Modelling Groundwater-River Interactions for Assessing Water Allocation Options

Karen Marie-Jeanne Ivković

September 2006

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 previously been submitted for a degree or diploma in any institution of higher education.

Karen Ivković

September 2006

Acknowledgments

"They do not step into the same rivers. It is other, and still other waters that are flowing" - *Heraclitus*

It is said that the journey of a thousand miles begins with a single step. For me the first step was walking to the printer at my workplace and seeing information on scholarships (printed by somebody else) interspersed within my own documents. From that point onwards the possibilities of undertaking PhD studies grew in my mind and were further nurtured by my husband Damir, who has been unfailingly supportive throughout my PhD journey. Damir and my father, Douglas, both proofread and commented upon penultimate thesis drafts. I'd also like to thank my mother, Monique, family and friends for their encouragement over the years.

I am grateful to my supervisors Professor Tony Jakeman, Dr Rebecca Letcher, Dr Barry Croke and Dr Mirko Stauffacher for their guidance. I'd especially like to thank Rebecca Letcher for her direction in conceptualising the thesis story so that it had a highly relevant, original and interesting plot, for her assistance with the programming and usage of ICMS, for her consistently clear and strategic advice, and for her enthusiasm. I am particularly grateful to Barry Croke for having shared his insights into model conceptualisation processes and for assisting me with the use and application of numerous in-house models. Barry gave generously of his time in teaching me to program (and debug!) Fortran code. Ray Evans was one of my key advisors, and although he was not a supervisor, he gave as much guidance as if he had been a supervisor. I'd like to acknowledge the encouragement he provided.

I'm grateful to have shared the PhD journey with a number of other PhD students including Patty Please, Kate Brooks, Prachi Dixon-Jain, Celina Smith, Amir Sadoddin and John Drewry. I am thankful for their moral support, assistance and friendship.

Thanks to Dr Colin Chartres and Audrey Lambert (Kate's Mum) for showing an interest in my research, and for having read and provided editorial comments on selected parts of the thesis. I'd also like to thank Dr Elke Stracke, who was particularly inspiring through her belief in "extra-ordinary" works!

I'd also like to acknowledge the stimulating learning environment of CRES and iCAM, as well as the great students and staff with whom I feel honoured to have studied. The inspiration to describe an aboriginal viewpoint of connected water resources came from a seminar given by Dr Deborah Bird Rose. I'd like to thank staff members Susan Cuddy, Adele Doust, Phil Greaves, Steve Leahy and Karl Nissen for their administrative and IT support, and particularly Susan Kelo of iCAM who provided heartfelt assistance in every way she could. A big thanks to Virginia Woodland from the Graduate Information Literacy Program for her help in formatting with MS Word. I'd like to thank Felix Andrews and Michael Kehoe for their assistance with model calibration, including more efficient ways to go about this task, and for allowing me the usage of some of their programs.

The progression of work presented in this thesis would not have been possible without the assistance of a large number of other professionals including:

Dr Noel Merrick from the University of Technology in Sydney who generously provided me with copies of his Namoi River catchment model reports and commented on my summaries of previous groundwater models developed for use in the catchment.

Mike Williams, George Gates, Peter Sinclair, Alex Springall, Angela McCormack, Andrew Cutler, Anthony Newland, Lee Vitry, Robert Braaten, Catherine Barret, Craig McNeilage, David Outhet, Dawit Berhane, Gary Hampton, Gary Coady, Guy Lampert, Amalia Short, Ken Gillespie, Krish Illungkoo, Mark Mitchell, Peta Hansen, Richard Myers, Ross Beasley, Sriyani Manchanayake, Sue Powell and Tikiri Tennakoon from the New South Wales Department of Natural Resources provided me with access to their data and background reports/materials. I'd especially like to thank Guy Lampert and Amalia Short for taking the time to accompany me into the field, show me some key river geomorphologic features and provide me with critical feedback on my aquifer-river interactions mapping assessment.

Going full-circle to the start of my PhD journey, I'd like to thank: my scholarship providers the Australian National University, the Cotton Research and Development Corporation and CSIRO Land & Water who provided financial support; as well as Dr Peter O'Brien, previously at the Bureau of Rural Sciences, who granted me leave to undertake this research.

The staff and irrigators associated with the Cotton Research and Development Corporation (CRDC) have shown a great deal of enthusiasm and interest in my research without ever having attempted to influence my research directions or findings. Furthermore, the CRDC provided me with some highly relevant educational experiences in science communication, writing in plain English, public speaking, tours to cotton farms and gins and allowed me insights into the cotton industry. CSIRO Land & Water has also remained an enthusiastic supporter of my research, and the generosity of their stipend allowed me to present my research methods at an International Association of Hydrogeologists workshop in Spain and to CEMAGREF in France. I am very grateful to the scholarship providers who made my PhD experience possible.

Abstract

The interconnections between groundwater and river systems remain poorly understood in many catchments throughout the world, and yet they are fundamental to effectively managing water resources. Groundwater extraction from aquifers that are connected to river systems will reduce river flows, and this has implications for riverine ecosystem health, water security, aesthetic and cultural values, as well as water allocation and water management policies more generally. The decline in river flows as a consequence of groundwater extractions has the potential to threaten river basin industries and communities reliant on water resources.

In this thesis the connectivity between groundwater and river systems and the impact that groundwater extractions have on river flows were studied in one of Australia's most developed irrigation areas, the Namoi River catchment in New South Wales.

Gauged river reaches in the Namoi River catchment were characterised according to three levels of information: 1) presence of hydraulic connection between aquifer-river systems; 2) dominant direction of aquifer-river flux; and 3) the potential for groundwater extraction to impact on river flows. The methods used to characterise the river reaches included the following analyses: 1) a comparison of groundwater and river channel base elevations using a GIS/Database; 2) stream hydrographs and the application of a baseflow separation filter; 3) flow duration curves and the percentage of time a river flows; 4) vertical aquifer connectivity from nested piezometer sites; and 5) paired stream and groundwater hydrographs.

The theoretical responses for gaining, losing and variably gaining-losing river reaches were conceptualised along with the processes that operate in these systems. Subsequently, a map was prepared for the Namoi River catchment river reaches indicating aquifer-river connectivity and dominant direction of flux. Large areas of the Upper Namoi River catchment were found to have connected aquifer-river systems, with groundwater extraction bores located in close proximity to the rivers. Accordingly, the potential for groundwater extraction to impact on river flows in these areas was considered significant. The Lower Namoi was assessed as having mostly disconnected aquifer-river systems.

In order to investigate the impacts of groundwater extraction on river flows in connected aquifer-river systems, a simple integrated aquifer-river model entitled IHACRES_GW was developed for use at the catchment scale. The IHACRES_GW model includes a dynamic, spatially-lumped rainfall-runoff model, IHACRES, combined with a simple groundwater bucket model that maintains a continuous water balance account of groundwater storage volumes for the upstream catchment area relative to the base of the stream, assumed to be the stream gauging station. The IHACRES_GW model was developed primarily: 1) to improve upon existing water allocation models by incorporating aquifer-river interactions; 2) to quantify the impacts of groundwater extraction on river flows within unregulated, connected aquifer-river systems; 3) to inform water policy on groundwater extraction; and 4) to be able to utilise the model in future integrated assessment of water allocations options at the catchment scale.

The IHACRES_GW model was applied within the Cox's Creek subcatchment in order to test its validity. The model was used to simulate a range of extraction scenarios which enabled the impacts of groundwater extractions on river flows to be assessed. In particular, the historical impacts of groundwater extraction on the timing, magnitude and frequency of baseflow events were quantified over a 15-year (1988-2003) simulation period. The IHACRES_GW model was also used to evaluate the implications of water sharing plans for the Cox's Creek subcatchment.

A spatially-lumped modelling approach in the management of water resources has a number of limitations, including those arising from the lack of spatial considerations. However, it offers a number of advantages including facilitating a better understanding of large-scale water management issues, assessing the impacts of water allocation and groundwater extraction on river flows at the catchment scale, and informing water sharing plans. In particular, this type of modelling approach lends itself to integrated assessments of water allocation options in which hydrological, ecological and socio-economic data sets are combined, and where data is commonly aggregated to a larger scale of interest in response to the requirements of policy makers. The research findings from this thesis provide some insights into how to better manage the impacts of groundwater extraction in connected aquifer-river systems.

Table of Contents

List of Figures

List of Tables

Chapter 1 Research Context

1.1 Motivation

This thesis focuses on the subject of groundwater and surface water connectivity. Groundwater and surface water systems are often managed as if each were an isolated component of the hydrological cycle, and yet these systems interact in a range of geological, topographical and climatic settings (Sophocleous, 2002; Winter, 1999). Many surface water features, such as rivers, lakes, dams and wetlands, will have varying degrees of connection with groundwater systems (Winter, 1999). Accordingly, water can move as a continuum between surface and groundwater systems and the use and/or quality of one resource can impact upon the other.

In contrast to the current paradigm of managing groundwater and surface water resources in isolation, the ancient Australian Aboriginal creation stories describe the intimate connection that exists between rain, river water and groundwater, with the rainbow serpent dwelling within each phase of the hydrological cycle providing the conduit for connectivity and regeneration (Figure 1-1, Painting by Nina Humbert Namanuk, "*Owlet Nightjar Dreaming*", main waterhole in the Wickham River at Victoria River Downs Station, courtesy of Deborah Rose).

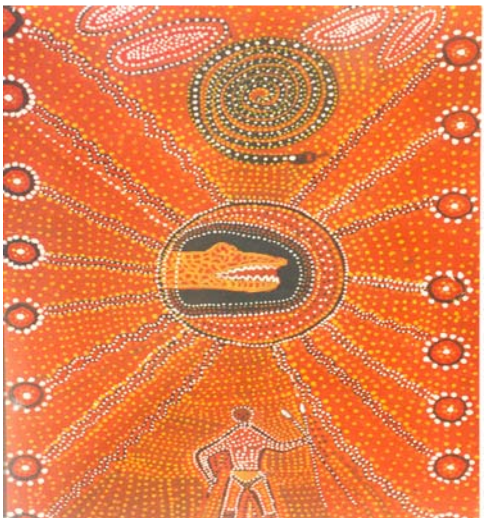


Figure 1-1 Painting by Nina Humbert Namanuk, "*Owlet Nightjar Dreaming*"

The earliest scientific researchers of hydrology also acknowledged the linkages between surface water and groundwater systems, with surface water hydrologists having long understood that part of the streamflow hydrograph was attributable to groundwater discharge (Boussinesq, 1877; Coutagne, 1948; Horton, 1933; Maillet, 1905) and referring to this discharge as baseflow. Hydrogeologists, or subsurface hydrologists, have also understood that groundwater commonly discharged to rivers and that those rivers also recharged aquifers. They knew that groundwater withdrawals could capture surface water flows and they derived analytical equations in order to calculate the impact of groundwater extraction on river flows (Boulton, 1942; Glover and Balmer, 1954; Jenkins, 1968; Theis, 1941). In spite of the awareness of groundwater-surface water connectivity within the broader hydrological community, the use of distinct research disciplines and methods, differing spatio-temporal scales and research objectives, and divisions within institutional jurisdictions have resulted in groundwater and surface water being managed separately.

The adverse consequences of managing these resources separately are becoming increasingly apparent as the evidence of the impacts of groundwater extraction schemes on declining river flows is documented (Chen *et al.*, 2003; Glennon, 2002; Smakhtin, 2001; Sophocleous, 2000; Sophocleous and Perkins, 2000). Groundwater extraction from aquifers that are connected with river systems will impact upon riverine hydrology by reducing river flows. It has been estimated that between 10% and 90% of the volumes of groundwater extracted within the Murray Darling Basin in southeastern Australia are sourced from water that would have otherwise discharged to a river (SKM, 2002). Altered river hydrology has implications for riverine ecosystem health, water security, aesthetic and cultural values, as well as water allocation and water management policies more generally. The decline in river flows as a consequence of groundwater extractions has the potential to threaten river basin industries and communities. These risks will become greater as the pressures on river and groundwater resources continue to grow as a result of drier than average climatic patterns and increased economic development within river basins.

In response to concerns about the degraded state of many Australian river systems, the Australian government launched a series of water reforms in 1994, culminating in the National Water Initiative (NWI) in 2004 (NWI, 2004). The NWI is broadly consistent with the concept of the European Water Framework Directive (European Communities,

2000) and other international regulatory frameworks directed to reforming water use and management (Letcher and Giupponi, 2005). It has the aims of increasing the productivity and efficiency of water use, whilst ensuring the health of river and groundwater systems. One of the key objectives of the NWI is to achieve 'recognition of the connectivity between surface and groundwater resources and for connected systems to be managed as a single resource' (NWI, 2004). Another key objective is for water allocation in catchments to be managed through integrated catchment management approaches that consider social and economic factors along with biophysical factors. The water reform objectives present a significant challenge to catchment managers.

The implementation of water reforms in Australia has particularly affected the more developed irrigation regions, such as the Namoi River catchment, which is situated within the Murray-Darling Basin in the state of New South Wales (NSW) (see Chapter 3 for catchment setting). The water reforms have resulted in decreased water entitlements for water users in the catchment in order to promote resource security and sustainability. However, a catchment-scale understanding of the interactions between groundwater and river systems remains incomplete. Consequently, the projected outcomes of reduced water allocations remain unclear and contentious. This thesis will explore these issues within the Namoi River catchment. The scope, research questions and aims are discussed below.

1.2 Scope, Research Questions and Aims

The Namoi River catchment was selected as a case study area for this thesis on groundwater-river connectivity for several reasons. Firstly, the Namoi River catchment is one of the most stressed and over-allocated groundwater irrigation regions in Australia (DLWC, 2002). Secondly, a recent scoping study (Braaten and Gates, 2003) indicated that significant regions of NSW, including the Namoi River catchment, have connected groundwater and surface water resources. This finding is consistent with that of a recent consultancy report by SKM (2003) that identified a number of subcatchments within the Namoi River catchment as priority areas for detailed studies on groundwater-river interaction. And thirdly, research in the Namoi River catchment would also add value to an existing regional economic-hydrological model developed for the whole of the Namoi River catchment to better understand the socio-economic trade-offs associated with water allocation and the water sharing plans (Letcher, 2002; Letcher *et al.*, 2004) as part of an integrated catchment management approach to reforming water use and management. One of the areas of input required to improve this hydro-economic model is the inclusion of groundwater-river interaction processes. In particular, the impact of groundwater extraction on river flows presents a risk to sustainable water allocation, which will be explored in this thesis.

Some of the key research questions being asked in the context of this research are:

- How do the interactions between groundwater and river systems change spatially and temporally along river reaches within the Namoi River catchment?
- How can existing water allocation models be improved through this knowledge?
- Are river flows reduced by groundwater extraction and, if so, can the impacts be quantified within the Namoi River catchment?
- How can a greater understanding of aquifer-river connectivity inform policy development, such as water sharing plans, within the Namoi River catchment?

Because of the complexities involved in a comprehensive basin-scale study, the current research has been limited to characterising the interactions between the Cainozoic alluvial aquifers interacting with gauged river systems, and will consider volumetric water allocation issues only (i.e., not water quality or salt mobilisation). The research will be based on available, pre-existing data.

The specific research aims of this thesis are:

1. To develop a broad-scale understanding of the spatio-temporal interactions occurring between aquifer-river systems in the Namoi River catchment, NSW;
2. To improve upon existing water allocation models through the development of a parsimonious, integrated aquifer-river model that is appropriate for considering the interactions between groundwater and river systems at the basin-scale; and
3. To inform water management and policy development.

1.3 Thesis Outline

This thesis has eight chapters which are outlined as follows:

Chapter 1: Research Context

This provides an introduction to the motivation for the thesis research topic, outlines the reasons for the selection of the Namoi River catchment case study area, and specifies the scope and aims of the thesis. An outline of the thesis structure is included.

Chapter 2: Groundwater-River Interactions: Principles

The basic physical principles that govern groundwater-river water interactions are described. The terms used to categorise the types of groundwater-river interactions that occur, and the processes which arise as a consequence of groundwater extraction, are introduced to the reader. The terms and concepts outlined in this chapter set the foundation for discussions in later chapters.

Chapter 3: The Namoi River Catchment

A synthesis of the physical attributes of the Namoi River catchment is provided together with an overview of water resource use and management, including the background history and implementation of water reforms. The response to the national water reform agenda by the State Government of NSW is described, as are some of the challenges to implementing water reforms.

Chapter 4: Characterisation of Namoi River Reaches

The methods commonly used to assess groundwater-river interactions are outlined, a system of classification to categorise groundwater-river interactions is provided, and a framework is developed and applied to characterise the interactions observed in the Namoi River catchment, NSW.

Chapter 5: Model Conceptualisation and Development

The modelling approaches commonly used in hydrological (surface and subsurface) studies are discussed. A summary of the groundwater models previously implemented in the Namoi River catchment is provided in order to demonstrate the need for a new type of groundwater model. The rationale for the development of a parsimonious, conceptual style of model for use in quantifying the impacts of groundwater extraction on river flows at the catchment scale is outlined. The streamflow characteristics that the model development has been intended to capture are listed. The derivation of the IHACRES_GW model, based on the IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data) model, is fully described and a sensitivity analysis is provided.

Chapter 6: Model Application

The IHACRES_GW model is applied within the Cox's Creek subcatchment in order to test the validity of the model derived in Chapter 5, and to demonstrate if, or how, a simple, conceptual model can be used to simulate the impact of groundwater extraction and other aquifer losses on river flows. A discussion of the model calibration, validation and performance criteria is provided and the overall model performance is assessed together with discussion of potential improvements to the model.

Chapter 7: Extraction Impacts and Water Policy

The IHACRES_GW model is used as a tool to investigate the impacts of groundwater extraction on river flows in the Cox's Creek subcatchment and to consider water management policies developed as part of the National Water Initiative water reforms. The research findings from this thesis are used to provide insights into how groundwater extraction impacts upon river flows, and some logical steps are suggested to assist with better managing the impacts of groundwater extraction in connected aquifer-river systems.

Chapter 8: Conclusions

The conclusions reached in this thesis, together with a summary of suggested further research, are presented in this final chapter.

Chapter 2 Groundwater-River Interactions: Principles

2.1 Introduction

The interconnections between groundwater and river systems remain poorly understood in many catchments throughout the world, and yet are fundamental to effectively managing water resources. In order to comprehend the full importance of groundwater-river interactions on water resource sustainability, knowledge of the basic principles and relationships guiding groundwater and river water interactions is required. This chapter provides an overview of the basic physical principles that govern groundwater-river water interactions. The terms used to categorise the types of groundwater-river interactions observed and the processes that arise as a consequence of groundwater extraction will be introduced, and the terms and concepts outlined in this chapter will underpin discussions in later chapters. It is assumed that basic terms and principles for groundwater systems are understood, for example *confined* and *unconfined aquifer systems, hydraulic head, transmissivity and storativity*. These terms are defined in a number of basic groundwater texts such as Heath (1987) should the reader wish to consult additional references.

2.2 Types of Interactions

Comprehensive reviews of the physical interactions that occur between groundwater and surface water systems have been provided by Sophocleous (2002), Winter *et al.* (1998), Winter (1999) and Woessner (2000). Reviews with an emphasis on the ecological significance of groundwater-surface water interactions are given by Boulton *et al.* (1998) and Brunke and Gonser (1997). In this section an overview of basic physical principles describing groundwater-river interactions is presented.

Rivers generally interact with groundwater in three basic ways (Winter *et al.,* 1998): 1) rivers gain water from inflow of groundwater through the river bed (gaining river; Figure 2-1); 2) they lose water to groundwater by outflow through the river bed (losing river; Figure 2-2); or 3) they do both, gaining in some reaches and losing in other reaches, or both gain and lose in the same river reach at different times (variably gaining-losing river reach; Figure 2-4) .

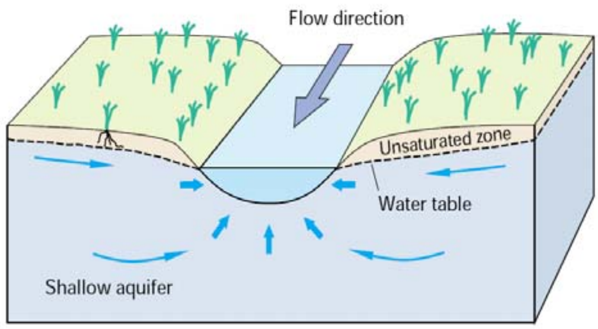


Figure 2-1 Connected gaining river reach (after Winter *et al.*, 1998)

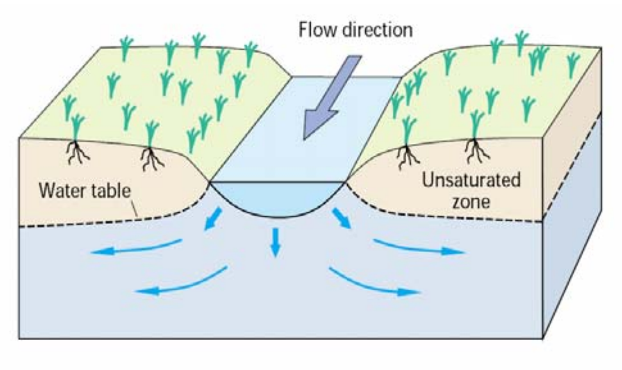


Figure 2-2 Connected losing river reach (after Winter *et al.*, 1998)

In order for groundwater to discharge to a river, the elevation of the groundwater surface adjacent to the river must be higher than the elevation of the river stage. Conversely, for river water to flow to groundwater, the elevation of the groundwater surface adjacent to the river must be lower than the elevation of the river stage. The direction of water flow between an aquifer and river system depends on the relative differences between the groundwater and river stage elevations. In both cases, there must be permeable material that will allow the movement of water between groundwater and river systems.

Losing streams can be connected to the groundwater system by a continuous saturated zone or, alternatively, they can be disconnected from the groundwater system by an unsaturated zone, as shown in Figure 2-3. In a disconnected system river water will drain under gravity, and the flux of water between the two systems will not be a direct function of the elevation of the groundwater; although unsaturated zone storage of water may play a role in maintaining some degree of connectivity (Bouwer and Maddock, 1997).

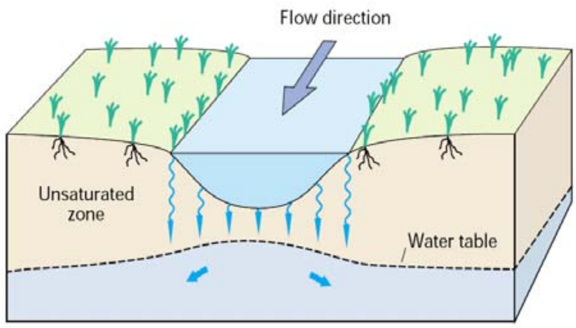


Figure 2-3 Disconnected losing river reach (after Winter *et al.*, 1998)

Bank storage (Figure 2-4) is a particular type of interaction that occurs when a rapid rise in river stage causes water to move from the river into the streambank (Winter *et al.*, 1998). This process is usually associated with intense rainfall events, rapid snowmelt, or a release of water from a dam. Most of the water in the streambank returns to the river within a few days or weeks. However, if the rise in stream stage is associated with a large flood event that tops the river bank, flooding a large land surface area, then the slow return of water through the subsurface may take longer, and occur over weeks, months or years if the flow paths are sufficiently long and/or slow.

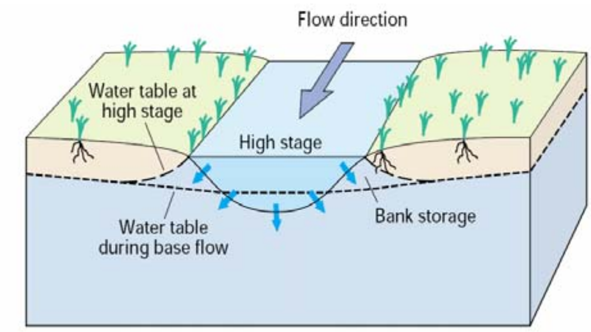


Figure 2-4 Connected variably gaining-losing reach (after Winter *et al.*, 1998)

The most important factor influencing the flux of water between a river and aquifer systems is the degree of connection between the river and the aquifer. The degree of connection will depend on the properties of the material comprising the river bed and its bank, the existence of aquitard or unsaturated aquifer material between the river and the aquifer, and the extent to which the channel of the river intersects the saturated part of the aquifer (Kirk and Herbert, 2002). The direction of the exchange varies with hydraulic head, whilst the quantity of flow (volume per unit time) depends on the sediment hydraulic conductivity.

Groundwater-river interactions occur on a variety of scales including the larger fluvial plain/river reach scale through to the channel bed scale (Woessner, 2000). Small-scale variability in groundwater and river exchanges in the bed of a channel, or hyporheic zone, can occur within larger reaches characterised as gaining or losing and the hinge line between a gaining and losing reach may rapidly change in response to a change in recharge-discharge dynamics.

The interactions between groundwater and river water systems are dynamic, changing temporally and spatially in response to both natural and anthropogenic factors. Natural climate variability, including seasonal variability, will influence the volumes of precipitation that are available within a catchment, including the volumes available for surface runoff and groundwater recharge processes. Anthropogenic factors, such as stream regulation, land use, the application of irrigation water and groundwater extraction, will also influence groundwater-river stage relationships by altering the hydraulic gradients between groundwater and surface water systems. The geology and geomorphology of the catchment influence where, and how quickly, water moves within the catchment.

For this thesis the impacts of groundwater extraction on river flows are of particular interest, and are discussed below.

2.3 Impacts of Groundwater Extraction on Rivers in Connected Systems

The effective management of water resources where exploited aquifers are in hydraulic connection with river systems requires an understanding of the response of hydrological systems to groundwater extraction.

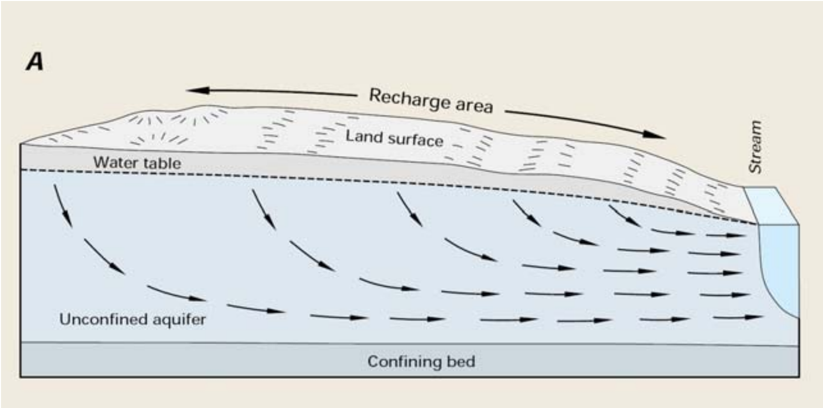
Under natural conditions, such as prior to groundwater development for irrigation or other purposes, a groundwater system is in a state of dynamic equilibrium, and the recharge into a groundwater system equals the discharge out of the system (Heath, 1987; Sophocleous, 2002; Winter *et al.*, 1998) (Figure 2-5A).

With the introduction of an extraction bore and the onset of pumping, a loss of water to aquifer storage occurs and a new state of dynamic equilibrium is approached. This state is accomplished either by a decrease in natural groundwater discharge, an increase in groundwater recharge, or a combination of the two (Sophocleous, 2002). The terms commonly used to describe the response of an aquifer system to a new state of equilibrium are 'captured discharge' and 'induced recharge'. These terms are described in more detail below.

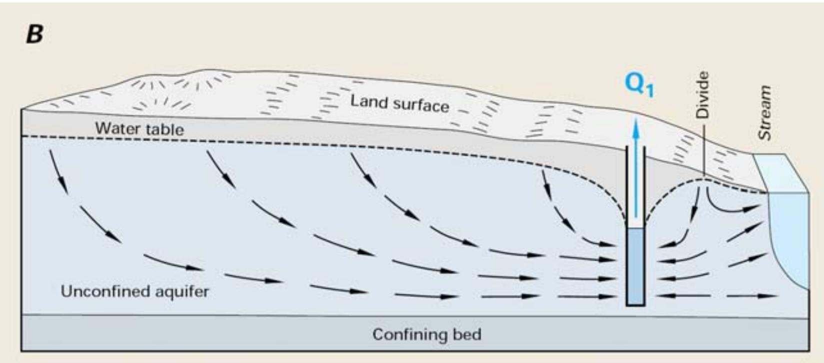
2.3.1 Captured Discharge and Induced Recharge

In an example of an aquifer system located within a connected shallow aquifer-river system, the volume of water that recharges the aquifer will, under natural conditions, equal the volume of groundwater that discharges to the river (Figure 2-5A). Groundwater extraction will reduce the volumes of groundwater stored within the aquifer, and a cone of depression will form as a consequence of pumping. The volume of water that is removed from groundwater storage through pumping will no longer be available as a baseflow discharge to the river because this volume of water has been intercepted by groundwater pumping (Figure 2-5B). The term applied in this case is "*captured discharge*".

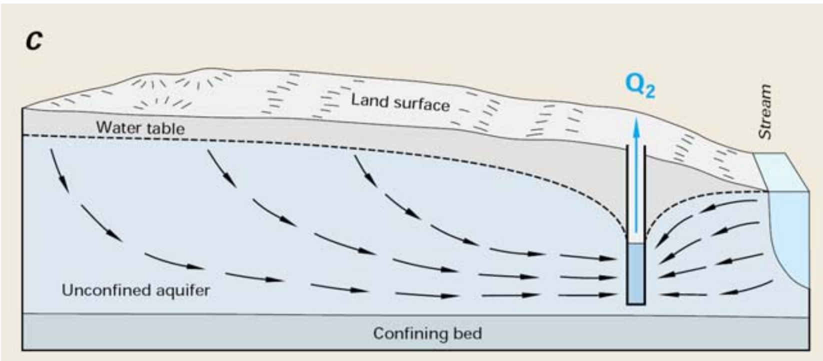
If an extraction bore is located adjacent to a river, or if it is pumped over a long time or at sufficiently high pumping rates, the cone of depression will expand towards the river and induce the movement of river water and other forms of previously rejected recharge into the aquifer. The term applied in the case where groundwater pumping causes more water to flow into the aquifer is "*induced recharge*" (Figure 2-5C). This situation can result in reversing the groundwater-river gradient such that a groundwater discharge site, where the river was once gaining, is changed into a groundwater recharge site, where the river loses water to the underlying aquifer and replenishes aquifer storage during pumping.



In a natural system recharge to the aquifer is equal to the discharge from the aquifer



The introduction of an extraction bore results in reduced groundwater storage and reduced discharge (baseflow) to the river (referred to as "captured discharge")



Groundwater extraction close to a river or over long periods of time may induce river water to flow into the aquifer (referred to as "induced recharge")

Figure 2-5 Impact of groundwater extraction on river water in a connected system (after Winter *et al.*, 1998)

The processes of captured discharge and induced recharge result in decreased volumes of baseflow and surface runoff in a connected aquifer-river system. The examples provided above illustrate the importance of considering the interactions between groundwater and river systems, and highlight the need to manage water resources in connected systems as a common, single resource. Another problem arising as a consequence of not considering connected water resources as a single resource is one of double accounting.

2.3.2 Double Accounting

Groundwater and river water exchanges commonly occur in hydraulically connected systems, as discussed above. As a consequence, double accounting of water resources may arise when connected aquifer-river systems are not managed as a single resource. An example of a situation where double accounting occurs is when groundwater extraction volumes are allocated according to the long-term average annual recharge to the aquifer, or allocated without limit. Yet the discussions above have highlighted the fact that groundwater extraction results in reduced river flows. Thus, if in the same catchment groundwater allocations have not considered the impacts on river flows, then a portion of the river water will inadvertently have been allocated to both the river and groundwater systems, and this situation results in double accounting of water volumes. Double accounting results in the over-allocation of water, erodes water security and compounds the impacts already arising from groundwater extraction on river systems, particularly in highly-stressed catchment systems.

2.3.3 Time Lags

A question commonly asked by water managers is in regard to the time lag between the onset of groundwater pumping and the impact upon a connected river system. The subject of time lags is introduced here, and will also be discussed in later chapters (5 to 7). The length of time it takes for groundwater pumping to impact on river flows in a hydraulically connected groundwater-river system as a result of induced recharge and captured discharge is complex. A wide range of possible time lags have been reported ranging from nearly instantaneously to hundreds of years, depending on the specific characteristics of the river catchment and aquifer systems. The most commonly reported factors that influence the time lag include: the degree of connection between the aquifer and river system; the rate of groundwater extraction relative to the natural recharge and discharge rates; the type of aquifer (confined, semi-confined or unconfined); the width of the river valley; aquifer and stream properties; aquifer diffusivity (expressed as the ratio of aquifer transmissivity to storativity, which expresses how fast a transient change in hydraulic head is propagated through the aquifer); and the distance of extraction bore from the river (Braaten and Gates, 2004; Kirk and Herbert, 2002). These specific characteristics must be considered for each catchment on a case-by-case basis, as time lags can vary considerably from catchment to catchment and over difference climatic periods.

2.4 Chapter Summary

The basic principles that govern groundwater-river water interactions have been outlined in this chapter in order to lay the foundation for discussions in later chapters. These principles have highlighted the importance of developing a greater understanding of the spatial and temporal interactions taking place between groundwater and surface water systems. The importance of managing connected systems as a single resource has been emphasised in order to better assure the sustainable management of water resources. The impacts of captured discharge, induced recharge and double accounting arising as a consequence of groundwater extractions and the associated decreases in baseflow discharge and surface runoff can have significant implications for riverine hydrology, ecology, and water security, and they may create friction between different water users that are competing for a limited resource. The Namoi River catchment was selected as a case study area for this thesis in order to explore some of these issues. An overview of the Namoi River catchment, including information on the water reform agenda and key water management issues, follows in Chapter 3. Characterisation of the types of groundwater-river interactions observed within the Namoi River catchment river reaches, and the methods used to determine interactions, is presented in Chapter 4.

Chapter 3 The Namoi River Catchment

3.1 Introduction

The Namoi River catchment was selected as a case study area in the thesis for further investigations into groundwater-river interactions. This chapter describes the catchment's physical attributes and provides background information on water usage, water management and the water reform agenda. The implementation of water reforms poses many difficulties for catchment managers, particularly in highly developed catchments, such as the Namoi, that are reliant on surface and groundwater irrigation. This chapter sets the context for the groundwater-river interaction studies and policy analysis undertaken.

3.2 Catchment Setting

The Namoi River catchment is arguably one of Australia's most developed irrigation areas where both surface and groundwater resources are heavily utilised for agricultural purposes. The catchment covers an area of approximately 42 000 km^2, located in the central-north of the State of NSW (Figure 3-1), and is situated within the larger Murray Darling Basin River system.

The Namoi River stretches over 350 km, flowing from the Great Dividing Range in the east to the Barwon River in the west. The major tributaries of the Namoi River drain from the upper reaches of the catchment, and include the Mooki River, Cox's Creek, Peel River, Manilla River and the Macdonald River, all of which join the Namoi upstream of Boggabri (DPMS 1996). The Namoi is a regulated river with three main surface water storages: Keepit Dam (42 000 ML) on the Namoi River above the junction with the Peel River; Chaffey Dam (62 000 ML) on the Peel River; and Split Rock Dam (397 000 ML) on the Manilla River. Farmers have also built around 140 000 ML of off-river storages as on-farm dams that are used for storing water pumped from natural inflows as off-allocation water, or water diverted during high flow periods and stored in dams for later use. The main uses of water in the region are irrigation, stock watering and domestic use (EPA, 1995).

