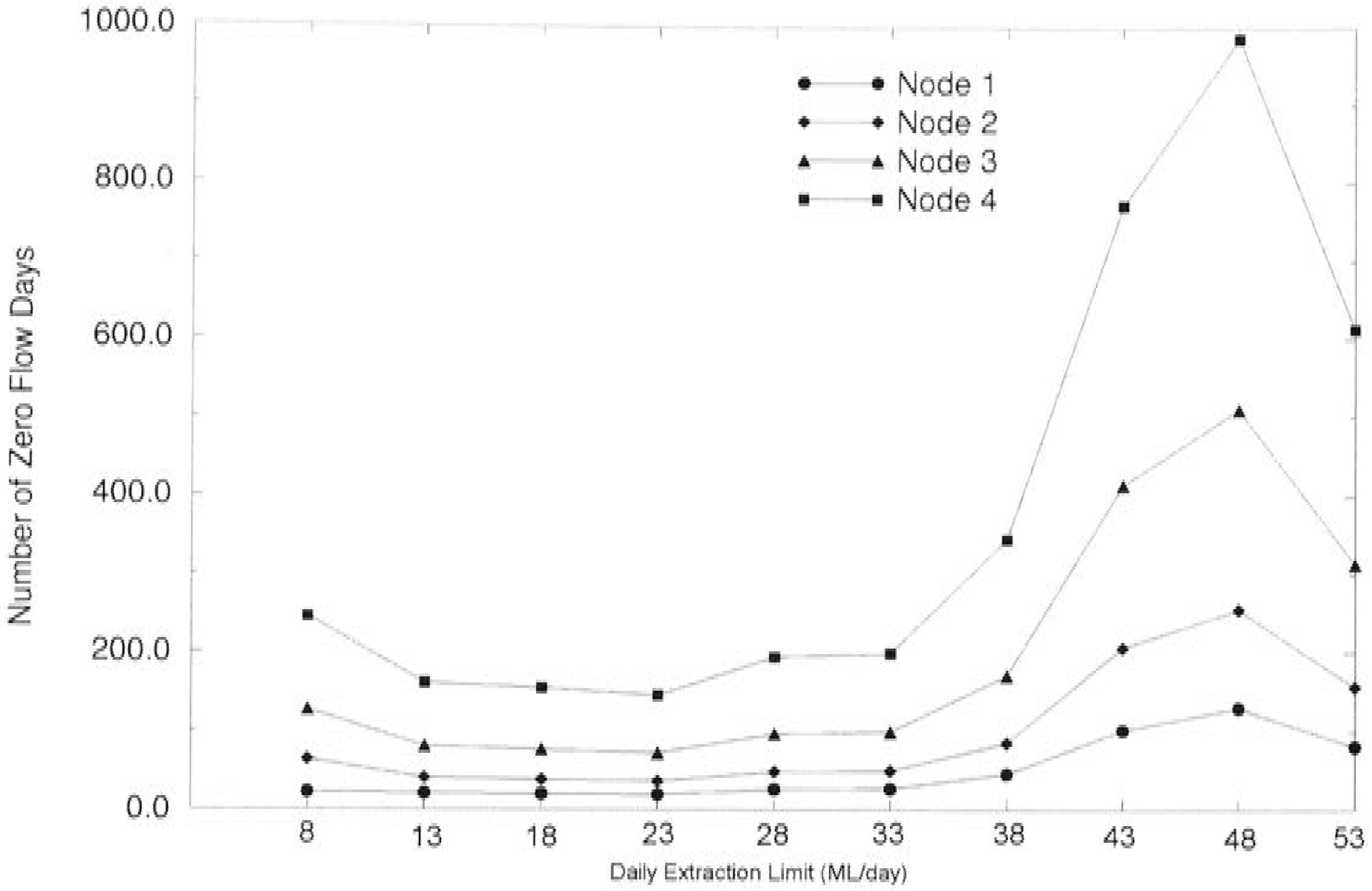

Figure 8.7: Model sensitivity of the number of zero flow days to changes in the daily extraction limit. Base Case value is shown as 28 ML on the horizontal axis

8.6 Land Available for Irrigated Activities

The variable, available irrigable land, was tested by varying the value of land available in 10% increments of irrigable land above and below the Base Case value. The indicators, profit and the median of non zero flows, were sensitive to the scenario changes. The hydrology indicator, number of zero flow days, was not sensitive to any changes in the variable.

Figure 8.8 shows the results for the profit indicator for each of the ten scenarios conducted. The model result shows that there is no change in profit at Node 4. The constraint defining maximum allowable land devoted to irrigated activities is activated at the Base Case. Hence variation in the land constraint would not be expected to produce a change in profit at Node 4. As expected, Node 1 is the most negatively sensitive to changes in the land available for irrigated activities. This is due to the model's selection of irrigated activities over other intensive activities at this node. At Node 2, the increase in profit is not as substantial because biophysical constraints prevent a large portion of the nodal area from being available to higher return activities such as lucerne and rotational cropping.

A threshold occurs between a 20% and 30% decrease in irrigated land use at Nodes 1 and 2. This result is shown in Figure 8.8. A 1.5% decrease in nodal profit is experienced at this threshold. Subsequent increases in available land above the Base Case value result in marginal increases in profit of approximately 0.36% for each 10% change in land available for irrigated activities up to a maximum of just over 3% at Node 2. This is to be expected as Node 2 has the largest area of potential use for irrigated activities given its biophysical attributes.

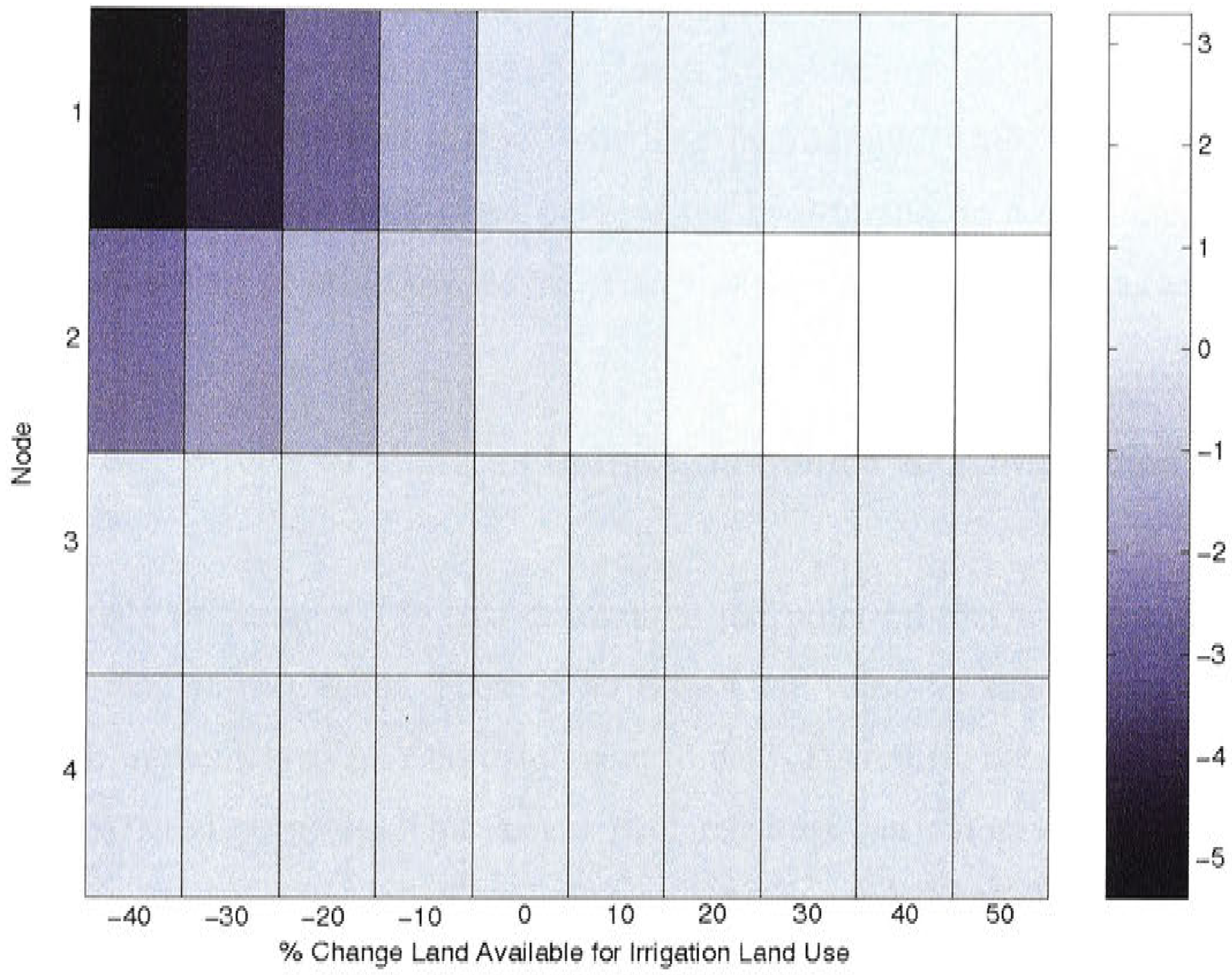

Figure 8.8: Sensitivity of profit as a result of percentage changes in land available to irrigated activities. The Base Case value is given by 0 on the horizontal axis

An increase in irrigable land at Node 1 of 10% results in a large decrease in the median of non zero flows compared to the Base Case model. This is due to the optimisation procedure allocating more land to lucerne and rotational cropping activities as the constraint on available irrigable land is relaxed. This results in more water being extracted from the stream to irrigate the crops. On average, the corresponding decrease in the median of non zero flows is between 4 and 220 megalitres over the simulation period across the nodal network. There is a threshold effect in raising available land for irrigation between 20% and 30% from the Base Case. At this threshold, the optimisation procedure devotes proportionally more land to irrigated activities given their economic viability.

The rate of change in the indicator is less where larger areas of irrigable land are available. A reduction in the available land between 40% and 50% of the Base Case does not result in any significant change in the hydrology indicators. This is due to the small area of land available for irrigated activities in the optimisation procedure. Generally, as the available land increases, the impact of percentage increases in land available on the median of non zero flows decreases as a result of additional extraction from the stream.

Once again, the number of zero flow days did not change. This is for the same reason given in Section 7.9. The policy module extracts a total volume for the irrigation season and redistributes the remaining flow over the hydrograph. Thus, it is possible for irrigators to extract water from other parts of the hydrograph on a daily basis without changing the number of zero flow events. This was shown to be the case in Section 7.7.

8.7 Model Sensitivity to changes in the Commence to Pump Rules

The commence to pump (CTP) rule determines the point on the hydrograph at which water users may extract water. There is no Base Case value for the CTP as the policy has not been implemented in Yass catchment to date. Therefore, the current situation is one of unrestricted pumping. This means that irrigators can pump water regardless of streamflow in the river (ie. low flow and high flow events). The CTP rules have been recommended as a measure to protect both high and low flow events. The annual allocation and daily extraction limit were held constant. The daily extraction limit was set at 28 ML per day as per the Base Case, being the physical pump capacity of irrigators in the catchment. The annual allocation was also set at 1578 ML, the current situation. Only the point on the hydrograph at which extraction can occur was varied.

Of the three indicators used to assess the CTP variable, only the median of non zero flows was sensitive to the scenario changes. Profit and the number of zero flow days were not sensitive to any of the scenarios.

The results in Figure 8.9 indicate that as irrigators are gradually restricted to extracting streamflow at peak events, the median of non zero flows increases. However, the number of zero flow days does not change from the Base Case value. This suggests that irrigators are able to obtain sufficient volume of water over the season to satisfy crop demand while protecting low flows. This is seen in the redistribution of extraction timing and the days on which extraction takes place while having no economic impact upon the profit indicator for lucerne and rotational cropping activities. The redistribution of extraction timing may also the reason why the number of zero flow days does not change.

Figure 8.9 indicates that the median of non zero flows starts to increase by as much as 35% when the commence to pump limit increases to 40 ML. Prior to this point, the median of non zero flows increases at a relatively constant rate up until a CTP of 30 ML per day. This is due to the fact that irrigators can extract water on more days resulting in a slight reduction in the median of non zero flow days across the hydrograph. It also means that the protection of low flows for environmental purposes would have the most impact for a CTP at, or above, 30 ML per day.

However, events above 40 ML per day are less frequent. If irrigators are restricted to commencing extraction at this volume, the model will extract a larger proportion of the event to satisfy the water requirements for the entire season. As profit at all nodes does not change across the nodal network, a CTP of 30 ML to protect low flows would have a significant environmental outcome without reducing the economic viability of agricultural production systems in the catchment, according to the sensitivity analysis. However, as Figure 8.9 shows, the impact upon median flows is most significant where the CTP is set at a higher volume. This result shows the trade-off between protecting low flow and high flow events while satisfying the economic viability of irrigators. The model could be used to investigate alternative environmental flow options.

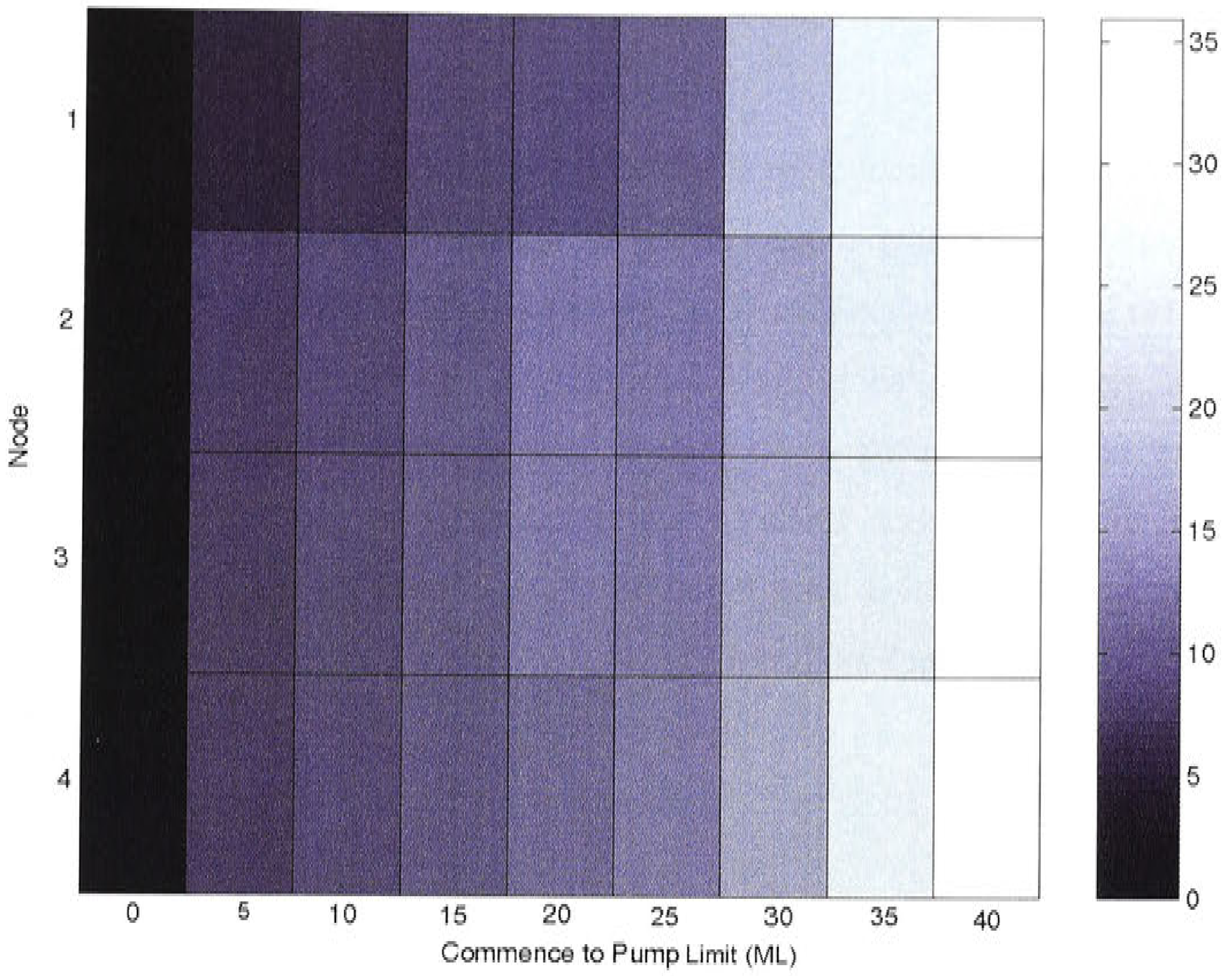

Figure 8.9: Model sensitivity of median of non zero flows to changes in the commence to pump (CTP) rule. Base Case at 0 located on the horizontal axis

8.8 Model Sensitivity to Rainfall Variation

Four climate scenarios were run through the integrated model to examine the sensitivity of the three indicators to daily rainfall reductions. The grid steps applied simultaneously across the entire network system consisted of 5%, 10%, 15% and 20% reductions in rainfall. Profit and the median of non zero flows were sensitive to the scenarios. The number of zero flow days was not sensitive.

A rainfall change has several points (direct and indirect) of potential impact within the model. A direct impact includes the use of daily rainfall as input to the hydrology model, determining available streamflow for extraction by in-stream irrigated activities and as input to the farm dams module to determine available runoff for potential capture by farm dams. A second direct impact is the use of daily rainfall to determine yield of cattle grazing activities. An indirect impact and point of integration between rainfall and the agricultural production system is the loss in runoff and hence available streamflow for in-stream irrigated activities as the fraction of the catchment given over to forestry production increases.

Figure 8.10 shows the change in profit as a result of reducing the daily rainfall. The result indicates that a linear reduction in profit occurs with each 5% reduction in rainfall. A decrease in profit of approximately 2% occurs across the nodal network with each incremental reduction in rainfall. Nodes 1,3 and 4 have the largest decrease in profit of approximately 6% where rainfall is reduced by 20%. This could be expected because of the large area of land devoted to dryland activities at this node. The reduction is not as great at Node 2 given the larger area devoted to irrigated activities that rely upon an in-stream water supply for agricultural production.

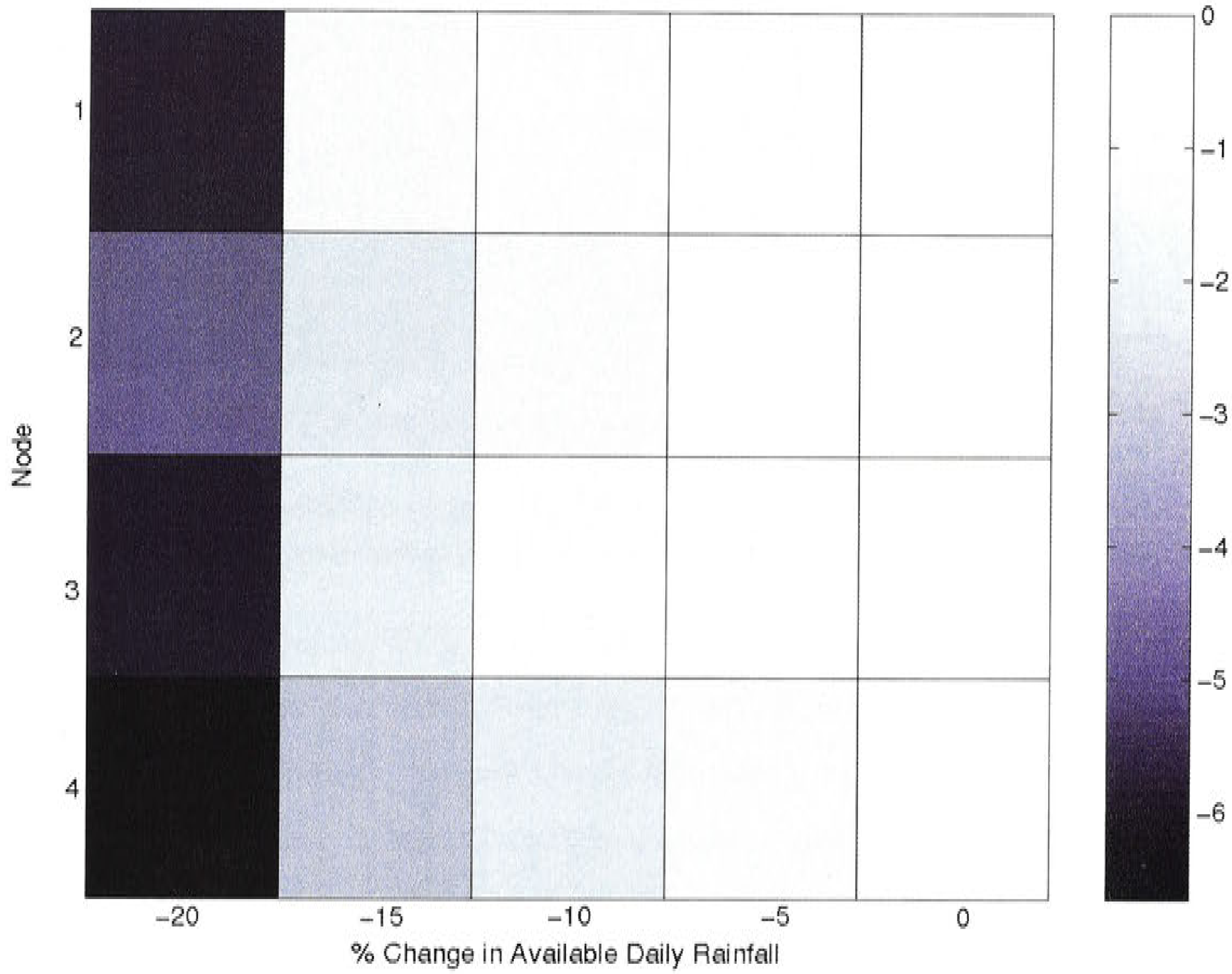

Figure 8.10: Model sensitivity of profit to percentage reductions in daily rainfall. Base Case value is located at 0 on the horizontal axis

Obviously, the hydrological modelling component is also sensitive to changes in rainfall. Figure 8.11 shows the resulting change in the median of non zero flows. The Base Case result is shown in white. A 5% reduction in rainfall reduces the median of non zero flows by approximately 5% across all nodes, but is slightly less at Node 4. The result shows that for each reduction in rainfall, a proportionate reduction in the indicator occurs. This is to be expected as a reduction in rainfall will reduce streamflow. A threshold effect occurs where the reduction in rainfall is 20% of the Base Case. In this case, the reduction in the indicator increases to approximately 25% in contrast to just 12% reduction in profit when rainfall is reduced to 15%.

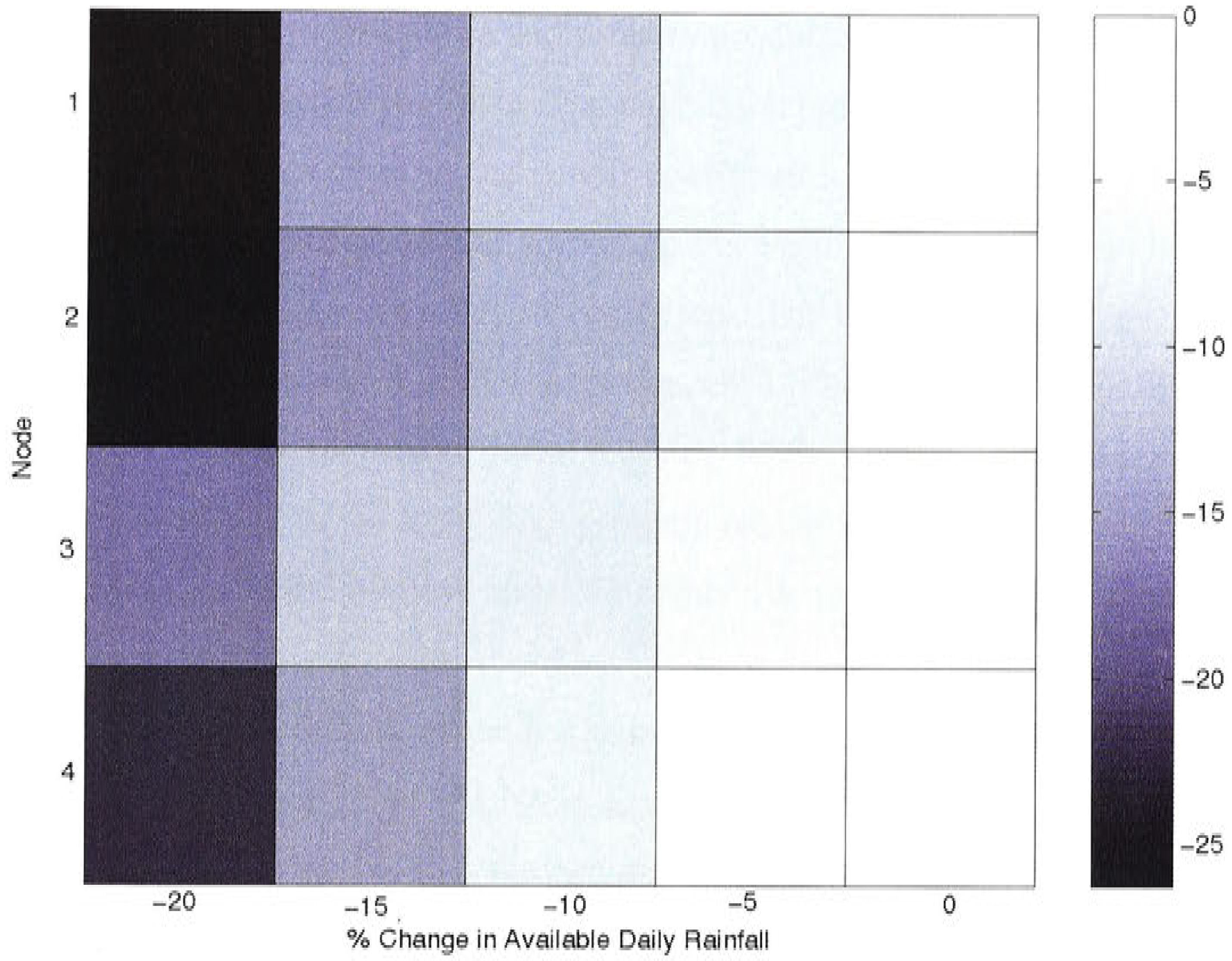

Figure 8.11: Model sensitivity of median of non zero flows to percentage reductions in daily rainfall. Base Case value is located at 0 on the horizontal axis

The reduction in both the agricultural production indicator, profit, and the hydrology indicator, the median of non zero flows, is consistent with what is expected from running the integrated model. Streamflow is obviously dependent on rainfall. Both dryland and supplementary irrigation activity viability depends on rainfall, for pasture production and farm dam capture respectively. Therefore a reduction in profit as rainfall decreases is consistent with the conceptualisation of the integrated model, and with the underlying system.

8.9 Model Sensitivity to Changes in the Runoff Coefficient

Model sensitivity was tested by varying the runoff coefficient across a sample grid from 0.1 to 0.55 at steps of 0.05. The runoff coefficient is the proportion of rainfall yielding streamflow. This was deemed an important hydrological variable given that the point of integration, between both viticulture and forestry production systems and the hydrology, is through the rainfall-runoff response. The indicators, profit and the median of non zero flows, are sensitive to changes in the runoff coefficient. The indicator, number of zero flow days, was not sensitive to the scenarios. As Figure 8.12 shows, nodal profit is highly sensitive to changes in the runoff coefficient. The largest change in profit was for the area belonging to Node 3, which experienced a 33% increase in profit when the runoff coefficient was increased from 0.21 to 0.55. This is expected as Node 3 corresponds spatially with the local wine growing region in Yass catchment. At Nodes 1 and 2, profit was increased by 26% and 23% respectively.

With the exception of Node 4, all nodes had a gradual change in profit with each 0.05 change in the runoff coefficient. At Node 1, each grid step resulted in a linear increase in profit of 3%. In contrast, Node 2 showed a slight variability in the indicator with each grid step, ranging from a 3.8% increase in profit where the runoff coefficient was sampled from 0.20 to 0.30, to a 3.9% linear increase where the runoff coefficient was sampled between 0.30 and 0.40. The largest change for any increase in runoff occurred at Node 3. With each variable increment sampled, profit increased by 5%.

Node 4 experienced no change in profit. At this node, the land constraint prevented any additional area being devoted to viticulture with an increase in the runoff coefficient. A change in the runoff coefficient affects three activities: viticulture, lucerne and rotational cropping irrigated activities. The area planted to the first is determined by available runoff and hence farm dam capacity to support the production systems. Changes in runoff alter available streamflow and hence water available to support lucerne and rotational cropping. However, dryland activities are not directly affected by changes in the variable. Where forestry occurs, forest cover impacts upon runoff. There is no point of integration between grazing and runoff. Grazing and forestry activities are integrated with the hydrology at the point of daily rainfall. Hence, changes in rainfall but not runoff have the potential to impact upon dryland activities.

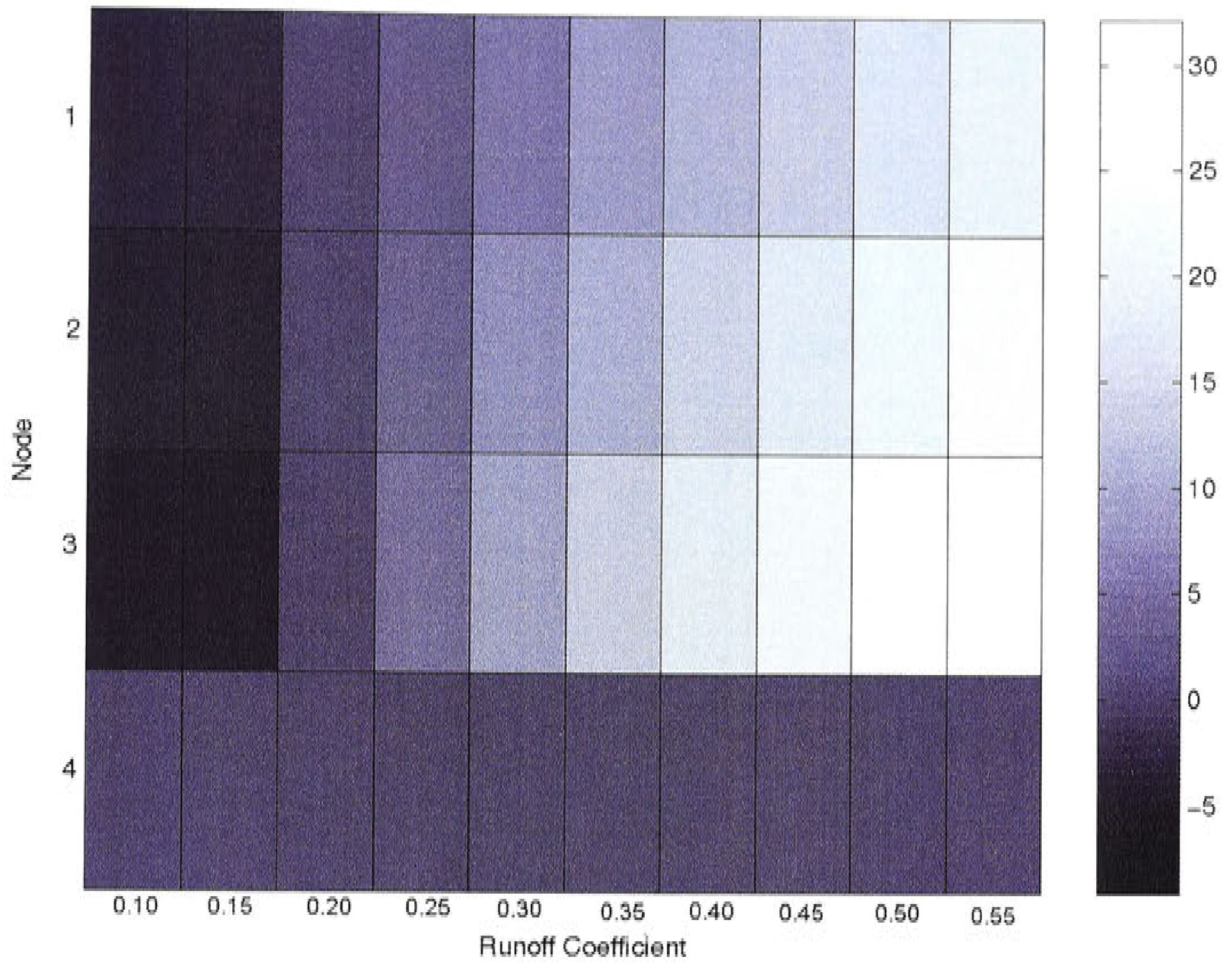

Figure 8.12: Model sensitivity of profit to changes in the runoff coefficient. Base Case value is 0.21

With changes in the runoff coefficient affecting the viability of both viticulture and in-stream irrigated activities, a change in the hydrology indicators is expected. The variation in the median of non zero flows is shown in Figure 8.13. Unlike the profit indicator, the hydrological component of the model is sensitive to changes in the variable at Node 4, in addition to the other three nodes. Nodes 1 and 4 show a relatively linear increase in the indicator as the variable changes. The hydrological indicator is sensitive at Node 4 as the model deducts extractions downstream. This is a downstream impact as a result of changes in agricultural land use upstream.