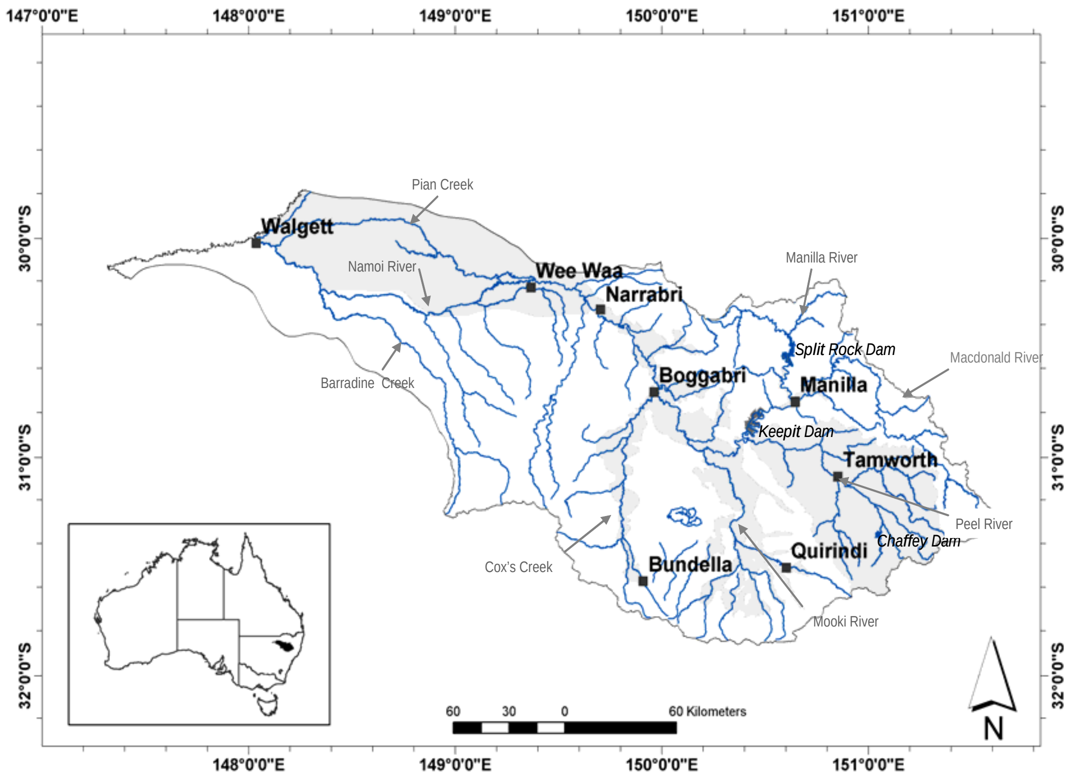


Figure 3-1 Location of Namoi River catchment, NSW Australia

The major population town centres include Tamworth, Gunnedah, Narrabri and Walgett. The 1996 census recorded the population of the Namoi River catchment as 93 965, which is mostly concentrated along the river and its major tributaries between Tamworth and Narrabri. The local Indigenous population (the Kamilaroi People) numbers about 4 500 (1996 census), although local knowledge suggests the figure is closer to 6 500 (DPMS, 1996).

3.2.1 Climate

The catchment has a slightly summer-dominated rainfall pattern, with an average annual rainfall of around 1100 mm at the top of the catchment in the Dividing Ranges through to 470 mm at Walgett in the west. Rainfall is extremely variable between years and seasons. Rainfall events are often short and of high intensity. Potential evaporation ranges from 1000 mm in the east through to 1750 mm in the west. Temperatures vary with elevation and show a large diurnal variation. The monthly maximum temperature is highest between November and March (up to 48ºC) and lowest during June, July and August (- 3.8ºC) (DPMS, 1996).

3.2.2 Landuse

The catchment has been used extensively for agricultural activities since the 1830's. There has been a mixture of sheep and cattle farming, as well as grain crops since the 1960's, with a gradually larger reliance on cattle (EPA 1994). In the 1960's, Keepit Dam was completed and cotton was introduced into the Narrabri/Wee Waa districts, producing 30 000 to 40 000 ha of irrigated cotton per year (EPA 1994).

A general map of landuse within the catchment is shown in Figure 3-2. The main agricultural activities today include irrigated cotton and broad acre cropping (mainly sorghum, sunflower and wheat). These occur predominantly along the alluvial floodplains of the Namoi River valley south of Boggabri, in the lower Cox's Creek subcatchment, and to the northwest of Boggabri through to Narrabri, Wee Waa and Walgett. Sheep and cattle grazing occur throughout the catchment, but are more widespread in the upper catchment area (EPA 1995).

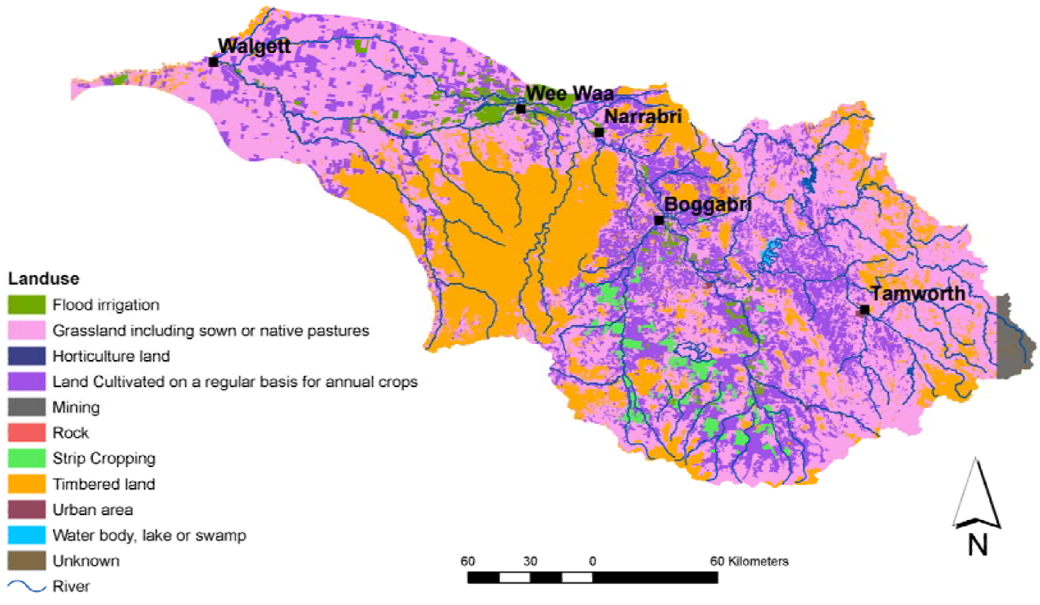


Figure 3-2 Landuse in the Namoi River catchment (data from DNR GIS database)

According to the Namoi River Catchment Management Authority (Namoi CMA, 2005), the agricultural production of the Namoi River catchment in 1996 was worth in excess of $800 million annually and accounted for 11% of the State's on-farm production from only 6.25% of the State's area. This amount included 15% of the State's cotton production. Irrigated cotton produces $230 million per annum; grazing enterprises contribute $250 million per annum; dryland agriculture $100 million per annum and other forms of agriculture over $150 million per annum (DPMS, 1996). The two largest employment sectors are agriculture and retail trade. The major growth areas are health and community services, manufacturing and education. Given the large income generated within the catchment from irrigated agriculture, reduced water allocations will have significant impacts on irrigators, towns and businesses within the catchment. Water allocations are migrating to the highest value commodities, such as cotton, in order to cover the high market costs of water.

3.2.3 Geology

The geology of the Namoi River catchment is both complex and diverse, with rocks ranging in age from Devonian through to Cainozoic. There is a vast body of literature on the geology of the region, and readers interested in detailed geological descriptions and historical overviews can find excellent syntheses in Gates (1980) and Lavitt (1999). A map of the simplified geology (Kingham, 1998) is shown in Figure 3-3.

The Namoi River catchment is divided east-west by the Hunter-Mooki Thrust, which is part of the New England Fold Belt. The thrust system separates the folded Upper Carboniferous to Lower Permian rocks (shown in purple colours in the east; Figure 3-3) in the New England Fold Belt from the Permian and Triassic strata of the Gunnedah Basin, which are largely covered by Cainozoic alluvium (shown in orange colours; Figure 3-3). The thrust runs in a north-north-westerly direction from the Great Dividing Range in the east of the catchment to the north. To the east of the fault zones that make up the Hunter-Mooki Thrust, the drainage systems are entrenched and relatively little alluvium is found in the valley floors. Granite outcrops throughout the Macdonald River catchment, whilst the Peel and Manilla river catchments are comprised mainly of Palaeozoic metasediments.

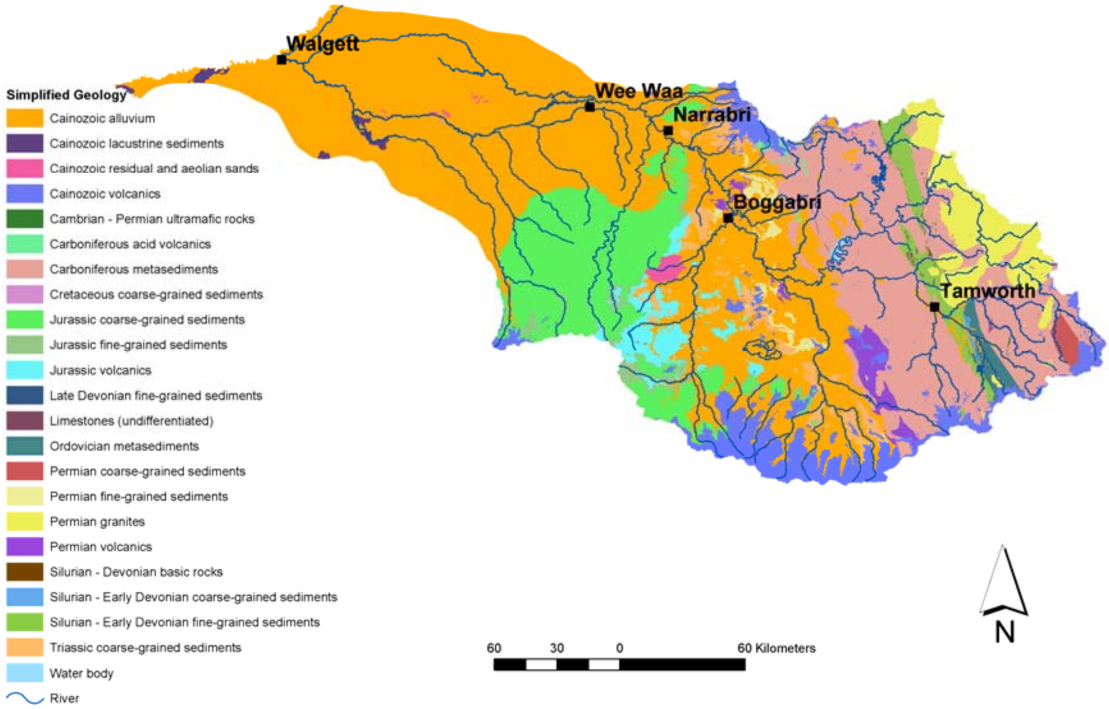


Figure 3-3 Simplified geology of the Namoi River catchment (after Kingham, 1998)

Basalts form the catchment boundary in the southern margins, with most recent volcanic activity having occurred in the Tertiary period. These basalt ranges have been deeply weathered and now make up the fertile floodplains that are used extensively for cropping within the Cox's Creek and Mooki River catchments that comprise the Liverpool Plains region (DPMS, 1996).

To the west of the Hunter-Mooki Thrust, fractured sedimentary deposits including sandstone, shale and conglomerate extend from the base of the Liverpool Ranges in the south towards the north into the adjacent Gwydir catchment. The alluviums to the west of the thrust generally consist of weathered basalts and granites, as well as widely dispersed clay, silt and gravel beds that were deposited with existing river systems and prior streams and palaeochannels. The alluvium is highly variable both locally and regionally across the catchment.

3.2.4 Soils and Physiographic Zones

The distribution of soils in the Namoi River catchment is a function of geology, topography and climate. The broad soil types are shown in Figure 3-4 (GIS data from the NSW Department of Natural Resources (DNR) Database).

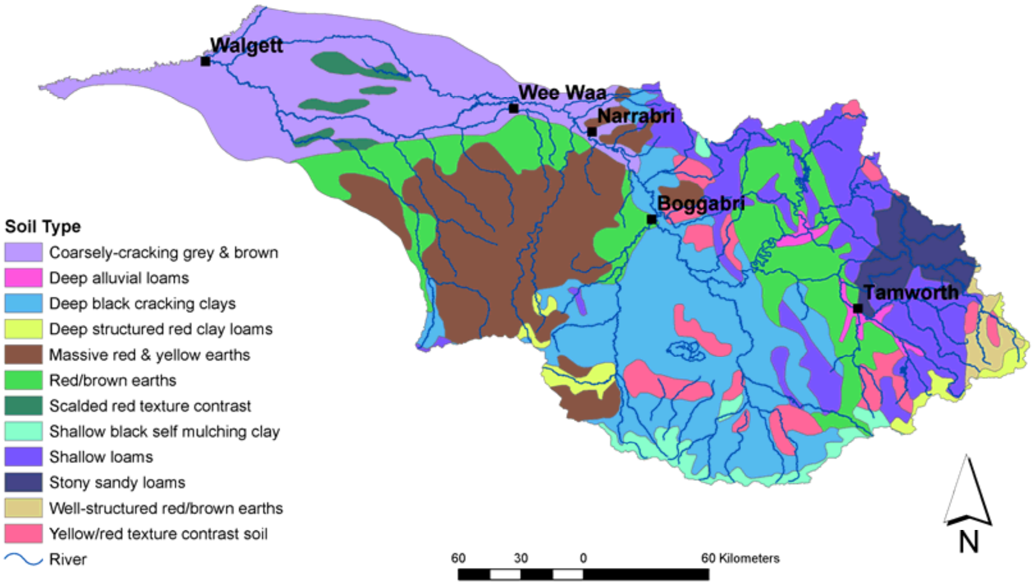


Figure 3-4 Soil types in the Namoi River catchment (data from DNR GIS database)

The Namoi basin can be divided into four natural physiographic subdivisions (EPA, 1994):

- *Ranges of the upper catchment* – This area is located to the east in the Great Dividing Ranges. The region is steep to rugged and was originally characterised by savannah woodland that has been mostly cleared.
- *Liverpool Plains* – This region comprises the Mooki and Cox's river catchments. The region is generally flat with slopes rarely exceeding 3°. The soils comprise cracking clays or clay loams with red clay subsoils. Grasses dominate this area, with some remnant patches of the original savannah woodland.
- *Riverine Zone* – This region follows the Namoi River and has an extensive flood plain. The soils comprise heavy clays and loams, and the landscape is naturally dominated by grassland. Stream banks, anabranches and natural wetlands

originally lined the flood plain, with natural vegetation communities such as river red gums existing alongside. The trees have since largely been cleared and the river now assumes characteristics of an inland delta.

- *Pilliga* – This region is located in the southwest of the catchment. This area is mostly flat, and is now predominantly State Forest with extensive woodlands dominated by cypress pine and ironbark.

3.3 Water Resources

The New South Wales Department of Natural Resources (DNR) administers the water resources in the catchment through the use of surface water and groundwater licenses. Water use falls into three main categories: unregulated and regulated surface water and groundwater. The unregulated systems include the portions of the catchment above the major dams (Keepit, Split Rock and Chaffey) and the tributaries that flow into the Namoi River such as Cox's Creek, Mooki River, Maules Creek and Barradine Creek (Figure 3-1). The regulated systems include the rivers below the dam storages (such as the Peel and Namoi rivers). Licenses exist for all forms of water use.

Both surface water and groundwater resources have been over-allocated and exceed sustainable levels of consumption because of outdated policies originally developed to encourage agricultural development in the region (DLWC, 1999). Groundwater users in particular have recently faced significant cuts in their allocation in order for the resource to be returned to a sustainable level of development as part of the water reform agenda, which is discussed further in Section 3.4.

3.3.1 Surface Water Supply

The combined effects of rainfall and evaporation provide the greatest influence on runoff and streamflow characteristics within the Namoi River catchment. Over 90% of the total runoff in the Namoi River catchment comes from the upper 40% of the catchment above Gunnedah. The average flow at Gunnedah is around 770 000 ML/year, which is 6% of the average catchment rainfall (DPMS, 1996). However, the annual rainfall is highly variable and river flows fluctuate enormously from year to year.

The allocation of surface water for irrigation is as much as 260 000 ML/year, which is about 45% of the natural median flow (EPA, 1997). In a typical year about 200 000 ML is extracted by the irrigation industry in the Namoi River catchment (DPMS, 1996). All of the allocation water is generally used, as well as a volume of off-allocation surface water that flows from unregulated tributaries or overflows from the dam storages when not allocated to other purposes such as environmental needs (EPA, 1997). The volume that water users can actually extract varies from year to year depending on the storage levels. The DNR announces allocations after allowing for essential reserves for town water supply, stock and domestic, high security entitlements and a carry over for the following year. Because of the drier climatic conditions over the last decade, the allocations given to the irrigators were commonly well below 100%. The surface water resources of the Namoi River catchment are considered to be fully committed for irrigation purposes and there are no plans for the development of additional large-scale storages (DPMS, 1996).

The combination of dam storages, water extractions and diversions has had substantial effects on the flow characteristics of rivers within the catchment. Seasonal patterns have changed, flow variability has been reduced (for regulated reaches) and flows in the lower parts of sub-catchments have been significantly reduced. For example, average flows to the Barwon River have now dropped by one third (DLWC, 1998). These factors have all contributed to the declining health of the rivers in the Namoi River catchment, resulting in increased algal blooms, declines in native fish stock numbers, increases in exotic fish species, loss of riparian vegetation and decline of wetlands (EPA, 1997). Little is currently known about the role of groundwater extraction on reduced river flows within the catchment, which is one of the key research areas for this thesis.

3.3.2 Groundwater Supply

Groundwater is a major resource in the Namoi River catchment and it is extensively used for irrigation, town, stock and domestic water supplies. Groundwater began to be used for irrigation in significant volumes around 1965 in the region around Narrabri and Wee Waa. There are twenty-one towns reliant on groundwater for domestic and human consumption.

The Namoi River catchment alluvium (Figure 3-5) is the most intensively developed aquifer system in NSW, accounting for nearly 40% of the total volume of good quality groundwater extracted in the State. Irrigation is the main use of groundwater. Its use varies from 140 GL to well over 200 GL per year, depending on seasonal conditions and the amount of water available from the dams. Groundwater allocations in the catchment are managed on the basis of groundwater management areas and zones, which were defined by the Department of Natural Resources based on distinct hydrogeological characteristics (Figure 3-5). The region has been divided into the Upper and Lower Namoi Alluvium and the Peel Alluvium for management purposes. The Peel Alluvium, although located in the Upper Namoi, is considered to be a separate management area. The total volume of groundwater entitlements in the Upper Namoi is approximately 253 GL and for the Lower Namoi is 156 GL, although these entitlements are currently being reviewed to ensure long term sustainable usage (see Section 3.4.2). There is little reported information on allocations within the Peel Management area. In a recent consultancy report (SKM, 2003), both the Lower and Upper Namoi Alluvium were listed as priority areas for detailed studies on stream-aquifer interaction.

3.3.2.1 Upper Namoi Alluvium

There are currently 12 Groundwater Management Zones comprising the Upper Namoi Alluvium (Figure 3-5). Detailed information on the hydrogeological characteristics for each groundwater zone within the Upper Namoi Alluvium is given in Brownbill (2000), whilst comprehensive studies on the geology, hydrogeology and hydrochemistry are available for the Cox's Creek (Broughton, 1994a) and the Mooki River catchments (Broughton, 1994b; Coram and Jaycock, 2003; Gates, 1980; Lavitt, 1999), along with numerous other departmental and miscellaneous reports for the region. Only limited surface water licenses are available for irrigation in the Upper Namoi, and consequently groundwater is the main source of water for irrigation in this management area.

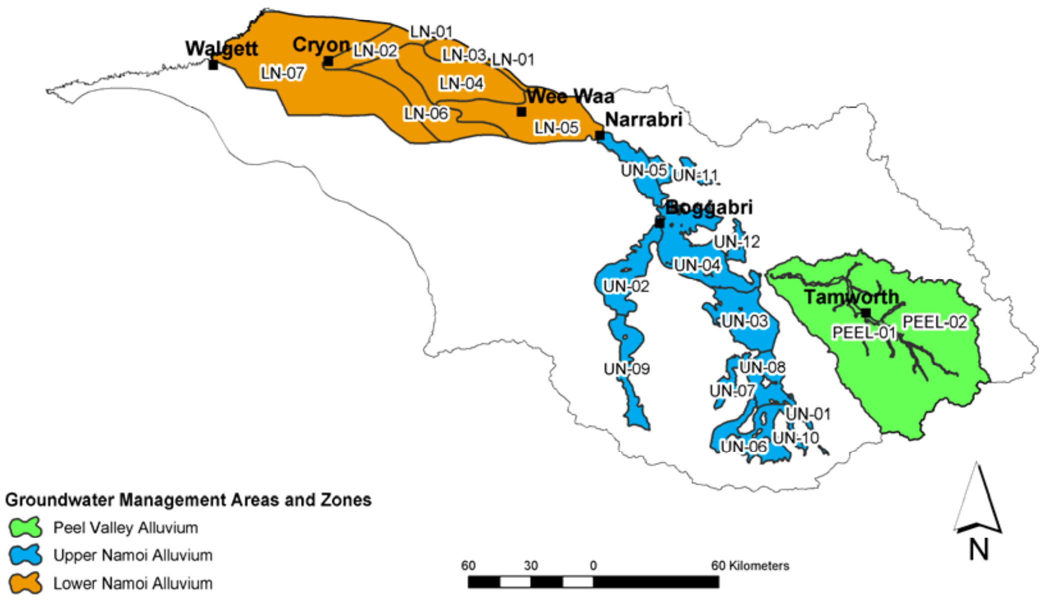


Figure 3-5 Groundwater management areas and zones within the Namoi River catchment

The main aquifer systems in the Upper Namoi Alluvium include the Narrabri and Gunnedah Formations, and comprise unconsolidated sediments associated with the Cox's Creek and the Mooki and Namoi rivers. The total area of alluvium in this region is in the order of 3 000 km^2 with a maximum thickness of 170 m. The Upper Namoi Alluvium yields large supplies of groundwater with a Total Dissolved Solids (TDS) concentration less than 3 000 mg/L.

The lower aquifer (Gunnedah Formation) contains gravels and sands, whilst the upper aquifer (Narrabri Formation) contains mostly clays and silts. Poorly-connected sand and gravel 'shoestring' aquifers can be found throughout the Narrabri Formation. The Narrabri Formation acts as a semi-confining layer, and the two formations are in partial hydraulic contact.

The hydraulic conductivity of the Gunnedah Formation is estimated to range between 10 to 100 m/day and is 1000 times higher than that of the Narrabri Formation, whilst the specific yield is 100 times lower in the Gunnedah Formation. This results in pressure transmission mainly through the Gunnedah Formation (Ringrose-Voase and Cresswell, 2000).

Recharge to the Gunnedah Formation is at the southern, upstream end of the aquifer where extensive alluvial fans have been deposited by the upland creeks on the lower hillslopes of the ranges. Diffuse recharge and occasional flooding on the alluvial plain contributes recharge to the Narrabri Formation. Upward flow to the Narrabri Formation occurs through vertical leakage from the underlying pressurised Gunnedah aquifer, which also receives upward vertical leakage from the underlying Basalt bedrock aquifer. Local water tables can be elevated due to the resulting poor drainage. Figure 3-6 (after Stauffacher *et al.*, 1997) provides a simple illustration that conceptualises how groundwater flows within the Mooki catchment.

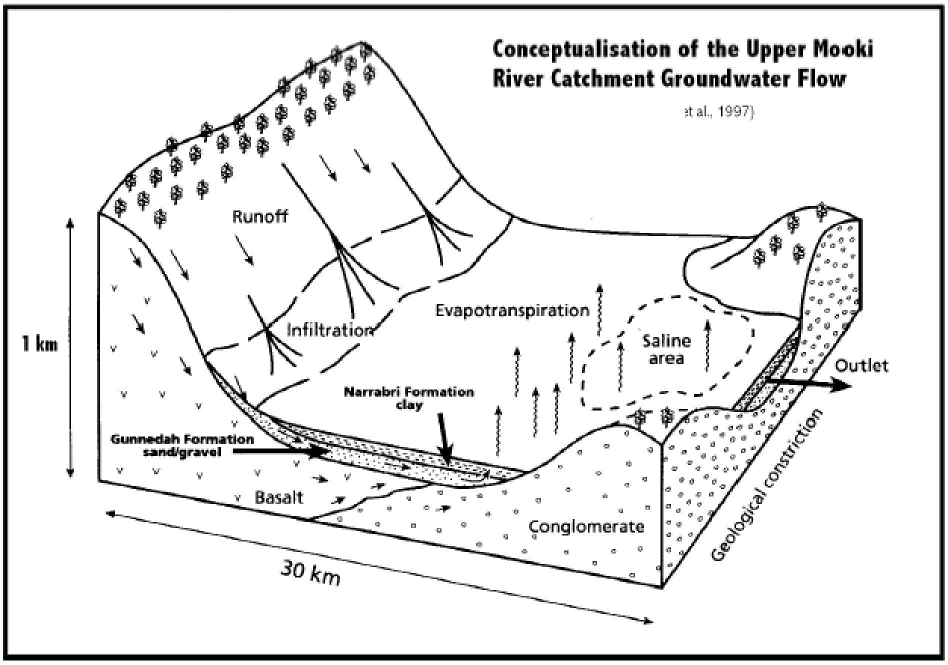


Figure 3-6 Conceptualisation of the Upper Mooki River Catchment groundwater flow system (after (Stauffacher *et al.*, 1997)

Narrow geological constrictions along the length of the Mooki River and Cox's Creek valleys have had a notable affect on how the alluvial sediments were deposited, and these constrictions influence groundwater movement in the Upper Namoi Groundwater Management Area. Hard basement rocks, through which groundwater moves very slowly, are located below and to the sides of the permeable alluvial valley fill material. In some areas the basement rocks form narrow valleys that restrict groundwater movement through the alluvial aquifers. The main constrictions occur between zones 4 and 5 (north of Boggabri), between zones 2 and 9 in Cox's Creek at Mullaley, and between zones 3 and 8 at the Mooki River at Breeza (Figure 3-5). These flow restrictions within the Gunnedah Formation have resulted in local surface salinisation where groundwater discharges to the soil surface.

3.3.2.2 Lower Namoi Alluvium

The Lower Namoi Alluvium extends from Narrabri to Walgett in the west of the catchment (Figure 3-5). The Lower Namoi Alluvium has seven management zones that are described in the DLWC (2000) Lower Namoi groundwater status report. Comprehensive overviews of the geology, hydrogeology and hydrochemistry can be found in Gates (1980), McLean (2003) and Williams (1997).

The groundwater resources in the Namoi Valley are largely contained within the unconsolidated Cainozoic alluvial sediments deposited along the Namoi River, its tributaries and ancestral palaeochannel. Three multiple aquifer systems in the Namoi River catchment have been classified on the basis of age and compositional differences (Gates, 1980; McLean, 2003; Williams, 1985; Williams, 1997). The Cainozoic alluvial sediments of the Lower Namoi Valley comprise interbedded clays, sands and gravels, which have been accumulating for more than 15 million years within the broad valley of the Namoi River. They form a highly heterogeneous alluvium which overlies the pre-Tertiary bedrock surface of the Great Artesian Basin. The alluvial deposits occur to a maximum depth of 120 m and have an areal extent of about 5 100 km^2. In the northwest of the catchment the Namoi River alluvium joins alluvium associated with the Barwon and Gwydir river catchments (DLWC, 2000).

In most areas there are two aquifer systems identified within the alluvium, but in some areas there are three. The relationship between the three aquifers is conceptualised in Figure 3-7 (after McLean, 2003). The upper Narrabri Formation aquifer occurs to about 40 m depth, and it is exploited as a secondary aquifer due to the high clay content that permits only low yields of fresh to saline groundwater. Transmissivities within the Narrabri Formation are generally less than 150 m^2/day (Williams, 1985) and the hydraulic conductivity has been estimated at 6 m/day (Merrick, 1999).The Narrabri Formation has a considerable clay content which usually yields a low and often poor quality water resource that is mostly used for stock and limited domestic purposes. The middle aquifer (Gunnedah Formation) is the most extensive aquifer in the region and occurs between 40 and 90 m depth. The deepest aquifer, the Cubbaroo Formation, has a thickness of up to 130 m and it is restricted to the main Namoi palaeochannel that is situated slightly north-northwest of the present-day river course. In some areas of the Lower Namoi Alluvium the three aquifer systems act as a single aquifer.

The sand and gravel deposits in the Gunnedah and Cubbaroo Formations provide the most productive aquifers for irrigation. Good bore yields with good quality water occur in the Gunnedah and Cubbaroo Formation aquifers, with water quality generally deteriorating to the west with the fining of sediments. The Gunnedah and Cubbaroo Formations have transmissivities ranging from 1000 to 2000 m^2/day and hydraulic conductivities of 31 and 23 m/day respectively, and they form the principal productive aquifers in the catchment (Merrick, 1999).

Recharge to the aquifer mostly occurs in the alluvial fan area in zone 5 (LN05 in Figure 3-5), which spreads westward from Narrabri. Groundwater flows are generally in a westward direction towards the town of Walgett. Only a small portion of the total groundwater flow comes from upstream of Narrabri (Upper Namoi Valley). The groundwater system in the Lower Namoi Alluvium is mostly recharged by river transmission losses and weir leakage, rainfall infiltration through the overlying clays, floods and farm water losses. Upward leakage from the deeper underlying Great Artesian Basin aquifer also recharges the alluvial aquifers (McLean, 2003).

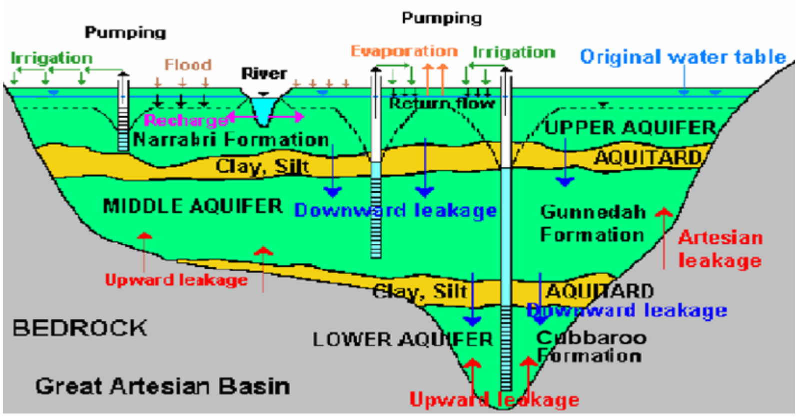


Figure 3-7 Schematic cross section of Lower Namoi hydrogeology and water movement processes (after McLean, 2003)

3.3.2.3 Peel Management Area

The alluvium deposits in the Peel Management Area are associated with the Peel River, and are generally less than 15m deep. Reasonable yields are obtained from this aquifer system sufficient to supply small areas of lucerne irrigation and other cropping regimes

(DPMS, 1996). No groundwater status reports have been prepared for the Peel Management Area.

3.4 Water Reform

Since the early days of Australian settlement water management in NSW has been primarily aimed at consumptive issues such as the provision of water for towns and the development of private and public irrigation schemes. The concept of water “conservation” revolved around storing water for use during drier times, the building of dams, using rivers as water supply channels and apportioning available water between competing individual interests. The water needs of the environment were given a low priority (Tan, 2002).

In the 1970s it became apparent that the water resources in many parts of NSW were over-allocated and that if all requests for water delivery were made, as per a licence or other agreement, the demand for water would exceed available surface water supplies. In order to address the problem of surface water over-allocation, new measures were introduced during the late 1970’s and through to 1984. These included: an annual volumetric allocation scheme; an embargo on new water allocation licence applications in over-allocated catchments; and “shortage powers” to suspend surface water extraction during times of water scarcity.

In 1984, problems regarding the administration of the State’s water resources prompted an audit of NSW water agencies, which resulted in a restructuring of the administration in rural water services and the development of the Water Administration Act 1986 and Water Authorities Act 1987. For the first time, the ecosystem requirements for water were acknowledged in water legislation (Tan, 2002).

3.4.1 Council of Australian Governments Water Reform Framework

The degraded health of the rivers within the Murray Darling Basin, and more generally within Australia, became an issue of national concern in the early 1990’s. In response to the poor state of the rivers, the Council of Australian Governments (COAG) developed a framework agreement for the reform of the water industry in Australia. The COAG water reform agenda of 1994 addressed the following key issues: (1) sustainable use of surface water resources; (2) provision of water for the environment; (3) pricing of water resources to achieve full cost recovery; (4) establishment of a water transfer market through separating rights to water from title to land; and (5) separation of operator and regulator functions in water resource management (COAG, 1994).

COAG membership comprises the Prime Minister, State Premiers, Territory Chief Ministers and the President of the Australian Local Government Association. COAG has the role of initiating, developing and monitoring the implementation of policy reforms of national significance where cooperative action by Australian governments is required. Policy reforms that are agreed to by COAG are developed and implemented by Commonwealth-State ministerial council committees that include responsible ministers from each government. Resolutions made by ministerial council committees require a unanimous vote, which means that decisions taken by the Council represent a consensus of government opinion and policy (Murray Darling Basin Commission, 1999). The Murray Darling Basin Ministerial Council (MDBMC) is responsible for issues of significance to the Murray Darling Basin region.

The MDBMC confirmed that increasing levels of surface water diversions were resulting in the decline in river health and decreased security for water users. Water use in the Basin was found to be growing primarily from the activation of previously unused licenses along with the growth in the use of "off-allocation" water, or water diverted during high flow periods and stored in dams for later use.

In order to ensure that adequate water remained within Murray Darling Basin river systems, the MDBMC announced the Murray Darling Basin Ministerial Cap in July 1995, or the Cap. The Cap gave an upper limit on the amount of water that could be taken from surface water systems, and was defined as "the volume of water that would have been diverted under 1993/94 levels of development". In unregulated rivers, the Cap was expressed as an end-of-valley flow regime (Murray Darling Basin Commission, 1999). Whilst a Cap was placed on surface water diversions, no Cap was placed on groundwater extractions in the context of their impact on surface water flows. This is an area of research that is of key importance to effectively managing the water resources in the Murray Darling Basin river catchments and will be explored in this thesis.

The sustainability of the nation's groundwater resources became an additional issue of concern to the COAG water reform agenda. The Agricultural and Resource

Management Council of Australia and New Zealand (ARMCANZ) prepared two landmark documents that made the COAG groundwater principles operational. These documents were entitled: "Towards a National Groundwater Management Policy and Practice" (November 1995) and "Allocation and Use of Groundwater – A National Framework for Improved Groundwater Management in Australia (December 1996). Some key recommendations included (ARMCANZ, 1996):

- Groundwater management policies should be directed at achieving sustainable use of the resource;
- Groundwater and surface water resource management should be better integrated; and
- Where allocations exceed the sustainable yield, strategies should be developed to reduce abstractions to sustainable levels within time-frames that minimize permanent damage to the resource.

COAG decided in 1995 that the implementation of the reforms would be included under the umbrella of the National Competition Policy. This meant that the National Competition Council (NCC) would assess and report to the Federal Treasurer on the progress of all States and Territories in implementing water reforms. The Australian Government commenced making National Competition Policy payments to the States and Territories (on a per capita basis) when they achieved satisfactory progress against the water reform obligations. The vision of the Government was for water reforms to be successfully implemented in order to assure an efficient, flexible, sustainable Australian water industry capable of delivering higher quality water with greater security of supply. Water would be properly priced and the rights to water extensively traded (Smith, 2000).

3.4.2 New South Wales Response to COAG Water Reform Framework

The water reform initiatives in NSW in response to COAG commenced in 1994, and were focused on delivering the COAG and ARMCANZ recommendations using the National Competition Policy tranche payments to the States to implement water reforms.

In 1997, the NSW Government announced a comprehensive water reform package aimed at improving the health of rivers and groundwater systems within NSW and delivering greater water security to all water users and regional communities.

The "New South Wales State Groundwater Policy Framework Document" was released in 1997 and included three component policies on Groundwater Quality Protection, Groundwater Quantity Management and Groundwater Dependent Ecosystems. The goal for the management of groundwater in NSW was stated as being (DLWC, 1997): "To manage the State's groundwater resources so that they can sustain environmental, social and economic uses for the people of New South Wales". These documents defined the concept of the "Ecologically Sustainable Yield", which required that total groundwater allocations in all groundwater systems in NSW should be no more than 100% of the long term estimated average annual recharge (EAAR) to the systems. Allocations in areas with groundwater-dependent ecosystems were to be made less than 100% of EAAR. According to these principles, groundwater allocations in NSW were reviewed and the Namoi Valley was highlighted as one of the priority areas where the groundwater resources were seriously over-allocated with regard to their corresponding EAAR (NGERP, 1999).

3.4.2.1 Namoi Groundwater Expert Reference Panel

The groundwater management policies of the early 1980's in the State of NSW allowed for up to one third of aquifer storage to be depleted over a specified time-frame. This policy of "controlled depletion" allowed annual allocations and extractions in excess of groundwater recharge. The ongoing increase in development in some groundwater zones within the Namoi resulted in regional water quality and water quantity declines within the aquifers, which were exacerbated during drought years.

The Namoi Groundwater Expert Reference Panel (NGERP) was appointed in 1999 to recommend to the Government a process to move the current groundwater entitlements in the Namoi Valley to within sustainable limits, and to advise on an appropriate structural adjustment package. The report of the NGERP contained 100 specific recommendations that were considered in the subsequent development of draft groundwater management plans for the catchment (NGERP, 1999). The recommendations on groundwater management were to be implemented over a 10-year period to minimise socio-economic impacts associated with reduced water allocations.

The groundwater management plans were later incorporated into groundwater sharing plans as per the Water Management Act 2000.

3.4.2.2 The Water Management Act 2000 (NSW)

The water reform process in NSW resulted in the development of the Water Management Act 2000, which was passed by the New South Wales State Parliament in December 2000. Prior to the development of the Water Management Act 2000 the main statutes for water were the Water Act 1912 and the Water Administration Act 1986. A range of other Acts dealt with more specific aspects of water management such as the Rivers and Foreshores Improvement Act 1948, Irrigation Corporations Act 1994, Private Irrigation Districts Act 1973, Water Supply Authorities Act 1987 and numerous others. The Water Management Act 2000 replaced all pre-existing acts in 2002. The principles in the new legislation focus on: improved environmental health for the State's waters; greater economic benefits for individuals and communities; and shared government and community responsibility for water management (DLWC, 2001).

3.4.2.3 Catchment Management Authorities

The Water Management Act 2000 provides the framework for natural resources management planning through a community-government partnership. Consistent with the new consultative focus on natural resource management, on 31 May 2000 the New South Wales Government (through the then Department of Land and Water Conservation or DLWC) established a number of Catchment Management Boards to develop natural resource management plans that would contribute towards meeting state and national legislation and policy objectives.

Each of the Catchment Management Boards produced 10-year integrated catchment management plans, commonly referred to as "catchment blueprints", which were the primary integrating mechanism for all natural resource planning.

The Catchment Management Authorities Act came into force in January 2003, establishing thirteen Catchment Management Authorities (CMAs) across the state as part of the broad set of natural resource management reforms. The CMAs replaced the Catchment Management Boards and their roles are to (CMA, 2004):

- Develop and implement catchment action plans;

- Provide loans, grants, subsidies or other financial assistance for authorised catchment activities;
- Contract work for authorised catchment activities;
- Assist landholders to further the objectives of the catchment action plan (such as providing information about native vegetation management);
- Provide educational and training courses/materials in connection with natural resource management; and
- To exercise any other function relating to natural resource management as is prescribed by the regulations.

The Minister responsible for the Department of Infrastructure, Planning and Natural Resources (previously called the Department of Land and Water Conservation and now called the Department of Natural Resources) and the Natural Resources Commission, which sets appropriate standards, must approve catchment action plans prepared by the CMAs.

Some specific responsibilities of the CMAs in the context of this study are to develop and implement the water sharing plans, within the context of the larger catchment action plans, and to engage regional communities in natural resource management and planning.

3.4.2.4 Water Sharing Plans

Water management plans were developed under the Water Management Act 2000 in order to ensure the protection, conservation and ecologically sustainable development of water resources. Water sharing plans are a specific type of water management plan under Section 388 of the Water Management Act 2000 and cover a period of 10 years. Water sharing plans within the Namoi River catchment were established for the Namoi Regulated Rivers, Namoi Unregulated Rivers (for the Mooki River subcatchment) and Namoi Groundwater. The water sharing plans are designed to establish environmental and cultural water rules, requirements for basic landholder rights, requirements for water extraction under access licenses and water sharing rules for licensed water users.

The draft water sharing plans were originally released for public comment in 2001-02, and were originally due to be implemented on 1 July 2002. However, the implementation of the water sharing plans was delayed due to the concerns of the agricultural community about some of the ramifications of the plans through decreased water (especially groundwater) allocations in many regions, potentially resulting in significantly decreased irrigated agricultural productivity and associated job losses. Table 3-1 gives the reductions required in each of the groundwater management zones in order that the total volumes of groundwater extractions do not exceed the long-term average annual recharge estimates. One can see from this table that irrigators in the Upper Namoi Zone 1, for example, should anticipate losing up to 87% of their aquifer share entitlement.

Table 3-1 Recharge, variations to recharge estimates, water requirements and licence reductions at the start of the water sharing plan for the Upper and Lower Namoi groundwater sources (DLWC, 2002)

Groundwater Source	Recharge (ML/y)	Possible variation to recharge (ML/y)	Basic landholder rights (ML/y)	Local water utility (ML/y)	Total licensed entitlement pre-plan (ML/y)	Reduction to aquifer access share components
Upper Namoi						
Zone 1	2 100	1 575 to 2 625	39	1 716	8 510	87%
Zone 2	7 200	5 400 to 9 000	359	59	23 801	70%
Zone 3	17 300	12 975 to 21 625	470	199	56 017	69%
Zone 4	25 700	19 275 to 32 125	667	4 660	82 590	73%
Zone 5	16 000	12 000 to 20 000	262	0	36 042	45%
Zone 6	14 000	10 500 to 17 500	274	0	11 448	0%
Zone 7	3 700	2 775 to 4 625	89	0	6 321	41%
Zone 8	16 000	12 000 to 20 000	166	56	48 204	67%
Zone 9	11 400	8 550 to 14 250	187	97	11 342	0%
Zone 10	4 500	3 375 to 5 625	36	0	1 420	0%
Zone 11	2 200	1 650 to 2 750	210	0	8 740	75%
Zone 12	2 000	1 500 to 2 500	73	0	7 487	73%
Total	122 100	–	2 832	6 787	301 922	–
Lower Namoi						
All zones	86 000	64 500 to 107 500	3 304	4 407	172 187	51%

With the exception of the inland groundwater plans, the water sharing plans came into effect on 1 July 2004. The NSW Government recognised that groundwater licence holders in the Namoi Valley were going to be significantly affected by reductions in groundwater supplies in response to the scaling down of allocations to ensure sustainable extraction. In June 2002, the NSW Government announced a $20 million Groundwater Structural Adjustment Program to assist irrigators and communities in the Namoi Valley adjust to significant reductions in groundwater access.

The implementation of the Upper and Lower Namoi Groundwater Sharing Plans was deferred to July 2004; however, to date (August 2006) the implementation has still not occurred.

3.4.3 National Water Initiative

COAG continued to note the imperative of increasing the productivity and efficiency of water use and the health of river and groundwater systems in Australia, and the National Water Initiative (NWI) was agreed to and signed at COAG's June 2004 meeting. The NWI refreshes the 1994 COAG water reform agenda by establishing actions to increase the productivity and efficiency of water use, sustain rural and urban communities, and to ensure the health of river and groundwater systems.

The NWI aims to achieve this in four ways (COAG, 2003):

1. Improving the security of water access entitlements, including by clear assignment of risks of reductions in future water availability and by returning over-allocated systems to sustainable allocation levels;

2. Ensuring ecosystem health by implementing regimes to protect environmental assets at a whole-of-basin, aquifer or catchment scale;

3. Ensuring that water is put to best use by encouraging the expansion of water markets and trading across and between districts and States (where water systems are physically shared), involving clear rules for trading, robust water accounting arrangements and pricing based on full cost recovery principles; and

4. Encouraging water conservation in our cities, including better use of stormwater and recycled water.

The Natural Resources Management Ministerial Council gained an enhanced role as the body responsible for overseeing implementation of the NWI Agreement and the National Water Commission (NWC) was established in 2005. The NWC is an independent statutory agency within the Prime Minister's portfolio, which is responsible for driving national water reform and investment. The Commonwealth Government has been providing funding to the NWC, and seven NWC commissioners were appointed. Members of the Commission were selected on the basis of their skills in the areas of 'audit and evaluation, governance, resource economics, water resource management, freshwater ecology and hydrology'. The NWC has been assigned a comprehensive reporting and coordinating brief and it is likely that its role will expand to provide support to regional catchment authorities as they struggle with a difficult implementation agenda (Connell *et al.*, 2004).

One of the key objectives of the NWI (NWI, 2004) is 'the recognition of the connectivity between surface and groundwater resources, and for connected systems to be managed as a single resource' (clause 23). The NWI also stipulates that all States and Territories agree to identify by the end of 2005 situations where close interaction between groundwater aquifers and streamflow exist (this had not been completed to date), and implement by 2008 systems to integrate the accounting of groundwater and surface water use (clause 83). Another key objective is for water allocation in catchments to be managed through integrated catchment management approaches that consider social and economic factors along with the biophysical factors (clause 78).

The implementation of the water reform agenda is particularly affecting Australia's most developed irrigation regions such as the Namoi River catchment. Water reforms have resulted in decreased water entitlements for water users in order to promote resource security and sustainability. However, a broad-scale understanding of the interactions between the groundwater and river systems remains lacking. Consequently, the projected outcomes of reduced water allocations remain unclear and contentious, and the degree to which groundwater extractions undermine the integrity of the Cap is unknown.

One of the targets of the water sharing plans is for the connectivity between groundwater and river systems to be mapped, with the intent of eventually quantifying the impacts of groundwater extraction on river flows in connected aquifer-river systems. Additional targets are for the ecological and cultural water requirements of the catchment to be assessed and met through the required river flow characteristics. Little research has been undertaken in these areas. An understanding of groundwater-river interactions is vital to achieving water sharing plan objectives. And unfortunately most catchment managers responsible for managing water resources would have little information on where rivers and aquifers are connected, nor the knowledge of how best to advance the management of these resources conjunctively.

3.5 Chapter Summary

This chapter has provided an overview of the Namoi River catchment setting, the use and management of water resources, and the water reform agenda. The implementation of water reforms poses many difficulties for catchment managers, especially in highly developed catchments reliant on surface and groundwater irrigation such as the Namoi River catchment. The implementation of the National Water Initiative will require that the connectivity between surface and groundwater resources is recognised, and that connected systems are managed as a single resource. This will present a significant challenge to water managers. A first step will be to identify connected aquifer-river systems and to clarify management objectives for these river reaches. The following chapter discusses a classification system for describing key types of groundwater-river interactions, and demonstrates the use of some relatively simple methods that were used to characterise the river reaches in the Namoi River catchment.

Chapter 4 Characterisation of Namoi River Reaches

4.1 Introduction

The principles described in Chapter 2 demonstrated the importance of developing a greater understanding of the spatial and temporal interactions taking place between groundwater and river systems. And Chapter 3 highlighted the requirement within the National Water Initiative reform agenda (NWI, 2004) that connected groundwater-river systems are managed as a single resource. An important first step to meet the water reform challenges is for connected groundwater-river systems to be identified, and for the types of interactions occurring between groundwater and river systems to be characterised. This chapter discusses the methods commonly used to assess groundwater-river interactions, outlines a system of classification and discusses a framework implemented in this research to characterise the interactions observed in the Namoi River catchment.

4.2 Classification of Groundwater-River Interactions

Developing an understanding of the types of interactions that occur between groundwater and river systems is essential for the effective management of water resources. In order to better conceptualise the nature of groundwater-river interactions, it is useful in the first instance to classify the types of interactions observed along river reaches.

Braaten and Gates (2002) undertook the first notable study in the State of New South Wales (NSW) that highlighted the importance of considering groundwater-surface water interactions in water allocation assessments. Furthermore, they applied a classification system to describe the types of groundwater-river interactions that occurred in the Murray Darling Basin river system. This study was influential in terms of setting some important research agendas regarding double-accounting and time lags. The report also produced a basin-wide map of aquifer-river connectivity. However, their study was conducted at a large scale using a limited data pool and methods. Consequently their mapping work was neither sufficiently detailed nor accurate for use in this study.

The system of classification applied by Braaten and Gates (2002) to describe groundwater-river interaction processes was based on distinguishing between connected and disconnected aquifer-river systems, and whether a river was gaining (Figure 2-1) or losing (Figure 2-2) based on the descriptions of Winter *et al.* (1998). A connected river reach system was defined as having a length of river in direct contact with the underlying aquifer via a zone of saturated material or by a narrow unsaturated zone (Bouwer and Maddock, 1997). Resource and Environmental Management (REM, 2002) proposed a classification system building on that of Braaten and Gates (2002) for the management of conjunctive water use in Australia which further identified the potential likelihood (high, medium, low, none) for impacts to manifest in surface water quantity (and quality) due to groundwater extraction. For this thesis the classification systems of Braaten and Gates (2002) and Resource and Environmental Management (REM, 2002) have been combined with some additional considerations.

Table 4-1 shows the elements combined from the Braaten and Gates (2002) and Resource and Environmental Management (REM, 2002) classification systems, with some modifications such as the addition of a variably gaining-losing type of river reach (Figure 2-4). Further consideration has also been given to the potential impacts of groundwater extraction from an aquifer system that is disconnected from the river, e.g. through captured discharge.

The simple classification system described in Table 4-1 facilitates the development of a conceptual framework for the characterisation of river-aquifer reaches, and hence also assists in prioritising areas where further study into groundwater-surface water interactions may be required. Whilst the Level 3 impacts listed in Table 4-1 are somewhat arbitrary, what is clear is that in the hydraulically-connected aquifer-river reaches the potential impacts of groundwater extraction on surface water resources can be significant. Hence in the catchments that have connected river reaches, it will be important to quantify the temporal dynamics of water fluxes between groundwater and river systems and to elucidate management priorities for water allocation.

Table 4-1 Classification system for river-aquifer interactions relevant to conjunctive use management (adapted from REM, 2002)

Level 1 Hydraulic connection	Level 2 Dominant direction of river-aquifer flux	Level 3 Potential for groundwater extraction to impact on river resources
Connected	Gaining Stream	High as a result of captured discharge and induced recharge
Connected	Losing Stream	Medium as a result of increases in induced recharge
Connected (may also be variably connected-disconnected)	Variable Gaining/Losing Stream	Medium to High, as per the two categories above
Disconnected	Losing Stream	No direct impact along disconnected river reach, although impacts will become evident at groundwater discharge site(s) as a result of captured discharge

In the following subsections the river reaches in the Namoi River catchment will be classified according to Levels 1 and 2 in Table 4-1. The potential for groundwater extraction to impact on river systems (Level 3) within the Namoi River catchment will also be evaluated in this chapter.

4.3 Methods to Characterise Aquifer-River Interactions

There are a range of methods that can be used to characterise aquifer-river interactions. Resource and Environmental Management (REM, 2002) reviewed some of the approaches commonly used, including:

- **Hydrological methods:** Surface water hydrographic separation, flow duration analysis and river-reach water balances. These approaches rely on the location and accuracy of the stream gauging sites and data availability.

- **Hydrogeological methods:** Groundwater hydrographs, water level contours, flow nets and analytical models using Darcy flow calculations. These methods are dependent on observation bore locations and data availability.
- **Tracers:** Tracers such as hydrochemical, temperature or flora/fauna communities, for example, can be used to develop a conceptual/perceptual model of interaction processes. These methods often have a high cost and also may lack temporal resolution.
- **GIS-based:** Spatial GIS applications can be used to examine groundwater level contours and to determine broad-scale groundwater flow directions. These approaches require a database of relevant groundwater data and an accurate Digital Terrain Model. The results are typically qualitative and semi-quantitative.

The study by Resource and Environmental Management (REM, 2002) concluded that there is no method, formula or computer model that can be universally applied, and that each method has its strengths and limitations. Some methods are better suited to small scale studies because of the high cost and/or detailed process characterisations which may not be easily or readily applied at the larger scale. The use of existing data is usually the first step in assessing aquifer-river interactions using a staged approach in which different techniques are used at different stages in the assessment, depending on the scale and study objectives. For this thesis both hydrological and hydrogeological methods were applied, with an emphasis on rapid assessment, data-driven approaches. The methods used in this thesis are discussed below, and include concepts discussed by Ivkovic *et al.*(2004) and Ivkovic *et al.* (2005c).

4.4 Hydraulic Connection

The first step in characterising the river reaches in the Namoi River catchment study area according to Level 1 in Table 4-1 was to determine if the major rivers were in hydraulic connection with the underlying aquifers through a saturated or near-saturated zone. This was achieved through the use of a GIS and groundwater database using groundwater data obtained from the NSW Department of Natural Resources. Hydraulic connection was assessed by comparing the differences between the elevation of the base of the riverbed and the elevation of the groundwater observed in shallow observation bores (<40m) located within 1km of the river. Some extrapolations were also made using data from more distant shallow bores where there were no bores located closer to the river. The potential for hydraulic connection was assumed to exist where measured groundwater levels were within 10m of the surface, which is the estimated difference between the elevation of the floodplain and the base of the rivers within the Namoi River catchment as reported in Braaten & Gates (2002). Whilst there would be localised spatial differences between riverbed and floodplain elevation throughout the catchment, the use of a uniform figure of 10m was considered reasonable given the uncertainties involved in using either a 250m or 25m digital elevation model in the absence of detailed surveys of the peri-stream region. With some exceptions, hydraulic connection was established between the shallow aquifer and the river for most of the upper portion of the Namoi River catchment from the town of Wee Waa eastwards through to the upper headwaters of the catchment, and also at the outlet of the catchment to the west of Walgett (Figure 4-1).

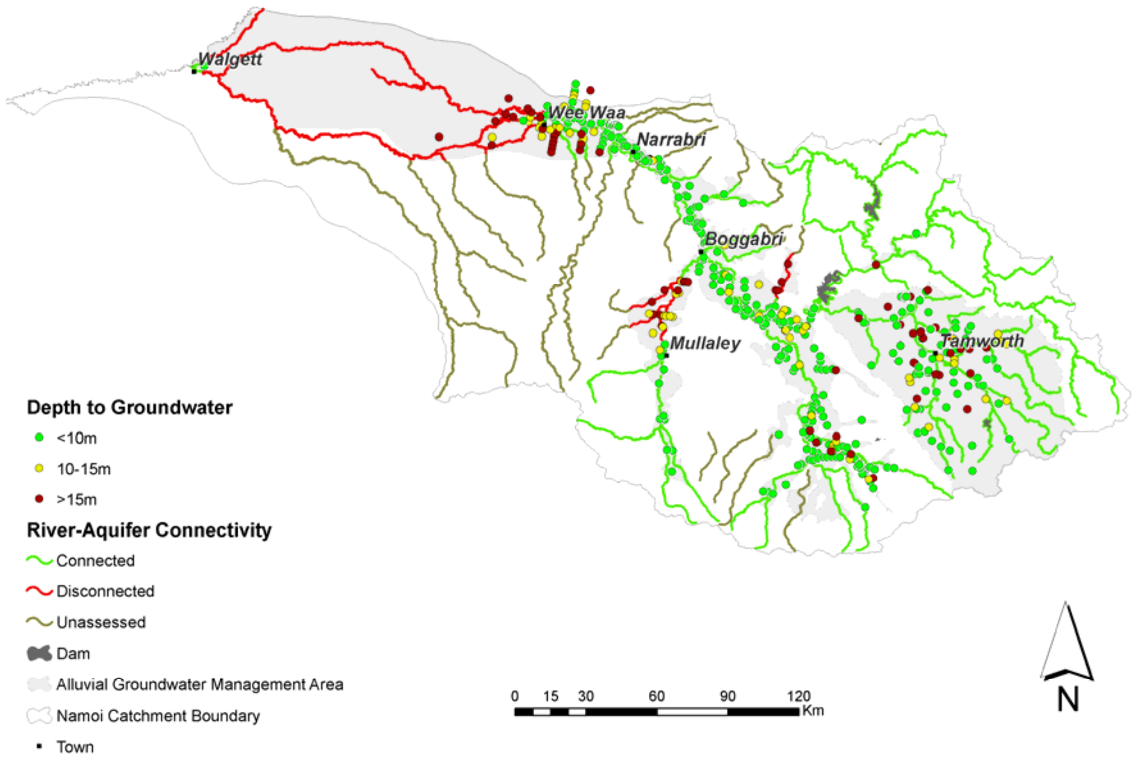


Figure 4-1 River-aquifer connectivity and depths to groundwater within the shallow aquifers (<40m) in the Namoi River catchment

The remainder of the river systems between Wee Waa and Walgett were considered as being disconnected from the groundwater system (i.e. with an unsaturated zone between the river and groundwater systems), although river transmission losses along this disconnected section play an important role in groundwater recharge (vertical subsurface hydraulic connectivity is discussed in sections 4.6.1 and 4.6.2).

The final map of connectivity in the Namoi River catchment is shown in Figure 4-2 and is an improvement on the large scale NSW map originally produced by Braaten and Gates (2002), in which the Cox's Creek and majority of the Mooki River subcatchments were mapped as disconnected reaches. The more detailed map of the Namoi River catchment prepared for this thesis (Figure 4-2) shows these regions as having connected aquifer-river systems. The dominant direction of flux will be addressed in the following section.

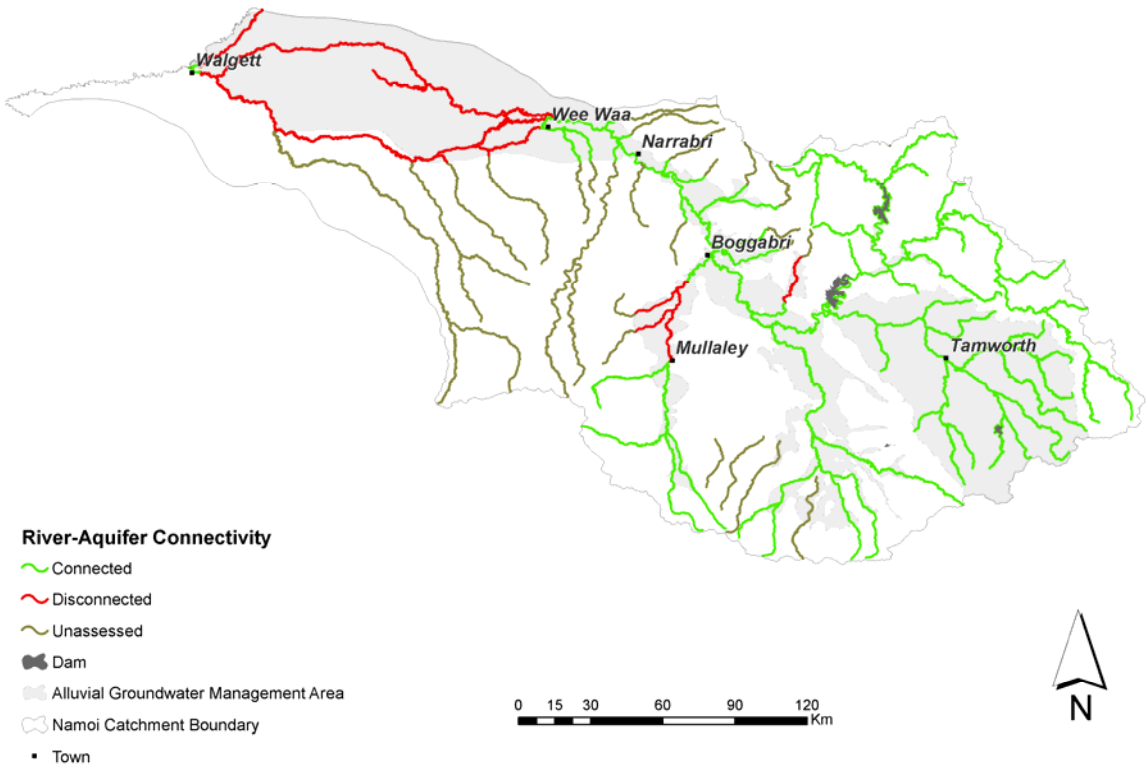


Figure 4-2 River-aquifer connectivity within the Namoi River catchment

4.5 Direction of Aquifer-River Flux

The second level of the classification framework outlined in Table 4-1 establishes the dominant direction of flux between the groundwater and river systems. The general absence of surveyed stream gauging stations and appropriately located piezometers transecting the river systems in the Namoi River catchment meant that it was difficult to establish detailed groundwater elevation-river stage relationships. Consequently, the direction of flux between aquifer and river systems had to be inferred though other methods. The two key methods used in this research to infer the direction of flux within the unregulated river systems include: 1) the shape of the stream hydrograph together with baseflow separation analysis, and 2) the use of flow duration curves and the percentage of the streamflow record over which measurable flows were recorded. The regulated and disconnected river systems were categorised as losing river systems. The methods used to characterise the flux between the aquifer and river systems are discussed further in the sub-sections that follow.

As a point of caution, it is important to be aware that there is a degree of subjectivity in classifying a river reach as a gaining, alternating or losing type of reach given the continuum in the hydrological cycle and the dynamic changes in both groundwater and river stage elevations in response to a range of factors. For example, river reaches classified as predominantly gaining reaches will at times behave as losing river reaches during periods of recession, and some of the variably gaining-losing river reaches may act primarily as losing systems, particularly within the more intermittent to ephemeral river systems. The direction of flux between groundwater and river systems will commonly vary along a river reach and depend on the timing and the scale of analysis (see e.g. Woessner, 2000). The fluxes between river and aquifer systems can also be affected by anthropogenic influences such as river regulation and water extraction, which must be taken into consideration.

The temporal scale of mapping has also been limited by the available data. Because data from stream gauging stations on the unregulated rivers have been used to determine the dominant direction of flux, the distance between gauging stations limits the scale of river reach mapping in the unregulated systems. The dominant direction of flux as determined from the stream gauging station data and associated techniques (e.g. baseflow separation and flow duration) in this research represents an aggregated response of the losses and gains upstream of the gauge over the available data period. Most river reaches will both gain and lose water, and consequently any baseflow signal will represent the net balance between any gains and losses occurring in the river upstream of the gauge.

The aquifer-river reach mapping undertaken for this thesis has been conducted primarily for use at the subcatchment scale. Hence, the local small-scale variations in flux along a river reach are not identified in this assessment.

The baseflow separation and flow duration analysis methods used in this research to determine the dominant direction of flux in the unregulated river systems and the rationale for the characterisation of regulated reaches are discussed in more detail in the following subsections.

4.5.1 Baseflow Separation

A typical stream hydrograph of discharge versus time can be separated into its component contributions of surface runoff and baseflow (Figure 4-3). There may also be an interflow component of streamflow arising from rainfall that has taken a temporary, shallow subsurface pathway to the river; however, the interflow component is assumed to be included within the other two pathways and is generally ignored in hydrograph analysis for reasons of practicality and identifiability. In this thesis the term surface runoff is used to represent the quickflow response to rainfall that is composed of water flowing on the land surface together with interflow. The term baseflow is used to represent groundwater discharge. These terms, and the processes they represent, are debatable. Nonetheless, these terms will be used in this research in order to broadly distinguish between surface water and groundwater (water stored within an aquifer) processes in an attempt to gain insights into river-reach scale groundwater-river interactions.

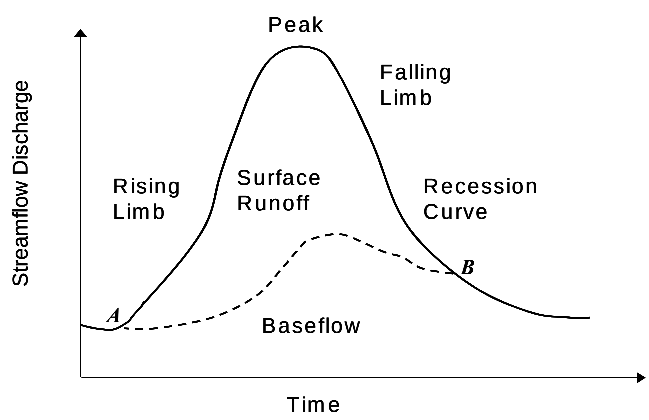


Figure 4-3 Typical stream hydrograph (adapted from Shaw, 1983)

The area above the A-B reference line in Figure 4-3 equates to surface runoff in direct response to a rainfall event, whilst the area below the A-B reference line equates to baseflow, or the other slower subsurface discharges from catchment storages such as groundwater. Methods of separating hydrographs into components are commonly based more on characteristics of the hydrograph shape than the actual origin of the streamflow, and thus the division is somewhat arbitrary (Gordon *et al.*, 2004). Grayson *et al.* (1996) stress that the results from any baseflow separation methods should not be regarded as the true amounts of surface and subsurface flow from the catchment until physical data (e.g. from tracers) are used to interpret processes. Despite its shortcomings, hydrograph separation can be a useful technique for groundwater-river interaction studies, in particular to assess the direction of flux between the river and groundwater systems as will be seen in the sections that follow.

Generally three stages can be identified within an 'ideal' stream hydrograph (Ward, 1975):

i. During a rainfall event, the streamflow will initially be dominated by surface runoff and characterised by a rising river stage that culminates in the streamflow peak (Figure 4-3). The elevated river stage drives the seepage of streamflow through the river bed and its bank, resulting in stream transmission losses to the subsurface.

ii. After a rainfall event the surface runoff will diminish and the river stage will begin to fall. Groundwater levels at this point in time will have usually increased in response to the infiltration of rainfall and streamflow, and as a result the groundwater levels may be more elevated than the river stage and the hydraulic gradient will be from the groundwater system towards the river. Baseflow will comprise the majority of the stream hydrograph at this time, and will be composed of both stream bank and groundwater discharges. The baseflow recession will commonly follow an exponential decay function as subsurface storages drain until the next rainfall event.

iii. At the end of a dry period, if there is flow in the river, the low flows will be composed entirely of baseflow.

In order for baseflows, or low flows, to be maintained by groundwater discharges: 1) the draining aquifer must be regularly recharged; 2) the water table must be shallow enough to be intersected by the stream and 3) the aquifer's size and hydraulic properties must be sufficient to maintain flows through the dry season (Smakhtin, 2001). The larger the aquifer storage, the less frequent the recharge events will need to be to maintain baseflows.

Baseflow separation can be a useful tool in groundwater surface water interaction studies when analysed with physiographic and anthropogenic (e.g. river regulation, dams, drains etc.) factors, and with an awareness of the limitations to this method. A key assumption in baseflow separation is that baseflow equates to groundwater discharge, although this is not always the case. For example, low flow discharges can be maintained through the drainage of saturated soils, perched groundwater released by springs, bank storages, surface water bodies and other drainage systems in hydraulic connection with rivers, as well as ice and snow melting. These types of inputs to a stream may influence the baseflow signal in the steam hydrograph and can sometimes obscure the "true" contribution of groundwater discharge alone (Halford and Mayer, 2000). There are also a number of anthropogenic factors that can impact on low flows, and hence alter the natural baseflow signal. Some of the factors discussed in Smakhtin (2001) include regulated river flow releases from dams and weirs, land use change such as urbanisation, direct river extraction, irrigation return flows and groundwater extraction.

4.5.1.1 Application of Baseflow Filter

The separation of the stream hydrograph into its runoff and baseflow components is somewhat arbitrary, and various techniques have been reported including manual graphical, empirical and automated approaches (Nathan and McMahon, 1990). Reviews of several approaches to baseflow separation and recession analysis are described in Hall (1968), Nathan and McMahon (1990), Chapman (1999) and Tallaksen (1995). The use of baseflow separation methods was originally applied to estimate the surface runoff component of a flood hydrograph, while their use in groundwater-surface water interaction studies has been more limited.

The recursive digital filter first described in Lyne and Hollick (1979) and later discussed in Nathan and McMahon (1990) was selected for use in this thesis because it can be easily automated and has had widespread acceptance for use in low flow hydrological studies. The filter was applied to daily streamflow data for 35 gauging stations on the unregulated river systems in the Namoi River catchment (Figure 4-4) using the Department of Natural Resources streamflow database (DIPNR, 2004).

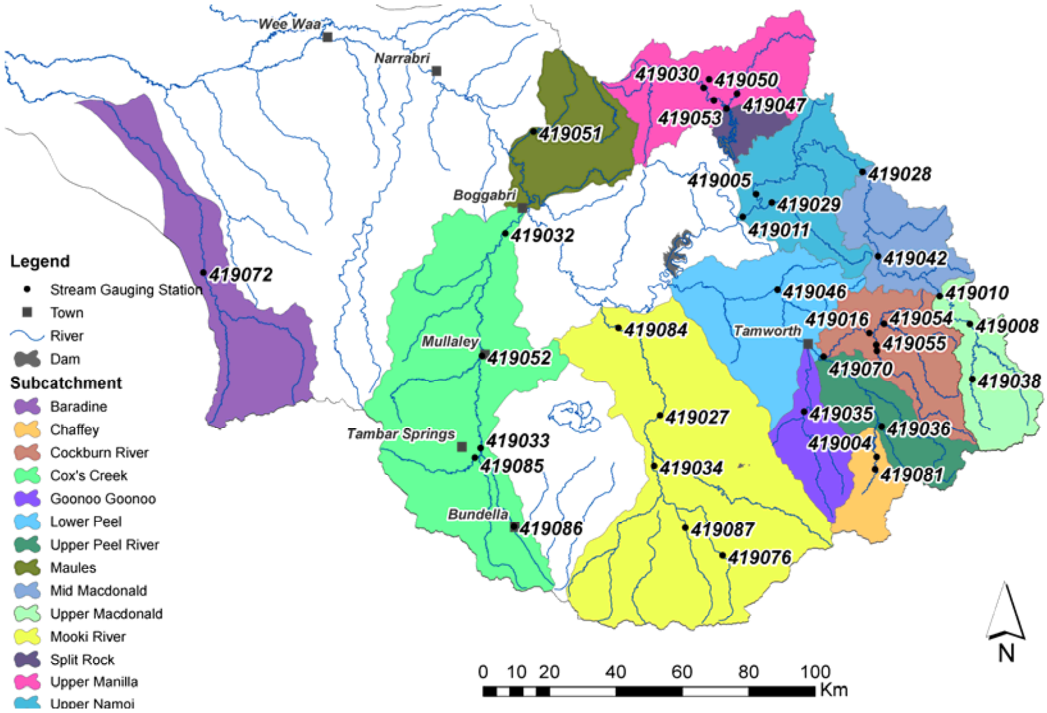


Figure 4-4 Location of stream gauging stations on the unregulated rivers of the Namoi River catchment

The recursive digital filter is based on signal processing theory and has the objective of separating high frequency quick flows, such as surface runoff, from low frequency slow flows, such as baseflow. Although this filtering approach has no physical basis, it provides an objective and repeatable estimate of baseflow contribution to streamflows which can be easily automated to provide a continuous baseflow signal (Nathan and McMahon, 1990). The filter parameter value of 0.925 was reported by Nathan and McMahon (1990) as providing a good estimate of baseflow and was selected for use in this thesis after analysing a range of filter values.