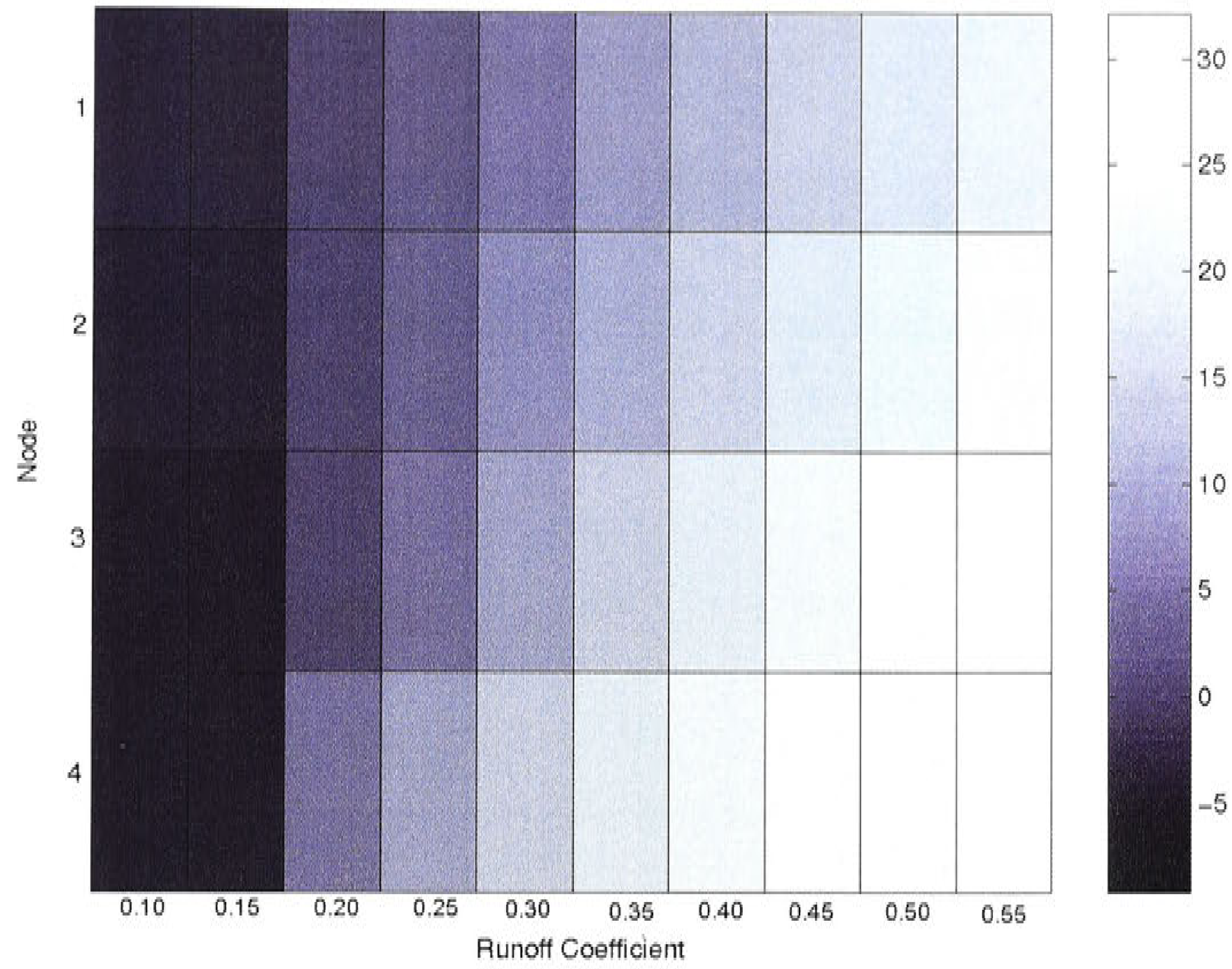

Figure 8.13: Model sensitivity of median of non zero flows to changes in the runoff coefficient. Base Case value of 0.21 is located at 0.20 on the horizontal axis

Table 8.4 indicates the magnitude and direction of change for Nodes 2 and 3 for the median of non zero flows. The results were separated from the other nodes to show the threshold change that occurs at these nodes and which cannot be seen in Figure 8.13 clearly. The result indicates that changes in the variable value between 0.35 and 0.40 have a large impact upon model output for Node 3 and between 0.20 and 0.25 for Node 2. At Node 2 this results in an increase in the median of non zero flows. At Node 3, a threshold change occurs in the indicator between a runoff coefficient value of 0.35 and 0.40.

Table 8.4: Model sensitivity to changes in the runoff coefficient at Nodes 2 and 3: Median of Non Zero Flows

	0.1	**0.15**	**0.2**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**	**0.55**
Node 2	3.8	4.0	4.4	11.9	18.0	19.7	19.7	21.4	23.1	24.1
Node 3	2.6	2.2	2.3	2.6	3.5	3.6	11.9	12.7	13.8	14.8

The number of zero flow days was not sensitive to changes in the runoff coefficient. This means that changes in the runoff coefficient increase the magnitude of flow events but do not change the number of zero flow days.

8.10 Model Sensitivity to The Farm Dams Policy: Allowable Runoff Capture of Farm Dams

The sensitivity of the model to changes in rainfall volume captured in dams was tested by variation from the Base Case value of 30%, which was considered to be the actual capture (see Schreider *et al.*, 2002). The indicators, profit and median of non zero flows, were sensitive to the scenarios. The number of zero flow days was not sensitive.

Model sensitivity of profit varied across the four nodes as indicated by Figure 8.14. The less sensitive result at Node 4 is consistent with previous results in this chapter. Node 4, although exhibiting a change in profit from 1.7% to 14% across the sample grid, was not as sensitive as Nodes 1, 2 and 3. Variation in allowable capture volume has a direct impact upon the viticulture activity in that it controls the volume of water captured in farm dams and hence used by supplementary irrigators to support the viticulture enterprise.

Node 3 was most sensitive to changes in this variable, resulting in a 28% change in profit across the sampled grid. Nodes 1 and 2 experienced a 20% and 26% increase in profit respectively over the grid sample. The increase in profit in response to the variable change occurs at a uniform rate for all changes at a given node.

Node 4 showed the least sensitivity to the profit indicator as its area contains a relatively small amount of land that is allocated to viticulture. In contrast, Nodes 1, 2 and 3 contain viticulture as well as a smaller area of land devoted to in-stream irrigated activities. Node 3 has the largest change in profit as it has the largest area devoted to viticulture. Hence, it is reasonable to expect that changing the variable would have the greatest impact upon Node 3.

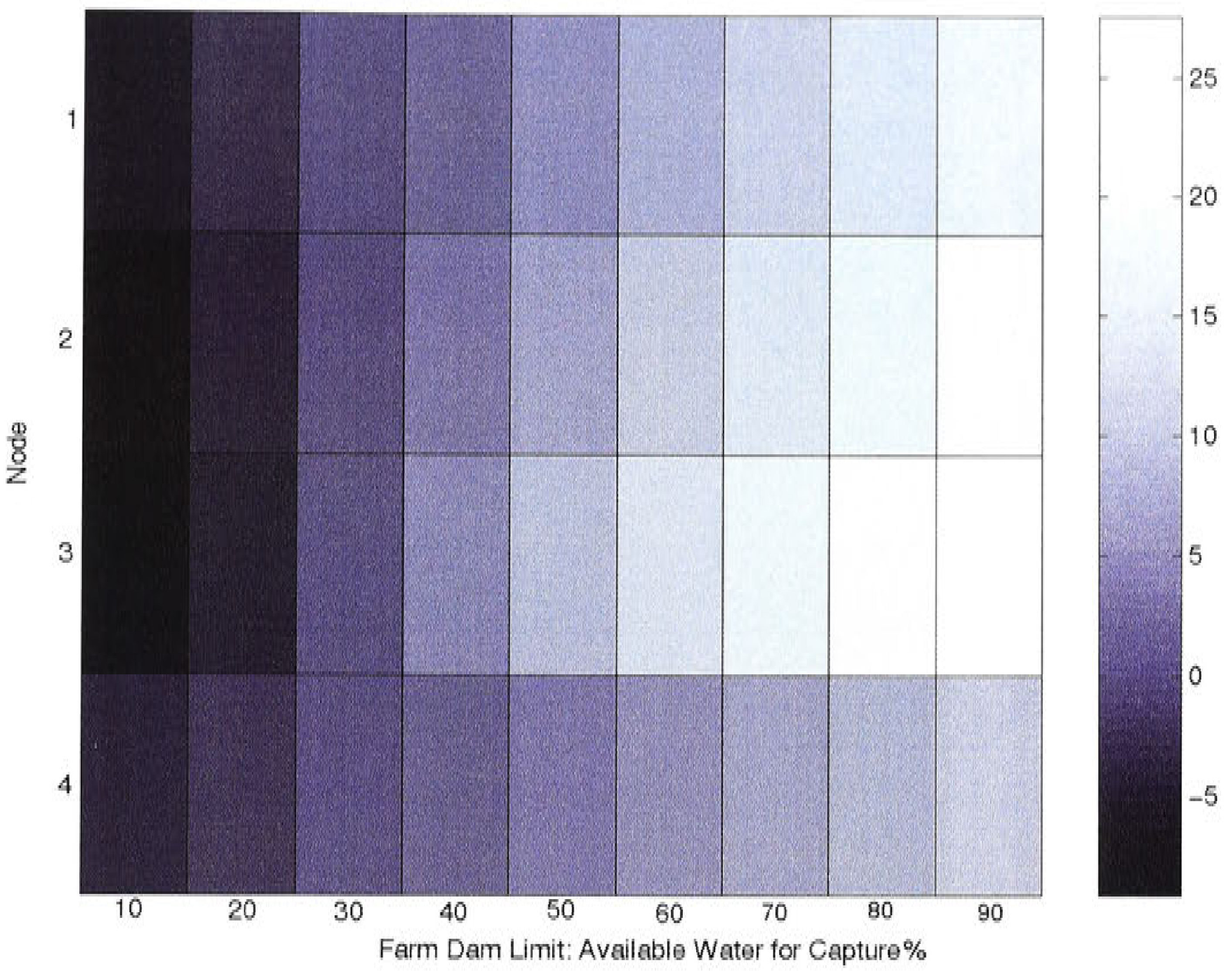

Figure 8.14: Model sensitivity of profit to percentage changes in allowable runoff capture for storage in farm dams. Base Case value located at 30% on the horizontal axis

Given that the variable controls the volume of water captured in farm dams, it would be reasonable to expect a change in runoff to the stream and a change in the hydrology indicators. The variable has no impact on the number of zero flow days. Figure 8.15 shows the direction of change in the median of non zero flows as a result of increasing the volume of farm dam capture across a sample grid of 10% increments.

The indicator is less sensitive than other variables previously tested. At Node 1 an initial change from capturing 40% to 50% of the Base Case runoff results in a slight decrease in the median of non zero flows. Across all nodes, the change in the median of non zero flow is small, resulting in a -0.02% change at Node 1 and incremental changes at Node 2, averaging just -0.013% for each grid step. Nodes 3 and 4 show similar model behaviour with the percentage change averaging -0.012% at Node 3 and -0.013% at Node 4. These changes are much smaller than the comparative impacts on profit as the impact on flows is indirect, filtered through much of the system, whereas the impact on production is a direct impact.

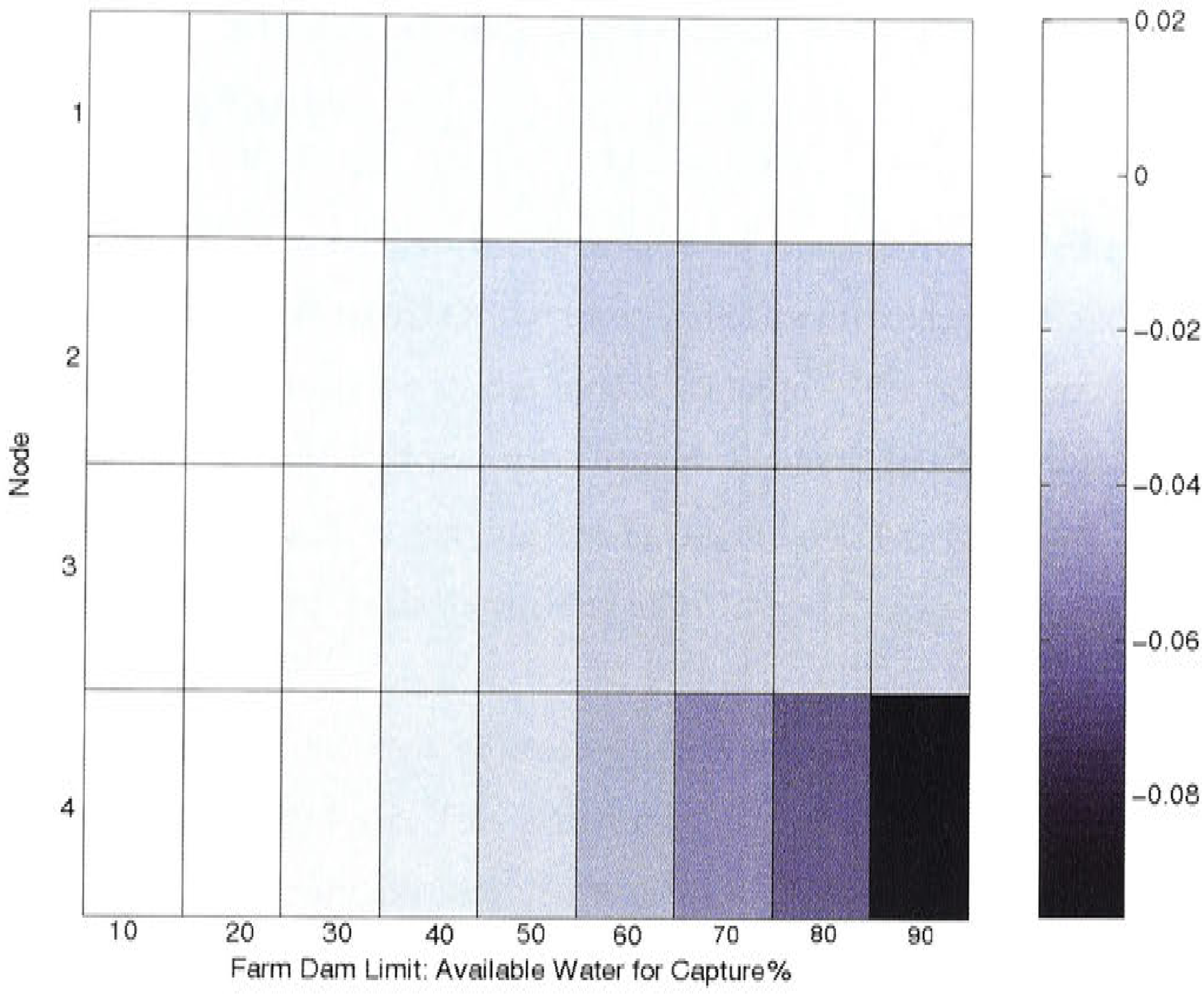

Figure 8.15: Model sensitivity of median of non zero flows to percentage changes in allowable runoff capture for storage in farm dams. Base Case value is located at 30% on the horizontal axis

8.11 Model Sensitivity to the Land Constraint on Viticulture

Viticulture and irrigated activities such as lucerne irrigation and to a lesser extent, rotational cropping, are (given available land and water) the most profitable agricultural production systems within the catchment. Therefore, with any increase in the land and water available for these activities, it could be expected that the optimisation procedure, given its profit maximising objective, should allocate more land to these activities. Viticulture is located in a different Land Management Unit to in-stream irrigated activities (see Section 4.5). In addition, unlike grazing, viticulture can not occur where irrigated activities occur. This reflects the assumption that irrigated activities are best suited to river flats and adjacent areas while viticulture activities would not generally be viable in these areas owing to the requirement for sloping, well drained soils for successful operation. In view of this assumption, where the land constraint on viticulture is increased, the model assumptions suggest that the optimisation procedure will always allocate more land and water resources to viticulture because of its highly profitable nature compared to dryland activities. However, the model will not allocate additional land to irrigated activities as they are excluded from areas where viticulture is operational and vice versa.

The sensitivity of the model to the area of land potentially available for viticulture production systems was tested. Of the three indicators tested, profit and the median of non zero flows were sensitive to the model scenarios. The indicator, number of zero flow days, was not sensitive to scenario changes. Figure 8.16 shows the impact upon the profit indicator as a result of varying the land available to viticulture. The Base Case value is indicated by zero on the horizontal axis.

Node 1 experienced an increase in profit of 25% where the area allocated experienced was 60% above the Base Case. This is expected as the model allows land use change to viticulture from less profitable dryland activities. Where the total area available for viticulture was reduced by increments of 10% of the Base Case, profit decreased by 15% at Node 1. Similarly, Node 2 experienced an increase in profit of 26% while Node 3 experienced a total increase of 24% when available land was increased. At Nodes 2 and 3, profit also decreased by approximtaly 15% when available land was decreased proportionatly across Nodes 2 and 3.

A larger proportional increase in profit at Node 3 is to be expected because its area is more suited to viticulture activities, and less land is given over to irrigated activities that exclude viticulture operation regardless of the land constraint. Node 4 experienced the smallest change in profit. This is due to the fact that viticulture can only occur over a smaller spatial area in this part of the catchment which is largely unsuitable for activities other than dryland. The increase in profit occurred linearly across the nodal network with each 10% increase in area.

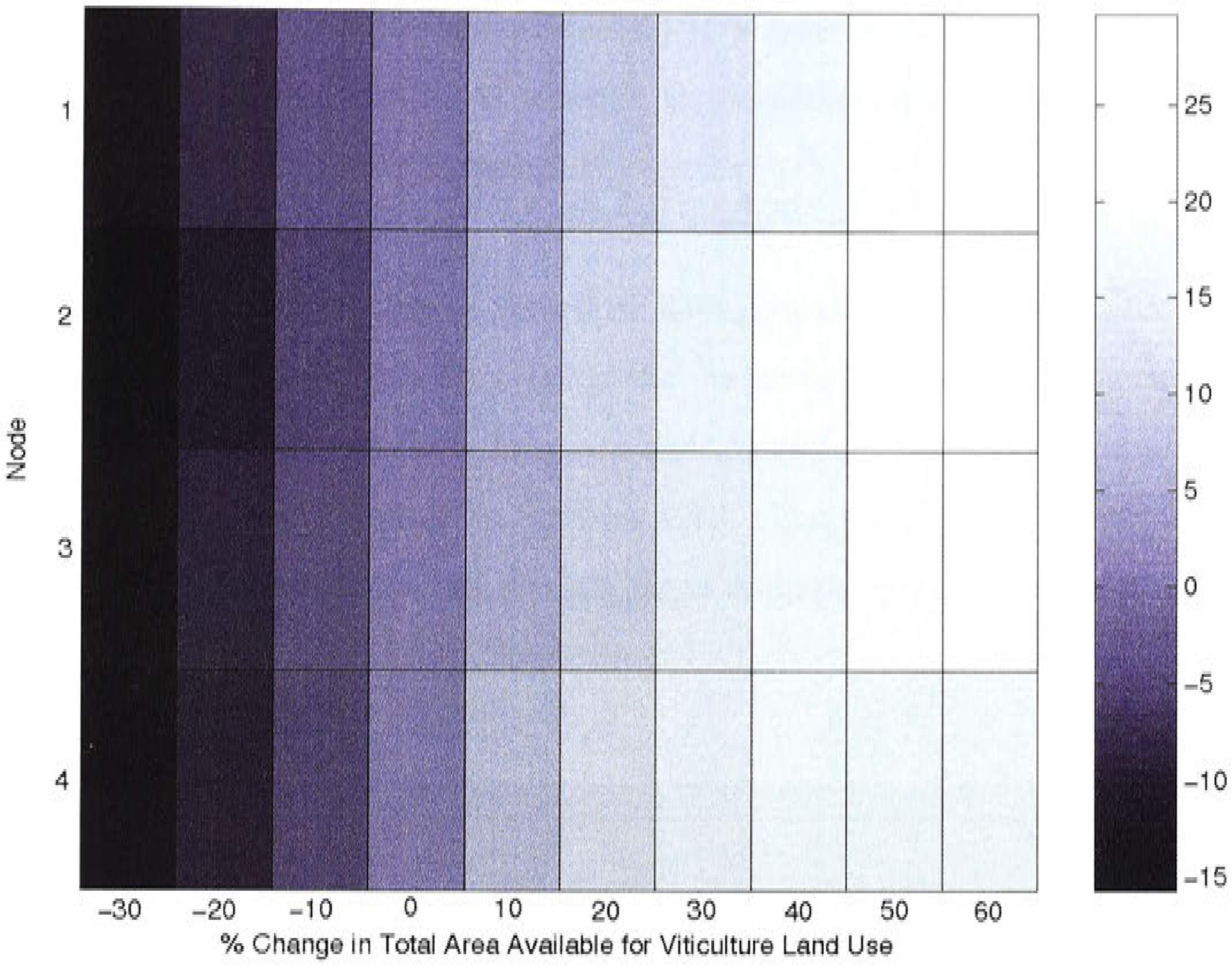

Figure 8.16: Model sensitivity of profit to percentage changes in the total area of land potentially available for viticulture. Base Case value is located at 0 on the horizontal axis

However, such land use change in the catchment has an adverse impact upon the hydrology as indicated by Figure 8.17. The result shows a decrease in the median of non zero flows at all nodes when land available for viticulture increases. The largest impact is at Node 1, resulting in a decrease in the indicator by up to 35% where the majority of the nodal area is planted to viticulture. The decrease in the median of non zero flows is slightly less at Nodes 2 and 3 with a reduction of approximately 31% and 12% respectively. Node 4 has a decrease in the indicator of 15% from the influence of reduced runoff and in-stream extractions from upstream.

Where an increase between 20% and 30% occurs, both Node 2 and Node 3 indicate a decrease in the median of non zero flows, from -11% to -16% of the Base Case value, while Node 1 has a decrease from -12% to -18%. The threshold is less visible at Node 3 but still results in a change from -4.1% to -5.7%, compared to a 1% decrease prior to the threshold.

The decrease in the median of non zero flows is expected downstream even though viticulture production (on a per hectare basis) is greater at Node 3 for the reason that streamflow is added downstream. As a result, the indicator will change given upstream impacts of extraction and changes in runoff.

The hydrology indicator, number of zero flow days, does not change with changes in the available land for viticulture. This could be expected. In devoting more land to viticulture, a larger number of farm dams are constructed resulting in alteration to runoff to streamflow. As already shown in Section 8.10, changes in runoff impact upon the magnitude of daily flow events but are not large enough to convert low flows to zero flow days.

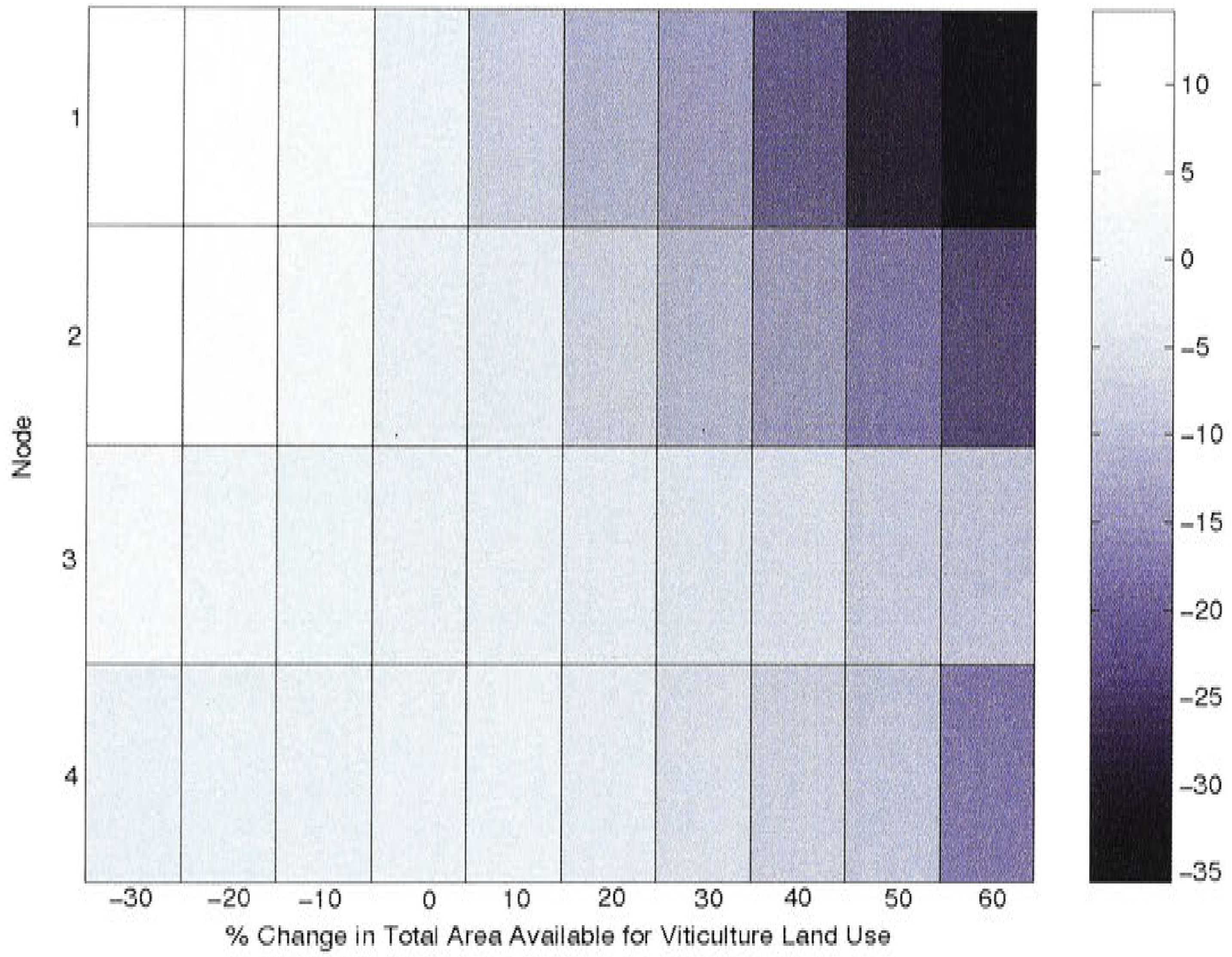

Figure 8.17: Model sensitivity of the median of non zero flows to percentage changes in the total area of land potentially available for viticulture. Base Case value is located at 0 on the horizontal axis

8.12 Model Sensitivity to Changes in Evaporative Loss from Farm Dams

The model calculates the total allowable farm dam capacity on a per hectare basis, allocates the total area of land to viticulture by the optimisation procedure, and finally determines the total volume captured by farm dams over the allocated area. Where the farm dam volume capacity is exceeded, the remaining runoff is passed to streamflow. However, if the farm dam capacity should not be exceeded due to evaporative losses, less runoff passes to streamflow. Rather, additional runoff is captured in the dam than otherwise would be the case if the evaporative loss was lower.

Model sensitivity was tested to changes in evaporative loss from farm dams. The Base Case evaporation loss is 65%. The variable was tested by changing the value in increments of 10% above and below this value. Two indicators were responsive to scenario options. They were profit and the median of non zero flows. The number of zero flow days was not sensitive. Figure 8.18 shows the change in the median of non zero flows as a result of variation in the evaporation from the farm dams.

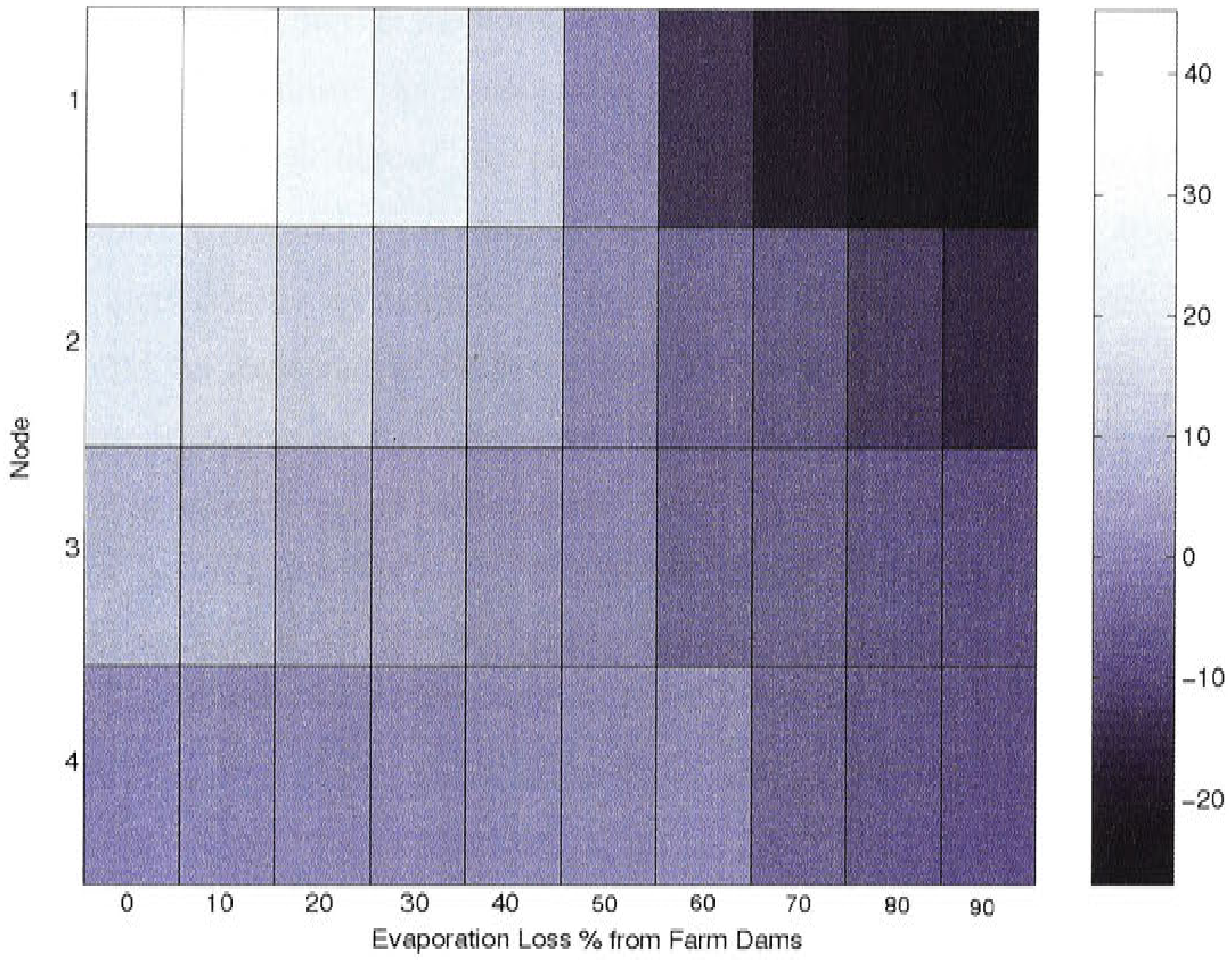

Figure 8.18: Model sensitivity of the median of non zero flow to changes in evaporation loss (%) from farm dams. Base Case value located ot 65% located at 60

Nodes 1 shows the largest reduction in the indicator up to 26% where evaporative loss from dams is increased to 90%. At 90% evaporative loss, the percentage change in this indicator results in a reduction of the median of non zero flows 25% at Node 2 and 14% at Node 3. The smaller change in the indicator in both directions at Node 4 is expected. Any impact upon the indicator is purely a result of upstream impacts on downstream flows. Hence the decrease in the median of non zero flows is consistent with the model conceptualisation.

The number of zero flow days did not change. In previous Sections 8.9, 8.10 and 8.11 it was shown that changes in runoff and farm dam capture did not affect the indicator. Given that this variable affects the volume captured to satisfy grape production (where a larger volume is required if evaporation loss is larger) it could be expected that the sensitivity of the variable is not of a large enough magnitude to convert days where there is low streamflow to zero flow.

Table 8.5 indicates the change in profit for each node with changes in evaporation loss from farm dams. Node 4 does not experience a decrease in profit given the very small area available for viticulture at the node. The land constraint prevents an additional area being devoted to viticulture. As evaporative loss increases from 70% to 90%, profit is reduced by up to 5.2% across the nodal network with the exception of Node 4. Similarly, where evaporative loss from farm dams is reduced from the Base Case to 10%, profit increases by as much as 12.3% at Node 2 and 10.6% at Node 3. A large increase would be expected at Nodes 2 and 3. These nodes correspond to the area around Murrumbateman in the catchment. This area contains the largest current and potential land devoted to grape production.

Table 8.5: Model sensitivity of profit to changes in evaporative loss from farm dams as a percentage increase from the Base Case

Value	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
Node 1	6.4	5.1	3.8	2.5	1.2	-1.2	0	-2.5	-3.1	-4.8
Node 2	12.3	8.6	4.9	6.4	1.6	-1.8	0	-3.5	-2.8	-5.2
Node 3	10.6	8.5	6.4	4.2	2.1	-1.0	0	-3.4	-4.1	-5.2
Node 4	0	0	0	0	0	0	0	0	0	0

8.13 Discussion and Conclusions on Model Sensitivity

Table 8.6 identifies whether or not there is sensitivity of model output to changes in the variables tested in this chapter. Table 8.7 summarises the major threshold points for each variable tested.

Nodal profit was very sensitive to changes in all variables as was the median of non zero flows. The number of zero flow days was sensitive to a more limited number of variables. Changes in this output indicator were limited to scenarios relating to changes in the daily extraction limits. The median of non zero flows was less sensitive to changes in the allowable farm dam capture than any other variable, except for forest cover. It was most sensitive to changes in the runoff coefficient, evaporative loss from farm dams and rainfall variability. The greater sensitivity is likely to be because these changes involve a relatively direct impact on streamflow.

The indicator, profit, was very sensitive to changes in land available for agricultural production activities including intensive irrigated activities, forestry and in-stream irrigated activities.

The agricultural system component was highly sensitive to changes in forest cover through nodal profit. The profit indicator was insensitive to changes in the commence to pump rule. The model determines the daily flow extraction limit and redistributes the number of days on which extraction takes place to maximise the extractive volume of irrigators. Hence, even though profit was not responsive, the median of non zero flows was sensitive because the model redistributes extraction across the annual available streamflow. Irrigators extracted the same volume but on different days.

A limitation of the modelling approach that was highlighted by sensitivity analysis was the impact on dryland agricultural systems compared to in-stream irrigated and supplementary irrigated activities as a result of rainfall change (see Section 8.8). The result showed that dryland production systems were less sensitive to changes in the biophysical system. This is due to the coarser nature of integration between the biophysical component and dryland systems. The point of integration for in-stream activities, intensive supplementary activities and dryland activities is streamflow, runoff and rainfall respectively. The dryland grazing production system has just two thresholds for changes in climate. If rainfall does not reach the threshold, yield and hence profit does not change even though in reality yield would respond to smaller changes in rainfall. In order to introduce greater flexibility and responsiveness of the dryland system to rainfall change (at least as sensitive as other irrigated and supplementary production systems), multiple yield responses to changes in rainfall are required. This would ensure the level of detail in response to the biophysical system was similar across all agricultural production systems.