The recursive digital filter has the form:

$$f_k = \alpha f_{(k-1)} + \frac{1+\alpha}{2}(y_k - y_{k-1}) \qquad (4\text{-}1)$$

where f_k is the filtered quick flow response at the *k*th sampling instant, y_k is the observed streamflow, and α is the filter parameter, which influences the baseflow recession. The filtered baseflow is determined by y_k - f_k. The filter is applied in three passes in order to result in a smoother baseflow signal. In both the second and third passes, the observed streamflow is replaced with the estimated baseflow from the previous pass. In the second pass, the filter is used backwards, and $(k+1)$ is used instead of $(k-1)$ (Equation 4-1). The reverse pass reduces any phase distortion of the data arising from the first pass of the filter. The output of the filter was constrained so that the separated slow flow was not negative or greater than the original streamflow. A table of streamflow characteristics for each of the unregulated river gauging stations analysed in this study is provided (Table 4-2) and includes the calculated baseflow index (BFI) using the recursive digital filter. The BFI is a non-dimensional ratio defined as the ratio between the mean baseflow of the separated hydrograph and the mean discharge of the total hydrograph (Smakhtin, 2001). A higher baseflow index suggests a greater contribution of groundwater to streamflow.

The baseflow index over the total length of the hydrograph record was expressed as a percentage and plotted for each gauging station on the unregulated rivers of the Namoi River catchment (Figure 4-5). The total length of the data record was used in order to assess the longest time series baseflow response possible since selecting synchronous stream gauging datasets alone would have substantially limited the data pool. Whilst the baseflow indices are not directly comparable because of the different date ranges of the datasets, baseflow contributions were found to range from 9% to 46% of the total streamflow volumes. There were no clear correlations evident between the BFI and the month of the year. The largest baseflow fractions were generally found for river reaches located in the steeper, upland regions – generally found in the east of the Namoi River catchment. The baseflow fractions generally decreased down-gradient within a given subcatchment, with this trend particularly evident in the Cox's Creek and Mooki subcatchments (refer to Figure 4-4 for subcatchment locations).

Table 4-2 Flow characteristics at unregulated river gauging stations

Station	Catchment	Record start	Record end	Record length (years)	Upstream area (km^2)	Mean discharge (ML/d)	Mean baseflow (ML/d)	BFI	% time river flowing	Dominant hydrological flux*
419072	Baradine	8/05/1981	21/12/2003	21.9	1 000	43	10	0.23	44	Variably Gaining-Losing (mostly losing)
419004	Chaffey	28/04/1915	30/09/1970	53.9	310	174	43	0.25	94	Gaining
419081	Chaffey	5/07/1991	18/06/2003	12.0	280	92	23	0.25	100	Gaining
419016	Cockburn	1/07/1936	1/12/2003	64.4	907	229	59	0.26	95	Gaining
419037	Cockburn	19/06/1965	21/05/1977	7.7	277	94	23	0.25	99	Gaining
419054	Cockburn	17/05/1974	2/08/2003	28.8	391	78	18	0.23	90	Gaining
419055	Cockburn	21/05/1974	2/08/1989	14.6	254	132	50	0.38	91	Gaining
419070	Cockburn	25/06/1980	27/06/2003	22.0	2 439	157	63	0.40	99	Gaining
419032	Cox's Creek	5/06/1965	21/12/2003	38.0	4 040	254	22	0.09	38	Variably Gaining-Losing (mostly losing)
419033	Cox's Creek	9/06/1965	13/12/2003	37.3	1 450	90	13	0.14	83	Variably Gaining-Losing (mostly gaining)
419052	Cox's Creek	1/08/1972	21/03/1989	16.3	2 370	167	20	0.12	41	Variably Gaining-Losing (mostly losing)
419085	Cox's Creek	6/06/1995	13/12/2003	8.4	556	29	6	0.19	97	Gaining
419086	Cox's Creek	5/12/1995	15/01/2003	7.7	150	29	5	0.17	98	Gaining
419035	Goonoo Goonoo	16/06/1965	5/12/2003	33.0	503	72	19	0.26	100	Gaining
419046	Lower Peel	1/07/1936	20/11/1946	8.8	3 880	355	115	0.33	99	Gaining
419051	Maules	8/06/1972	14/12/2003	31.4	454	59	15	0.29	97	Gaining
419010	Mid Macdonald	26/10/1927	10/08/2003	75.5	829	360	130	0.35	99	Gaining
419028	Mid Macdonald	20/05/1965	3/12/2003	24.2	1 760	488	180	0.37	97	Gaining
419042	Mid Macdonald	26/04/1968	27/11/1987	18.8	1 120	393	145	0.36	98	Gaining
419027	Mooki	3/09/1957	21/12/2003	45.7	3 630	322	53	0.17	88	Variably Gaining-Losing (mostly gaining)
419034	Mooki	10/06/1965	12/12/2003	38.0	2 540	210	28	0.13	87	Variably Gaining-Losing (mostly gaining)
419076	Mooki	15/06/1982	8/07/2003	21.4	150	32	7	0.23	97	Gaining

Station	Catchment	Record start	Record end	Record length (years)	Upstream area (km^2)	Mean discharge (ML/d)	Mean baseflow (ML/d)	BFI	% time river flowing	Dominant hydrological flux*
419084	Mooki	29/06/1994	21/12/2003	9.3	6 104	462	60	0.13	53	Variably Gaining-Losing
419087	Mooki	7/12/1995	14/01/2003	7.6	426	24	6	0.26	75	Variably Gaining-Losing (mostly gaining)
419031	Split Rock	2/06/1965	30/06/1986	16.7	1 370	194	47	0.24	99	Gaining
419008	Upper Macdonald	5/06/1924	16/06/2028	3.8	699	192	87	0.45	100	Gaining
419038	Upper Macdonald	22/06/1965	30/11/1987	21.8	358	182	71	0.39	100	Gaining
419030	Upper Manilla	28/05/1965	21/05/1988	20.5	568	124	41	0.34	98	Gaining
419047	Upper Manilla	27/05/1970	21/12/2003	26.9	581	110	31	0.28	97	Gaining
419050	Upper Manilla	1/06/1972	11/08/1992	15.5	73	7	15	0.19	52	Variably Gaining-Losing
419053	Upper Manilla	23/08/1972	30/04/2003	30.7	791	99	26	0.26	99	Gaining
419005	Upper Namoi	10/12/1915	19/08/2003	86.1	2 510	691	268	0.39	100	Gaining
419011	Upper Namoi	15/06/1936	30/09/1953	15.0	3 110	773	278	0.36	99	Gaining
419029	Upper Namoi	22/05/1965	30/11/2003	37.3	389	56	20	0.35	100	Gaining
419036	Upper Peel	17/06/1965	5/12/1986	21.3	93	32	15	0.46	86[+]	Gaining

* Based on analysis of flow duration data together with the shape of the stream hydrograph.

[+] Note data quality codes indicate considerable parts of streamflow record are unavailable for release and were given zero flow reading which has lowered the expected value.

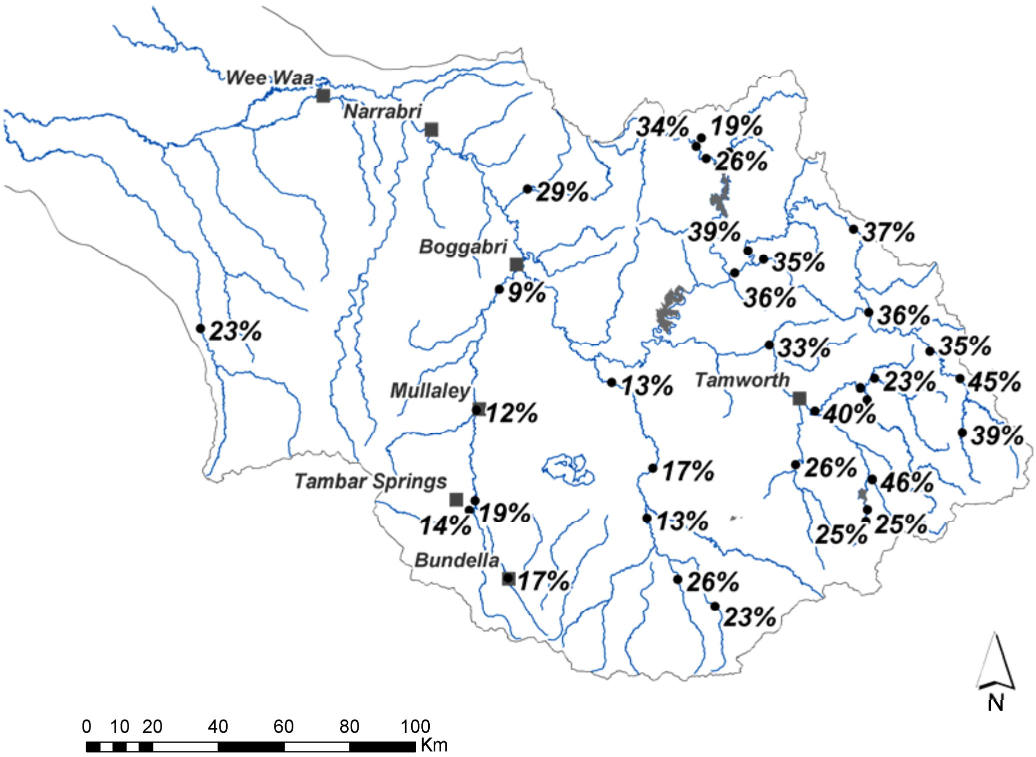


Figure 4-5 Baseflow indices expressed as a percentage for stream gauging stations on the unregulated rivers in the Namoi River catchment, NSW

The larger baseflow fractions that characterised the upper parts of the subcatchments are consistent with systems in which the upper catchment reaches receive a gain of baseflow, in this geomorphic setting, from the fractured rock and volcanic aquifers into which the upper reaches are incised. The downstream river reaches commonly have a lower baseflow index, perhaps because of the varying geomorphology, rainfall patterns at lower elevations and/or widespread use of groundwater in the valleys, which has reduced baseflows as a result of captured discharges. The association between rainfall, extraction and baseflow will be further analysed within the Cox's Creek subcatchment in Chapters 6 and 7. The analysis of the geological, topographical, climatic, geomorphic and anthropogenic influences on the BFI was beyond the scope of this thesis, but would be an important study for further understanding the roles of these factors in influencing baseflow characteristics along the lines of research undertaken by Lacey and Grayson (1998) and Larkin and Sharp (1992).

A decrease in baseflow index within the downstream reaches was commonly associated with a decrease in the percentage of time the river flowed within a given subcatchment (Table 4-2). Using the Cox's Creek as an example, gauging station 419086 in the upper catchment has a BFI of 0.17, and at this point along the river streamflows are measured at the gauge 98% of the time. In contrast, gauging station 419032 located at the catchment outlet has a BFI of 0.09 and streamflows are measured only 41% of the time.

The BFI alone was not found to be useful in determining the direction of flux between aquifer and river systems. The flow duration data, however, were found to be extremely useful in determining the direction of flux when analysed in conjunction with the shape of the stream hydrograph. The use of flow duration data is discussed in the following subsections.

4.5.2 Flow Duration Analysis

The percentage of time where flow has been recorded in the river over the length of the streamflow record was calculated for use in this research in order to assist with characterising river reaches; in particular, to assist with distinguishing gaining from variably gaining-losing river reaches (Figure 4-6).

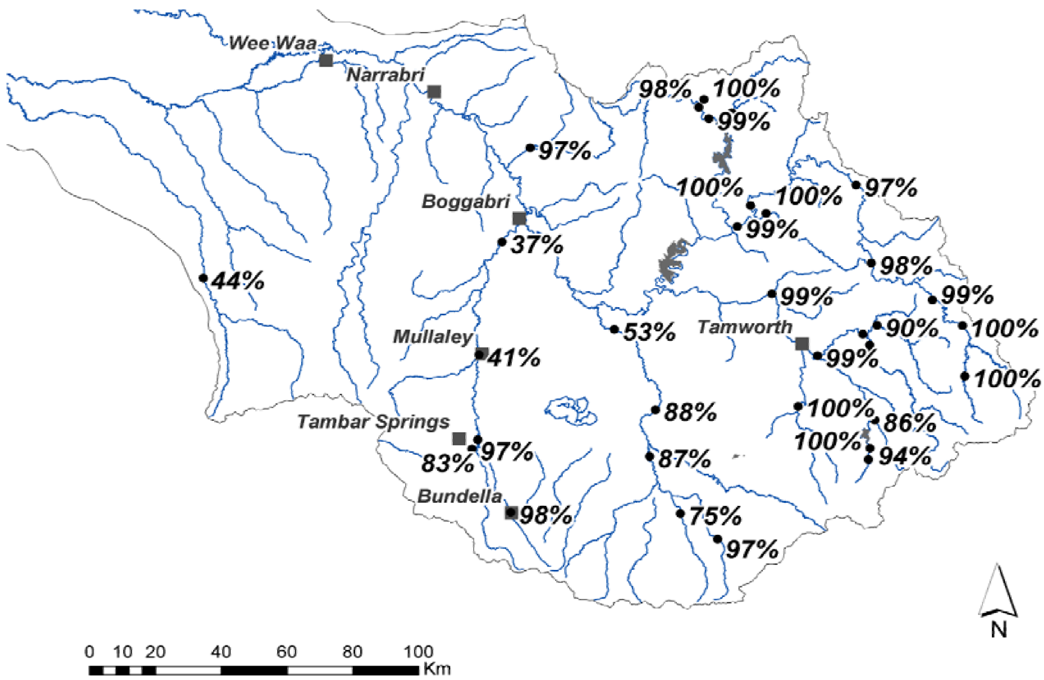


Figure 4-6 Percentage of streamflow record over which measurable river flows (>0.01 ML/day) have been recorded by a stream gauging station

The percentage of time the river flows gives an indication of the extent to which a stream is perennial, intermittent or ephemeral. The definitions of these river types vary in the literature and appear to be somewhat arbitrary. For the purposes of this research a perennial stream is defined as having a streamflow that is measurable throughout the year, with the exception of drought periods when flows may temporarily cease. An intermittent river is defined as having measurable flows throughout most of the streamflow record, but it may also be dry for some periods of time. An ephemeral river is one that flows occasionally, and at these times the streamflow predominantly comprises surface runoff.

The river reaches in the Namoi River catchment were classified as gaining reaches for the purposes of this research where they had river flows measured over 90% or more of the streamflow record and where connection between the aquifer and river was previously established (refer to Figure 4-2, Figure 4-6 and Table 4-2). The rationale behind selecting an arbitrary cut-off of 90% is that within a semi-arid zone such as the Namoi River catchment, if flows are maintained throughout most of the record, e.g. the river is perennial, then the size and hydraulic properties of the aquifers must be sufficient to maintain flows throughout dry periods and hence the gains to the river will be from groundwater storage.

The shorter the duration of measurable flow, the more intermittent to ephemeral is the river system. Assuming a similar physiographic environment, the shorter the period of measured flow, the more likely it is that the water table is below the level of the stream, otherwise baseflows would be maintaining river flows between rainfall events. Hence the predominant flux in an intermittent river reach will be from the river to the groundwater system and it would be characterised as a losing river reach. An intermittent river reach can become a gaining river reach during wetter climatic periods when there has been sufficient groundwater recharge to the underlying connected aquifer to result in groundwater levels that eventually exceed river stage heights, resulting in a reversal of the hydraulic gradient. Intermittent rivers, according to this system of classification, will commonly behave as variably connected-disconnected/gaining-losing river reaches. Ephemeral river reaches will tend to behave as disconnected-losing river reaches.

In addition to the percentage of time where flow has been recorded in the river over the length of the streamflow record, the shape of the flow duration curve can provide further information about the relative contribution of groundwater flow to streamflow as an aggregate response for the upstream catchment area.

Flow duration curves (FDC) display the relationship between a given value of streamflow discharge and the percentage of time the given discharge is equalled or exceeded. Although the use of FDCs in hydrological studies is relatively commonplace, there is little published in the literature on their use, and their potential has not yet fully been explored (Smakhtin, 2001).

FDCs can be plotted in a variety of ways (Chow, 1964). For the purposes of this research, daily streamflow discharge data and the percentage of time-probability for the complete length of the streamflow record were plotted, with streamflow discharges shown in log scale in order to more clearly display the high and low ends of the curve and its slope. The FDC plots are included in Appendix A, with selected examples provided in this chapter.

River reaches that receive a significant input of baseflow will have a lengthy period of low flows characterised by a flat slope in the low-flow portion of the FDC (Figure 4-7). This was evident in the river reaches that had measurable flows for more than 90% of the record, and which for the purposes of this research were characterised as gaining reaches. By contrast, a steep slope suggests a variable and/or low baseflow contribution, and this was evident in reaches characterised as variably gaining-losing/mostly losing reaches.

The flow duration data together with the shape of the stream hydrograph, which provided a visual reference to distinguish baseflow or surface runoff dominated periods within a streamflow record, were the two most important tools used in this research to classify river reaches according to the dominant direction of flux.

The classification of groundwater-river interactions according to the dominant direction of flux, and how these classes appear in the data are discussed in more detail below using selected examples. Note that in the subsections below the term ‘river reach’ is used to connote a length of river between gauging stations, with data from a gauging station representing an aggregate response of upstream catchment processes.

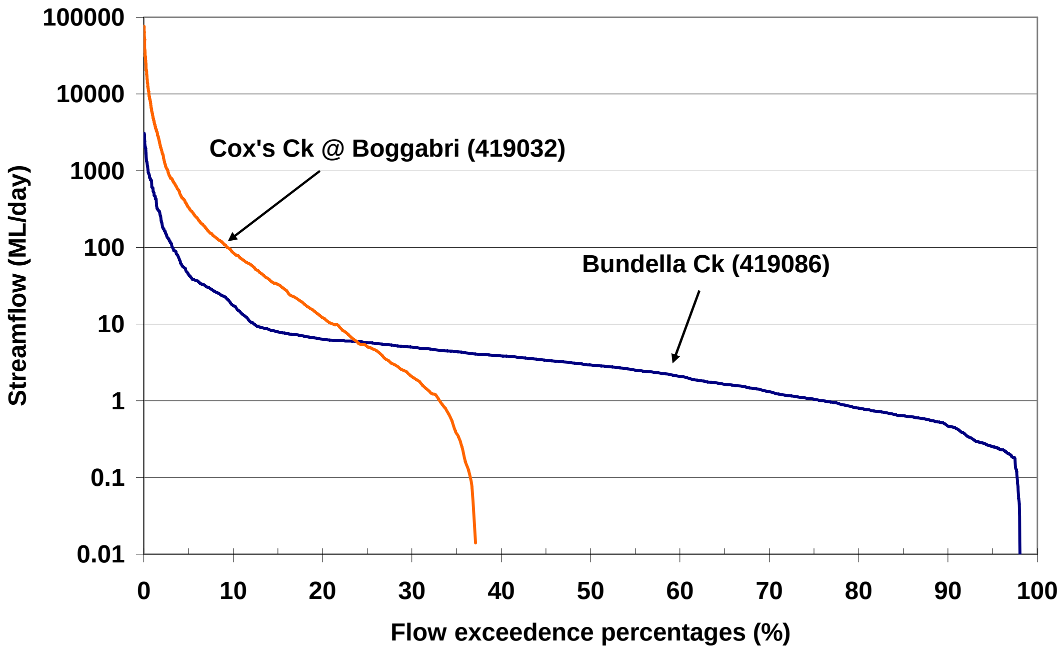


Figure 4-7 Typical flow duration curves representing the probability of flows at gauging station 419032, the Cox's Creek at Boggabri (intermittent reach) and at gauging station 419086, Bundella Creek tributary to Cox's Creek (perennial reach)

4.5.3 Connected Gaining River Reach

A connected-gaining river reach is in direct hydraulic contact with the underlying aquifer through a zone of saturation (as established in Figure 4-2), and the direction of groundwater flow is predominantly into the river. This type of river reach is characterised by a stream hydrograph which has a continuous, or nearly continuous, baseflow contribution to streamflow that can be observed in the filtered stream hydrograph. An example is provided using data from gauging station 419086 on Bundella Creek, one of the upper tributaries of the Cox's Creek (Figure 4-8). Bundella Creek is a perennial stream with river flows occurring for over 98% of the record. Baseflow comprises 17% of the total flows (BFI=0.17; Table 4-2). The flow duration curve for Bundella Creek is characterised by having a flat slope (Figure 4-7) that is typical of a baseflow-dominated river, with low flows (between 0.8 and 10 ML/day) occurring for over 80% of the streamflow record. Whilst this reach sometimes behaves as a losing reach during periods of streamflow recession and, furthermore, the river is dry for some periods of time, this reach has been categorised as a gaining reach because it continues to flow through all but the very driest of periods. Hence, the river flows along this reach for most of the streamflow record are principally derived from groundwater discharges. The relatively low BFI (0.17) determined for this site is perhaps surprising for a gaining reach; this low figure arises as a consequence of the periodic high streamflow discharges that dominate the low flow discharges when expressed as a BFI ratio from mean data values.

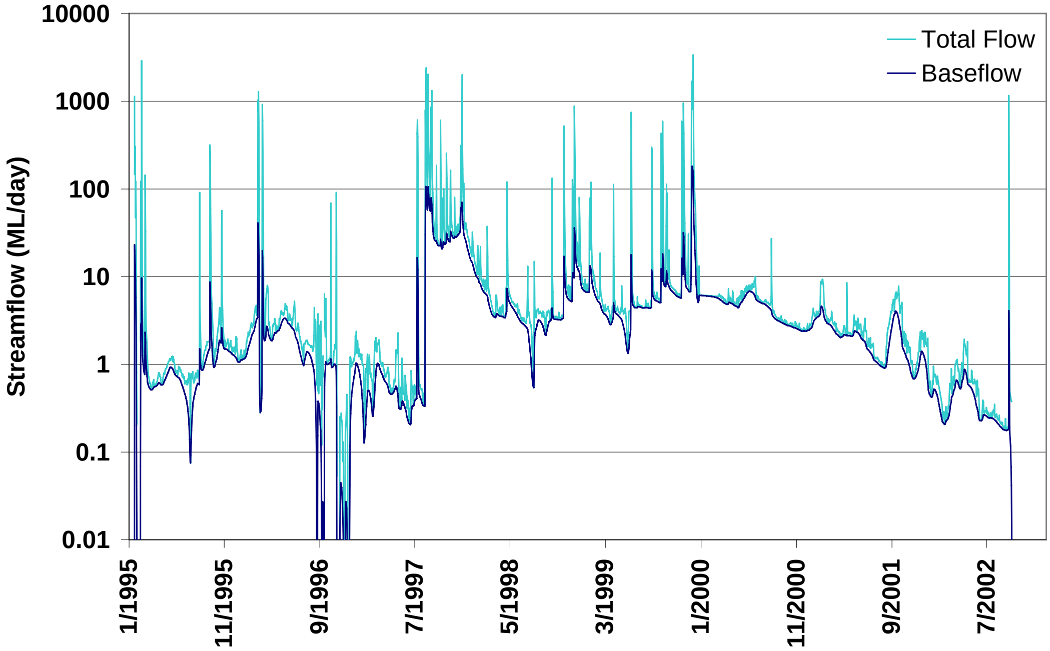


Figure 4-8 Typical baseflow hydrograph for a connected-gaining river reach, Bundella Creek, Cox's Creek subcatchment (gauging station 419086)

4.5.4 Connected Variably Gaining-Losing Reach

A connected, variably gaining-losing river reach is in direct hydraulic connection with the underlying aquifer (as established in Figure 4-2), and the river alternates between being a gaining and losing river. Whether the river is gaining or losing will depend on the relative differences between the groundwater and river stage elevations. These relationships can change seasonally with varying climatic regimes or through changes arising from anthropogenic influences such as surface water and/or groundwater extraction and irrigation. For some periods of time, the groundwater and river systems may become disconnected, such as might occur during dry seasons if groundwater levels fall below the base of the river in the absence of any rainfall recharge events, or during the irrigation season as a consequence of groundwater extraction.

A connected, variably gaining-losing reach is characterised by having a stream hydrograph that alternates between having spiked peaks of short duration, composed of surface runoff, interspersed with wider peaks of longer duration, composed of baseflow. An example hydrograph is provided using data from gauging station 419032 on the Cox's Creek at Boggabri (Figure 4-9), which is typical of a connected-variably gaining-losing reach.

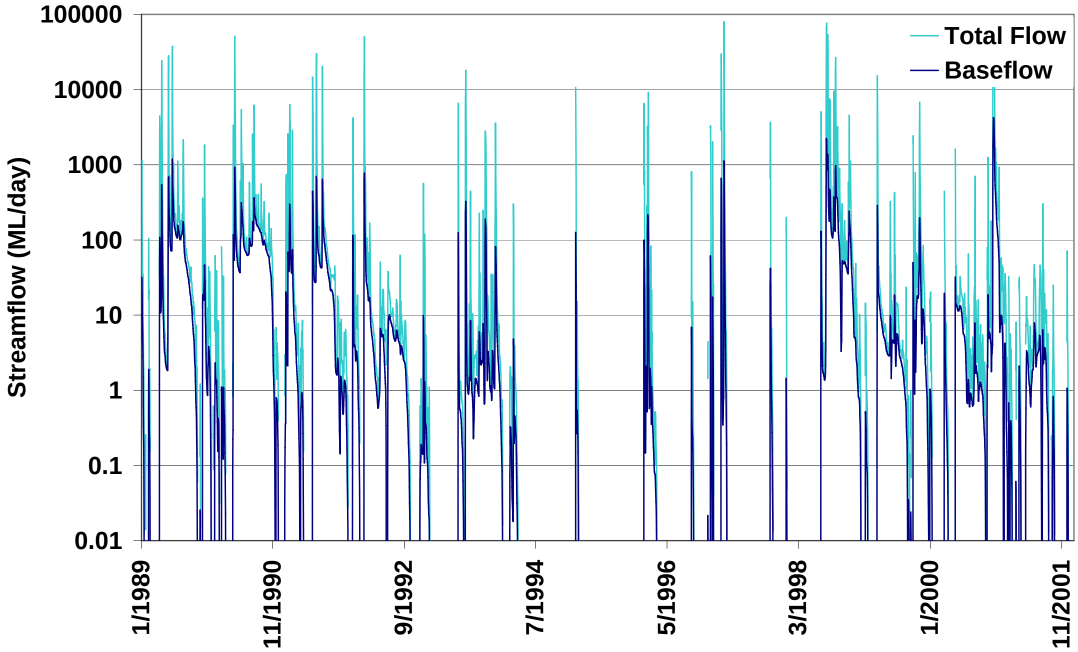


Figure 4-9 Typical baseflow hydrograph for a connected-variably gaining-losing river reach, Cox's Creek subcatchment at Boggabri (gauging station 419032)

The reach of the Cox's Creek at Boggabri is an intermittent river reach, with streamflows occurring for only 37% of the record. Whilst this river reach mostly loses water, it has been categorised as a variably gaining-losing reach in order to reflect the important dynamics in flux which take place between the groundwater and river systems. The flow duration curve has a steep slope (Figure 4-7) indicative of a variable discharge, and for most of the record (63% of the time) flow does not occur in the river. The baseflow contribution to this reach is only 9% of total average flows, which is a much lower BFI than that observed for a gaining reach such as Bundella Creek (which had 17% of total average flows composed of baseflow) (Table 4-2). Whilst for most of the record this river reach is losing water (based on the flow duration data) one can see in Figure 4-9 that there are periods within the streamflow hydrograph when baseflow contributions to streamflow are considerable, lasting for more than a year. Accordingly, this reach has been categorised as variably gaining-losing, with a mostly losing sub-category.

In a variably gaining-losing type of reach, a river will initially lose water at the start of a rainfall event when runoff processes dominate. During wet periods and flood events the infiltration of rainwater and streamflow provides a source of recharge to the underlying aquifer. Groundwater elevations will increase as a result of groundwater recharge, and eventually the elevation of the groundwater system may become higher than that of the river stage. At this point the flow gradient will be reversed in the near stream area, and seepage to the riverbed will occur in the form of baseflow and bank storage discharges. When the baseflow component ceases, in this situation after the water table returns to a level that is below the base of the river, the river channel dries out until the next rainfall-runoff-recharge event takes place.

Groundwater extraction can also cause the hydraulic gradients to fluctuate during the irrigation season by lowering the water table and reversing flow directions such that a gaining stream becomes a losing stream. Groundwater extraction can also result in an increased frequency and duration of periods with reduced baseflow. The characterisation of river reaches for the purposes of this thesis does not distinguish between the various underlying reasons that can cause a change in flux, but merely highlights the fact that a change in the direction of flux is observed. Some of the observed impacts of groundwater extraction on baseflows are further discussed within this chapter in Section 4.6, and more fully in Chapter 7.

4.5.5 Connected Losing Reach

A connected-losing river reach is in direct hydraulic connection with the underlying aquifer (as established in Figure 4-2). In these systems seepage occurs through the base of the riverbed and flows towards the underlying groundwater system. In this research, these reaches were identified where the depth to groundwater was within 10m of the floodplain surface and where the river system was regulated. In the current study all of the regulated river systems were classified as losing systems because regulated flows result in elevated river stages throughout the irrigation season (over the September – March period). Along these river reaches regulated streamflows provide a source of recharge to the underlying aquifers for most of the year. Note the distinction for the purposes of this research between a connected, variably gaining-losing river reach that is mostly losing, versus a connected losing reach. In the connected, variably gaining-losing type of reach baseflow discharges provide a significant input of water to the overall streamflow volumes despite the fact that over most of the record the river loses water to the underlying groundwater. In the connected-losing reaches the artificially high river stage as a consequence of river regulation drives the flux of water from the river to the underlying aquifer. Whilst at times connected losing systems may receive a gain of baseflow, the dominant process is one that primarily encompasses stream transmission losses. Neither baseflow filtering nor flow duration curve analysis was of use in classifying connected-losing reaches because river regulation has altered the natural streamflow characteristics of these river reaches.

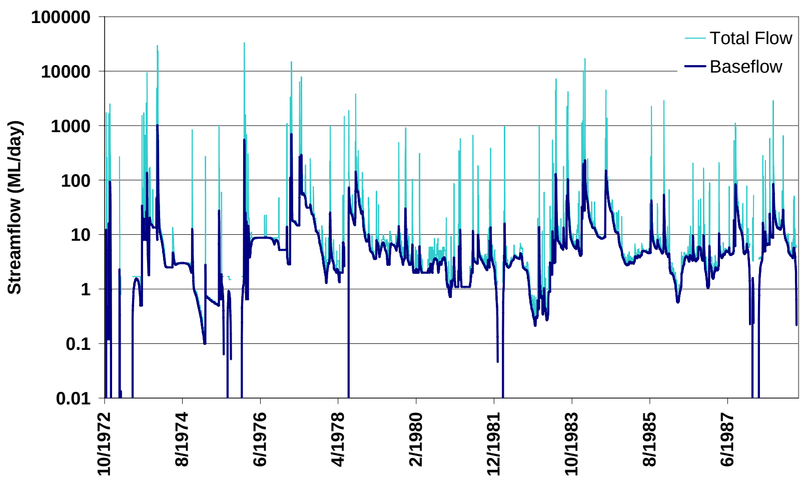
4.5.6 Disconnected Losing Reach

A disconnected-losing stream reach is characterised by having an unsaturated zone between the base of the river and the underlying aquifer (as established in Figure 4-2), and thus there is no direct hydraulic connection between the two systems. In these river reaches water will be lost via seepage through the base of the river channel to the subsurface and the underlying aquifer. The seepage rate will be limited by the hydraulic conductivities of the riverbed material and unsaturated zone sediments. The reaches in the Namoi River catchment mapped as disconnected-losing included river reaches overlying aquifers where the water table for the shallow bores adjacent to the river were deeper than 10 m. The depth to groundwater in the regions mapped as being disconnected was usually less than 25 m, and so a degree of recharge to the semi-confined aquifers as a result of stream transmission loses would be expected assuming sufficient permeability of the river bed and unsaturated zone sediments (see also sections 4.5.1 and 5.5.2 for additional data on vertical connectivity in the Namoi River catchment).

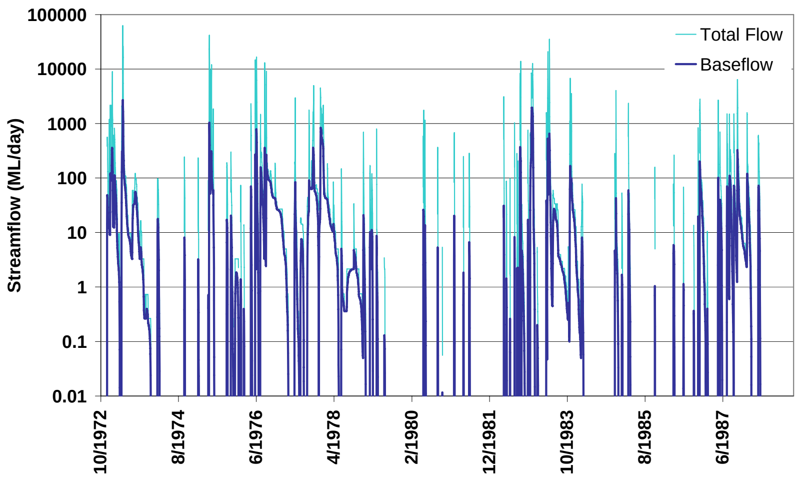
4.5.7 Longitudinal Baseflow Profile within the Cox's Creek Subcatchment

In order to conceptualise the baseflow processes longitudinally within a given subcatchment, the stream gauging stations having synchronous data sets in the Cox's Creek subcatchment were more closely analysed with the objective of further demonstrating the applicability of the system of classification described in the previous sections. There were three stream gauging stations in the Cox's Creek subcatchment with overlapping date ranges: stations 419033, 419052 and 419032 (Figure 4-4), listed from upstream to downstream. The streamflow hydrographs for these three stations together with the filtered streamflow data were plotted over the 11/10/1972 to 20/1/1989 overlapping data period (Figure 4-10), and the streamflow characteristics were re-calculated for this period (Table 4-3). The flow duration curves for the three gauges are shown in Figure 4-11.

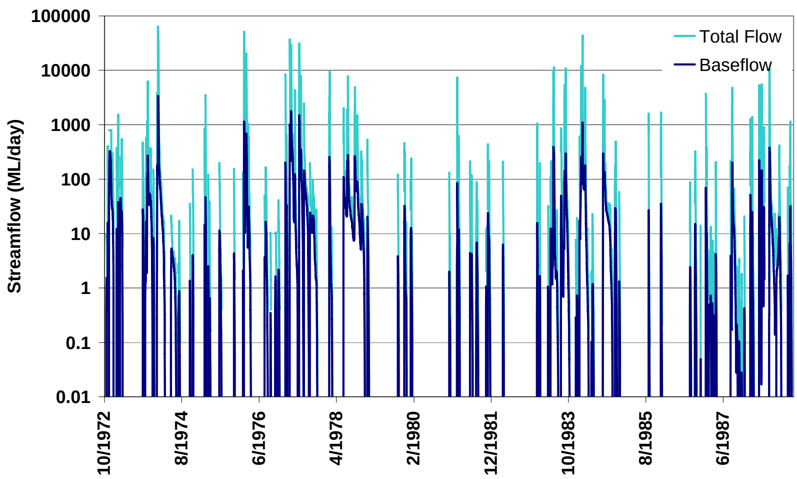
Starting from the most upstream gauge, 419033 at Tambar Springs, one can observe a continuous baseflow signal in the stream hydrograph (Figure 4-10a), with the exception of some rapid drop offs which may be a result of instrument failures and data quality issues. This upper tributary to the Cox's Creek is a perennial stream with flows occurring for over 97% of the period analysed, with low flows occurring over most of the flow duration record (Figure 4-11). The baseflow comprises about 12% of the total flow volumes (Table 4-3) and whilst this fraction is relatively small because of the relatively large volumes of surface runoff that are at times recorded, baseflow occurs throughout the record and provides a constant source of water to the river. The shallow aquifer in this region of the Cox's Creek subcatchment was found to be hydraulically connected with the river (Figure 4-2). The combination of characteristics determined from this gauged site over the period analysed is consistent with a connected gaining reach, as was previously discussed in Section 4.5.3, as an aggregate measure of processes occurring upstream of the gauge.



a) Tambar Springs, Cox's Creek (419033) – Connected Gaining River Reach



b) Mullaley, Cox's Creek (419052) – Connected Variably Gaining-Losing River Reach



c) Boggabri, Cox's Creek (419032) – Connected Variably Gaining-Losing River Reach

Figure 4-10 Filtered stream hydrographs for stream gauging stations 419033, 419052 and 419032 in the Cox's Creek subcatchment over the 11/10/1972 to 20/1/1989 period

Table 4-3 Flow characteristics for gauges in the Cox's Creek subcatchment over the 11/10/1972 to 20/1/1989 period

Station	Upstream area (km^2)	Mean discharge (ML/d)	Mean baseflow (ML/d)	BFI	% time flowing
419033	1 450	79	9.4	0.12	97
419052	2 370	164	19.7	0.12	41
419032	4 040	211	16.6	0.08	34

It is interesting to note that over this particular period of analysis (11/10/1972 to 20/1/1989) the gauged data characteristics from station 419033 suggest that the upstream river behaves as a gaining system, as described above, whilst over the whole record (6/6/1965 to 13/12/2003) the upstream reach behaves as a variably gaining-losing (mostly gaining) reach with flows occurring over only 87% of the record (compare data for gauge 419033 in Table 4-3 with that in Table 4-2). This contradiction presents some difficulty in the absolute characterisation of a river reach using the methods outlined. Some difficulties stem from data quality issues – the streamflow record has lots of zero value recorded flows in the early portion of the record that may be a result of faulty recordings. Moreover, there is considerable data infilling throughout the streamflow record. Additional difficulties in characterising river reaches stem from varying dynamics in flux as a result of varying climatic patterns over the length of a particular data record. The variability in flow characteristics and flux over time for a given gauge highlights the fact that characterising river reaches by assessing only a limited portion of the streamflow record can influence interpretation and gives insight into the difficulty of undertaking an assessment using data collected over limited periods of time.

The hydrographs for the midpoint gauge (419052 at Mullaley) (Figure 4-10b) and the gauge at the catchment outlet (419032 at Boggabri) (Figure 4-10c) both exhibit streamflow patterns that vary between surface-runoff dominated, baseflow-dominated and zero flow events. (The baseflow-dominated events for station 419032 are perhaps more clearly evident in Figure 4-9 where the data record covered relatively wetter climatic periods.) This combination of characteristics suggest that the connected reaches are behaving as connected-variably gaining-losing river reaches, with periods of disconnection occurring at times when groundwater levels fall below the level of the river bed (as an aggregate measure of processes occurring upstream of these gauges), as was previously described in Section 4.5.4. This is consistent with the characterisation of these reaches over the complete data record (Table 4-2).

Streamflows were measured at the Mullaley (419052) and Boggabri (419032) gauging stations over 41% and 34% of the period analysed respectively, indicating that the Cox's Creek changes from a perennial stream to an intermittent stream at some point downstream of the Tambar Springs gauge (419033) and prior to the Mullaley gauge (419052). The slopes of the flow duration curves for the Mullaley (419052) and Boggabri (419032) gauging station data are steep when compared with that of the Tambar Springs gauge (419033), with the steepness reflecting the greater variability in measured discharges in these intermittent systems in contrast to the perennial nature of the river system at Tambar Springs (Figure 4-11). The broader shape of the FDC in the lower flow range for gauge 419052 (Mullaley) when compared with that of gauge 419032 (Boggabri) suggests that baseflows contribute more to the duration of streamflows at 419052 than at 419032. This is consistent with the lengthier baseflow periods observed in Figure 4-10b in comparison to those seen in Figure 4-10c, and the larger mean baseflow volumes calculated at gauge 419052 (19.7 ML/d) versus those calculated at gauge 419032 (16.6 ML/d) over the same period (Table 4-3).

The mean baseflow volume calculated at 419033 (Tambar Springs) is the lowest measured at all the gauges (16.6 ML/d). This is because the volumes of baseflow contributed on a daily basis at station 419033 are low, commonly less than 10 ML/day, compared to those contributed at the other gauges, up to 100 ML/day (Figure 4-10). Thus the distinction between a gaining and variably gaining-losing reach is not based on comparing the volumetric input of baseflow. The reach upstream of Tambar Springs was characterised as a gaining reach because of the constant input of baseflow throughout the streamflow record, even if the volumes contributed were relatively low compared to the volumes contributed at the gauges lower down in the catchment. In the variably gaining-losing reaches the absolute volumes of baseflow contributed might be greater, but gains in baseflow also alternate with the significant loss of streamflow during surface-runoff dominated events.

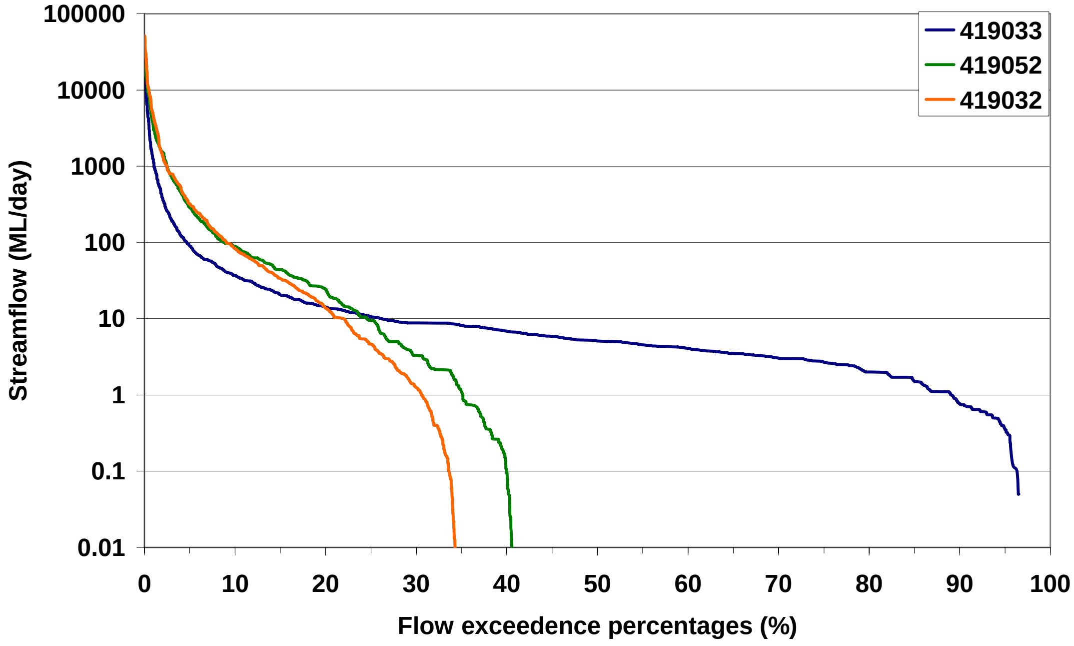


Figure 4-11 Probability of flows for gauging stations in the Cox's Creek subcatchment over the 11/10/1972 to 20/1/1989 period

The BFI calculated at gauge 419052 was identical to that calculated for gauge 419033 (0.12) and suggests that the overall proportion of baseflow relative to the total measured flow has remained the same between the upstream catchment gauge at Tambar Springs and the midpoint gauge at Mullaley. In contrast, the BFI at gauge 419032 at Boggabri demonstrates a drop in the BFI to 0.08 (Table 4-3), suggesting that the baseflow contribution relative to the overall streamflow volume has dropped by a third. These data indicate that there is a large drop in the proportional contribution of baseflow to streamflows between the Mullaley and Boggabri gauges.

There is a distance of about 30 km of mapped disconnection between the aquifer and river system between the Mullaley and Boggabri gauges (Figure 4-2) in an otherwise connected aquifer-river system, making a large part of this section of the river a disconnected-losing reach. A combination of stream transmission losses and evapotranspiration over the length of the disconnected reach, together with the large volumes of groundwater extracted downstream of Mullaley, where most of the groundwater extraction occurs in the subcatchment, may play a role in the observed reduction in baseflow volumes between Mullaley and Boggabri.

Through the examples given above, the applicability of the methods used to characterise the groundwater-river interactions in the Cox's Creek subcatchment has been demonstrated, with some limitations, namely the inter-comparison of gauged data collected over different date ranges and the scale of river reach mapping limited to the distance between gauges (refer to gauging station locations in Figure 4-4). If a river reach did not have any gauging stations but was located in a similar catchment setting to a nearby river that was gauged, a similar flux was attributed. If no similar data were available, the reach remained unassessed.

4.5.8 Aquifer-River Reach Connectivity and Dominant Direction of Flux for the Namoi River catchment

Through the application of the methods discussed in the sections above, a map of aquifer-river hydraulic connection and dominant direction of flux was prepared for the Namoi River catchment (Figure 4-12).

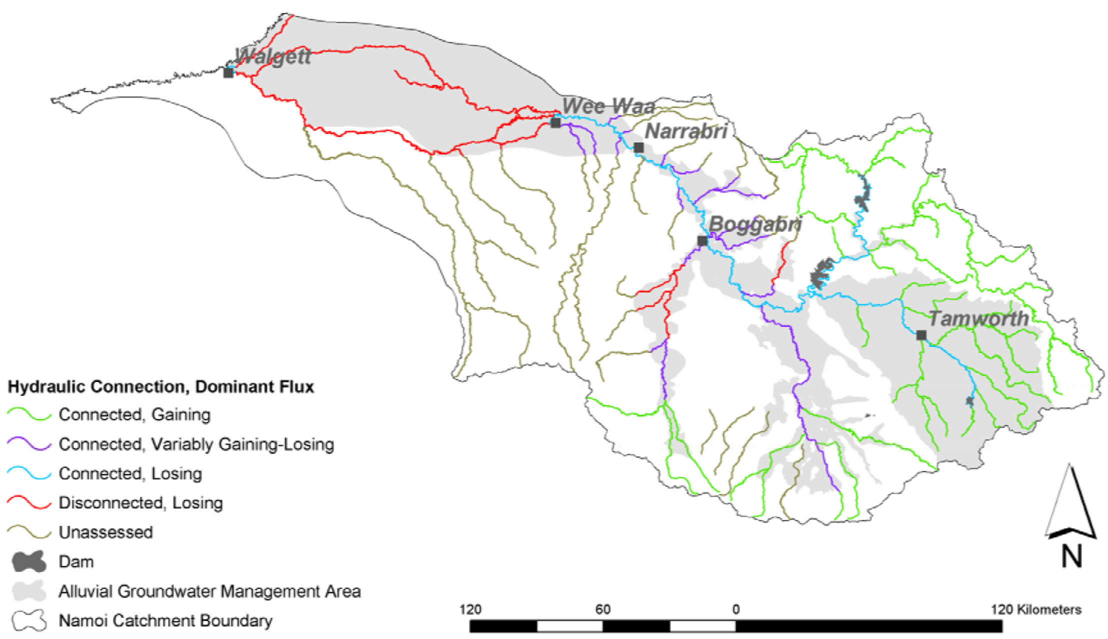


Figure 4-12 Aquifer-river reach connectivity and dominant flux in the Namoi River catchment

Many of the ungauged river systems remain unassessed because of the lack of data. Although there are a number of regionalisation techniques that could be utilised to employ the framework for ungauged catchments, see for example Littlewood *et al.* (2003), it was beyond the scope of this thesis to perform such an analysis.

The resulting classification of the river systems, by inference, also incorporates features of the catchment and its geology, consistent with the Braaten and Gates (2003) report in that:

- Disconnected river reaches tend to occur in the more mature middle to lower reaches within a catchment. These types of reaches provide continual leakage to underlying aquifers, assuming there is permeable material between the base of the river and the aquifer, and hence these reaches are also classified as losing reaches;
- Connected river reaches commonly occur in the shorter, less mature reaches in the upper to middle parts of a subcatchment. These river reaches are generally gaining or variably gaining-losing reaches where direct interaction with the fractured rock or alluvial aquifers occurs; and
- Connected river reaches are also found in the lower, more mature reaches of the major rivers where geological conditions impose regional groundwater flows towards surface drainage features.

Figure 4-12 can be used to assist with the conceptualisation of aquifer-river water management issues within the Namoi River catchment. The classification of river-aquifer reaches according to direction of aquifer-river flux represents the “dominant processes”, knowledge of which may be of assistance in the prioritisation of integrated water resource management objectives such as water quality, water quantity and ecosystem function objectives. The perennial river systems that comprise the connected-gaining river reaches might, for example, have ecosystems that are particularly vulnerable to altered low flow characteristics. These river reaches might also have unique salinity or other water quality parameters due to the proportionally larger baseflow discharges from the underlying fractured rock aquifers that might differ in hydrochemistry to those waters of the variably gaining-losing reaches. Similarly, the variably gaining-losing river reaches would be expected to have their own unique ecosystem function, water quantity, water quality and water security issues particular to these types of reaches. Each category of river reach would likely have its own water management priorities that may require special consideration.

It is clear that for the connected aquifer-river systems, however, it will be critical to understand the potential impacts that groundwater extraction may have on river flows and to capture the key driving factors that influence the dynamics.

4.6 Potential Impacts of Groundwater Extraction on River Flows

The potential impacts of groundwater extraction on river flows from a theoretical perspective were discussed in Section 2.3, where an overview was provided about how groundwater extraction from aquifers that are connected by a continuous or near continuous, saturated zone with the base of a river system can impact upon river flows.

The locations of the groundwater extraction bores in the Namoi River catchment were plotted together with the mapped river reaches in order to assess the potential for groundwater extraction to impact on river flows. It is evident in Figure 4-13 that groundwater extraction bores are commonly located within a few kilometres of connected aquifer-river systems; especially in the upper, eastern parts of the Catchment. Consequently, the potential for groundwater extraction to impact on river flows in the Upper Namoi River catchment is high.

The potential for groundwater extraction to impact upon river flows is further analysed in the following sections. In Section 4.6.1 the vertical connection between aquifers is assessed in order to give insights into whether the exploitation of a deeper aquifer might impact upon shallow aquifer systems that might be in connection with a river system. In section 4.6.2 paired stream and bore hydrographs are analysed in order to give further evidence of groundwater-river interaction processes (hence providing an additional cross-validation of the connectivity mapping in Figure 4-2), and to gain insights into the impacts that groundwater extraction might have on river flows.

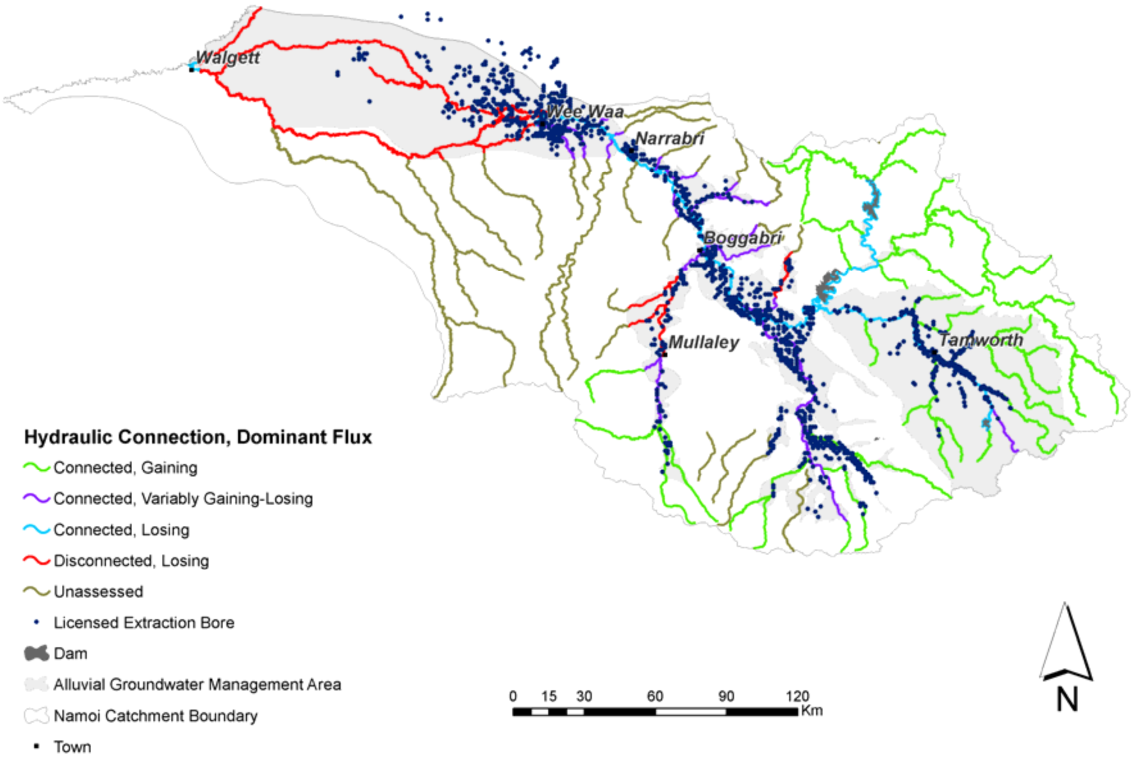


Figure 4-13 Location of extraction bores and river reach classification in the Namoi River catchment

4.6.1 Assessment of Vertical Connection between Aquifers

In general, only the shallowest aquifers in an alluvial aquifer system will be in direct hydraulic connection with a river. However, if vertical flow components exist between a connected shallow aquifer-river system and a deeper underlying aquifer, then the river and the deeper aquifer may indirectly interact with each other. Pumping from a deeper aquifer can result in a downward, vertical hydraulic gradient that may cause groundwater to move from the overlying shallow aquifer into the deep aquifer. This might result in a reduction in groundwater levels in the shallow aquifer, which in turn could alter the extent of the hydraulic connection between the shallow aquifer and river system. Consequently pumping from a deeper aquifer could affect the hydraulic gradient as well as the direction and magnitude of flux between a shallow aquifer in connection with a river system. In order to assess any vertical components of groundwater movement, bore hydrograph data from nested observation bores screening three or more aquifer depths were analysed.

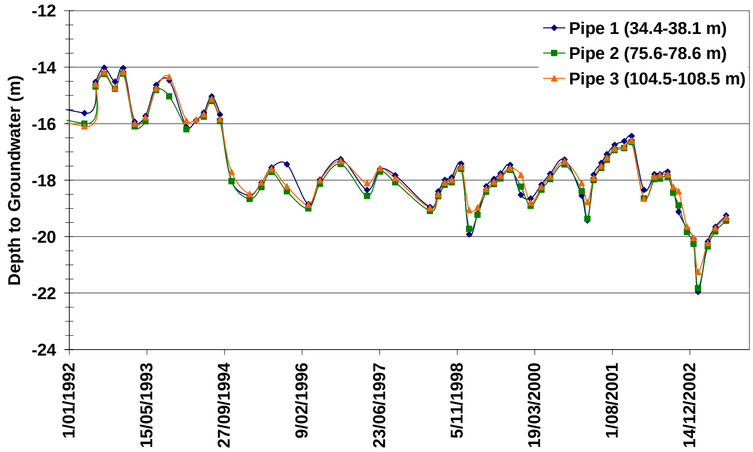
Bore hydrographs can provide meaningful data for assessing the local behaviour of a groundwater system. They are particularly useful in assessing the changes to aquifer storage arising from varying recharge-discharge dynamics. Changes in aquifer storage over time will result in increasing or decreasing water levels, depending on whether the overall volume of water stored in the aquifer has increased or decreased (which can be assessed from the bore hydrograph).

Groundwater hydrographs will differ spatially throughout the catchment, even for a given aquifer, in response to local factors. The variation in aquifer responses to a hydraulic perturbation will be a function of the distance to recharge/discharge sites from the observed aquifer, as well as a function of local hydraulic gradients, and the hydraulic conductivities and porosities of the material through which groundwater flows. In this research the nested observation bores were analysed with the objective of assessing vertical connection between aquifer systems. One would expect the aquifers demonstrating vertical connection to respond similarly to the types of factors listed above.

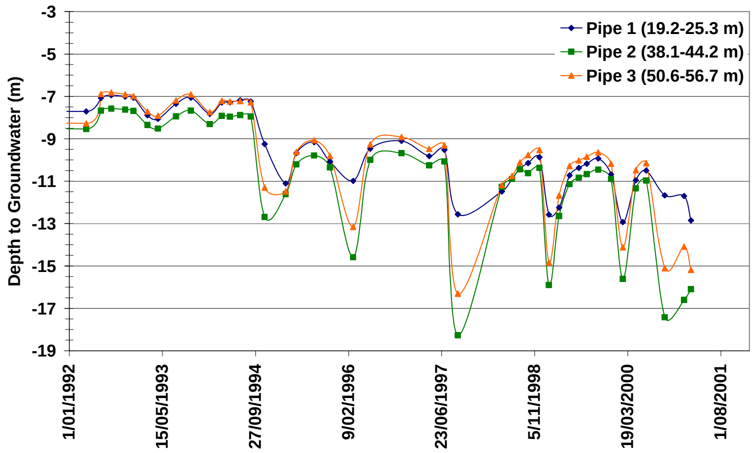
4.6.1.1 Bore Hydrograph Categorisation

There were a total of 184 nested observation bore sites in the Namoi River catchment that had data for three or more screened aquifer intervals. The bore hydrographs were classified into three categories based on a visual inspection, including hydrographs that suggest: 1) strong vertical connection; 2) good vertical connection; and 3) poor vertical connection. A summary table of the bore hydrograph categorisation is provided in Appendix B, with typical examples provided in Figure 4-14 as discussed below.

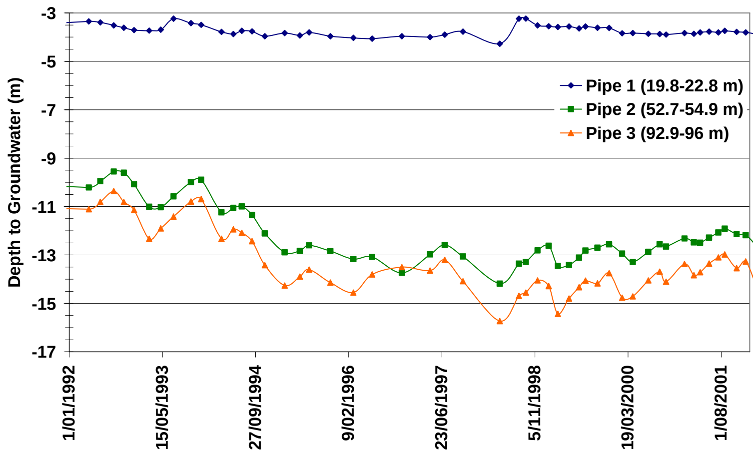
An example of a typical bore hydrograph suggesting strong vertical connectivity is shown in Figure 4-14a for piezometer GW030379 located in the Mooki Subcatchment. Note the regular perturbation in groundwater levels arising from groundwater extraction during the irrigation season. A key characteristic of a hydrograph showing strong vertical connection is that the groundwater response within each of the screened intervals behaves in an identical, or nearly identical, way over time. This type of response suggests that the aquifer is behaving as a homogenous, single aquifer system, and therefore the degree of vertical connection has been categorised as strong.



a) GW030379 in Mooki Subcatchment



b) GW030008 in Mooki Subcatchment



c) GW030433 in Mooki Subcatchment

Figure 4-14 Typical examples of nested bore hydrographs demonstrating a) strong b) good and c) poor vertical hydraulic connection

An example of a typical bore hydrograph that suggests good, as opposed to strong, vertical connectivity is shown in Figure 4-14b using data for piezometer GW030008 in the Mooki Subcatchment. Note the regular perturbation in groundwater levels arising from groundwater extraction from the middle and lower aquifers during the irrigation season. In this example, the measured depths to groundwater within all three screened intervals follow a similar pattern. However, the water levels do not follow an identical pattern as was observed for the piezometer demonstrating strong vertical connection in Figure 4-14a. Groundwater extraction from the deeper aquifers is resulting in a decline in groundwater pressures/levels in the shallow aquifer, suggesting a downward, vertical hydraulic connection. Post the irrigation season, after which time aquifer storage levels recover, there is a corresponding increase in groundwater levels within all three screened aquifer intervals. These periods of aquifer recovery are commonly characterised by vertical, upward (in contrast to vertical, downward) groundwater pressures from the deeper screened interval/aquifer through to the shallower screened intervals. These events in the hydrograph are indicated by periods when water levels measured within the deepest screened interval (Pipe 3) are more elevated than those measured for the shallowest screened interval (Pipe 1). The movement of groundwater in this example has been demonstrated to occur vertically in both the downward and upward directions. Each screened interval behaves as a distinct unit however, suggesting some degree of confinement between aquifer units.

The last of the three examples is for a bore hydrograph that suggests poor vertical connectivity, using data for piezometer GW030433 in the Mooki Subcatchment Figure 4-14c. In this example the groundwater levels remain distinct within each of the screened intervals throughout the length of the data record. Although some possible connectivity could be inferred between the two deepest aquifers based on their exhibiting similar response patterns, no interaction between the shallow and deeper aquifers is evident.

Each of the 184-piezometer datasets were analysed and categorised according to the three categories described above. The results were plotted together with the classification of river reach connectivity (Figure 4-15). Noteworthy is the large number of piezometer sites categorised as having good or strong vertical aquifer connectivity that are located alongside connected aquifer-river reaches. Given the widespread vertical hydraulic connectivity throughout the Namoi River catchment, the potential for groundwater extraction bores to impact on river systems in the connected aquifer-river reaches is substantial.

The fact that only nested sites with three or more screened intervals were assessed left the more shallow aquifer systems such as the Peel Alluvium in the east of the Namoi River catchment unmapped in this assessment. However, aquifer-river interactions within the shallow aquifer systems were assessed in the paired bore and stream hydrograph analysis discussed further below in Section 4.6.2. The Peel alluvium is known to be shallow, generally less than 15m in depth, and is in direct hydraulic contact with the Peel River as shown by the connected aquifer-river reaches demonstrated in Figure 4-15 for the eastern portion of the Namoi River catchment. Thus the potential for groundwater extraction to impact on river flows is also high within the Peel subcatchment, even though there are no nested piezometer sites located in that region.

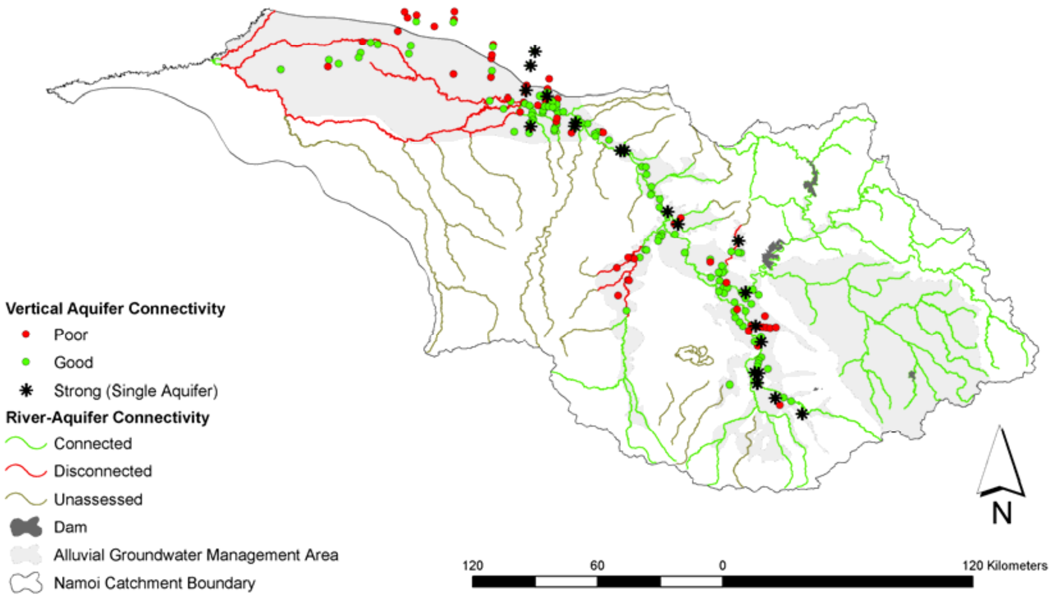


Figure 4-15 Vertical connectivity at nested piezometer sites (with three or more nests)

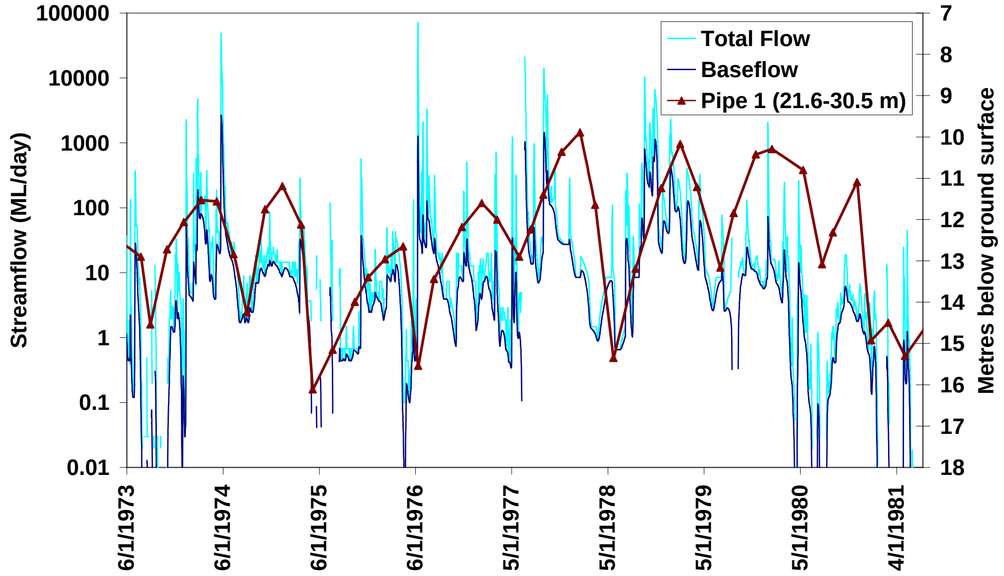
4.6.2 Paired Stream and Bore Hydrographs

In areas where hydraulic connection exists between an aquifer and river system, an observation bore located adjacent to a stream gauging station would be expected to demonstrate a response in groundwater levels that can be related to streamflow. Accordingly, an analysis of paired stream and bore hydrograph data sets can provide additional evidence as to whether groundwater-river interactions may be occurring and, moreover, they may provide insights into how groundwater extractions impact upon river flows.

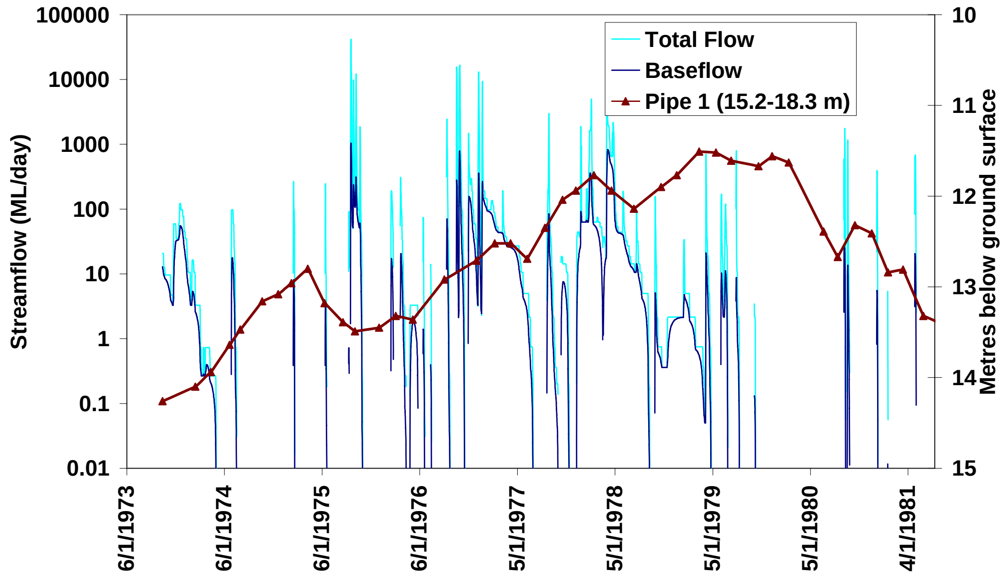
There were 140 pairs of observation bore and stream gauging station data sets where an observation bore was located within 5km of a gauging station, and for which there were coinciding data records. The distance of 5km was arbitrarily chosen as a reasonable cut-off distance for this analysis because few observation bores were located directly adjacent to a stream gauging station. Direct comparisons of river stage and groundwater elevations could not be made because the gauging stations in the Namoi River catchment have been surveyed relative to an arbitrary reference point, rather than relative to the natural ground surface. Whilst surveyed elevation data for the groundwater and river systems would ideally have been used to determine interaction processes, including the direction of flux (previously discussed in Section 4.5), these were generally not available, and as a result comparisons were made between the responses associated with paired streamflow discharges and groundwater level records.

Nonetheless, this type of analysis provides a way forward in conceptualising the temporal groundwater-river interaction processes within the catchment in the absence of the types of data sets required for a more objective study (e.g. surveyed paired bore and piezometer transects with data loggers). It should be noted for completeness that there was a small number of surveyed gauging stations and piezometer transects located within the Peel subcatchment; however, the data record was both short (less than 3 years) and the data record was interrupted, and so no reliable assessment of the direction of flux could be made using that data.

The paired stream and bore hydrograph data sets analysed in this research were categorised as demonstrating either: 1) good or 2) poor evidence of aquifer-stream interaction. A summary table is provided of each analysed pair in Appendix C, with selected examples shown in Figure 4-16 as further discussed below.



a) Good evidence of aquifer-river interaction: paired bore and stream hydrograph for gauging station 419034 on the Mooki River at Caroona with observation bore GW026742



b) Poor evidence of aquifer-river interaction: paired bore and stream hydrograph for gauging station 419052 on the Cox's Creek at Mullaley with observation bore GW035834

Figure 4-16 Typical examples of paired stream and bore hydrographs illustrating categories demonstrating a) good evidence, or b) poor evidence, of aquifer-river interactions

An example of a paired stream and bore hydrograph that demonstrates good evidence of aquifer-stream interaction is shown in Figure 4-16a. The paired data sets are for stream gauging station 419034 on the unregulated Mooki River at Caroona and observation bore GW026742. Gauging station 419034 is located on a reach that has been mapped as a connected, variably gaining-losing (mostly gaining) river reach (refer to Table 4-2 and Figure 4-12). One can see from Figure 4-16a that rises in groundwater levels coincide with baseflow-dominated events and lower groundwater levels with runoff-dominated events. Furthermore, increases in groundwater levels follow high-flow, flood events. These types of patterns provide good evidence that groundwater-river interactions are occurring. The screened aquifer interval of observation bore GW026742 is 21 to 30 m below the surface (Department of Natural Resources Database). The material above the screened aquifer has been described within the driller's log as a clayey sand, and is clearly sufficiently permeable to allow the transmission of water between the aquifer and river systems. This finding is consistent with the strong and good vertical hydraulic connectivity in this part of the catchment (Figure 4-15).

The relative infrequency in the collection of groundwater level data, collected at most quarterly, compared with the daily collection of streamflow records makes the direct comparison of flux response between the groundwater and river systems somewhat difficult to interpret, especially in systems where groundwater pumping dominates the bore hydrograph. Nevertheless, the data patterns provide reasonable evidence that river and groundwater interactions are taking place at this site (Figure 4-16a).

An example of a paired stream and bore hydrograph that demonstrates poor evidence of aquifer-stream interaction is shown in Figure 4-16b. The paired data sets used in this example are from stream gauging station 419052 on Cox's Creek at Mullaley and observation bore GW035834. Gauging station 419052 is located at the junction between a connected, variably gaining-losing river reach (upstream of the gauge) and a disconnected, losing river reach (downstream of the gauge). Observation bore GW035834 is located downstream of the gauge in the portion of the Cox's Creek catchment where the river and underlying aquifer have been mapped as disconnected. The screened interval of GW035834 is 15.24 to 18.28 m below the natural surface and the groundwater levels vary from 11 to 15 m below the surface. The groundwater levels appear to be following the residual rainfall pattern for the Cox's Creek subcatchment (Figure 6-4), which suggests very slow infiltration of rainfall recharge water through to the underlying aquifer along with any river water that might also infiltrate to the underlying aquifer. The material above the screened aquifer has been described within the driller's log as 'alluvial type' material (Department of Natural Resources

Groundwater Database), which is somewhat surprising given the slow recharge through the unsaturated zone as evidenced by the bore hydrograph, and so it is probable that the aquifer material includes a considerable fine grain fraction that is slowing down the vertical movement of water.