A second major limitation identified by the sensitivity testing is the conceptualisation and integration of the extractive policy model. As shown by the results in this chapter, the policy model applies the flow rule to the entire hydrograph and then redistributes streamflow over the hydrograph for the irrigation season. This means that the daily sequence of streamflow does not determine the area devoted to irrigated activities. It is only the seasonal volume that restricts the model. As shown in Section 7.7.1, it is possible to obtain enough water for irrigation to allow the model to devote land to irrigated activities even if the number of consecutive days of zero streamflow is too high to support the activity on a day to day basis (this is a particularly important limitation in Yass catchment where water is not held in farm dams for future irrigation during low flow periods). As a result, the model is likely to underestimate the impact of dry sequences on profitability. It also means that the influence of pumping on flows may be underestimated. Changing this assumption, such that the volume required on the day could only be pumped from the river on the day (rather then source from a peak in the hydrograph over the irrigation season), would result in irrigators pumping low flows to support the irrigated crops. Consequently, the number of zero flow days may be a more informative indicator of change than has been the case with the assumptions used in this integrated model in the thesis.

Where the level of detail in integration was greater (such as in the viticulture, lucerne and rotational production systems), threshold effects were more often observed than for the dryland counterparts. An example is the response of the median of non zero flows to changes in the daily extraction limit on in-stream irrigated land use (see Section 8.6). This indicator is not intially sensitive for the reason that changes in the daily limit at first result in a redistribution of extractive days (see Section 6.5.1 and Section 6.5.3 for operation of the extractive policy module). However, where the allowable extraction limit is greatly increased, the volume extracted is no longer redistributed over the irrigation season. Rather, the total daily volume extracted increases at a certain volume. The sensitivity testing results shows the level of detail required in both modelling components and the type of integration required to investigate 'what if' scenarios for specific water allocation questions that focus upon examining trade-offs between agricultural production systems and the hydrological system.

Table 8.6: Indicator response to sensitivity testing of selected variables

Variable Tested	**Nodal Profit**	**Median of Non Zero Flows**	**Number of Zero Flow Days**
Forest Cover	Yes	No	No
Annual Allocation Limit	Yes	Yes	No
Daily Extraction Volume	Yes	Yes	Yes
Land Available for viticulture	Yes	Yes	No
Commence to Pump Rule	No	Yes	No
Climate variation in daily rainfall	Yes	Yes	No
Runoff coefficient	Yes	Yes	No
Farm dam limit on allowable runoff capture	Yes	Yes	No
Land Available to Irrigated Activities	Yes	Yes	No
Evaporation loss from farm dams	Yes	Yes	No

Table 8.7 shows two of the model indicators were highly sensitive to all changes in policy variables as well as changes to variables in both the hydrological modelling component and the agricultural production system component. However, the number of zero flow days indicator was not sensitive to changes in the majority of variable values. Sensitivity testing of the model was specified for a small number of the total variables that could be tested in the model. The variables tested here were selected to demonstrate broadly the applicability and behaviour of the model for examining the three selected water policy options that have been the foundation for model conceptualisation and development. The aim of this was to demonstrate the relative strength of the model integration by testing variables from one component and analysing output indicators from the integrated model.

Table 8.7: Summary of threshold behaviour for variables tested

Variable Tested	Nodal Profit	Median of non zero flows	Zero Flow Days
Forest Cover	Linearly sensitive to 10% change in forest cover	Threshold between 50% and 60% forest cover	No change
Evaporation loss from farm dams	Linear sensitive to changes in evaporative loss	Linear change across sample grid	No change
Farm dam limit on allowable runoff capture	Linearly sensitive to changes in farm dam limit resulting in an increase of 1.8% for Node 1, 3.8% at Node 2.5% at node 3 and 1% at node 4 for each grid sample	Linear change less sensitive with a maximum change of 0.02% with each grid step	No change
Runoff coefficient	Linearly sensitive to 5% changes in variable	Threhsold at 0.3 - 0.4 for Node 2 and 3 Threshold of 0.6-0.7 at Node 4	No change
Land Available to Irrigated Activities	A threshold occurs between 20% and 30% change in available land	A threshold occurs between 20% and 30% change in available land area	No change
Annual allocation for irrigators	Linearly sensitive of 0.44% across sample grid	Linear change with each grid step	No change
Climate variation in daily rainfall	Threshold at 5% reduction in daily rainfall	Linear response of 6%-8% reduction across sample grid	No change
Land Available for viticulture	Linear change across entire range of 4.8% for Node 1, 6.2% at Node 2, 5.4% at Node 3, 0% at Node 4	Threshold at 50% of catchment area planted to viticulture	No change
Commence to Pump Rule	No change	Small threshold at 30ML -30ML per day across the grid	No change
Daily Extraction Limit	Linear change of 1.5% across sample the grid	Threshold at 33 - 38 ML per day across the grid	Threshold at 45ML - 50ML per day across the grid

A more detailed sensitivity analysis would be required to thoroughly test the applicability of the model for use as a tool to support decision making. The limited number of variables selected resulted in 120 model runs, with each run taking 50 minutes CPU time to complete. This excludes the some 600-700 model runs that were required to isolate any problems in building the model and debugging of the model code prior to sensitivity analysis and scenario runs. In addition, variables selected for testing have been limited to a select group of assumptions in the integrated model.

Variables that would be selected for analysis in a thorough testing of the model would involve the Base Case data inputs, such as prices and yields selected. In particular, a more thorough testing of the hydrological model component would be ideal given that streamflow was estimated for ungauged catchments. Future testing could involve analysis of the catchment moisture deficit function to isolate the impact on the integrated model of the ungauged estimation procedure. In particular, the procedure used to calculate daily catchment rainfall would be subject to testing and uncertainty analysis.

Chapter 9 Conclusions

9.1 Introduction

This chapter summarises the major findings and outcomes from this thesis. Given the volume of integrated model output, and therefore countless potential points for discussion, the conclusions are kept relatively brief by synthesising the thesis outcomes into two key sections. The thesis is discussed from the perspective of: 1) integrated model performance (Section 9.2); and, 2) individual system components and integrated methods and approaches (Section 9.3). Model performance in this case is composed of i.) the strength and contribution of the conceptual framework; and, ii) the integrated model results and output.

The extent to which the integrated model could be applied to other catchments is also discussed in Section 9.3.5, particularly where data sets are sparse and policy analysis needs to be rapid.

9.2 Integrated Model Performance

This section outlines the strengths and weaknesses found in developing the integrated modelling approach presented in this thesis. It focuses on the conceptualisation as well as conclusions that can be drawn from running the integrated model.

9.2.1 Strengths, Contributions and Weaknesses of the Conceptualisation

Chapter 1 (see Section 1.4) outlined a 7-step procedure used to construct the integrated model of the type developed in this thesis. The use of 7-step procedure allowed a consistant set of boundaries to be set up to ensure model development did not stray from the modelling objectives. This is a risk in constructing an integrated model that involves the development of many small system components to analyse the selected policy options.

The model conceptualisation overcomes many of the shortcomings in previous approaches that assess land and water policy options. The most recent and comprehensive approaches are typically aimed at presenting the economic and hydrological conceptual components in such a way as to analyse a single policy and resultant impacts and responses from the integrated system. The approach developed in this thesis goes beyond these limitations by developing a conceptual framework (and analytical approach) capable of examining multiple land and water policy options and their impacts. This methodological approach is more consistent with the current water reform agenda where multiple policies are often implemented at any point or space in a catchment, and where multiple policies have the potential to achieve seemingly conflicting outcomes. Hence the approach developed in this thesis involves a more complex representation of the policy environment and its processes, rather than focusing on building greater system complexity but only being capable of analysing a single policy option in isolation.

Following from this, a second major outcome, and contribution of the conceptualisation, is that the approach treats both the agricultural production systems and the hydrological system at the same level of detail. The approach developed three levels of integration between system components. Many past approaches, even where the level of detail is balanced between disciplines, do not go beyond using model output of a single system as input into the other (ie ignoring feedback and complex system interactions). The approach in this thesis has recognised the unique impact of both dryland and irrigated the agricultural production systems on the hydrological system, and the impacts of the hydrological system on these agricultural production decisions. The approach balances model detail and considers several points of integration rather than simply coupling a complex disciplinary model with a second simplified disciplinary model. The end result is an approach that is flexible enough to examine land and water policy issues from both supply and demand side perspective's. This enables both environmental and economic impacts of a range of agricultural production systems to be simultaneously considered.

In developing an integrated model that is of benefit for analysing current land and water policy options, the approach has also focused on developing a conceptualisation capable of isolating spatially defined economic and environmental impacts as a result of imposing various policy options at the catchment scale. This was achieved using a nodal network approach to integration. This allows spatially disaggregated outputs to be produced and analysed at each node to allow investigation of trade-offs between environmental and economic outcomes throughout the catchment.

In focusing on balancing the disciplinary contribution and points of interaction of relevance to the current management practices, several assumptions and limitations were identified (see Sections 7.9.3 and 8.13). A necessary compromise in model component detail is that of aggregating agricultural production model decisions and operation to a regional level or Land Management Unit. Although several model limitations stemmed from this (refer to the above mentioned sections), these limitations were a result of allowing the conceptualisation detail and process representation to be driven by the policy options selected from the catchment (and data set availability, see Sections 3.15 and Section 9.3.1).

A key feature of developing this approach for building an integrated model is that the initial development of the conceptual foundation was directed by data availability in addition to the policy options currently of interest in the catchment; the scale at which they operate and the likely scale of impact. This focus directed decisions as to what processes were to be included, aggregated and disaggregated in developing the modelling approach.

9.2.2 Model Output Performance: Issues in Integration

Sensitivity testing of the model conducted in Chapter 8 was undertaken to consider whether or not the model conceptualisation was sufficiently detailed to obtain an appropriate model response that would be expected given the imposition of a policy option. The agricultural production system appears to have been conceptualised well, both in process and level of detail given its consistent response in the form of changes in profit and area devoted to activities under the imposition of all three policy options. The sensitivity testing revealed a strength in the integration between one of the three policy options and the hydrology system. The imposition of a Salinity Management Policy for smaller spatial areas did not produce the hydrological impact that was expected when compared to imposing the same policy option over a larger spatial area. This demonstrates the integrated models ability to highlight the relative magnitude of direct and indirect impacts as a result of policy imposition. The impact upon the agricultural production system was direct, resulting in a larger change in profit for each agricultural activity. However, the hydrological response was filtered through changes in rainfall-runoff, resulting in a smaller, indirect impact on the hydrological system. This shows that the integrated model can differentiate between system response from the hydrological system and that of the agricultural system, and that not all response need be large or direct if the system is conceptualised well. However, further investigation of the validity of the hydrological model for simulating changes in flow as a result of re-afforestation is needed before these results can be used for policy analysis.

A more obvious solution to a point of integration that (although producing the correct direction of change consistently), could be targeted for further conceptual refinement is the point of integration between the dryland agricultural production system and the hydrological system. In this case, the solution is found simply in the addition of information relating yield to climate inputs. However, for the purpose of this thesis, the added detail was not deemed necessary. The dryland model component containing forestry activities did not extend to examining salt loads as a result of forestry plantation. Although this is a considerable limitation given that the Policy option focused on salinity management through forestry plantation, it was decided to focus on water quantity aspects of plantation imposition in recognition of the fact that model development needed to remain concise and manageable. Secondly, the level of detail required to model salt loads was considered beyond the scope of the thesis given its main aim. Certainly, model responsiveness in future applications would benefit from refinement of this relationship. The model in its current form does, however allow for the consideration of water quantity based trade-offs between water allocation and salinity management options. This is rarely considered in current modelling projects of water allocation or salinity.

Model integration between in-stream production systems, supplementary-irrigation systems and the hydrology component was consistently sensitive to policy imposition, as shown in the model response and output in Chapters 7 and 8. The process detail and type of integration developed in Chapter 4 for both of these agricultural production systems appears to be well defined for examining the land and water policy issues of interest in the integrated model.

The sensitivity testing was successful in corroborating parts of the system where a satisfactory level of conceptual detail for integration exists, and in identifying those components that require further refinement. This also served to elicit from the integrated model where the level of process detail was sufficient for analysing the three policy issues of interest at the required scale. Sections 9.3.3 and 9.3.4 discuss the strength of the individual model components.

9.3 Individual System Components and Integrated Methods and Approaches

Important lessons were learnt for developing an integrated model of the type developed in this thesis. These include, for each of the model components (hydrological and agricultural production systems), the appropriate level of detail of processes, parameterisation of the model, and hence, the data set resolution required to build the hydrological and agricultural production system models.

9.3.1 Data sets: Resolution and Quality for model parameterisation

A key aim of the 7-step procedure put forward in Section 1.4 was to assess data availability and resolution very early in the process of integrated model construction. This step was proposed as being an early requirement in developing an integrated modelling approach. It was deemed at the outset of model development that the model should not be heavily parameterised and should avoid becoming too difficult for use by policy makers. Section 3.15 showed the time series and spatial data sets used in the approach. In all, just three time series data sets and seven spatial data sets were used for construction of the integrated approach. In addition, data sets for the agricultural production systems were obtained largely from gross margins estimates from State Government agencies.

The approach shows that in working with available, and often sparse data early in the process, a conceptual framework can be developed around the data limitations to strengthen the over-all architecture of the integrated model, and ultimately the quality of model results. The integrated model results in Chapter 7 and 8 indicate that the data set resolution used was sufficient to address the land and water policy options of interest.

Data quality remains an issue to be addressed with regard to some of the spatial data sets. An example is soil type. The data set assumed just two soil types. Clearly, the model could be refined by sub-classification of these soil types in order to tighten the integrated model constraints.

9.3.2 Implications for developing an Integrated Model for Analysing Land and Water Policy Issues

The results from Chapter 7 illustrate that the integrated model was capable of producing the plausible thresholds, directions and order of magnitude of change for policy evaluation. In particular, the type of model output is potentially useful for informing decision makers as to spatial trade-offs and thresholds of change as a result of policy imposition. For example, the model was sensitive enough to indicate, that for the imposition of several Farm Dams Policy options a threshold could be reached where additional agricultural production losses would yield no more environmental benefit.

Of course, the usefulness of the model results must be interpreted within the context of the representation of the system by the base case model. In this case, several lessons were learnt. Firstly, the use of an optimisation algorithm where just a single objective is being optimised (in this case, profit) meant that the model over-estimated land uses that were of a higher economic value per hectare. Given that land use change as a result of policy imposition was required in the integration, it was important that the links between land use change and the imposition of a policy option be assessed and tested carefully. Where an optimisation algorithm is used to maximise profit, care needs to be taken that the optimisation does not mask or hinder the integration with the policy option. In this case, the tendency of the optimisation was to devote land to value added activities such as viticulture. This is a result of simplifying the representation of decision making in the model, ignoring non-profit oriented motives as well as social and biophysical constraints. This potential masking of the policy option impact was partially overcome by paying particular attention to the biophysical constraints placed on valued added activities (in this case, viticulture). Without such careful consideration, the model would devote areas to value added activities and be potentially insensitive to policy options that could result in land use change. This aspect of the integrated model requires further refinement and testing to be suitable for simulating decisions making behaviour of farmers in a catchment in response to policy imposition.

A second lesson was the usefulness of the hierarchical conceptualisation in facilitating integration of the hydrological and agricultural production systems. As Section 4.4.2 and Section 6.3.5 described, the Farm Dams Policy was implemented at the lowest level in the hierarchy. This was essential to prevent the integrated model from allowing more grapes to be planted than water available to irrigate them. Similarly, the Salinity Management Option had to be imposed at the Land Management Unit level. Given its impact upon land use choices, the policy option had to be imposed prior to profit maximisation. The two examples demonstrate the importance of conceptualising the policy option at the appropriate modelling level where, as in this case, several policy options may be imposed. Were a single option to be selected for analysis in the thesis, the confounding effects of other policy options and their potential interfering impacts on the system deemed important for the operation of other policy options may not be of such a high priority in model conceptualisation. As a result, attention to the point of integration of a policy option with other system components may not be a high priority. In this case, the hierarchical modelling structure allowed for a consistent and logical approach to integrating policy with the other system components.

As demonstrated in the synthesis of results from Chapter 7, the integrated model was capable of identifying thresholds, order of magnitude and direction of change as a result of imposing any three of the land and water policy options selected for analysis in the thesis. This was identified as a key requirement in Section 2.10, Chapter 3 and Appendix B for developing a model useful for policy makers. In this thesis, every attempt was made to identify key processes for inclusion in the approach. A major outcome of the thesis has been in developing an integrated model that minimises the number of parameters and variables required for model development while at the same time capturing a level of detail sufficient enough for scenario analysis to be informative for policy makers at the catchment scale. The results contained within Chapter 7 and Chapter 8 show that the detail captured supports this outcome.