There is almost no similarity in patterns when comparing the observed stream and bore hydrographs, which suggests that very little interaction is taking place between the river and aquifer systems. It could be argued, however, that the groundwater level response is delayed by about a year when compared to the baseflow signal, indicating that there could be some degree of upstream leakage of river water to the aquifer as would be expected at the junction of a connected-disconnected river reach. If rain water, as well as some river water, were infiltrating to the underlying groundwater at a rate of approximately 15m/year (e.g. where the depth to groundwater is on the order of 15 m and the delay in aquifer response between a measured streamflow event and any associated rainfall processes is one year) this would be consistent with the hydraulic conductivity of a clayey, fine-grained sand. This relatively slow rate of recharge would be in keeping with the poor vertical connectivity of this area as assessed through the analysis of nested bore hydrographs (Figure 4-15). This region has been experiencing falling groundwater levels in response to the use of groundwater for irrigation within the subcatchment (Brownbill, 2000). The falling water tables in this area may be explained in part by the poor vertical connectivity and hence the absence, or near absence, of river recharge to the underlying aquifer.

The data pair categories were spatially plotted together with the aquifer-river connectivity mapping (Figure 4-17), providing an independent validation of the characterisation work undertaken for this thesis. In the areas mapped as having connected aquifer-river systems, the paired hydrographs also give good evidence of aquifer-river interaction. The regions mapped as having disconnected aquifer-river systems generally have paired hydrographs that demonstrate poor evidence of aquifer-river interaction. There are some exceptions, however, within the disconnected reaches in the area between Wee Waa and Walgett along the northern branch of the Namoi River (Pian Creek). In this area the hydrograph pairs suggest that stream-aquifer interactions are occurring, and that river leakage is recharging the underlying aquifers. This is supported by the map of vertical connectivity that shows good to strong vertical connection in this region, and by previous hydrochemical studies in the Lower Namoi

(McLean, 2003; Williams, 1997) that suggested that the river system is recharging the underlying aquifers in this area. The hydrochemical studies conducted in the Mooki subcatchment (Coram and Jaycock, 2003; Lavitt, 1999) also provide supporting evidence of groundwater recharge to the shallow aquifer by river water, consistent with the paired hydrographs.

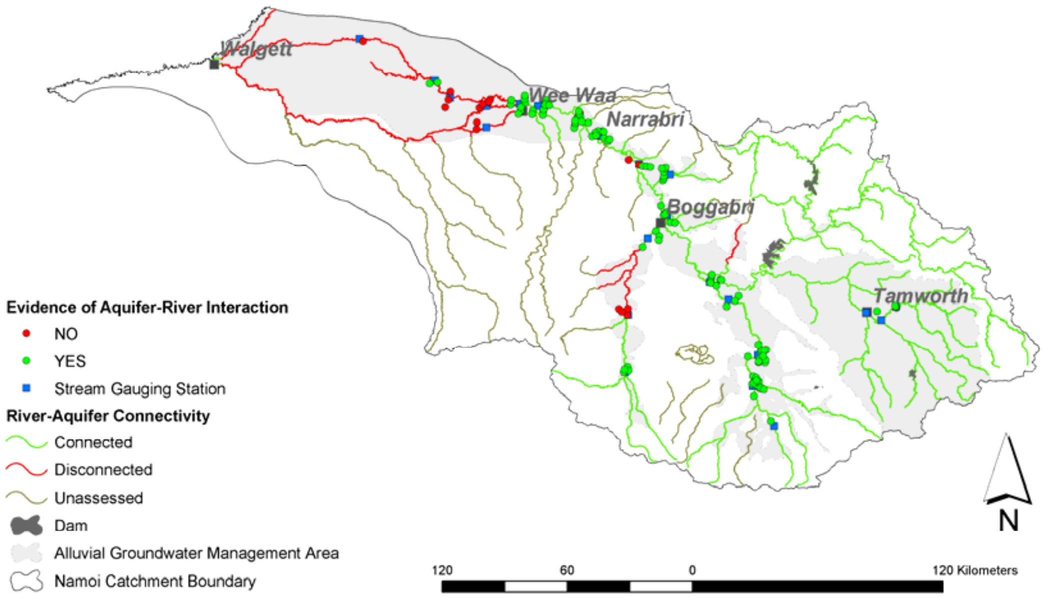


Figure 4-17 Evidence of aquifer-river interaction in the Namoi River catchment based on the analysis of paired stream and bore hydrographs

The analysis of paired stream/bore hydrographs was particularly useful in illustrating the potential impact that groundwater extraction may have on river flows in connected aquifer-river systems. Figure 4-18 provides an example of data for a connected-variably gaining-losing river reach for stream gauging station 419032 on Cox's Creek at Boggabri and observation bore GW036002, located approximately 5 km down gradient from that station.

The three aquifers screened at this site (GW036602) demonstrate good vertical hydraulic connectivity, with the shallower aquifers responding to the pressure variations from groundwater extraction in the deepest aquifer (Figure 4-18). The groundwater levels fluctuate in response to seasonal irrigation pumping, with the lowest groundwater levels found in late February, towards the end of the irrigation season. Groundwater levels subsequently recover to varying extents after the irrigation season, when the aquifers are recharged during periods with streamflow events (and the associated rainfall-runoff-recharge processes), as well as through hydrostatic rebound of the aquifer post the pumping season as a consequence of equilibrating groundwater pressures over the region.

The period 1993-1997 shows a pattern of groundwater levels being increasingly drawn down over time, with less post-irrigation season water level recoveries evident. This period of time coincides with a period of rapid increase in the number of properties using groundwater during the 1994-95 drought, as well as the introduction of the Murray Darling Basin Ministerial Cap which placed an upper limit on the volumes of surface water that could be extracted, resulting in an increased use of groundwater for irrigation. The stream hydrograph during this period is characterised by having interspersed spikes of short duration flows, composed of surface runoff lasting only days, instead of the lengthier flows previously observed lasting weeks to months. The baseflow contributions to flow over this period are significantly reduced.

From 1998-2000, groundwater pressures begin to recover during the post-irrigation season due to a return to wetter climatic conditions, coupled with a reduction in the volumes of groundwater extracted compared to the previous period. The stream hydrograph during this period once again shows the streamflow events are of longer duration due to increased baseflow contribution to streamflow.

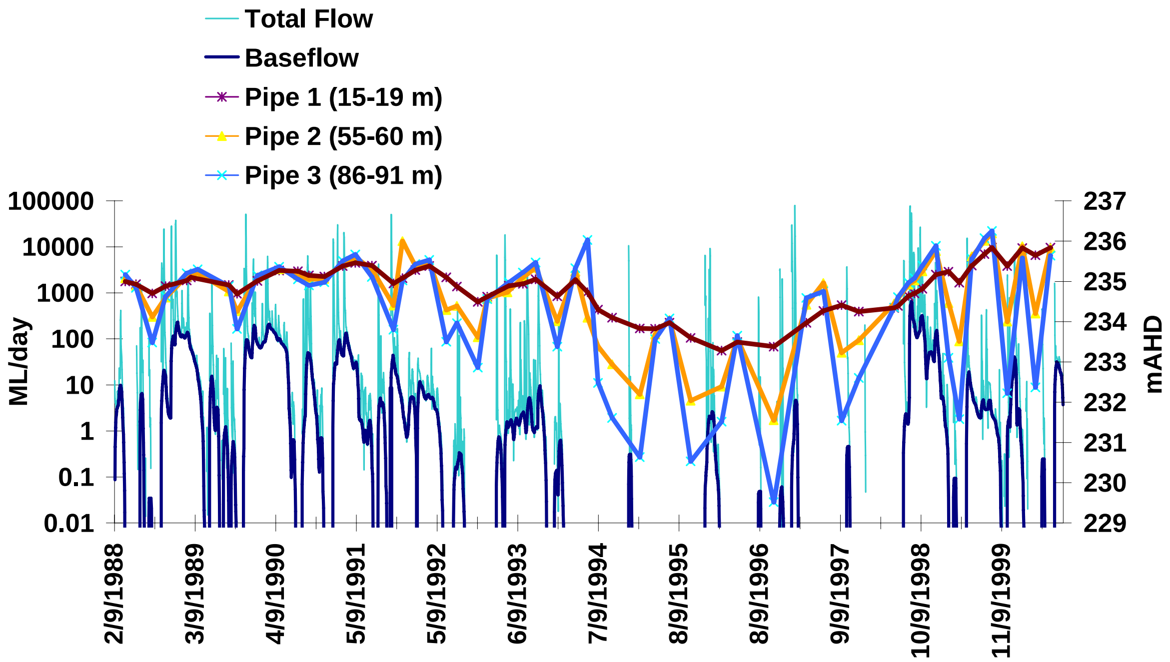


Figure 4-18 Paired bore and stream hydrograph for gauging station 419032 on the Cox's Creek at Boggabri with observation bore GW036602

It is evident from this example, that in regions where aquifers exhibit vertical connectivity, groundwater extraction from a deep aquifer can impact on the connectivity between the shallow aquifer and river system and result in reduced baseflow volumes. In the connected aquifer-river reaches of the Namoi River catchment it will be important to quantify the temporal dynamics of water fluxes between groundwater and river systems arising as a consequence of groundwater extraction, and to elucidate management priorities for water allocation. A more detailed analysis of groundwater extraction data will be undertaken in this thesis using this site as a focus area in order to better understand the relationship observed between reduced groundwater levels and the apparent association with reduced baseflow events. In Chapter 5, the development and conceptualisation of a simple model appropriate for investigating the impacts of groundwater extraction on river flows at the catchment scale is discussed, with model validation and application following in Chapters 6 and 7.

4.7 Chapter Summary

In this chapter a framework was developed to characterise the river reaches within the Namoi River catchment according to the types of groundwater-river interactions observed. River reaches were characterised according to three levels of information; namely: 1) presence of hydraulic connection; 2) dominant direction of aquifer-river flux; and 3) the potential for groundwater extraction to impact on river flows. The methods used to characterise the river reaches included: 1) a comparison of groundwater and river channel base elevations using a GIS/database; 2) an analysis of stream hydrographs and the application of a baseflow separation filter; 3) an analysis of flow duration curves and the percentage of time a river flows; 4) an analysis of vertical aquifer connectivity from nested piezometer sites; and 5) an analysis of paired stream and groundwater hydrographs. The theoretical responses for gaining, losing and variably gaining-losing river reaches were detailed along with the processes that operate in these systems. A longitudinal baseflow profile for the Cox's Creek subcatchment was evaluated in order to conceptualise the baseflow processes in that subcatchment and to demonstrate the applicability of the system of classification. The characterisation of aquifer-river interactions outlined in this chapter will be used as a basis for further model development and validation. A discussion of model conceptualisation and development follows in Chapter 5.

Chapter 5 Model Conceptualisation and Development

5.1 Introduction

The importance of quantifying the impacts of groundwater extraction on river flows within the connected aquifer-river systems of the Namoi River catchment was established in earlier chapters of this thesis, with aquifer-river reach connectivity and dominant direction of flux mapped for the Namoi River reaches in Chapter 4. This chapter advances the thesis objectives by leading the reader through the development of a simple integrated aquifer-river model appropriate for investigating the impacts of groundwater extraction on river flows in connected aquifer-river systems for use at the catchment scale. Some of the modelling approaches commonly used in hydrological studies are outlined in order to provide a context for the model conceptualisation and development undertaken for this thesis. A summary of the models previously implemented in the Namoi River catchment is also given. The rationale for the selection of the IHACRES rainfall-runoff model and its further development within the context of the current research objectives is outlined, and the derivation of the IHACRES_GW model for use in this study is fully described along with a sensitivity analysis of each model parameter.

5.2 Modelling Approaches

The journal literature covers a wide range of modelling approaches for application in aquifer-river interaction studies, with each modelling approach differing in terms of the degree to which physical processes are represented, the data requirements and associated data/computational costs, the model capabilities and the form of model outputs.

Each type of modelling approach has its strengths and limitations. Often there is no ‘best’ model for all applications and the most appropriate model will depend on the intended use and data availability. Surface-groundwater modelling has commonly tended to take either a surface water or groundwater focus, with the non-primary domain represented adequately, but in less detail. More fully functioning integrated models are being developed (Camp and Dresser & McKee Inc., 2001).

5.2.1 Model Categories

Mathematical models in the discipline of hydrology (including surface and subsurface) generally fall into three main categories: empirical or statistical/metric, conceptual and physically-based (Wheater *et al.*, 1993). The distinction between empirical, conceptual and physically-based models is sometimes not a clear one and is somewhat subjective. Models commonly contain a mix of modules from each category or may be a hybrid of two or more types. The three types of model categories commonly used are discussed below along with some of their strengths and limitations.

5.2.1.1 Empirical (or Metric) Models

Empirical models are generally the simplest of all the model types, and they are used to describe the behaviour between variables on the basis of observed data alone. Often the relationship between observed variables is described with a simple mathematical function without any assumptions made regarding the underlying physical processes (Wheater *et al.*, 1993).

The equation describing baseflow recession, which is expressed as the exponential decay of groundwater discharge within a stream, is an example of a commonly used empirical model.

$$Q = Q_0 e^{-kt}$$

where Q_0 is the discharge at the start of the baseflow recession, Q is the discharge at any time over the recession period, k is the recession constant and time t is the time since the recession began. The value of the recession constant, k, is typically estimated empirically from continuous hydrograph records over an extended period (U.S. Army Corps of Engineers, 1999).

Another example of an empirical model is the unit hydrograph theory commonly applied in the simulation of catchment scale rainfall-runoff relationships (Chow, 1964). In this modelling approach the streamflow response to each unit of effective rainfall (the portion of the rainfall that becomes streamflow) is calculated as a linear, time invariant function. A major strength of this modelling approach is that once the streamflow and effective rainfall components of an observed response have been separated, a unit hydrograph can be derived that allows for the event response to be characterised. The variability of the unit hydrograph can be established by analysing data from a range of events (Wheater *et al.*, 1993).

Empirical models tend to be used equally by both surface and subsurface hydrologists because of their simplicity. Empirical models can have high predictive powers within the range of data available, but often lack explanatory depth. They are usually specific to the conditions under which data were collected and in these situations should not be extrapolated to other conditions or other catchments (Mulligan and Wainwright, 2004). These types of models are often criticised for not considering the physical attributes of the system and for ignoring the inherent non-linearity of a system.

5.2.1.2 Conceptual Models

The use of the term *conceptual model* can be somewhat confusing because of the various denotations. A conceptual model can be described as the basic idea or construct of how a system operates (Bredehoeft, 2004; Konikow and Bredehoeft, 1992). To a hydrogeologist, a conceptual model includes factors such as the geological framework, the location, types and characteristics of the aquifers in the study area, the identification of recharge and discharge sites and the direction of groundwater flow for the region to be modelled. An equivalent term commonly used in the field of hydrology is the *perceptual model* (Beven, 2000a). In either case the terminology describes a mental model that is based on a researcher's experience, prior knowledge, familiarity with datasets and knowledge about the study area; the formulation is qualitative.

In contrast, the use of the term *conceptual model* in the discipline of surface hydrological modelling refers to a type of model incorporating a relatively simple mathematical description for each of the processes being considered. A conceptual model typically represents a catchment by a series of internal storages, with individual storages representing key aspects of, or processes within, the system. Some examples of conceptual models that have been used to model groundwater-river interactions include Croke *et al.* (2000), Dietrich *et al.* (1989), Jakeman *et al.* (1989) and Moore and Bell (2002). This style of modelling is traditionally preferred by surface hydrologists because subsurface processes are mostly inferred from the stream hydrograph.

Nonetheless, conceptual models are increasingly being used by hydrogeologists to represent subsurface processes in data limited, highly heterogeneous and/or large catchments, and where only a final equilibrium response to a stressed system is of interest (Dawes *et al.*, 2004; Dawes *et al.*, 2001).

Traditionally, conceptual models for hydrological modelling apply a lumped modelling approach where the catchment (or storage components within the catchment) is represented as a single unit with state variables representing average values over the catchment area (Beven, 2000a). Conceptual models may also be applied in a semi-distributed manner by disaggregating a catchment into linked subcatchments over which the model is applied (Kokkonen *et al.*, 2001; Merritt *et al.*, 2003).

The observed relationship between variables (or storages) in conceptual models is described by functional forms that incorporate parameter values. Each of the model storage components are generally made up of empirical models, so many of the limitations of empirical models can apply to conceptual models. However, the configuration and relationships between storages can provide additional insights into the physical processes governing the system behaviour (Mulligan and Wainwright, 2004).

Parameter values for conceptual models are typically obtained through calibration against observed data, such as stream discharge. Due to the requirement that parameter values are determined through calibration against observed data, conceptual models tend to suffer from problems associated with the identifiability and non-uniqueness of their parameter values (Jakeman and Hornberger, 1993; Merritt *et al.*, 2003) because there may be several possible 'best' parameter fits that provide an equally good explanation of the data relationships or 'equifinality' (Beven, 2000b). Such problems with parameter identification can be minimised through limiting the number of parameters to be estimated and by using knowledge of the system to limit the range of possible values (Dunn, 1999; Koivusalo and Kokkonen, 2003; Seibert and McDonnell, 2002; Uhlenbrook and Sieber, 2005). The lack of uniqueness in parameter values for conceptual models means that the parameters in such models may have limited physical meaning (Wheater *et al.*, 1993).

5.2.1.3 Physically-Based Models

Physically-based models operate through solving mathematical equations describing fundamental physical principals. These models often apply a distributed modelling approach whereby a catchment is descretised into a large number of elements or grid squares, and model predictions are distributed in space (Beven, 2000a). The spatially distributed, physically-based type of groundwater model is the only type of model available that allows for the groundwater system to be modelled in two or three dimensions, and hence is a powerful tool in groundwater management. State variables representing local averages, such as hydraulic conductivity for example, are applied to each descretised unit of space, and mathematical equations representing physical processes are solved for each region. In theory, the parameters used within physically-based models are measurable, for example, through field or laboratory measurement and sampling, and hence have known values. In practice, the large number of parameters required to represent key physical processes and characteristics arising from spatial heterogeneities render many parameters unknown (Beven, 2000b).

Where parameters cannot be measured in a catchment they must be determined through calibration with observed data. Parameter estimates that are calibrated often have non-unique values, a problem also found when using empirical and conceptual models, and hence the physical interpretability of the values may be questionable. Where measurements can be made, point data from localised areas are often used to represent large areas, and the data sets are aggregated to the scale required for descretisation. Differences between that scale at which measurements were made and the scale at which the model algorithms apply sometimes creates additional uncertainty in model outcomes (Wheater *et al.*, 1993).

The industry-standard model code used for modelling hydrogeological systems is a spatially distributed, physically-based model code entitled MODFLOW (McDonald and Harbaugh, 1988), which solves the governing differential equation for groundwater flow in three dimensions:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W = S_s \frac{\partial h}{\partial t}$$

where K_x,K_y and K_z are values of hydraulic conductivity along the *x,y* and *z* coordinate axes; *h* is the hydraulic head; *W* is a flux term that accounts for pumping, recharge , or other sources and sinks; S_s is the specific storage; and *t* is time. The MODFLOW capability (and that of other spatially distributed physically-based models) is continually being developed, with the current focus on increasing the functionality of integrated surface and groundwater modelling (integrated types of models are also discussed in sections 5.2.3 and 5.3). MODFLOW continues to be a commonly used tool for modelling the management problems associated with surface-groundwater flow, and as such the applications are too vast to review. Some examples include research by Sophocleous *et al.* (1998), Rodríguez *et al.* (2006) and several of the reports listed in Table 3-1.

Physically-based models make a good attempt to represent the physical processes that occur within a catchment to the limit possible given data limitations and the validity of the assumptions built into the model, and they are extremely useful in developing an understanding of how a system works. The risk of physically-based modelling approaches is that they become over-parameterised (Beven, 1993; Beven, 2001). Overly complicated models with large numbers of processes considered together with the associated parameters run the risk of having a high degree of uncertainty associated with model inputs, which can be translated through to the model outputs resulting in lower predictive capability, particularly at larger catchment scales.

Konikow and Bredehoeft (1992) argue that groundwater models when applied to a field study area cannot truly be validated because of inadequate parameter estimation, perceptual model deficiencies, and numerical errors, and hence the models can only be tested and invalidated. However, it is through this model testing and evaluation of errors that models are improved and a better understanding of the problems and associated model conceptualisation are gained.

Another type of physically-based modelling approach is one based on solving analytical equations. There are numerous equations that have been derived, for example, to calculate the impact of groundwater extraction on streamflow depletion rates and volumes (Anderson, 2003; Boulton, 1942; Fox *et al.*, 2002; Glover and Balmer, 1954; Hantush, 1965; Jenkins, 1968; Kirk and Herbert, 2002; Knight *et al.*, 2005; Pulido-Velazquez *et al.*, 2005). The assumptions required to solve the most commonly used analytical equations such as those of Jenkins (1968), which assume the presence of an unconfined aquifer and a river which fully penetrates the aquifer (in other words it is not possible to drawdown groundwater levels below the base of the river), make these types of streamflow depletion calculations limited in practice.

The trade-offs between the modelling approaches tend to be that of parsimony versus complexity, the associated predictive versus explanatory powers, and the data/computational requirements versus the costs.

5.2.2 Spatial and Temporal Considerations

Models can also be categorised according to the way an area/space is represented by the model, i.e. lumped, semi-distributed or distributed (Mulligan and Wainwright, 2004). Lumped models simulate an area as a single, lumped value, regardless of the degree of spatial heterogeneity. Semi-distributed models may have multiple lumps representing identifiable units such as catchments. Distributed models break an area into discrete units which are represented by square cells (raster or grid), triangular irregular networks or irregular objects. All distributed models lump data to the scale of the raster or other discrete unit space, and the spatial unit of a model may represent one, two or three dimensions.

Some models explicitly account for time, for example in models considering system dynamics or non-steady state conditions, and other models may not consider time.

5.2.3 Comments on Integrated Models

Whilst numerous surface and groundwater models have been extensively developed and used throughout many years of research and testing from field applications, very few models have been developed with the objective of fully integrating both surface and subsurface components of the hydrologic cycle. More commonly models will have their origin in either surface or groundwater applications and, as a result, either the surface or subsurface component will tend to be overly simplified. Groundwater models, for example, will commonly have a predefined boundary condition for surface water flows, and surface water models will commonly have an unaccounted loss term that is attributed to groundwater. New generations of modelling tools, however, are starting to become more fully integrated.

Camp, Dresser and McKee (2001) evaluated 75 models for use in integrated surface-groundwater modelling by conducting a literature review of existing models. The scope of their study was limited to reviewing the most commonly available physically-based 3-D numerical groundwater models for use with surface water models. Conceptual, lumped parameter and other types of models were not considered. The study concluded that three models in widespread use (MIKE-SHE, MODFLOW, and DYNFLOW) show the most potential considering a range of functionality issues (cost, regulatory acceptance, ease of use, inter-model connectivity, GIS integration, service/support, model limitations, model size limitations, expandability, operating systems, experience required, percent market share, documentation and training). The two main technical challenges highlighted in modelling river-aquifer interactions were associated with spatial and temporal descretisation. This is because surface water models generally treat the model area as a set of subcatchments or river reach segments that transect a number of different groundwater model grid cells or nodal elements, and consequently the spatial scales of interest differ. On the issue of temporal scales, surface water models often use small time increments (minutes to days) to capture rapid hydrological changes whilst groundwater models require longer time periods (weeks to months) to simulate slower groundwater movement and solute transport. Given the larger data requirements of fully integrated models appropriate for considering river-aquifer interactions, model simulation would require more time for development, calibration and simulation relative to a surface or groundwater model and the costs would be considerably greater (Camp and Dresser & McKee Inc., 2001). Consequently, the use of a fully integrated surface water/groundwater model might not be appropriate for all projects and the specific type of model needs to be considered for each project depending on the model requirements for a particular purpose.

5.3 Groundwater Models Developed for the Namoi River catchment

There are a number of groundwater models that have been developed for use within the Namoi River catchment (Table 5-1), most of which were developed to assist with the determination of sustainable groundwater yields. The majority of the groundwater models developed were spatially distributed, physically-based, three-dimensional models. The exception was a conceptual model developed for the Liverpool Plains which used the one-dimensional FLOWTUBE model (Stauffacher *et al.*, 2003) to simulate groundwater level trends and land salinisation processes in the catchment. All but one of the physically-based, three dimensional models used the MODFLOW source code (McDonald and Harbaugh, 1988) and were run on a monthly time step: The exception was a study by Lawson and Treloar (1988) that used SAM3 (Carr, 1987), which is a finite element model.

The report series for the Lower Namoi by Noel Merrick (see Table 5-1) provides more than 20 years of comprehensive modelling research that has undergone a series of revisions since 1982, including changes in conceptualisation, modelling software and computer hardware. The Lower Namoi Model has also been subject to post-audit recalibration on several occasions as well as peer review. Over most of the Lower Namoi region the aquifers are disconnected from the river systems (Figure 4-12), and hence for this area the critical aspect of the groundwater river interactions modelled was the influence of river recharge on groundwater storage volumes. However, within the connected aquifer-river systems between Narrabri and Wee Waa, Merrick (1989) simulated exchange volumes in cells (2.5 x 2.5 km grid) downstream of Narrabri for time-varying river levels over three year periods (representing normal and drought conditions in the early to mid 1980's) at a monthly time step. Model simulations suggested that this portion of the river gains water from the shallow aquifer following periods of high river levels such as floods, otherwise the river behaved as a losing system. A simulation assessment of the changes in river exchange budgets from a pre-development to a groundwater extractive regime suggests that groundwater discharge to the river decreased from 8 GL/year to 2 GL/year and that river recharge to the aquifers increased from 9 GL/year to 41 GL/year (Merrick, 2003b). This research also indicated a marked increase in depth to groundwater from the pre-development period as a result of groundwater extraction.

In order to adequately capture the temporal aquifer-river interactions at the river interface, the Lower Namoi Model would ideally be run on a daily time step and at a finer spatial scale. The lack of data at a finer scale (including driller logs, aquifer characteristics, river bed characteristics, stream and bore hydrographs, extraction rates, recharge rates) coupled with the intense computational demands of running a complex model on a daily time step have halted further developments at this point. Future detailed modelling work on a coupled groundwater-river model for the Cox's Creek is currently being considered and developed (Merrick pers. comm., (2006).

Table 5-1 Summary of previous groundwater models developed for the Namoi River catchment

Reference	Study area	Model used	Groundwater-river interactions considered
Merrick (1989) Merrick (1998a) Merrick (1998b) Merrick (1998c) Merrick (1999) Merrick (2000) Merrick (2001b) Merrick (2003b)	Lower Namoi	MODFLOW (McDonald and Harbaugh, 1988)	Month time step simulations of exchange between Narrabri and Wee Waa for time-varying river levels. Monthly time step river exchange budgets from pre-development to a groundwater extractive regime suggested that groundwater discharge to the river decreased from 8 GL/year to 2 GL/year and that river recharge to the aquifers increased from 9GL/year to 41 GL/year. Widespread increases in depths to groundwater in the Lower Namoi as a result of extraction.
Salotti (1997)	Borambil Creek, Upper Namoi (parts of Zone 1 and 8)	MODFLOW (McDonald and Harbaugh, 1988)	Not considered because of insufficient data.
Lawson and Treloar (1988)	Gunnedah to Narrabri, Upper Namoi (Zones 4 and 5, and parts of Zone 2 and 3)	SAM3 (Carr, 1987) Finite Element Model	Broadly considered using average monthly streamflow data. No estimates of baseflow contributions to streamflow were reported. Concluded that stream-aquifer interactions are a major controlling factor in the catchment hydrological balance.
Debashish et al (1996)	Gunnedah (Zones 3 and 4)	MODFLOW (McDonald and Harbaugh, 1988)	Water balance estimates of baseflow contribution to river flow over 11 year calibration period (1979-1990) reported as 1GL/year (11.5GL in total).
Kalf and Associates (2000)	Zone 8 of Mooki Valley, Upper Namoi	MODFLOW (McDonald and Harbaugh, 1988)	River recharge to groundwater system considered for losing condition, but not gaining. Baseflow proportion of water balance outflow from the study area was not reported.
Merrick (2001c)	Zone 8 of Mooki Valley, Upper Namoi	MODFLOW (McDonald and Harbaugh, 1988)	1.7GL/year of baseflow contributed to river system over calibration period (1979-2000) (or ~35.7 GL in total).
Merrick (2003a)	Zone 3 of Mooki Valley, Upper Namoi	MODFLOW (McDonald and Harbaugh, 1988) and GAMSFLOW (Merrick, 2001a)	Scenarios run to determine optimal groundwater yields and drawdown levels along the river. No baseflow estimates reported.
Stauffacher et al (2003)	Upper Mooki (Pine Ridge and Lake Goran) Liverpool Plains, Upper Namoi	FLOWTUBE (Stauffacher *et al.*, 2003)	Scenarios suggested rising groundwater levels in the upper catchment of the Mooki over the next 20 years.

None of the models developed for use in the Upper Namoi considered groundwater-river interactions to the degree of detail that would allow for the temporal interactions to be well understood, largely because of the monthly time step used. The model by Lawson and Treloar (1988) (only draft report cited) made an attempt to consider river behaviour in relation to groundwater, but the monthly model time step used for the ephemeral river tributaries to the Namoi River (Maules Ck, Rangira Ck, Cox's Ck, Mooki River) rendered these rivers primarily as losing reaches, despite acknowledging that some reaches occasionally behaved as gaining reaches. The models by Debashish (1996) and Merrick (2001c) reported water balance estimates that included baseflow contributions to streamflow over the length of the calibration period. The model by Stauffacher *et al.*(2003) indicated that the Pine Ridge and Lake Goran subcatchments of the Mooki River Catchment may experience slightly rising groundwater levels and associated salinisation over the next 20 years because of land clearing, and as a result the streams in the upper catchments may show a small increase in salt concentration. However, no estimates of baseflow reduction specifically as a consequence of groundwater extraction were made for any of the existing model assessments. This is because the models were inadequate for this purpose given the time scales.

5.4 Model Selection for Current Study

A debate continues around the appropriate selection of models (empirical, conceptual and physically-based models) for use in hydrological studies. Physically-based models are often considered by physical scientists to be superior to the others. The implication is that the use of equations that are theoretically correct at a certain scale can be applied at any scale with equally good results, implying a degree of accuracy that may not actually exist (Grayson *et al.*, 1996) particularly when field data is not available at the scale(s) used by the model. In reality processes that are important at one scale may not necessarily be important at other, larger or smaller, scales (Sivapalan *et al.*, 2003). Whilst each type of model has its advantages and disadvantages, it is important to see the different model approaches as complementary, and not competing, with each approach providing different insights into a system. The selection of model type and modelling approach ultimately depends on the research objectives and constraints.

5.4.1 Modelling objectives and selected approach

The key modelling objectives within the context of this thesis are: 1) to consider how water allocation models might be improved through an understanding of aquifer-river interactions; 2) to quantify the impacts of groundwater extraction on river flows within the connected aquifer-river systems of the Namoi River catchment; 3) to better inform water policy on groundwater extraction; and 4) to be able to utilise the model in future integrated assessment of water allocations options at the catchment scale (Letcher *et al.*, 2004). The scope of the research has been further refined to limit the study to an analysis of the alluvial aquifers (from which most groundwater is extracted) that interact with the gauged and unregulated river systems. The gauged and unregulated river systems were selected for two reasons: 1) the river gauges provide a source of data by which to measure river flow characteristics, including any changes to flow characteristics; and 2) the unregulated river systems and their associated ecosystems may be more vulnerable to altered hydrology. The regulated river systems are thought to be of lesser concern in the first instance because they have already been heavily altered by dam flow releases throughout much of the irrigation season.

River and groundwater resources are separately managed and allocated in Australia. River water is often allocated using rainfall-runoff models and/or monitoring of upstream flows, and groundwater resources are allocated based on the 'sustainable yield', which is an estimate of the long term average annual recharge to the exploited aquifer system. A shortcoming of managing aquifer systems based on their sustainable yield is that the interactions between groundwater and river systems are not considered, and hence the impacts of groundwater allocations on river flows usually remain unassessed. Combining a rainfall-runoff model with a simple groundwater model is a sensible progression in water allocation model development in order for aquifer-river interaction processes to be considered.

The groundwater resources in the Namoi River catchment are managed by groundwater management zones (refer to Section 3.3.2). The water sharing plans specify the permissible annual groundwater extraction volumes for each groundwater zone based on an estimation of the sustainable groundwater yield. Stream gauging stations can generally be found at the junction of each groundwater zone, with water policies for both surface and groundwater directed at the subcatchment level. The model or models developed for this study then ideally need to be detailed enough to model the fluxes between groundwater and surface water systems at the subcatchment scale, and yet be general enough to inform water allocation and other management initiatives. The type of model envisaged in order to achieve the research objectives would be a parsimonious-conceptual style of model, making use of lumped parameter estimates, which can adequately apportion dynamic exchanges of water volumes between surface and groundwater systems within the subcatchment on a daily time step. A simple model is preferred for this research for a number of reasons including: the requirement for subcatchment-scale water budget accounting in order to assess water sharing plans; the requirement to model streamflows, including baseflows, on a daily time step; the requirement for a model that could be later used in integrated assessments; the limited data pool and time with which to parameterise a complex model; and the uncertainties associated with validating models that are over-parameterised.

5.4.2 Top-down Modelling Approaches

A top-down or downward approach to model building was first introduced to the discipline of hydrology by Klemeš (1983). The top-down modelling approach was described in the context of predicting overall catchment response based on the interpretation of observed responses at the scale of interest. A key characteristic of the top-down approach to modelling is that the model structure, including what processes to explicitly include and in which way, is inferred from the data (Sivapalan *et al.*, 2003). This style of model building focuses on attempting to learn from the data about how a system works by trying to relate the inputs of a system to the outputs, for example through the use of transfer functions, without being overly concerned as to the physical processes occurring (Beven, 2000a). Developing an understanding of the rainfall-runoff relationships and the influence of groundwater extraction and climate variability on river flows are fundamental to this study if we are to better understand how groundwater extraction might alter river hydrology over time. Such a downward approach to modelling may give insights into the key driving factors as evidenced by the data itself and the information contained within the data alone.

5.5 IHACRES and the Development of a Groundwater Module

The applicability of the IHACRES (Identification of Unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data) rainfall-runoff model (Jakeman and Hornberger, 1993; Jakeman *et al.*, 1990; Littlewood and Jakeman, 1994) was assessed and subsequently further developed for use within this research project. The IHACRES model was selected for this study because it has previously been used to model surface water allocation options for integrated assessments within the Namoi River catchment (Letcher *et al.*, 2004). Furthermore, IHACRES has been proven to predict streamflow well in a variety of Australian catchments (Croke *et al.*(2001b); Jakeman *et al.,* (1993); Ye *et al.*, (1997)) and has an international reputation for being a robust and simple rainfall-runoff model. IHACRES has been widely described in international journal papers (Dye and Croke, 2003; Jakeman *et al.*, 1993; Kokkonen *et al.*, 2003; Littlewood, 2002) as well as in hydrological textbooks, see for example Beven (2000a) and Anderson and Bates (2001). Whilst IHACRES in its current configuration does not include a groundwater model component module, a modification could be made to the IHACRES model to allow for an account of groundwater storage volumes to be maintained. This development is discussed further below.

The IHACRES model consists of two modules: a non-linear loss module that transforms observed rainfall and temperature data to effective rainfall (the amount of rainfall that contributes to streamflow) (Croke and Jakeman, 2004; Evans and Jakeman, 1998; Jakeman and Hornberger, 1993), and a linear module that transfers effective rainfall to streamflow (Figure 5-1).

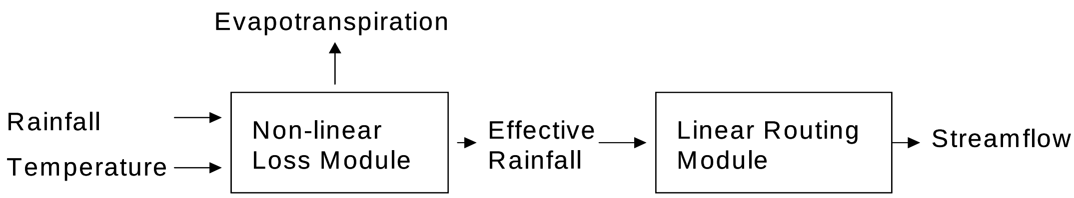


Figure 5-1 Conceptual diagram of the IHACRES rainfall-runoff model

Hybrid empirical-conceptual models, such as IHACRES, are formulated in a top-down manner based on broad hydrological concepts in relation to available rainfall and streamflow data (Young, 2003). The non-linear module of IHACRES is a conceptual style of model that transforms rainfall and temperature data into effective rainfall based on assumed functional forms representing the wetting and drying processes. The linear module of IHACRES is an empirical type of model that uses transfer functions to represent the total unit hydrograph. The linear module is discussed in detail below in Section 5.5.1, and will be the focus of further model development in this thesis whereby the slow flow transfer function is converted to a conceptual groundwater module (discussed in Section 5.5.2).

5.5.1 IHACRES Linear Routing Module

The linear routing module of IHACRES is based on transfer function theory that relates inputs to outputs through transformation equations (Whitehead and Young, 1975; Young, 1974). In this case, the effective rainfall is used as a model input that is transformed into streamflow output by two parallel transfer functions. The transfer functions are represented by exponential equations. One equation represents the quick flow and shallow, subsurface (interflow) pathway (Equation 5-1), and the other represents the slow flow pathway (Equation 5-2). The sum of the two exponential equations gives the modelled streamflow (Equation 5-3).

$$Q_t^{(q)} = \beta_q U_t A - \alpha_q Q_{t-1}^{(q)} \qquad (5\text{-}1)$$

$$Q_t^{(s)} = \beta_s U_t A - \alpha_s Q_{t-1}^{(s)} \qquad (5\text{-}2)$$

$$Q_t = Q_t^{(q)} + Q_t^{(s)} \qquad (5\text{-}3)$$

where $Q_t^{(q)}$ and $Q_t^{(s)}$ are the modelled quick and slow flow volumes at time step *t*, and Q_t is the modelled total streamflow. The parameters β_q and β_s govern the height of the unit hydrograph peaks of the quick and slow flow components respectively (e.g. the peak responses to a unit of effective rainfall input over one time step) and U_t is the effective rainfall at time step *t*. The A term represents the catchment area and is used to convert mm of rainfall to ML of streamflow. The parameters α_q and α_s define the rates of quick and slow flow recession. $Q_{t-1}^{(q)}$ and $Q_{t-1}^{(s)}$ are the modelled quick and slow flow volumes from the previous time step.

The IHACRES model assumes that the partitioning of the effective rainfall into its quick and slow flow component volumes is linear and constant in time. Thus, if v_s

represents the $v$olume of effective rainfall that is partitioned as slow flow, then the volume partitioned as quick flow is $v_q = 1 - v_s$. For the purposes of this research, the quick flow pathway, with a fast recession, will be referred to as surface runoff $Q_t^{(q)}$, and the slow, subsurface pathway, with a slower recession, will be referred to as baseflow $Q_t^{(s)}$ and equated to groundwater discharge. (Whilst the author acknowledges that these terms and their processes/definitions are contentious, a degree of pragmatism was required in order to progress the development of the groundwater module described in the sections that follow.) These relationships are shown in Figure 5-2.

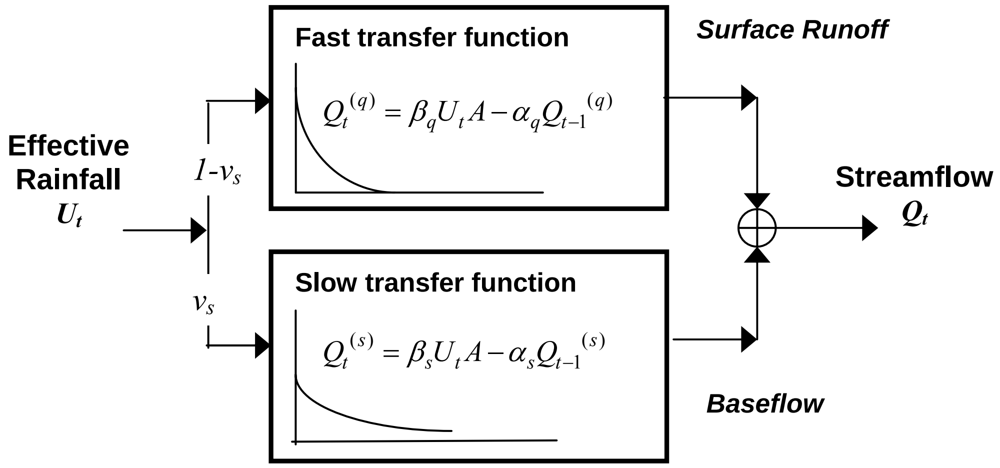


Figure 5-2 IHACRES linear module structure

An overview of the model inputs, calibrated and derived parameters and outputs of the IHACRES linear module is provided below for clarification.

IHACRES Inputs

The model inputs are effective rainfall, U_t, and catchment area, A.

IHACRES Calibrated and Derived Parameters

The parameters α_q and α_s, which define the recession characteristics of the hydrographs, can be expressed as time constants, τ_q and τ_s, for the quick and slow flow components of streamflow decay:

$$\tau_q = \frac{-\Delta}{\ln(-\alpha_q)} \tag{5-4}$$

$$\tau_s = \frac{-\Delta}{\ln(-\alpha_s)} \tag{5-5}$$

where Δ is the sampling interval, in this instance, one day.

The relative volumes of quick (v_q) and slow (v_s) flow can be expressed in terms of *α* and *β:*

$$v_q = 1 - v_s = \frac{\beta_q}{1+\alpha_q} = 1 - \frac{\beta_s}{1+\alpha_s} \tag{5-6}$$

$$\beta_q = v_q(1+\alpha_q) \tag{5-7}$$

$$\beta_s = v_s(1+\alpha_s) \tag{5-8}$$

The IHACRES model can be calibrated by fitting the transfer functions to different values of τ_q, τ_s and v_s until the best model fits are achieved based on comparing the modelled output with the observed streamflow through visual and objective function fits (see Section 6.4 for details on model calibration). The parameters v_q, β_q, and β_s are derived parameters.

IHACRES Outputs

The modelled outputs are $Q_t^{(q)}$, $Q_t^{(s)}$ and Q_t.

5.5.2 Development of a Groundwater Module

The IHACRES model is parametrically parsimonious and, because of its structural simplicity, lends itself to modification, such as through the development of a groundwater module. A requirement of using the IHACRES rainfall-runoff model in the current study is to develop a groundwater module component. This model component will need to have the functionality of maintaining a continuous account of groundwater storage volumes in order to allow the influences of groundwater extraction and other groundwater losses to be modelled. The development of such a groundwater module will also have the added benefit of improving the performance of rainfall-runoff modelling in intermittent to ephemeral types of river systems. Many rainfall-runoff models, such as IHACRES, are not formulated to represent intermittent or ephemeral streamflow behaviour because the modelled streamflows are represented by the sum of two exponential equations that do not allow for the possibility of zero flows. The volume of groundwater stored within a catchment commonly influences intermittent to ephemeral streamflow behaviour, as was discussed in Chapter 4, in particular the timing of baseflow events. Consequently, the addition of a simple groundwater model component that is able to account for changes in groundwater storage has the potential to improve rainfall-runoff model performance in these types of river catchments (see for example Moore and Bell (2002)). In particular, a continuous water balance that accounts for changes in groundwater storage during periods of zero flow is required to correctly simulate the onset of baseflow. Moreover, in catchments where groundwater extractions are significant, the ability to model the changes in groundwater storage arising from extraction is critical to developing an understanding of how groundwater extraction might impact on baseflow discharges to a river system.

The new model version of IHACRES which includes the groundwater module has been entitled IHACRES_GW, and its derivation is now discussed.

The IHACRES_GW model is based on the IHACRES rainfall-runoff model previously described; however, in IHACRES_GW the slow transfer function component of the IHACRES model has been modified by incorporating a groundwater storage module (Figure 5-3).

Groundwater storage can be conceptualised as a single reservoir similar to a bucket. The areal extent of the bucket is the catchment area upstream of a stream gauging station. The volume of water released from groundwater storage, or the bucket, to the river system is represented by the baseflow component of streamflow. Groundwater extraction and other losses behave as additional outflows from the volume of water held in groundwater storage.

The volume of water that recharges the groundwater storage is determined by the proportion of effective rainfall partitioned as slow flow, which is calibrated in the model. The remaining fraction of effective rainfall is apportioned to surface runoff. The sum of baseflow and surface runoff gives the total modelled streamflow. Two assumptions include: 1) there is a baseflow contribution at the gauge when storage volumes are above a reference point, e.g. above the base of the river at the groundwater discharge site(s), such that the groundwater storage bucket overflows to the river; and 2) that the slow flow transfer function signal represents groundwater discharge. To summarise this in the context of a physical system, groundwater is discharged as baseflow to a river in response to groundwater recharge that mobilises older, pre-event groundwater stored near the river (Wittenberg and Sivapalan, 1999).

The relationship between the volume of groundwater discharged as baseflow and the total volume of groundwater stored can be expressed as a simple, linear, reservoir-type of relationship (Boussinesq, 1877; Chapman, 2003; Chow, 1964; Maillet, 1905),

$$Q_t^{(s)} = \begin{cases} aG_t & if \quad G_t > 0 \\ 0 & otherwise \end{cases} \tag{5-9}$$

where $Q_t^{(s)}$ is the modelled slow flow at time step t, G_t is the volume of groundwater stored above the catchment outlet (or above the point where baseflow activates) at time step t, and a is a dimensionless constant equivalent to the storage coefficient. The a parameter represents the range of transmissivities and hydraulic gradients for the groundwater systems at a lumped catchment scale, and represents an average value that is calibrated over a number of events. Accordingly, the baseflow contributions to streamflow will be a function of groundwater storage and the aggregated aquifer properties.

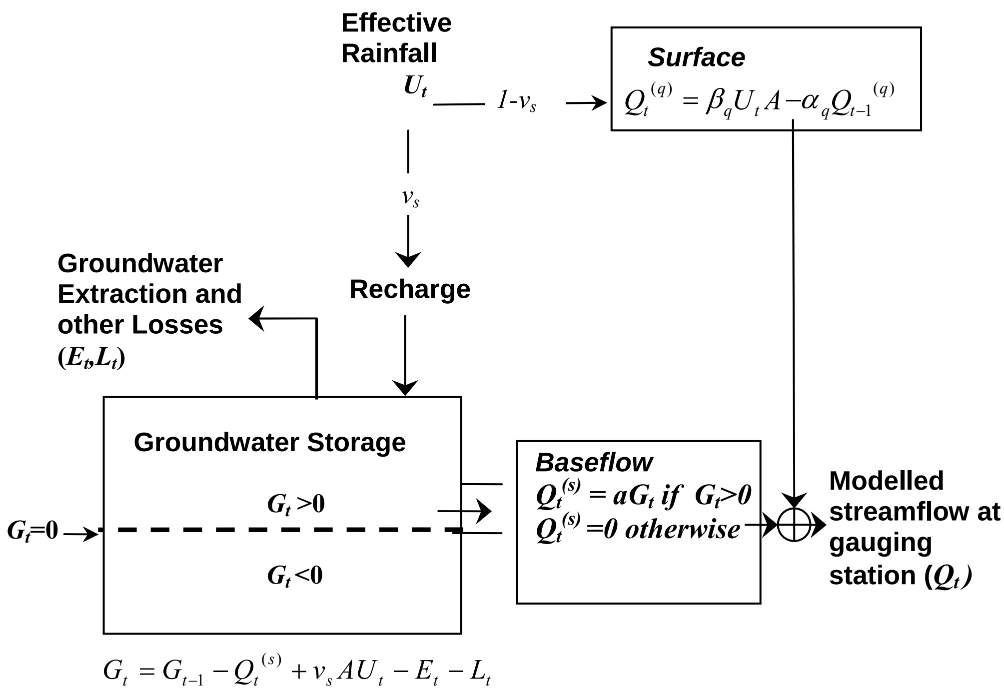


Figure 5-3 IHACRES_GW Model Structure

The mass balance equation for groundwater storage, including extraction and other losses can be described by

$$G_t = G_{t-1} - Q_t^{(s)} + v_s AU_t - E_t - L_t \tag{5-10}$$

where E_t is the groundwater extraction at time step t, which is obtained from available data. L_t represents any losses from groundwater storage at time step t, including subsurface outflow below the level of the stream gauging station, evapotranspiration and other losses (or gains if the loss term is negative such as would be the case with irrigation returns and river infiltration resulting in groundwater inflow). L_t is calibrated using streamflow data through fitting the parameter to the decay observed in the stream hydrograph (refer to Section 6.4 on model calibration).

The Q_s term in Equation (5-10) can be substituted with the aG term from Equation (5-9) yielding

$$G_t = \begin{cases} G_{t-1} - aG_t + v_s AU_t - E_t - L_t & \textit{if} \quad G_t > 0 \\ G_{t-1} + v_s AU_t - E_t - L_t & \textit{otherwise.} \end{cases} \tag{5-11}$$

which can be arranged as

$$G_t = \begin{cases} \dfrac{1}{1+a}(G_{t-1} + v_s AU_t - E_t - L_t) & \textit{if} \quad G_t > 0 \\ G_{t-1} + v_s AU_t - E_t - L_t & \textit{otherwise.} \end{cases} \tag{5-12}$$

Solving for Equation (5-12) allows for a continuous accounting of groundwater storage volumes to be maintained.

Multiplying Equation (5-12) through by a allows for $Q_t^{(s)}$ to be calculated by using Equation (5-9), resulting in

$$Q_t^{(s)} = \begin{cases} \dfrac{1}{1+a} Q_{t-1}^{(s)} + \dfrac{a}{1+a}(v_s AU_t - E_t - L_t) & \textit{if} \quad G_t > 0 \\ 0 \quad \textit{otherwise.} \end{cases} . \tag{5-13}$$

Equation (5-13) has a similar functional form to the equation for the slow transfer function in Equation (5-2), however, without the added extraction and loss terms, and therefore:

$$\alpha_s = \frac{-1}{1+a} \tag{5-14}$$

$$\beta_s = v_s \frac{a}{1+a} \tag{5-15}$$

Solving Equation (5-14) in terms of a yields,

$$a = \frac{-(\alpha_s + 1)}{\alpha_s} \tag{5-16}$$

The slow flow contribution at time step t is then calculated by solving Equation (5-12) for G_t, when G_t is greater than zero, multiplying through by a as per Equation (5-9). If G_t is less than zero, then the slow flow is zero. The parameter a is calculated with Equation (5-16) using the calibrated τ_s parameter, running the IHACRES_GW model over a number years in which streamflow events demonstrate some baseflow components to flow, and solving for α_s using Equation (5-5).

The IHACRES_GW model takes effective rainfall as input, and streamflow is generated as model output. Calibration of the four parameters, τ_q, τ_s, v_s and L_t is performed through visual inspection of streamflow data and flow duration curves to achieve the best model fit, as well as through minimising the relative bias objective function (see Section 6.4 for additional information on model calibration). Automated optimisation is not employed due to the difficulty with finding objective functions for ephemeral river systems in which measured flows are commonly zero. Plots of the modelled versus observed flows are visually assessed in log space in order to focus on the baseflow component of model fits (see Section 6.5 for calibration plots).

The conceptual model for IHACRES_GW was developed through discussions with Croke (personal communication, 2003), based on concepts first developed in Croke *et al.* (2000), and described in Ivkovic *et al.* (2005a).

5.5.3 Groundwater Model Assumptions

A model is a simplification of reality, and consequently a number of assumptions are inherent in any model formulation, including IHACRES_GW. A key to successful modelling involves being aware of model assumptions and their validity in the context of a particular study. The assumptions in IHACRES_GW are:

i. The slow flow component of the linear module represents baseflow expressed as an exponential decay function.

ii. The baseflow contribution to streamflow can be estimated using mathematical filtering and the baseflow represents groundwater discharge.

iii. The proportion of effective rainfall that recharges the groundwater storage is constant in time.

iv. The baseflow contribution to streamflow is a scalar multiple of the groundwater storage volumes above the point at which groundwater storage begins to contribute to streamflow (observable at the stream gauging station). Hence the model also assumes that a linear functional form is adequate for the range of groundwater storage volumes and hydrogeological characteristics encountered, such as variable hydraulic conductivity and transmissivity.

v. All baseflow comes from a single groundwater store or, if there are two or more stores, their behaviour is similar to that of a single store.

vi. Baseflow contributions to streamflow occur immediately when groundwater storage levels are above the stream gauging station-measuring point, and hence, there are negligible hysteresis effects associated with the amount of groundwater held in storage and the associated hydraulic gradients.

vii. Bank storage effects on the streamflow hydrograph are a relatively minor component of the filtered baseflow signature.

viii. The L_t term (for groundwater losses other than extraction) is constant (i.e. not dependent on groundwater storage or other factors).

ix. Groundwater extraction and other modelled losses impact on groundwater storage volumes during the same time step.

x. Transient groundwater flow and the distance of extraction bores from the river do not significantly influence the timing of the baseflow contribution from groundwater storage to streamflow.

xi. Groundwater extraction influences predominantly occur upstream of the stream gauging station at the outlet of the drainage system. Groundwater extraction influences downstream of the gauging station will present as additional groundwater losses.

xii. Groundwater flow across the catchment boundary will present as an additional volume of loss or as a gain to groundwater storage volumes (negative loss).

Assumptions *i-iii* are inherent in the formulation of the IHACRES rainfall-runoff model, and are common to streamflow recession analysis. Assumption *iv* arises because the exponential equation that describes slow flow recession transforms into a linear groundwater reservoir model when derived (Boussinesq, 1877). Assumptions *v* to *viii* are "reasonable approximations" in view of the purpose of the model and in order to keep the model parsimonious in its initial formulation. While the addition of more model parameters would allow for more detailed processes to be modelled from a theoretical point of view, the predictive capability of the model may not be improved. Assumptions *ix* to *x* also exist to keep the model formulation simple; these assumptions are supported by scenario modelling using MODFLOW (for narrow alluvial river valleys characterised by semi-confined aquifer systems) that has suggested the rapid transmission of aquifer pressures during pumping (Braaten and Gates, 2004). Assumptions *xi* and *xii* provide cautionary points as to where the model can be used with the best results. The IHACRES_GW model is well suited to modelling unregulated and gauged river systems in narrow, semi-confined and narrow, shallow unconfined alluvial valleys with strong aquifer-river connectivity where groundwater extraction occurs predominantly upstream of the stream gauging station at the outlet of the drainage system. The Upper Namoi River catchments are commonly characterised by these types of aquifer systems, as are many other upper catchments within the Murray Darling Basin. It is important to maintain awareness of these model assumptions when using IHACRES_GW and in the selection and assessment of modelled catchments and their outputs.

5.6 Calculation of Effective Rainfall

The non-linear module of IHACRES (Figure 5-1) is usually used to transform observed rainfall and temperature data to effective rainfall. However, the spatial coverage of rain-gauging stations throughout much of the Namoi River catchment is poor and the rainfall patterns tend to be non-uniform (Croke *et al.*, 2006). As a result, the errors in deriving catchment average rainfall data and the associated uncertainty with the non-linear loss module masked out the signal from the influence of groundwater extraction within the linear module. In particular, there was significant uncertainty around modelling the timing and volume of baseflows. Consequently, an additional "top-down" modelling approach was employed that relied on the streamflow data to calculate effective rainfall data.

In order to calculate the effective rainfall for model input to IHACRES_GW, the observed streamflow series was first filtered to generate its quick and slow components. To do this, the streamflow data series was put through a minimum baseflow filter developed by Croke *et al.* (2001a). This filter is particularly useful in separating quick flow events, especially when compared to the recursive digital filter used in Chapter 4, which sometimes overestimates baseflow volumes in ephemeral systems (and hence underestimates quick flow volumes) for the reasons outlined in Chapman (1991).

The minimum baseflow filter is applied in two-steps. The first step involves running a minimum filter of width 2n+1 time steps whereby, at each time step *t*, the minimum of the observed flows from time step *t*-n to *t*+n is determined. The resulting time series is then smoothed using a running average (or boxcar) filter of the same width. A filter width of 5 time steps (n=2) was adopted, which is the width also used by the Institute of Hydrology BFI filter (Gustard *et al.*, 1992). The filtered streamflow values provided the baseflow contribution to streamflow. Subtracting filtered baseflow volumes from total flow volumes yielded the quick flow contribution to streamflow. The effective rainfall was then calculated as

$$U_t = \begin{cases} \dfrac{Q_t^{(q)} + \alpha_q Q_{t-1}^{(q)}}{\beta_q A} & if \quad Q_t > Q_{t-1} \\ 0 \quad otherwise \end{cases} \tag{5-17}$$

where U_t is the effective rainfall and $Q_t^{(q)}$ is the filtered quick flow at time step *t*. β_q is the height of the unit hydrograph peaks of the quick flow and *A* is the catchment area.

Assumptions in this formulation include: 1) that the filtered quickflow volume provides the effective rainfall input to the model; 2) that for effective rainfall to be generated there must be a measurable quick flow; and furthermore 3) that the quick flow signature has not changed over time in response to groundwater extraction. Any errors in the calculation of quick flow from the baseflow filter are likely to be relatively small in quick flow dominated systems. These assumptions render the calculation to be more suitable for intermittent/ephemeral types of river systems which are quick flow dominated.

5.7 Model Parameter Sensitivity

Each model parameter has an influence on the model calculations and therefore on the model outputs. Sensitivity analysis (SA) is the process of defining model output sensitivity to changes in model parameters (Saltelli *et al.*, 2000). Developing an understanding of how a change in parameter value influences model output, for example as part of the model calibration process, is critical to using and evaluating the model. A SA has been undertaken for this thesis in order 1) to assess the identifiability/ambiguity of model parameter values selected during the model calibration process; 2) to assess the potential parameter interactions arising from generating effective rainfall values from steamflow data using Equation 5-17; and 3) to compare parameter influences on modelled streamflows using an independent effective rainfall series as model input. Sections 5.7.1 to 5.7.3 provide SA on the current configuration of IHACRES_GW using streamflow data to generate effective rainfall whilst Section 5.7.4 provides an SA comparison using a separate effective rainfall series as input to IHACRES_GW.

There is a range of approaches by which to undertake a sensitivity analysis, many of which are described by Saltelli *et al.* (2000). Here One-at-a-Time and Two-at-a-Time methods have been utilised.

5.7.1 One-at-a-Time Parameter Perturbations

In most sensitivity analyses a single parameter is varied incrementally around its normal value, whilst all other parameters remain unaltered (Mulligan and Wainwright, 2004). This type of SA is termed One-at-a-Time (OAT). In this thesis the parameter values were varied by +/- 10%. An overview of each of the parameters used by IHACRES_GW and their effect on model output is discussed in the subsections below. A sensitivity analysis is presented for days 4753 to 4933 (5/6/1978 to 2/12/1978) of the streamflow record in order to show the impact of varying model parameters for a detailed portion of the record that had both surface runoff and baseflow events. OAT SA of the flow duration are also shown; these data represent the whole streamflow record (1/6/1965 to 20/6/1980) and indicate the longer-term influence of parameter values on the frequency of flows. The reference parameter set used for the OAT comprises the calibrated values (refer to Section 6.5). The υ_s, τ_s and τ_q reference parameter values used were 0.09, 15 days and 1 day, respectively, and the loss parameter, L_t, was set to 6 ML/day.

5.7.1.1 Slow Flow Volume

The slow flow volume (υ_s) is used in the calculation of the groundwater storage mass balance and represents the volume of effective rainfall partitioned to groundwater storage as recharge (refer to Equation 5-10). This parameter has a value between 0 and 1, but it is likely to be far less than 1 due to the nature of the runoff dominated catchments found in the Namoi River catchment. Perturbed values of υ_s (0.081, 0.09, 0.099) were used in the model in order to assess the influence of this parameter on model outputs. The τ_s and τ_q values were fixed at 15 and 1 day(s), respectively, and the loss fixed to 6 ML/day. Plots of modelled streamflow (Figure 5-4), groundwater storage (Figure 5-5) and flow duration (Figure 5-6) illustrate the influence of changing the υ_s parameter.

One can see from Figure 5-4 that as the volume of slow flow increases (i.e. as the parameter value increases) the modelled streamflow also increases when there is a baseflow component to streamflow (e.g. when the groundwater storage is above zero in Figure 5-5). Increasing υ_s also increases the amount of effective rainfall that goes to groundwater recharge (refer to Equation 5-11) which results in increased groundwater storage volumes (Figure 5-5), with a corresponding decrease in υ_q. Increased groundwater storage volumes provide greater baseflow contributions to streamflow (Equation 5-9) that will result in streamflows that persist longer, as is evident in the flow duration curve (Figure 5-6). In practice, the model was calibrated to achieve a good fit to observed streamflows based on a visual inspection. Here, the emphasis is to show how a change in one parameter value alters model output when the other parameters remain fixed.

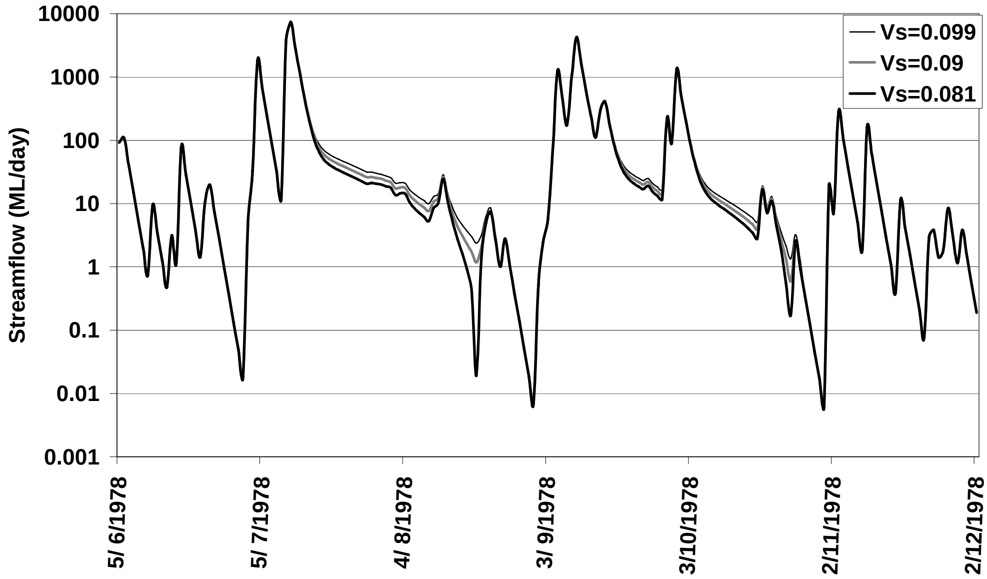


Figure 5-4 Modelled streamflow with varying slow flow volumes

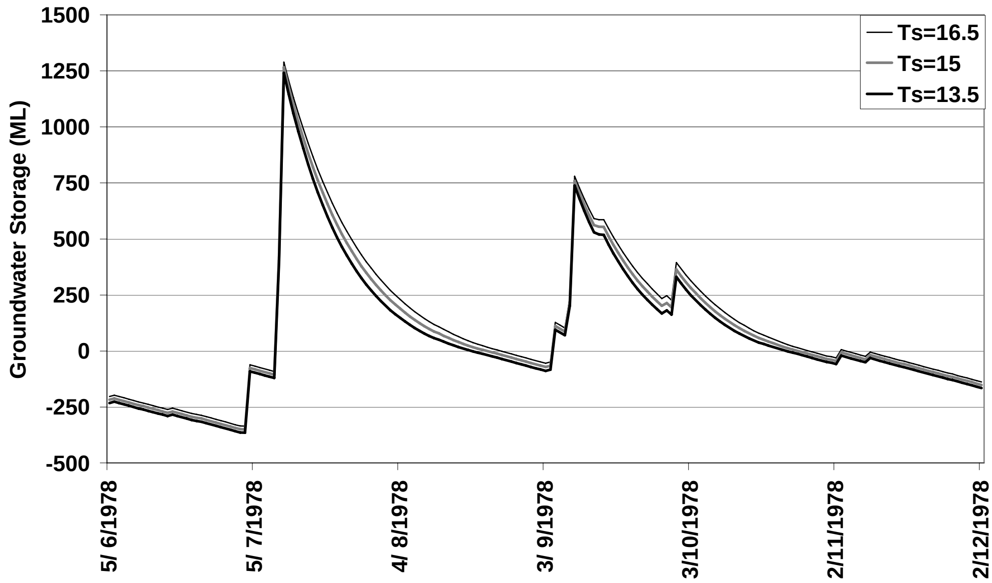


Figure 5-5 Modelled groundwater storages with varying slow flow volumes

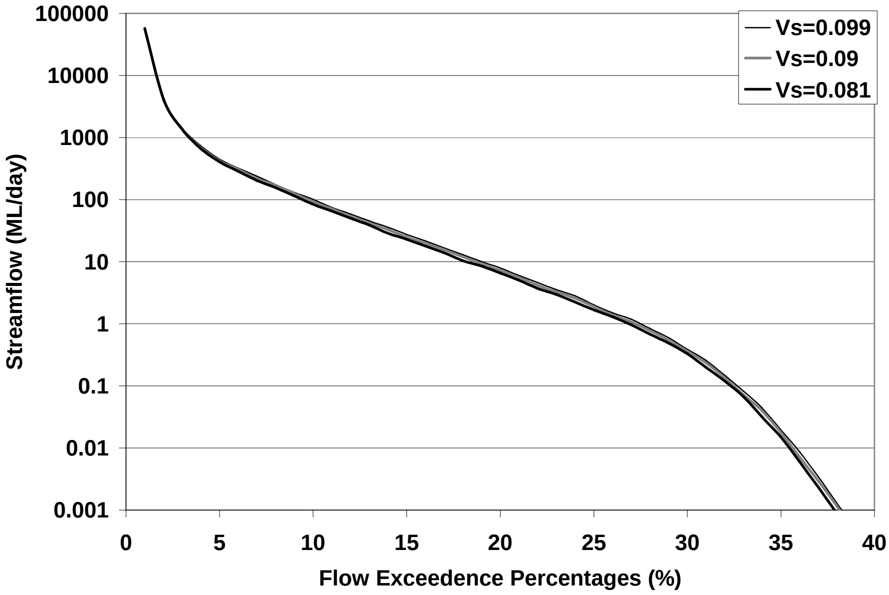


Figure 5-6 Modelled flow exceedence percentages with varying slow flow volumes

5.7.1.2 Slow Flow Time Constant

The slow flow time constant (τ_s) defines the recession characteristic of the slow flow component of the stream hydrograph (Equation 5-5). This parameter is made larger during model calibration to accommodate baseflow-dominated events, and commonly has a value greater than 10 days. Otherwise the parameter behaves as a quick flow with a shorter time constant. Model runs using perturbed τ_s values (13.5, 15 and 16.5 days) were performed in order to assess the influence of this parameter on model outputs, whilst the τ_q , v_s and loss values were fixed at 1 day, 0.09 and 6 ML/day respectively.

An increase in the value of τ_s results in a slower rate of streamflow recession for the slow flow component of the hydrograph. The slower rate of baseflow recession is evident in Figure 5-7 where the descending limb of the hydrograph has a flatter slope, particularly over the dates where the groundwater storage values approach the zero reference in Figure 5-8. An increase in τ_s has the effect of increasing the proportion of baseflow in the stream hydrograph, and hence there is a corresponding increase in groundwater storage volumes as demonstrated in Figure 5-8. As a consequence the lower magnitude streamflow events (dominated by baseflow) will persist over a longer duration as can be seen in the flow duration plot (Figure 5-9).

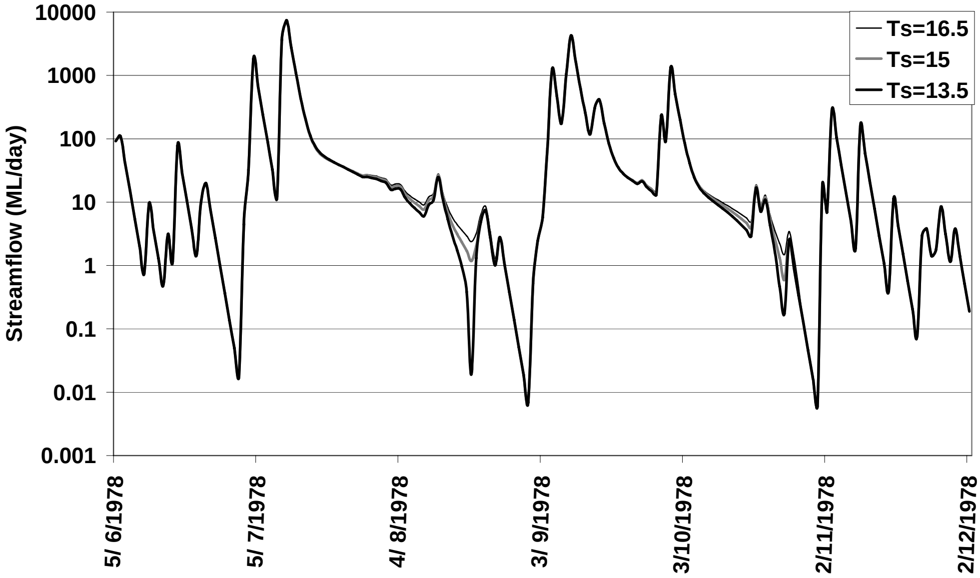


Figure 5-7 Modelled streamflow with varying slow flow time constants

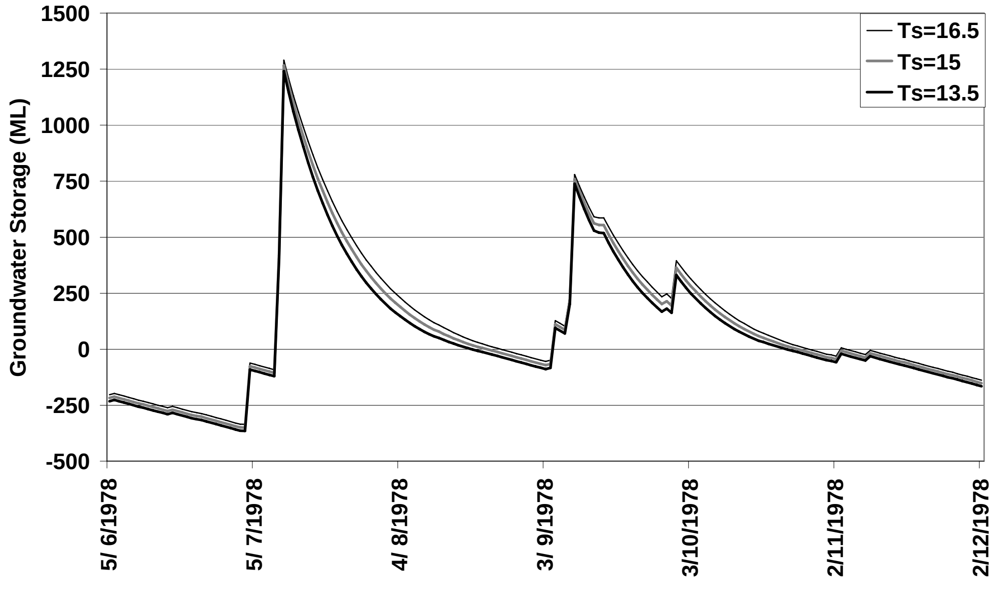


Figure 5-8 Modelled groundwater storage with varying slow flow time constants

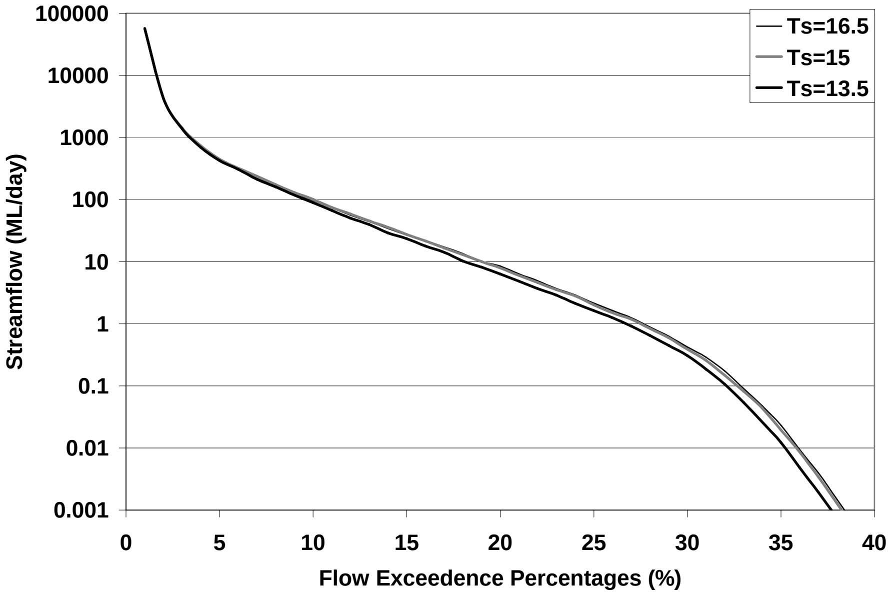


Figure 5-9 Modelled flow exceedence percentages with varying slow flow time constants

5.7.1.3 Quick Flow Time Constant

The quick flow time constant (τ_q) defines the recession characteristic of the quick flow component of the stream hydrograph (Equation 5-4). This parameter commonly has a value of less than 5 days. Perturbed τ_q values (0.9, 1 and 1.1 days) were used in the model in order to assess their influence on model outputs. The τ_s , v_s parameter values were fixed at 15 days and 0.09, and the loss parameter was set to 6 ML/day.