9.3.3 Hydrological System Development: Regionalisation

A regionalisation approach was applied to modelling the hydrological system of Yass catchment. The approach provided stream flow estimates by relating biophysical subcatchment attributes to the conceptual rainfall-runoff model, IHACRES. The contribution of the regionalisation to the integrated model objectives contained within the thesis was twofold. Firstly, in applying the regionalisation procedure with good estimation results to the Macquarie catchment, the procedure demonstrated that estimation of stream flow on unregulated catchments (such as Yass), where stream flow records are unavailable was sufficient for producing an estimate to assess water allocation policy options.

A second contribution of the regionalisation approach was its ability to estimate stream flow from attributes derived at the catchment scale. This was demonstrated in the use of model inputs such as areal catchment rainfall and evapotranspiration estimates from catchment scale land cover.

To preserve consistency of scale, and ensure that effort in developing a regionalisation approach was applied to the appropriate hydrological processes, it was stated in Section 5.2 that an estimate of runoff and peak flow (given the policy option requirements) would be required. The application of the catchment scale regionalisation ensured model sensitivity to policy options was maintained throughout all points of integration. Efforts were concentrated on estimating well, that part of the hydrograph that would be subject to in-stream policy option imposition. Efforts were also concentrated on partitioning evapotranspiration into runoff given the integrated model was required to be sensitive to changes in the Farm Dams Policy. This ensured sufficient sensitivity of the hydrological modelling component when applied in the integrated model.

However, the integrated model would benefit from further testing of the hydrological model component. As Chapter 8 showed, a limited testing of the parameter values demonstrated the sensitivity of the model to key hydrological parameters. Further refinement of the regionalisation method would involve testing of the conceptual rainfall-runoff model with other catchment attributes and refining the modelling effort in estimating the entire unit hydrograph (as opposed to concentrating effort on that part considered essential for policy analysis in the integrated model).

9.3.4 The Agricultural Production Model: Issues and Contributions

This section identifies the contribution of the agricultural production model by examining the major assumptions made in the model formulation in Chapter 6, and the extent to which these benefited or hindered its usefulness in the integrated model.

A major contribution of the aggregation process to the Land Management Unit level is the relative ease of parameterisation of the agricultural production model (see Section 6.4). The model formulation in Chapter 6 shows that the agricultural production system integrated at three points in the hydrological cycle. It shows the way in which decisions are sensitive to changes in land and water resources. This is particularly useful in ensuring efforts were focused on conceptualising the links between the hydrology system and the agricultural production system correctly. This is the case as can be seen by the sensitivity of profit and the patterning of spatially defined impacts throughout the model results presented in Chapters 7 and 8. However, a major limitation is that farming decisions are also sensitive to other socio-economic issues (from microeconomic to macroeconomic). The integrated model could be adjusted and refined to include some of these other factors that influence farmer behaviour at the microeconomic level.

Another shortcoming of the agricultural production systems model was in its treatment of capital investment as static. Capital costs were considered to be unavoidable once a land use choice is made, and no option existed for upgrading or investing in improved technology. In imposing policy options with the aim of examining land use change, the model may not be as sensitive to policy option imposition were farmers capable of adjusting through technological change or efficiency measures. As this was not the case, the integrated model results are likely to be over-sensitive to policy options that may result in land use change. In this case, where an option is imposed, farmers may only adjust by area reduction or land use change. In reality, other options are available for adjustment. The integrated model would benefit greatly from including in the formulation an option to adjust through technological change or capital investment.

9.3.5 Applications to other Unregulated Catchments

The modelling approach, consisting of the three level hierarchy, could be applied to other unregulated catchments. Given that the approach conceptualised a dryland, supplementary-irrigation and extractive Land Management Unit types, it would be possible to apply the framework in other unregulated systems using a similar agricultural systems classification and conceptual framework. The generic classification of land management systems incorporated activities that used rainfall, farm dam fed water and in stream extraction. It is possible, that catchment activities in Australian unregulated systems could be classified under one of these three types.

Secondly, the regionalisation approach for estimating streamflow in unregulated systems is generic enough to be applied to other catchments. As demonstrated in this approach, all that is required is good quality land use data and daily rainfall estimates in addition to catchment area to develop the regionalised hydrological model.

9.4 Summary of Achievements

The major achievements of this thesis can be summarized as:

- The development and testing of the integrated conceptual framework that is capable of addressing land use change and hydrological changes in response to policy imposition
- Development of a general 7-step procedure for developing an integrated modelling approach to analyse land and water policy issues
- A regionalisation of the hydrological system for predicting daily flows
- Development of simple agricultural production models for dryland, supplementary-irrigation and extractive activities
- Application of the integrated model to Yass catchment to consider three land and water policy options specific to the catchment.

References

ABARE (1999) Wine Grapes: Projections of wine grape production and winery intake to 2001-02. ABARE Research Report No 99.15. Australian Bureau of Agriculture and Resource Economics. A report for the Grape Wine Research and Development Corporation, Canberra.

ABARE (2000) Australian Wine Grape and Production Winery Intake: Projections to 2002-03. ABARE Research Report No 2000.14. Australian Bureau of Agriculture and Resource Economics. A report for the Grape Wine Research and Development Corporation, Canberra.

Abbot, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., and Rasmussen, J. (1992) An introduction to the European hydrological system - Systeme Hydrologique Europeen, "She",2: Structure of a physically-based, distributed modelling system. *Journal of Hydrology*, 87: 61-77.

ABS (1996) 1996 Census of Population and Housing: Yass (A) Statistical Local Area-New South Wales. Australian Bureau of Statistics, Sydney.

ABS (1999) Australian Commodities and Statistics, 2000-2001. Catalogue No. 7312.0. Australian Bureau of Statistics, Sydney.

ABS (1999a) 1999-00 Viticulture Australia. Catalogue No. 7310.0. Australian Bureau of Statistics, Sydney.

ABS (1999b) 1998-99 Viticulture Australia. Catalogue No. 7310.0. Australian Bureau of Statistics, Sydney.

Acworth, R.I., Broughton, A., Nicoll,C., and Jankowski, J. (1997) The role of debris-flow deposits in dryland salinity development in the Yass River Catchment, New South Wales. *Hydrogeology Journal*, 5(1): 22-36

AFFA (2000) *About ARMCANZ.* Agriculture, Fisheries and Forestry- Australia. Canberra

Amir, I., and Fisher, F. (2000) Response of near-optimal agricultural production to water policies' *Agricultural Systems*, 64: 115-130

Avissar, R. (1991) A statistical-dynamical approach to parameterise subgrid-scale land surface heterogeneity in climate models. *Surv. Geophys*, 12: 155-178

Banens, B., Lovett, S., and Young, B. (1996) The Environmental Flows Decision Support Program. Natural Resources Management Strategy Project No. R 6066. Murray Darling Basin Commission, Canberra

Banens, B., Sharley, T., and Blackmore, D. (1994) Integrated Flow Management: The Murray Darling Basin Commission Approach. pp143-150 In: Brierley G J and f. Nagel (eds) Geomorphology and River Health in NSW. *Proceedings of Conference. Macquarie University*, October 4, 1994. Sydney. (Graduate School of the Environment, Macquarie University, working Paper 9501)

Barbier, B., and Bergeron, G. (1999) Impact of policy interventions on land management in Honduras: results of a bioeconomic model'. *Agricultural Systems*, 60: 1-16.

Baron, B.C., Pilgrim, D.H., and Cordery, I. (1980) Hydrological relationships between small and large catchments. *Australian Water Resources Council Technical Paper No. 54.* Australian Government Publishing Service. Canberra.

Bates, B.C. (1994) Regionalisation of hydrologic data: a review. *A report as part of Project d2. Regionalisation and scaling to hydrologic data.* Cooperative Research Centre for Catchment Hydrology. Report No 94/5.

Bayley, W.A. (1973) Yass Municipal History. Yass Municipal Council, Yass.

Beare, S., and Rosalyn, B. (1998) Efficiency of Water Use and Access Rights to Infrastructure. *Australian Commodities*, 5(4): 494-503.

Beck, M.B. Model structural identification from experimental data, in Halfon, E., (Ed) *Theoretical Systems Ecology: Advances and Case Studies*. Academic Press, New York. 1979. 259-289.

Becker, A. (1995) Problems and progress in macroscale hydrologic modelling. In: Feddes, R.A (Eds). *Space and time scale variability and interdependencies in hydrological processes*. Cambridge University Press. pp 135.

Becker, A., and Braun, P. (1999) Disaggregation, aggregation and spatial scaling in hydrological modelling. *Journal of Hydrology*, 217: 239-252.

Becker, A., and Numec, J. (1987) Macroscale hydrologic models in support of climate research. In : Soloman, S.I., and Beran, M., Hoog, W. (eds). *The influence of climate change and climatic variability on the hydrologic regime and water resources*. IAHS, pp431. Publication No. 68.

Berbel, J., and Gomez-Limon, J.A. (2000) The impact of water-pricing policy in Spain: an analysis of three irrigated areas. *Agricultural Water Management*, 43: 219-238

Bernet, T., Oritz, O., Estrada, R.D, Quiroz, R., and Swinton, S.M. (2001) Tailoring agricultural extension to different production contexts: a user-friendly farm-household model to improve decision making for participatory research. *Agricultural Systems*, 69: 183-198

Beven, K. (1981). Comment on; A stochastic-conceptual analysis of rainfall-runoff processes on a hillslope. by Freeze, A. *Water Resources Research*, 17(2): 431-432.

Beven, K. (1989) Changing ideas in hydrology - the case of physically based model. *Journal of Hydrology*, 105: 157-172.

Beven, K. (1997) TOPMODEL: A critique. *Hydrological Processes*, 11: 1069-1085.

Beven, K., (1987) Towards a new paradigm in hydrology. In, *Water for the Future: Hydrology in Perspective*, IAHS Publication, 164: pp393-403.

Beven, K., and Binley, A. (1992) The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes,* 6: 279-298.

Binley, A., and Beven, K. (1989) A physically based model of heterogenous hillslopes. 2. Effective hydraulic conductivities. *Water Resources Research*, 25(6): 1227-1233

Bjornlund, H., and McKay, J. (1998) Factors affecting water prices in a rural water market: A south Australian experience. *Water Resources Research*, 34(6): 1563-1569

Bouman, B.A.M, Hansen, H.G.P., Schipper, R.A., Nieuwenhuyse, A., Hengsdijk, H and Bouma, J. (1999). A framework for integrated biophysical and economic land use analysis at different scales. *Agriculture, Ecosystems and Environment*, 75: 55-73.

Brad, J.M., Turner, J.V., and Waite, T.D. (1991) Final report of hydrogeochemical and isotope techniques in relation to dryland salinisation and waterlogging in Williams Creek, Yass, New South Wales. ANSTO Report/C210.

Braun, P., Molnar, T., and Kleeberg, H.B. (1997) The problem of scaling in grid-related hydrological process modelling'. *Hydrological Processes*, 11: 1219-1230.

Brennan, D., and Scoccimarro, M. (1999) Australian Water markets. *The Australian Journal of Agriculture and Resource Economics*, 43(1). March 1999. Blackwell Publishers.

Broughton, A.K. (1994) Mooki river catchment hydrogeological investigation and dryland salinity studies. Department of Water Resources. New South Wales. Sydney.

Brutsaert, J. Evaporation in the atmosphere: theory, history and applications. Kluwer Boston Press. Canada. 1982

Bryant, K.J., Mjelde, J.W., and Lacewell, R.D. (1993) An intraseasonal dynamic optimization model to allocate irrigation water between crops. *American Journal of Agricultural Economics*, 75: 1021-1029.

Burn, D.H. (1988) Delineation of groups for regional flood frequency analysis. *Journal of Hydrology*, 104: 345-361.

Calder, I.R., and Newson, M.D. (1979) Land-use and upland water resources in Britain: a strategic look. *Water Resources Bulletin*, 15(6): 1628-1639.

Chakravorty, U., and Roumasset, J. (1991) Efficient spatial allocation of irrigation water. *American Journal of Agricultural Economics*, 165-173.

Chapman, T.G., (2001) 'Modelling Stream recession Flows' in Ghassemi, F., Post, D., Sivapalan, M., and Vertessy, R. (eds) *MODSIM 2001: International Congress on Modelling and Simulation*. The Australian National University, Canberra, Australia. 10-13 December. pp 65-70.

Characklis, G.W., Griffin, R., and Bedient, P.B.,(1999) Improving the ability of the water market to efficiently manage drought. *Water Resources Research*, 35(3): 823-831.

Chatterjee, B., Howitt, R.E., and Sexton, R.J. (1998) The optimal joint provision of water for irrigation and hydropower. *Journal of Environmental Economics and Management*, 36: 295-313.

Chiew, F.H.S., and McMahon, T.A. (1994) Application of the daily rainfall-runoff model MODHYDOLOG to twenty-eight Australian catchments. *Journal of Hydrology*, 153: 383-416.

Chiew, F.H.S., Pitman, A.J., and McMahon, T.A. (1996) Conceptual catchment scale rainfall-runoff models and AGCM land-surface parameterisation schemes. *Journal of Hydrology*, 179: 137-157.

Chiew, F.H.S., Stewardson, M.J., and McMahon, T.A. (1993) Comparison of six rainfall-runoff modelling approaches. *Journal of Hydrology,* 147: 1-36.

Clarke, R.T. (1973) A review of some mathematical models used in hydrology, with observations on their calibration and use. *Journal of Hydrology,* 19: 1-20.

COAG (1994). *Communique, Report of the Working Group on Water Resource Policy.* Council of Australian Governments.

Cohan, L.J and Marks, D.H. (1975) A review and evaluation of multi-objective programming techniques. *Water Resources Research*, 11(2): 208-220.

Collins, D., Hall. N., and Scoccimarro, M. (1996) COAG water reforms and farm incomes in the southern Murray-Darling Basin. *Outlook 96.* pp 1-13. Published by ABARE, Canberra.

Cornish, P.M. (1989) The effect of radiata plantation establishment and management on streamflows and water quality - a review. Forestry Commission of NSW, Technical Paper No. 49, 53pp

Cornish, P.M., and Vertessy, R.A. (2001) Forest age induced changes in evapotranspiration and water yield in a eucalypt forest. *Journal of Hydrology*, 242: 43-63

Crawford, N.H., and Lindsey, R.K. (1964) A conceptual model of the hydrological cycle. *Proceedings of the International Assembly and. Association for Science and Hydrology, Berkeley.* California. No. 63 pp573-587.

Crissman, C.C., Antle, J.M., and Capaldo, S.M. (1997) Economic, environmental and health trade-offs in agriculture: pesticides and the sustainability of Andean potato production. Kluwer Academic Publishers. The Netherlands.

Croke, B.F.W., A technique for deriving the Unit Hydrograph from streamflow data, in preparation, 2001.

Croke, B.F.W., and Jakeman, A.J. Revised IHACRES CMD model, in preparation, 2001.

Dandy, G., and Crawley, P. (1992) Optimum Operation of a Multiple reservoir System Including Salinity Effects. *Water Resources Research*, 28(4): 979-990.

Das, P., and Haimes, Y.Y. (1979) Multiple objective optimisation in water quality and land management. *Water Resources Research*, 15(6): 1313-1322.

Davis, J.R., and Young, W.J., (1998) A Decision Support System For Planning Environmental Flow Allocations, In D.P Loucks (ed). Restoration of Degraded Rivers: Challenges, Issues and Experiences, pp 357-376. Kluwer Academic Publishers. Netherlands.

Dawes, W.R., Gilfedder, M., Walker, G.R., and Evans, W.R. (2001) 'Biophysical modelling of catchment-scale surface water groundwater response to land-use change'. in Ghassemi, F., Post, D., Sivapalan, M., and vertessy, R. (eds) *MODSIM 2001: International Congress on Modelling and Simulation*. The Australian National University, Canberra, Australia. 10-13 December. pp 535-540.

Dawson, J.A., (1957). 'The demand for irrigation water in the Ainsworth area of Nebraska, Unpublished PhD Thesis, University of New England, Armidale.

Department of Natural Resources and Environment (2000). Australian wine grape crush survey 2000, Victoria / New South Wales. Department of Natural Resources and Environment, Melbourne.

Dervis, K.J., DeMelo, J., and Robinson, S. General equilibrium models for development policy. Cambridge University Press. 1982.

Dimitrios, A.G and Lakakis, J.N. (1997) Policy analysis for an amicable, efficient and sustainable inter-country fresh water resource allocation. *Ecological Economics*, 21: 231-242.

Dinar, A., and Letey, J. (1996) Modelling economic management and policy issues of water in irrigated agriculture. Connecticut. Praeger Publishers.

DLWC (1993) Dryland salinity in the Yass river catchment: Processes and Management. New South Wales Department of Land and Water Conservation, AGPS, Canberra

DLWC (1997a) *Information For Water Users*, New South Wales Department of Land and Water Conservation, Sydney.

DLWC (1997b) Information for Water Users. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1997c) The stressed Rivers Assessment Report: Murrumbidgee Catchment. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1997d) Water Sharing: NSW Water Reforms. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1998a) Water Sharing the Way Forward: Enhancing and Extending Water Trading in NSW. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1998b) Building a more secure future for the Murrumbidgee: Progress Report. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1998c) Water Sharing the Way Forward: The Cap: A Basis for the Evolution of Water Management. The New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1998d) Water Sharing the Way Forward: Volumetric Conversions. The New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1998e).Overview of the New South Wales Water Initiatives. The New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1998f). A Draft Five Year Strategy for Water Management in New South Wales 1999-2003. The New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1998g) The Farm Dams Policy. The New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1999a) Water Sharing The Way Forward: NSW Progress on the Water Reforms 1995 to 1998. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1999b) *Water Sharing IN NSW-access and Use: Discussion Paper*, New South Wales Department of Land and Water Conservation, Sydney.

DLWC (1999c) Advice to Water Management Committees: Water extraction and daily flow shares in unregulated rivers. Department of Land and Water Conservation, Sydney.

DLWC (1999d) *Catchment Management Boards*. New South Wales Department of Land and Water Conservation, Sydney.

DLWC (1999e) A Proposal for Updated and Consolidates Water Management Legislation in New South Wales: A White Paper. New South Wales Department of Land and Water Conservation. Sydney. December 1999.

DLWC (1999f) Trading Within a Planning Framework: Water Trading Development and Monitoring. The New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1999g) Water Sharing The Way Forward: Water Trading on Unregulated Rivers. The New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1999h) Rural Production and Water Sharing: A Farm Dams Assessment Guide. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (1999i) Interim North West Unregulated Flow Plan. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (2000a) An overview of the proposed new water legislation for New South Wales. . New South Wales Department of Land and Water Conservation.

DLWC (2000b) An Overview of the Proposed New Water Legislation for New South Wales. The New South Wales Department of Land and Water Conservation. Sydney.

DLWC (2000c) Yass Valley: Land Use and catchment Condition. New South Wales Department of Land and Water Conservation, Regional Office, Yass.

DLWC (2000d) Draft NSW Water Conservation Strategy. New South Wales Department of Land and Water Conservation. Sydney.

DLWC (2001a) Estimates of extraction from unregulated streams in Yass catchment. Unpublished report. The New South Wales Department of Land and Water Conservation.

DLWC (2001b) Digital land use map of Yass catchment. The New South Wales Department of Land and Water Conservation. Leeton

Dooge, J.C.I. (1968) The hydrologic cycle as a closed system'. *Bulletin of the International Science of Hydrology*, 13(1): 58-68

Dowlatabadi, H., and Morgan, M.G. (1993) A model framework for integrated assessment of the climate problem. *Energy Policy*. 21: 209-221

DPIE (2000) Getting started in farm forestry: plant trees for profit. Department of Primary Industries and Energy farm forestry program. Department of Primary Industries and Energy, Adelaide.

Duckstein, J., and Opricovic, S. (1980) Multiple-objective optimisation in river basin development'. *Water Resources Research*, 1(16): 14-20.

Dudley, N.J. (1998) Volume Sharing of Reservoir water. *Water Resources Research*, 24(5): 641-648.

Dudley, N.J., and Hearn, B. (1993) Systems Modelling to Integrate River Valley Water Supply and irrigation Decision Making Under Uncertainty. *Agricultural Systems*, 42: 3-23.

Dudley, N.J., and Scott, B.W. (1993) Integrating irrigation water demand. Supply, and delivery management in a stochastic environment. *Water Resources Research*, 29(9): 3093-3101.

Dumsday, R. (1999) Contributions from the Social Sciences, in Chisholm, A., and Dumsday, R., (eds) *Land Degradation, Problems and Policies*, Cambridge University Press, Cambridge.

Eeles, C.W.O., and Blackie, J.R. (1993) Land-use changes in the Balquhidder catchments simulated by a daily streamflow model. *Journal of Hydrology*, 145: 315-336.

Elgy, J. (1989) A physically based model of heterogenous hillslopes 2. Effective Hydraulic conductivities. *Water Resources Research*, 25(6): 1227-1233.

Ellis, J (1998) Hillslope erosion and erosion potential in Yass catchment. Unpublished Report.

EPA (1999). Water Quality and River Flow Interim Environmental Objectives: Guidelines for River, Groundwater and Water Management Committees. Environment Protection Authority, Sydney.

EPA (2001).Water Quality and River Flow Interim Environmental Objectives: Murrumbidgee River and Lake George. Environment Protection Authority. Sydney.

Evans, J.P and Jakeman, A.J. (1998) Development of a simple, catchment scale, rainfall-evapotranspiration-runoff model. *Environmental Modelling and Software*, 3(3-4): 385-393.

Evers, A.J., Elliott, R.L., and Stevens, E.W. (1998) Integrated decision making for reservoir, irrigation and crop management. *Agricultural Systems*, 58(4): 529-554.

Ewen, J., Sloan, W.T., Kilsby, C.G., and O'Conell, P.E. (1998) A modelling system for large scale hydrology: deriving large-scale physically-based parameters for the Arkansas-Red river basin. *Hydrology and Earth System Sciences*, 47: 123-167

Fedra, K., Weigkricht, E., and Winkelbauer, L. (1993) Decision Support and information Systems for Regional Development Planning. International Institute for Applied Systems Analysis. Austria.

Flinn, J.C. (1969) The demand for irrigation water in an intensive irrigation area'. *Australian Journal of Agricultural Economics*, 13(2): 128-143.

Franchini, M., and Pacciani, M. (1991) Comparative analysis of several conceptual rainfall-runoff models. *Journal of Hydrology,* 122: 161-219.

Freeze, R.A. (1971) A three-dimensional transient saturated-unsaturated flow in a groundwater basin. *Water Resources Research*, 7(2): 347-366.

Fresco, L.O. (1995) Agro-ecological knowledge at different scales. In. Bouma, B.A.M., Luyten, J.C., Zandstra, H.G., (eds). *Eco-Regional Approaches for sustainable land use and food production.* Kluwer Academic Publishers, the Netherlands. pp 133-143.

Frick, G.E., and Andrews, R.A. (1967) Aggregation bias and four methods of summing farm supply functions. *Journal of Farm Economics*, 49: 107-118.

Gan, T.Y., and Burges, S.J. (1990) An assessment of a conceptual rainfall-runoff model's ability to represent the dynamics of small hypothetical catchments 1.Models, Model properties, and experimental design. *Water Resources Research*, 26(7): 1595-1604.

Gavan, J.D., and Tyers, R. (1982) Agricultural analysis for energy planning, *In Energy Planning for Developing Countries: A Study of Bangladesh.* Lucia, R.J and Jacoby, H.D (eds). John Hopkins University Press.

Geoffrion, A.M. (1976) the purpose of mathematical programming is insight, not numbers. *Interfaces*, 7(1): 81-92

Ghassemi, F., Jakeman. A.J., and Nix, H.A. (1995) *Salinisation of Land and Water Resources: Human Causes, Extent, Management and Case Studies.* Centre for Resource and Environmental Studies, Australian National University. Canberra.

Giannias, D., and Lekakis, J. (1997) Policy analysis for an amicable, efficient and sustainable inter-country fresh water resource allocation. *Ecological Economics*, 21: 231-242.

Goetz, R.U. (1997) Diversification in agricultural production: a dynamic model of optimal cropping to manage soil erosion. *American Journal of Agricultural Economics*, 79: 341-356.

Goreaux, L.M and Manne, A.S. (1973) Multilevel planning: case studies in Mexico. North Holland, New York Publishing.

Grayson, R.B., Moore, I.D., and McMahan, T.A. (1992) Physically based hydrologic modelling: 2. Is the concept realistic? *Water Resources Research*, 26: 2659-2666.

Greiner, R., and Hall, N. (1995) Integrating catchment hydrology and farm management in a programming model for policy analysis. *International Congress on Modelling and Simulation*. Vol. 1. Agriculture, Catchment Hydrology and Industry, 1995.

Griffin, R., and Hsu, S. (1993). The potential for Water Market Efficiency when Instream Flows Have Value. *American Journal of Agricultural Economics Association*, 75: 292-303.

Gupta, V.J., and Sorooshian, S. (1985) The automatic calibration of conceptual catchment models using derivative-based optimisation algorithms. *Water Resources Research*, 21(4): 473-485.

Gupta, V.K., and Dawdy, D.R. (1995) Physical interpretations of regional variations in the scaling exponents of flood quantiles. In: Kalma, J.D., Sivapalan, M. (eds). *Scale issues in hydrological modelling*. Hohn Wiley and Sons pp105-119.

Haimes, Y.Y and Hall, W.A. (1974) Multi-objectives in water resources systems analysis: The surrogate worth trade-off method. *Water Resources Research*, 10(4): 615-624.

Hall., N, Poulter, D., and Curtotti, R. (1994) ABARE Model of Irrigation Farming in the Southern Murray-Darling Basin. ABARE Research Report 94.4. Australian Bureau of Agricultural and Resource Economics, Canberra.

Hansen, D.P., Ye, W., Jakeman, A.J., Cooke, R. and Sharma, P. (1996) Analysis of the effect of rainfall and streamflow data quality and catchment dynamics on streamflow prediction using the rainfall-runoff model IHACRES. *Environmental Software*, 11: 193-202.

Harper, R.J., Hatton, T.J., Crombie, D.S., Dawes, W.R, Abott, L.K., Challen, R.P., and House, C. (2000) Phase farming with trees. A report for the RIRDC/LWRRDC/FWPRDC joint venture agroforestry program. RIRDC publication No 00/48. Canberra.

Hauhs, M., (1990). Ecosystem modelling: Science or technology'. *Journal of Hydrology*, 116: 25-33.

Hewitt, J., and Hanemann, W. (1997) A discrete/continuous approach to residential water demand under block water pricing. *Land Economics*, 71(2): 173-180.

Hillel, D (1986) Modelling in soil physics: A critical review. *Future Developments in Soil Science Research*. 35-42

Hope, C., Anderson, J., and Wenman, P. (1993) Policy analysis of the greenhouse effect: An application of the PAGE model. *Energy Policy*. 21: 327-338.

Huges, D.A. (1995) Monthly rainfall-runoff models applied to arid and semiarid catchments for water resources estimation purposes. *Hydrological Sciences Journal,* 40(6): 751-770.

Hutchinson, M.F. (1995) Interpolating mean rainfall using thin plate smoothing splines, *International Journal of Geographical Information Systems*, 9:385-403.

IAG (1997) Review of Cap Implementation 1996/7. A report by the Independent Audit Group for The Murray Darling Basin Commission, Canberra.

IAG (1998) *Review of the Cap Implementation 1997/8 including responses by the four State Governments*. Murray Darling Basin Commission, Canberra.

ICESD (1996) Summary report on the Implementation of the National Strategy for Ecologically Sustainable Development. The Intergovernmental Committee for Ecologically Sustainable Development 1993-1995.

Jakeman, A.J., and Letcher, R.A. (2001) Integrated Assessment and Information Systems for Catchment Management. in Ghassemi, F., Post, D., Sivapalan, M., and Vertessy, R. (eds) *MODSIM 2001: International Congress on Modelling and Simulation*. The Australian National University, Canberra, Australia. Vol. 1 December. pp 31-41.

Jakeman, A.J., Hornberger, and G.M. (1993) How much complexity is warranted in a rainfall-runoff model. *Water Resources Research,* 29: 2637-2649.

Jakeman, A.J., Hornberger, G.M., Littlewood, I.G and Whitehead, P.G., Harvey, J.W and Bencala, K.E. (1992) A systematic approach to modelling the dynamic linkage of climate, physical catchment descriptors and hydrologic response components. *Mathematical Computers and Simulation*, 33: 359-366.

Jakeman, A.J., I.G. Littlewood, and P.G. Whitehead. (1990) Computation of the Instantaneous Unit Hydrograph and identifiable component flows with application to two small upland catchments, *Journal of Hydrology,* 117: 275-300.

Jakeman, A.J., Littlewood, I.G and Whitehead, P.G. (1993) An assessment of the dynamic response characteristics of streamflow in the Balquidder catchments. *Journal of Hydrology*, 145: 337-355.

Jakeman, A.J., Littlewood, I.G., and Symons, H.D. (1991) Features and applications of IHACRES: A PC program for identification of the unit hydrograph and component flows from rainfall, evapotranspiration, and streamflow data, In Vichnevetsky, R and Miller, J.J.H (eds). *Proceedings of the 13th IMACS World Congress on Computation and Applied Mathematics*. Vol.4. pp 1963-1967. Dublin, Ireland.

James, L.D., and Burges, S.J. (1982) Selection, calibration, and testing of hydrologic models. *American Society for Agriculture and Engineering Monographs,* 5: 437-472.

Jankowski, J., and Acworth, R.I. (1997) Impacts of debris-flow deposits on hydrogeochanical processes and dryland salinity development in the Yass River Catchment, New South Wales. *Hydrogeology Journal*, 5(1):71-88.

Jansen, D.E., Stoorvogel, J.J., and Jansen, J.G.P. (1997) A quantitative tool for regional land-use analysis. In: Teng, P.S., Kropff, M., and Berge, H.F.M., Dent, J.B., Lansigna, F.P., and van Laar, H.H., (eds). *Applications of systems approaches at the farm and regional levels.* Kluwer Academic Publishers, Dordrecht. The Netherlands, Vol. 1 pp399-412.

Jansen, W.G. (1995) Aggregating economic knowledge for use at national, regional, sector and farm level. In. Bouma, B.A.M., Luyten, J.C., Zandstra, H.G (eds). *Eco-Regional Approaches for sustainable land use and food production.* Kluwer Academic Publishers, the Netherlands. pp143-166.

Johnston, P.R., and Pilgrim, D. (1976) Parameter optimisation for watershed models. *Water Resources Research*, 12(3): pp477-486.

Kleissen, F,M., Beck, M.B., and Wheater, H.S., (1992) 'The identifiability of conceptual hydrochemical models'. *Water Resources Research*, 26(12): 2979-2992.

Klemes, V. (1986) Operational testing of hydrological simulation models, *Hydrological Sciences Journal*, 31: 13-24.

Kokkonen, T.S., Jakeman, A.J., and Young, P.C. (in press) Predicting daily stream flows in ungauged catchments - Model regionalization from catchment descriptors at Coweeta, Journal of Hydrology

Kruseman, G., and Bade, J. (1998) Agrarian policies for sustainable land use: bio-economic modelling to assess the effectiveness of policy instruments. *Agricultural Systems*, 58(3): 465-481.

Lamb, D., and Borschmann, G. (1998) Agroforestry with high value trees, RIRDC/LWRRDC/FWPRDC Joint venture agroforestry program. Technical Report No 98/142. Rural Industries Research and Development Corporation. Canberra

Landsberg, J. (1999) The ways trees use water' in (Ed) Landsberg, J. Water and salinity issues in agroforestry No.5. The joint venture agroforestry program: agroforestry to balance catchment health and primary production project'. RIRDC publication No 99/37. Canberra.

Lee, D,J., and Howitt, R.E. (1996) Modelling regional agricultural production and salinity control for water quality policy analysis. *American Journal of Agricultural Economics*, 78: 41-53.

Letcher, R. (2002) Issues in Integrated assessment and modelling for catchment management. PhD thesis, Centre for Resource and Environmental Studies, The Australian National University.

Littlewood, I.G., and Jakeman, A.J. (1994) A new method of rainfall runoff modelling and its applications in catchment hydrology, in *Environmental Modelling*, Vol2, edited by P Zannetti. South Hampton. England. pp143-171

Loomis, J.B. (1994) Water transfer and major environmental provisions of the central valley project improvement act: a preliminary economic evaluation. *Water Resources Research*, 30(6): 1865-1871.

LWRRDC (1997) Integrated catchment management for dryland salinity control in the Liverpool Catchment Plains: a preliminary study from en economic perspective. Occasional Paper No 12/97. Land and Water Resources Research and Development Corporation, Canberra.

LWRRDC (1998). 'The National Dryland Salinity Management Program Management Plan 1998-2003. Land and Water Resources Research and Development Corporation, Canberra.

Mahendrarajah, S., Jakeman, A.J., and Young, P.C. (1996) Water supply in monsoonal Asia: modelling and predicting small tank storage. *Ecological Modelling,* 84: 127-137.

Mahendrarajah, S., Warr, P.G., and Jakeman, A.J. (1992) Optimal extraction of small scale surface water storage in Asia. *Water Resources Research*, 28(5): 1206-1219.

Marsden Jacobs and Associates (1999) Water Trading Development and Monitoring: Executive Summary. Marsden Jacobs and Associates. Sydney.

McCarl, B.A., Dillon, R.R., Keplinger, K.O., and Williams, R.L. (1999) Limiting pumping from the Edwards aquifer: an economic investigation of proposals, water markets, and spring flow guarantees. *Water Resources Research*, 35(4): 1257-1268.

McCormack, B., Kerruuish, J.R., Antilla, E., and Stewart, M. (2000) Harvesting trees on farms. A report for the RIRDC/LWRRDC/FWPRDC Joint venture agroforestry program. Technical Report No 00/46. Rural Industries Research and Development Corporation. Canberra

McDermott, G.E., and Pilgrim, D.H. (1982) Design flood estimation for small catchments in New South Wales Department of Natural Energy. Australian Government Publishing Service. Canberra.

McDonald, W. (1998) Matching Pasture production to livestock enterprises: southern tablelands and south west slopes. New South Wales Agriculture. Agnote DPI 213. Tamworth.

McEwan, A. (1971) Development of alternatives in Pakistan: A multi-sectoral and regional analysis of planning problems. Harvard University Press. Cambridge.

McKinney, D., Cai, X., Rosegrant, M., Ringler, C., and Scott, C. (1999) *SWIM Paper: Modelling Water Resources Management at the Basin Level: Review and Future Directions'* International Water Management Institute, Sri Lanka, Columbo.

MDBC (1996) Setting the Cap. A Report by Independent Audit Group for the Murray Darling Basin Commission. Canberra.

MDBC (1999) Murray Darling Basin Cap on Diversions: Water Year 1997/1998. Striking the Balance. Murray Darling Basin Commission, Canberra.

MDBC (2000a) *The Murray Darling Basin Ministerial Council,* Murray Darling Basin Commission, Canberra.

MDBC (2000b) *Review of the Operation of the Cap: Draft Overview Report of the Cap Project Board,* Murray Darling Basin Commission, Canberra.

Mehrez,A., Percia, C., and Oron, G. (1992) Optimal operation of a multisource and multiquality regional water system. *Water Resources Research*, 28(5): 1199-1206.

Michaud, J and Sorooshian, S. (1994) Comparison of simple versus complex distributed runoff models on a midsized semiarid watershed. *Water Resources Research*, 30(3): 593-605.

Moore, R.M. Australian Grasslands. Australian National University Press. 1970

Mosley, M.P. (1980) Delimitation of New Zealand Hydrologic Regions. *Journal of Hydrology,* 49: 173-192.

Nash, J.E and Sutcliffe, J.V. (1970) River flow forecasting through conceptual models. Part 1 - a discussion of principles. *Journal of Hydrology,* 10: 1-38.

Nash, J.E., and Barsi, B.I. (1983) A hybrid model for flow forecasting on large catchments. *Journal of Hydrology*, 65: 125-137.

Nathon, R.J., and McMahon, T.A. (1990) Identification of homogenous regions for the purposes of regionalisation. *Journal of Hydrology*, 121: 217-238.

NCDC (1981) Waters of the Canberra Region: Metropolitan Planning Issues. National Capital Development Commission, Canberra. Technical Paper No.30.

NCP (2002) A viable and sustainable water industry. National Competition Council, Australian Government Publishing Service, Canberra.

Newham, L. (2002) Catchment scale modelling of water quality and quantity. Unpublished PhD thesis. Centre for Resource and Environmental Studies, Australian National University.

NGERP (1999) Report of the Namoi Groundwater Expert Panel on the Groundwater Allocation Adjustment Process in the Namoi Valley. Namoi Expert Reference Panel. Namoi.

NSW Department of Agriculture (2000). Digital map of soils in Yass Catchment, Department of Agriculture, Orange.

NSW Department of Agriculture (2001a) Farm Enterprise Budget: Beef cattle gross margin budget. New South Wales Department of Agriculture, Orange.

NSW Department of Agriculture (2001b) Grazing management of lucerne. Agnote DPI-198. New South Wales Department of Agriculture. Tamworth.

NSW Department of Agriculture (2001c) Farm Enterprise Budget: Lucerne establishment gross margin budget. New South Wales Department of Agriculture, Orange.

NSW Department of Agriculture (2001d). Lucerne Varieties: 2000-2001. Agfact. No. P2.5.13. New South Wales Department of Agriculture. Tamworth.

NSW Department of Agriculture (2001e) Farm enterprise budget: Water budget for summer 2001/2002: Murrumbidgee Valley. New South Wales Department of Agriculture. Orange.

NSW Rural Assistance Authority (2000) Water reform and structural adjustment program. NSW Rural Assistance Authority, Sydney

Oweis, T., and Hachum, A. (2001) Reducing peak supplementary irrigation demand by extending sowing dates. *Agricultural Water Management*, 50: 109-123.

Parkin, G., O'Donelle G., Ewen, J., Bathurst, J.C., and O'Connell, P.E. (1996) Validation of catchment models for predicting land-use and climate change impacts. 2. Case study for a Mediterranean catchment. *Journal of Hydrology*, 175: 596-613.

Parson, E.A. (1995) Integrated Assessment and environmental policy making: In pursuit of usefulness. *Energy Policy*, 23(4/5): 463-475

Peck, S.C., and Teisberg, T.J (1993) Global warming uncertainties and the value of information; an analysis using CETA. *Resource and Energy Economics.* 15(1): 71-97

Peel, M.C., Chiew, F.H.S., Western, A.W., and McMahon, T.A. (2000) Extension of unimpaired monthly streamflow data regionalisation of parameter values to estimate streamflow in ungauged catchments. National Land and Water Resources Audit Theme - 1 Water Availability' Centre for Applied hydrology. University of Melbourne.

Petheram, C., Zhang, L., Walker, G.R, and Grayson, R. (2000) Towards a Framework for predicting impacts of land-use on recharge: A review of recharge studies in Australia. Technical Report 28/00, CSIRO Land and Water, Canberra pp34

Pezzey, J (1992) Sustainability development concepts: an interdisciplinary guide. *Environmental Values*, 4(1): 321-362

Philbrick, C.R., and Kitanidis, P.K. (1998) Optimal conjunctive use operations and plans. *Water Resources Research*, 34(5): 1307-1316.

Pilgrim, D.H, Cordery, I., and Doran, D.G. (1979) Assessment of runoff characteristics in arid western New South Wales, Australia. *International Association for Hydrological Sciences*. IAHS Publishing. 128: 141-150.

Pilgrim, D.H. (1983) Some problems in transferring hydrological relationships between small and large drainage basins and between regions. *Journal of Hydrology*, 65: 49-72.

Pilgrim, D.H., Chapman, T.G., and Doran, D.G. (1988) Problem of rainfall-runoff modelling in semi-arid regions. *Hydrological Sciences Journal*, 33(4): 379-400.

Pillai, C.R.S and Raju, S.K. (1996) Ranking irrigation management alternatives by multicriterion analysis. *International Journal of Water Resources Development*, 12: 329-345.

Post, D.A., and Jakeman, A.J. (1996) Relationships between physical attributes and hydrologic response characteristics in small Australian mountain ash catchments. *Hydrological Processes*, 10: 877-892.

Post, D.A., and Jakeman, A.J. (1999) Predicting the daily streamflow of ungauged catchments in S.E Australia by regionalising the parameters of a lumped conceptual rainfall-runoff model. *Ecological Modelling*, 123: 94-104.

Raju, K.S., and Kumar, D.N. (1999) Multicriterion decision making in irrigation planning. *Agricultural Systems*, 117-129.

Ramsden, S.J., Reed, G.V and Rayner, A.J. (1996) Farm level adjustment to CAP reform: an integer programming approach. Discussion Paper No. 96. Department of Economics, Nottingham University.

Ravetz, J.R. (1997) ULYSSES: Urban lifestyles, sustainability and integrated environmental assessment. ULYSSES Working Paper. Darmstadt University of Technology. Centre for Interdisciplinary Studies in Technology. Germany.

Rogers, P. (1974) A sectoral planning model for water and agriculture in Bangledesh. *ITCC Review*, 3(2): 110-119.

Rogers, P., Hurst. C., and Harshadeep, N. (1993) Water resources planning in a strategic context: linking the water sector to the national economy. *Water Resources Research,* 29(7): 1895-1906.

Rotmans, J., and Van Asselt, M. (1996) Integrated assessment: a growing child on its way to maturity. An Editorial Essay. *Climatic Change*, 34: 327-336.

Ruprecht, J.K., and Schofield, N.J. (1991) Effects of partial deforestation on hydrology and salinity in high salt storage landscapes. II. Strip, soils and parkland clearing. *Journal of Hydrology*, 129: 39-55

Salman, A.Z., Al-Karablieh, E.K., and Fisher, F.M. (2001) An inter-seasonal water allocation systems (SAWAS). *Agricultural Systems,* 68: 233-252.

Schilizzi, S.G.M., and Boulier, F. (1997) Why do farmers do what they do? Validating whole-farm models. *Agricultural Systems,* 54(4): 477-499.

Schneider, I., and Whitlach, E. (1991) User Specific Water Demand Elasticities. *Journal of Water Resource Planning and Environmental Managemen*t, 17(1): 43-52.

Schofield, N.J., and Ruprecht, J.K. (1989) Regional Analysis of Stream Salinisation in South-West Western Australia. *Journal of Hydrology*, 112: 19-39.

Schreider, S,Yu., Jakeman, A.J., and Pittock, A.B. (1996) Modelling rainfall-runoff from large catchment to basin scale: the Goulburn Valley, Victoria. *Hydrological Processes*, 10: 145-152.

Schreider, S,Yu., Jakeman, A.J., Letcher, R.A, Nathan, R.J, Neal, B.P and Beavis, S.G. (2002) Detecting changes in streamflow response to changes in non-climatic conditions: farm dam development in the Murray-Darling basin, Australia. *Journal of Hydrology*, 262: 84-98.

Scown, J. (2000) Yass Valley Land Use and Catchment Condition: January 2000. Department of Land and Water Conservation, Yass.

Scown, J., and Nicoll, C. (1993) Dryland Salinity in the Yass river Catchment: Process and Management. Technical report for The Natural resources Management Strategy. The NSW Department of Conservation and Land Management, Yass.

Sefton, C.E.M., and Howarth, S.M. (1998) Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales. *Journal of Hydrology*, 211(1): 1-16.

Servat, E., and Dezetter, A. (1993) Rainfall-runoff modelling and water resources assessment in north-western Ivory Coast: Tentative extension to ungauged catchments, *Journal of Hydrology*, 148: 231-248.

Shepherd, A. (1999) Wine Grapes: Projections of wine grape production and winery intake to 2001-2002. ABARE Research Report 99.15 Australian Bureau of Agricultural and Resource Economics. Canberra.

Shepherd, A. (2000) Australian wine grape production and winery intake: Projections to 2002-03. ABARE Research Report 2000.14 Australian Bureau of Agricultural and Resource Economics. Canberra.

Sher, A., and Amir, I. (1993) Fuzzy linear constraints for agricultural production planning. *Agricultural Systems*, 45: 421-441.

Simonovic, S. (1999) A new modelling approach for water resources policy analysis'. *Water Resources Research*, 35(1): 295-304.

Singh, I., Squire, L., and Strauss, J. (1986) Agricultural household models: extensions, applications and policy. John Hopkins University Press, Baltimore.

Singh, I.P., Kaur, P., and Millward-Brown, I. (2000) Analysing the impacts of changes in upstream water diversions on agriculture in the floodplains-a case study of the Lowbidgee in NSW. *A contributed paper at the 44th Conference of the Australian Agricultural and Resource Economics Society, Sydney, Australia*, 23-25th Jan, 2000.

Smith, D. (1998) *Water In Australia: Resource and Management.* Oxford University Press, Melbourne.

Soil Conservation Service of NSW. (1986) Dryland salinity in the South East Region. Soil Conservation Service of New South Wales, Sydney.

Sorooshian, S., and Gupta, V.K. (1983) Automatic calibration of conceptual rainfall-runoff models: The questions of parameter observability and uniqueness. *Water Resources Research*, 19(1): 251-259.

Sorooshian, S., and Gupta, V.K. (1985) The analysis of structural identifiability: Theory and application to conceptual rainfall-runoff models. *Water Resources Research*, 21(4): 478-495.

Stanton, R. (2001) An Overview of timber plantation development in Australia - Drivers, trends and prospects. In Sadanandan, E.K., and Brown, G., (Eds). *Proceedings of a national workshop on plantations, farm forestry and water, water and salinity issues in agroforestry* No.7 20-21 July, Melbourne.

Stephenson, G.R., and Freeze, R.A. (1974) Mathematical simulation of subsurface flow contributions to snowmelt and runoff: Reynolds Creek Watershed. *Water Resources Research*, 10: 284-294.

Stern, J.J. (1982) Macroeconomic analysis' *In Energy Planning for Developing Countries: A Study of Bangladesh.* Lucia, R.J and Jacoby, H.D (eds). John Hopkins University Press.

Stigter, J.D., and Beck, M.B. (1994) A new approach to the identification of model structure. *Environmetrics*, 5: 315-333.

Stockle, C., Martin, S., and Campbell, S. (1994). CropSyst, a cropping systems simulation model: Water/nitrogen budgets and crop yields. *Agricultural Systems*, 46: 335-359.

Stovall, J.G. (1966). Sources of error in aggregate supply estimates. *Journal of Farm Economics,* 48: 477-480.

Strayer, J.K. (1989) Linear Programming and its applications. Springer Verlag Publishing. New York.

Taylor, K., Walker, G., and Abel, D. (1999) A framework for model integration in spatial decision support systems. *International Journal of geographic Information Science.* 13(6): 533-555 Van den Bergh, J.C.J.M., and Nijkamp, P (1994)

Todini, E. (1988) Rainfall-runoff modelling: Past; present and future. *Journal of Hydrology*, 100: 341-352.

Topp, V., and McClintock, A. (1998) Water Allocations: Efficiency and Equity Issues. *Australian Commodities*, 5(4): 504-510.

UNEP United Nations Environment Program. (1992) Saving Our Planet: Challenges and Hopes. Nairobi. UNEP.pp200

Van den Bergh, J.C.J.M., and Nijkamp, P (1994) Dynamic macro-modelling and materials balance: economic-environmental integration for sustainable development. *Economic Modelling*. 11(3): 283-307

Varis, O., and Kuikka, S., and Taskinen, A. (1994) Modelling for water-quality decisions - Uncertainty and subjectivity in information, in objectives, and in model structure. *Ecological Modelling*, 74(1-2): 91-101

Varis, O. (1997) Bayesian decision analysis for environmental assessment models by a bayesian meta-model: the Baltic salmon case. *Ecological Modelling*, 102(2-3): 341-351

Varis, O., and Lahtela, V. (2002) Integrated water resources management along the Senegal river: Introducing an analytical framework. *International Journal of Water Resources Development,* 18(4): 501-521

Vedula, S., and Kumar, S. (1996) An integrated model for optimal reservoir operation for irrigation of multiple crops. *Water Resources Research*, 32(4): 1101-1108.

Veldkamp. A., and Fresco, L.O. (1996). CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. *Ecological Modelling*, 91: 231-248.

Wagner, R. (1987) Yass Catchment Water Supply Study. A Technical Report for Yass Shire Council, Yass.

Wheater, H.S., Jakeman, A.J., and Beven, K.L. *Progress and directions in rainfall-runoff modelling, in Modelling Change in Environmental Systems*, edited by Jakeman, A.J., Beck, M.B., and McAleer, M.J. Chapter 5. Pp 101-132. John Wiley, New York, 1993.

Williams, J., Jones, C., Kiniry, J., and Spanel, D. (1989) The EPIC crop growth model. *Transactions of the ASAE*. 32(2): 497-511.

Williams, J.R, Jones, C.A and Dyke, P.T. (1987) EPIC, the erosion productivity impact calculator'. U.S Department of Agriculture, Agricultural Research Service, Economics Research Service, and Soil Conservation Service. Temple, Texas.

Wood, E.F., Sivapalan, M., and Beven, K.J. (1990) Similarity and catchment storm response, *Review of Geophysics,* 28(1): 1-18.

Xihua, Y., Amri, S. and McLean, A. (1998) Simulating River Pollution Movement Using GIS Network Analysis. Department of Land and Water Conservation, Wagga.

Yakowitz, S. (1982) Dynamic programming applications to water resources. *Water Resources Research,* 18(4): 673-696.

Yaron, D. (1967) Empirical analysis of the demand for water by Israeli agriculture. *Journal of Farm Economics,* 49:461-473.

Yass Shire Council (1997) State of the Environment Report. Yass Shire Council, Yass.

Yass Shire Council (2000) State of the Environment Report. Yass Shire Council, Yass.

Ye, W., Bates, B.C., Viney, N.R., Sivapalan, M., and Jakeman, A.J. (1997) Performance of conceptual rainfall runoff models in low yielding catchments. *Water Resources Research*, 33: 153-166.

Young, R. (1996) Measuring economic benefits for water investments and policies. World Bank Technical Paper No. 338, Washington. World Bank.

Young, W.J., Booty, W.G., Cuddy, S.M., Farley, T.F., Lam, D.C., and Whigham, P.A. (1998) Ecological and Environmental Flow Regimes Using Decision Support Software. CSIRO Land and Water Report, Canberra.

Young, W.J., Davis, J.R., Bowmer, K.H., and Fairweather, P.G. (1995) The Feasibility of a Decision Support System for Environmental Flows: Final report to the Murray Darling Basin Commission, Consultancy Report No. 95/19. CSIRO Division of Water Resources, Canberra.

Yu, B. (1989) Regional relationships for the runoff routing model (RORB), revisited. *Civil Engineering Transactions: Institute of Engineers of Australia*,CE31(4): 186-191.

Zhang, L., Dawes, W.R., and Walker, G.R. (2001) The response of mean annual evapotranspiration to vegetation changes at the catchment scale. *Water Resources Research*, 37: 701-708.

Zorzetto, A., and Chudleigh, P. (1999) Commercial Prospects for low rainfall agroforestry. RIRDC/LWRRDC/FWPRDC Joint venture agroforestry program. Technical Report No 99/152. Rural Industries Research and Development Corporation. Canberra.