Analogous to the slow flow time constant effect, increasing the value of τ_q results in a slower rate of streamflow recession for the quick flow component of the hydrograph (Equation 5-4). This is evident in Figure 5-10 where the descending limb of the hydrograph has a flatter slope with increasing τ_q. A slower rate of recession (larger value of τ_q) has the effect of reducing the value of the β_q parameter (Equation 5-7). A reduction in β_q results in increased generation of effective rainfall (U_t) using Equation 5-17. An increase in U_t results in a greater volume of water available for partitioning between quick and slow flow, and hence there is a slight increase in groundwater storage (Figure 5-11). Increased volumes of groundwater storage will result in more baseflow discharges and as a result streamflow will be of longer duration (Figure 5-12). If IHACRES_GW were used with the non-linear loss module in order to generate effective rainfall, as with the original formulation of IHACRES (Figure 5-1), then the τ_q

parameter would only affect the quick flow, and not the slow flow or groundwater storage.

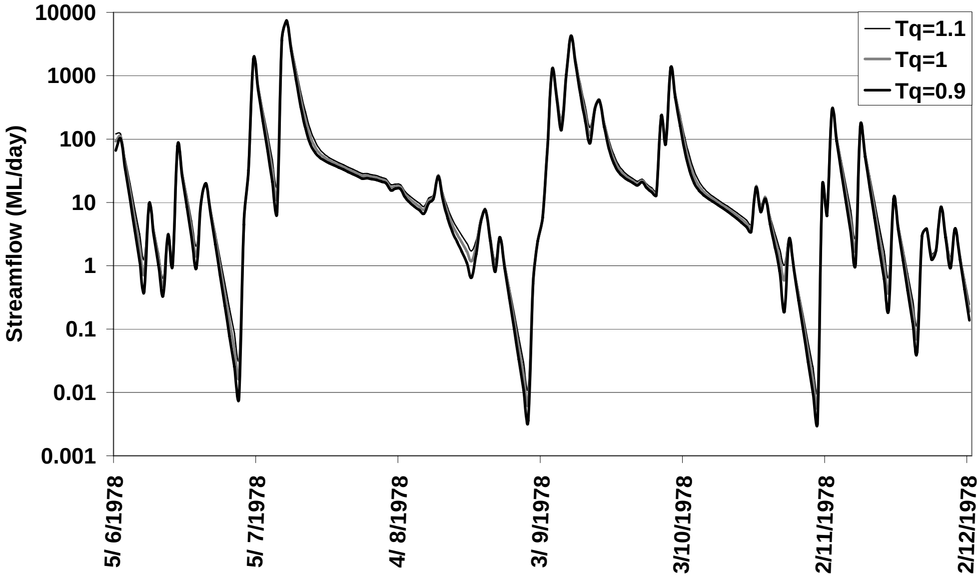


Figure 5-10 Modelled streamflow with varying quick flow time constants

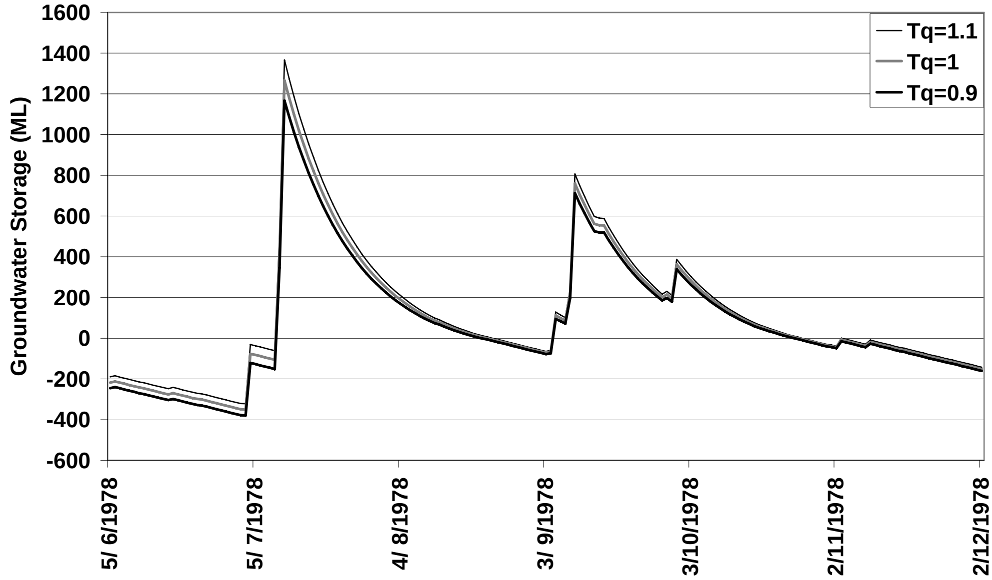


Figure 5-11 Modelled groundwater storage with varying quick flow time constants

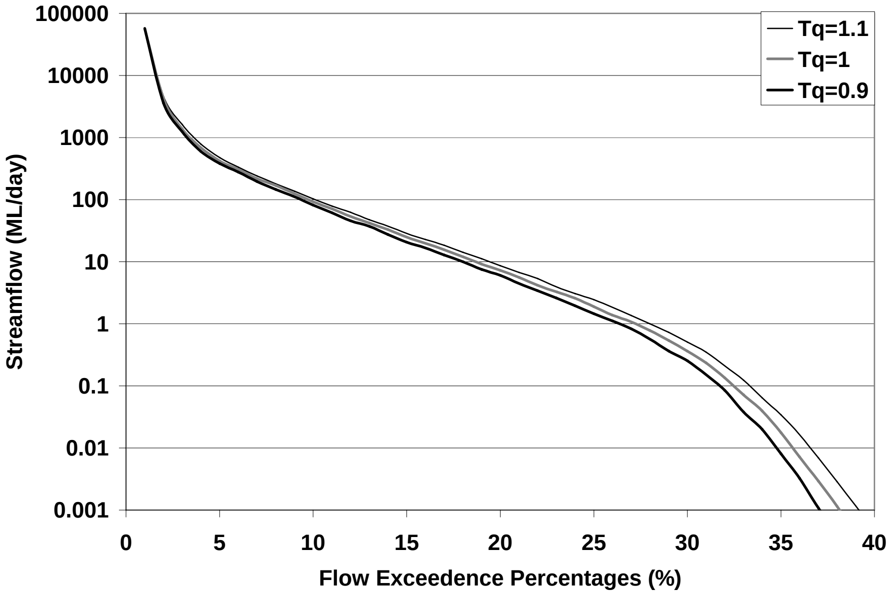


Figure 5-12 Modelled flow exceedence percentages with varying quick flow time constants

5.7.1.4 Groundwater Loss

The groundwater loss parameter (L_t) in IHACRES_GW (Equation 5-10) accounts for any losses (or gains in the case of a negative value) that might occur to groundwater storage through processes such as subsurface outflow of groundwater below the level of the stream gauging station or across the catchment boundary, evapotranspiration, infiltration through the base of the stream to the underlying aquifer, irrigation returns and groundwater extraction (there is a separate parameter explicitly for groundwater extraction that takes place upstream of the stream gauging station). The sensitivity of the IHACRES_GW model to this parameter is assessed through model simulations in which the loss term is varied between zero and +/- 6 ML/day, whilst the other parameters remained fixed. Each model run assumes groundwater extractions are zero, so the loss term represents the only loss to groundwater storage other than baseflow discharges. Groundwater extractions have a similar impact to the groundwater loss term and would provide an additional source of loss.

One can see from Figure 5-13 that setting the loss term to zero results in the exponential decay of streamflow, with no switching off of the baseflow component, which is how streamflow is modelled using the original formulation of IHACRES. A loss of positive 6 ML/day alters the behaviour of modelled flows such that the baseflow recession component of the stream hydrograph decays more rapidly because of the impact that daily loss has to groundwater storage volumes; consequently, the baseflow component of flows switches off when the storage volumes fall below the zero reference point. The use of a positive loss value results in modelled streamflows that can more accurately fit/resemble those observed in intermittent to ephemeral river systems. A loss of negative 6 ML/day provides a constant daily gain to the river system resulting in river flows that never fall below 6 ML/day.

The modelled groundwater storages with varying loss values are shown in Figure 5-14. A loss term set to zero maintains groundwater storage volumes above the zero reference point in the absence of any other losses such as extraction. If groundwater storages remain above the level of the stream gauging station there is a continuous baseflow component of streamflow. A loss term of – 6 ML/day is, in effect, a gain to the groundwater system of 6 ML/day, such as from subsurface flows into the catchment, and results in a groundwater storage volume that maintains streamflows above 6 ML/day. A loss of + 6 ML/day allows for groundwater storages to fall below the zero reference point, and at these times any modelled river flows are composed entirely of quick flow. One can see that the addition of a loss term allows for the accounting of changes in groundwater storage to be kept during periods of zero flow, which allows for the simulation in the switching behaviour of baseflow in intermittent to ephemeral river systems to be more accurately modelled.

The modelled flow duration curves arising from setting the loss parameters to zero and +/- 6 ML/day are shown in Figure 5-15. As discussed above, a loss of -6 ML/day provides streamflow that persists throughout the modelled record and which never falls below 6 ML/day. Setting the loss parameter to zero has resulted in the persistence of flow for the whole of the modelled record, continuing below the 0.001 ML/day vertical axis shown on the flow duration plot, at very low volumes. This is because in the absence of a loss to groundwater storage, the streamflow continues to decay exponentially until the next rainfall event.

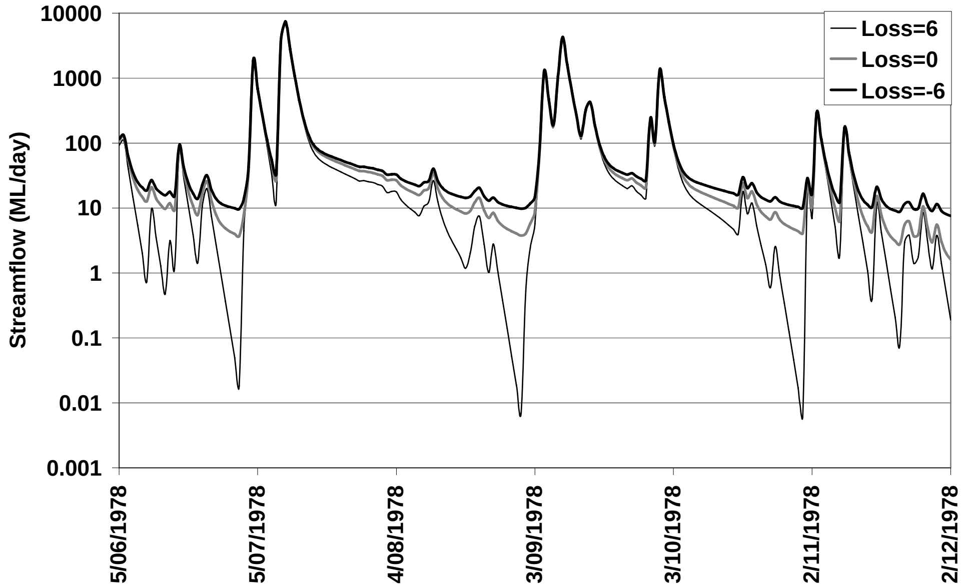


Figure 5-13 Modelled streamflow with varying loss parameter

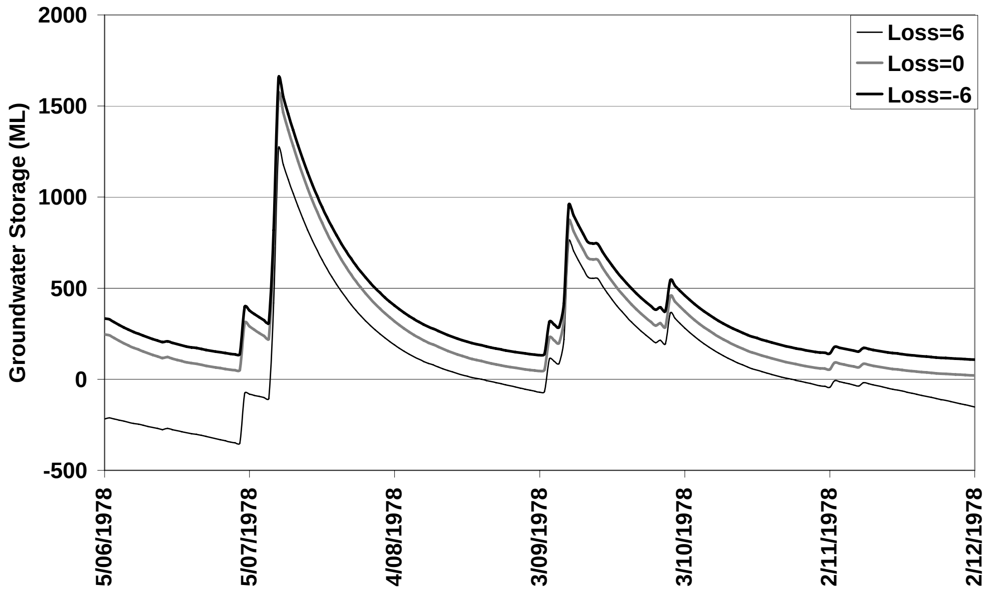


Figure 5-14 Modelled groundwater storage with varying loss parameter

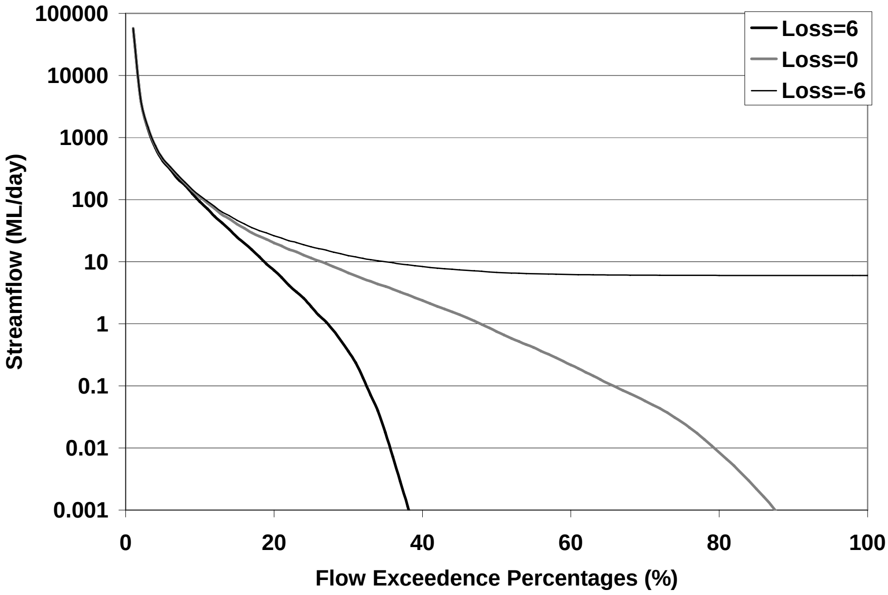


Figure 5-15 Modelled flow exceedence percentages with varying loss parameter

5.7.1.5 Groundwater Extraction

The groundwater extraction parameter of IHACRES_GW allows for the effects of extraction losses from groundwater storage to be modelled. The impact of the groundwater extraction parameter on model simulation behaviour is the same as that observed for the loss parameter previously discussed because groundwater extraction is a specific type of groundwater storage loss.

5.7.1.6 Initialisation of Groundwater Storage

A sensitivity analysis was performed in order to better understand the impact of the initial value of groundwater storage at the start of a model run on modelled output. Recall that the zero reference point for groundwater storage equates to the point above which baseflow activates (as observed at the stream gauging station) and that the groundwater storage volumes are measured relative to this reference point. Initial values of zero, +/- 100 and +/- 1000 ML were applied in IHACRES_GW, and the resulting modelled groundwater storage values are shown in Figure 5-16. For initial values of zero, +/-100 and +1000 ML the modelled groundwater storage values converge after a 50-day run time. The use of an initial groundwater storage value of –1000 ML requires approximately 225 days before modelled storage values converge. The results of these simulations indicate that if a model run starts near the onset of baseflows (i.e. the groundwater storage volumes are not too far from the zero reference), using an initial groundwater storage value of zero is appropriate with due consideration that the first 50 days of model output may be subject to error. Starting a model run after a prolonged dry period may increase uncertainty in model outputs for the first 225 days or so, depending on the severity of the dry period. The best option is to start the model where the baseflow either commences or ceases when the groundwater storage will be close to the zero reference point.

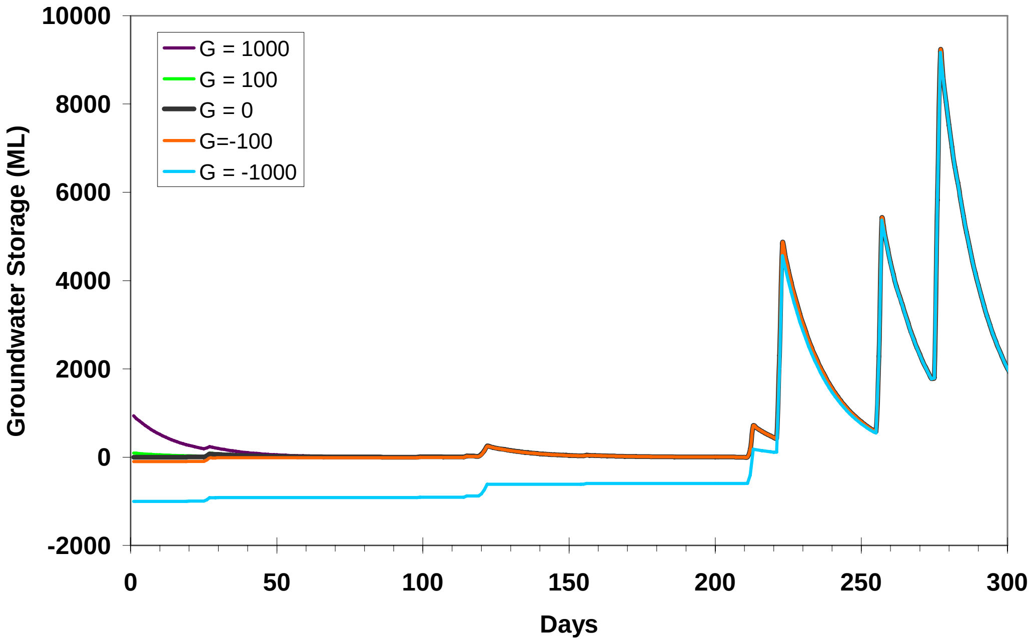


Figure 5-16 Modelled groundwater storages with varying initial values

5.7.2 Two-at-a-Time Parameter Perturbations

The effect of a change in one parameter value (or OAT) on model output, as was discussed above in Section 5.7.1, may be quite different to the effect of changing two or more parameter values simultaneously (Turányi and Rabitz, 2000). In this section a sensitivity analysis is undertaken to consider Two-at-a-Time (TAT) parameter changes in order to assess existing parameter interactions.

The sensitivity (*S*) of the model output, in this case streamflow, to a change from the reference parameter value set was calculated by:

$$S = \frac{\frac{1}{n}\sum_{t=1}^{n}\left(\log R_t - \log P_t\right)}{\Delta} \qquad (5\text{-}18)$$

where R_t is the modelled streamflow using the reference parameters at time t, P_t is the modelled streamflow using the perturbed parameters at time t, n is the number of time steps in the record being simulated and Δ is the change in parameter value from the reference to perturbed. Using an average of modelled streamflow values allows for the sensitivity to be assessed over the selected modelled period, but the sensitivity will vary in time depending on the hydrological dynamics at each time step. The log transformation has been used to give similar weighting to both low and high flows.

The reference parameter values selected were τ_q = 1 day, τ_s = 15 days, v_s =0.09, and each combination of parameter values was perturbed by +/-10% with the sensitivity calculated using Equation 5-18. The results are given in Table 5-2 where negative values indicate an underestimation in steamflow volumes relative to the reference parameter set and positive values indicate overestimations.

The greatest sensitivity is found for the τ_q parameter, and hence this parameter has the largest influence on modelled streamflows. The combination of τ_q and v_s has a slightly larger influence than the combination of τ_q and τ_s. The combination of v_s and τ_s has the least influence, with the τ_s parameter the least sensitive of all three parameters. The sensitivity to modelled streamflows is greatest when the parameter values are changed in the same direction.

Table 5-2 S values for Two-at-a-Time parameter sensitivity analysis of modelled streamflow

v_s \ τ_s	**13.5**	**15**	**16.5**
0.081	-0.90	-0.60	-0.29
0.09	-0.36	–	0.18
0.099	0.16	0.39	0.59

v_s \ τ_q	**0.9**	**1**	**1.1**
0.081	-1.52	-0.60	-0.22
0.09	-0.77	–	0.67
0.099	-0.34	0.39	1.03

τ_s \ τ_q	**0.9**	**1**	**1.1**
13.5	-1.24	-0.36	0.42
15	-0.77	–	0.67
16.5	-0.58	0.18	0.85

The highest sensitivity was found for a 10% reduction in both parameters from the reference value, with the second highest value determined for a 10% increase in both values (Table 5-2). When the parameters are perturbed in opposite directions, e.g. if one value is increased and the other decreased, modelled streamflows remain similar to that produced with the reference parameters. This indicates that there may be some difficulty in finding a unique parameter solution for any pair when using S as an objective function as an overestimation in one parameter value may be compensated for by a decrease in another parameter's value. However, both the OAT and TAT SA demonstrate that for a 10% change in parameter value, the imperfections in fit from the reference are perceptible, but not extremely large.

The influence on modelled streamflows for the v_s and τ_s parameter combinations is shown in Figure 5-17. In this figure one can see that an increase in the τ_s parameter has the effect of increasing baseflow volumes to provide for a longer slow flow recession, which has a similar effect to an increase in v_s. Accordingly, the impacts of the perturbed τ_s and v_s parameter values are evident during periods characterised by baseflow recessions, as would be expected given their influences on baseflow behaviour. Moreover, the sensitivity is greatest when the parameters are perturbed in the same direction which is also expected given their mutually reinforcing influence on baseflows. The residual differences between modelled streamflows using the reference parameter set for the perturbed v_s and τ_s parameter combinations are shown in Figure 5-18. This figure clearly shows that the sensitivity of modelled streamflows to changes in v_s and τ_s parameter is limited to parts of the record where baseflow recessions occur. The residuals in modelled streamflows for a 10% perturbation are seen to be relatively small in the range of +1.8 to -0.5 ML/day.

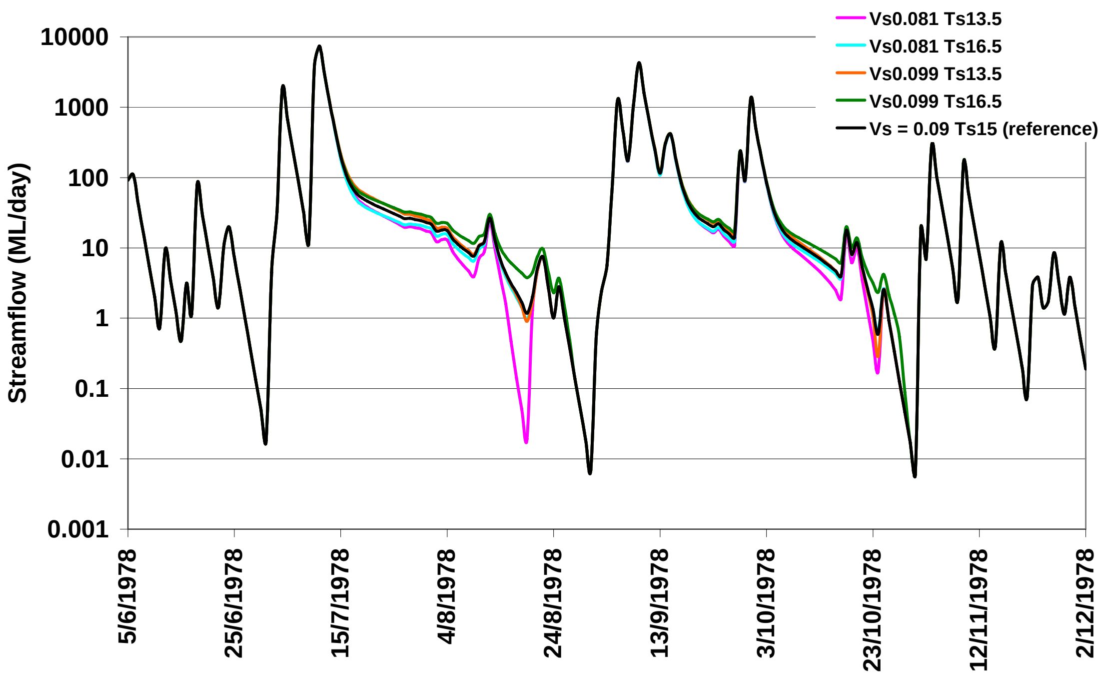


Figure 5-17 Modelled streamflow for perturbed v_s and τ_s parameter values

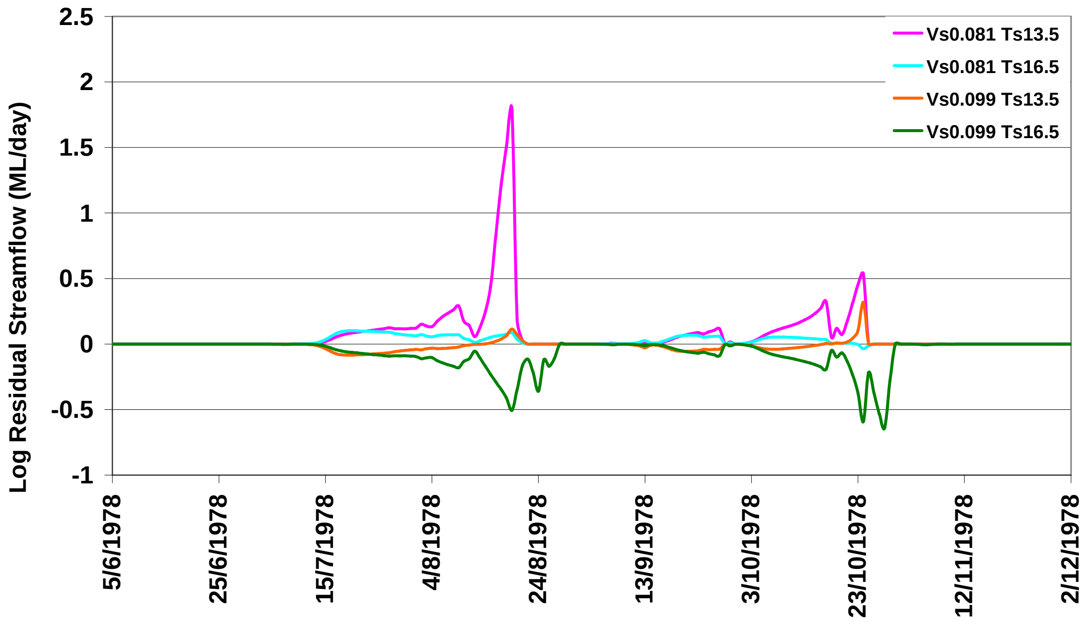


Figure 5-18 Residual difference between modelled streamflows using the reference parameter set and the perturbed v_s and τ_s parameter combinations

The influence of the τ_q and v_s parameter combination on modelled streamflow is shown in Figure 5-19. Here the impact on streamflows is evident for both runoff and baseflow recession periods. An increase in the τ_q parameter has the effect of increasing the effective rainfall, as was previously discussed in Section 5.7.1.3. A larger volume of effective rainfall provides more water that is available to be partitioned between quick and slow flow, and as a consequence the volumes of baseflow are also increased.

The residual differences between modelled streamflows using the reference parameter set and the perturbed τ_q and v_s parameter combinations are shown in Figure 5-19. In this figure one can clearly see the influence of the τ_q parameter throughout the modelled record, especially at the tail end of baseflow recessions, which is an artefact of using streamflow to calculate effective rainfall.

It must be emphasised that the point of this type of SA is to demonstrate the influence of each parameter on modelled flows in order to better understand model behaviour. In practice parameter values would be selected to fit observed flows, and so the errors in parameter selection would tend to be lower – well within the range of +2.3 ML/day to -0.4 ML/day as shown in Figure 5-20, assuming the model adequately represents the observed processes (this is further assessed in Chapter 6).

The relatively strong sensitivity of the model to the τ_q parameter indicates that one would approach model calibration by first fitting this parameter to observed streamflows, whilst paying particular attention to fitting this parameter to the end of baseflow recession periods.

In Figure 5-21, the impact of changing the τ_s and τ_q parameters is evident for both runoff and baseflow recessions, as was seen for the v_s and τ_q parameter combinations previously discussed. In the current configuration of IHACRES_GW, an increase in the τ_q parameter provides additional recharge to groundwater storage through a consequent increase in the effective rainfall series. This will have a similar effect to an increase in the v_s parameter, as was previously discussed, which will result in an increased baseflow component of flows. Hence an increase in the τ_q parameter will also have an effect on the behaviour of the τ_s parameter (as well as the v_s parameter). Consequently, the sensitivity is greatest when these parameters are perturbed in the same direction.

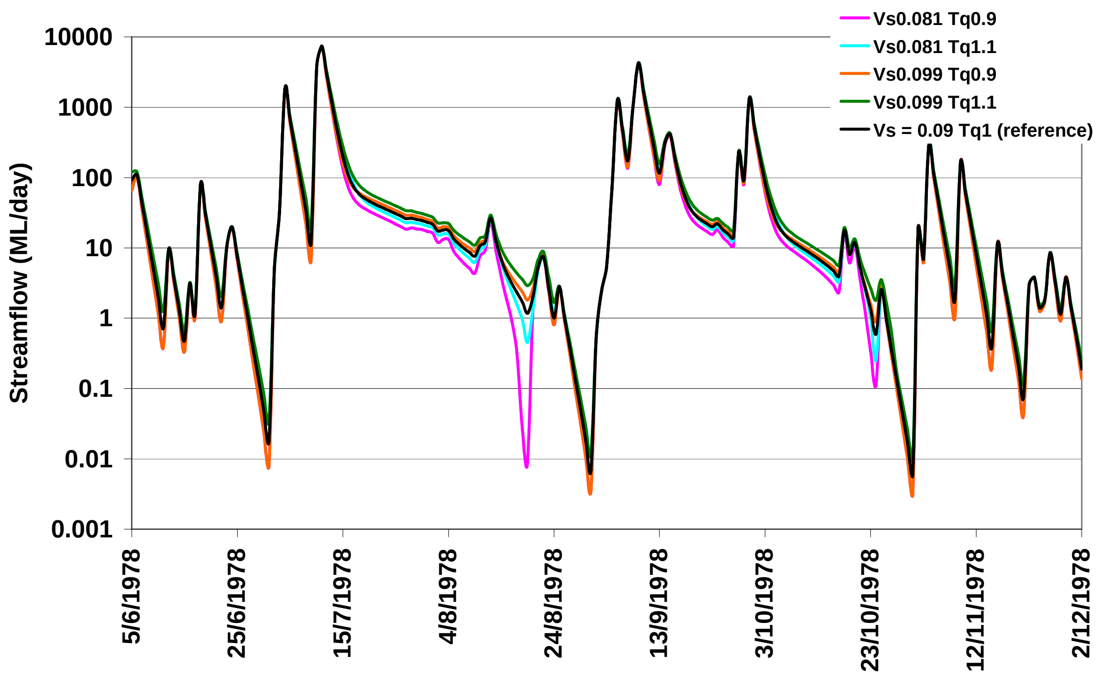


Figure 5-19 Modelled streamflow for perturbed v_s and τ_q parameter values

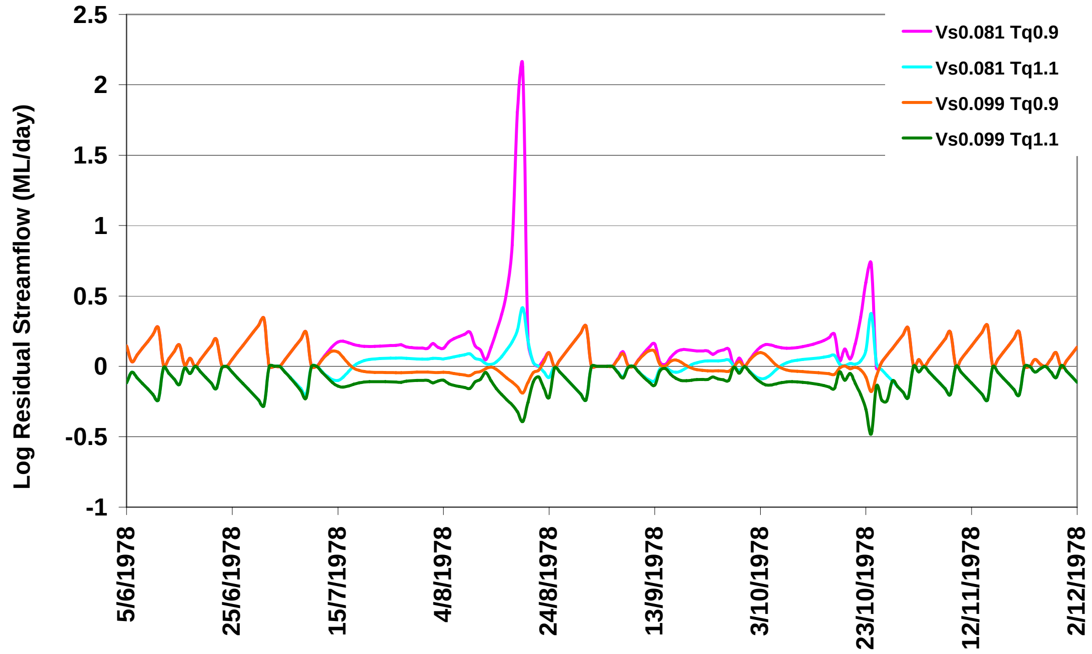


Figure 5-20 Residual difference between modelled streamflows using the reference parameter set and the perturbed τ_q and v_s parameter combinations

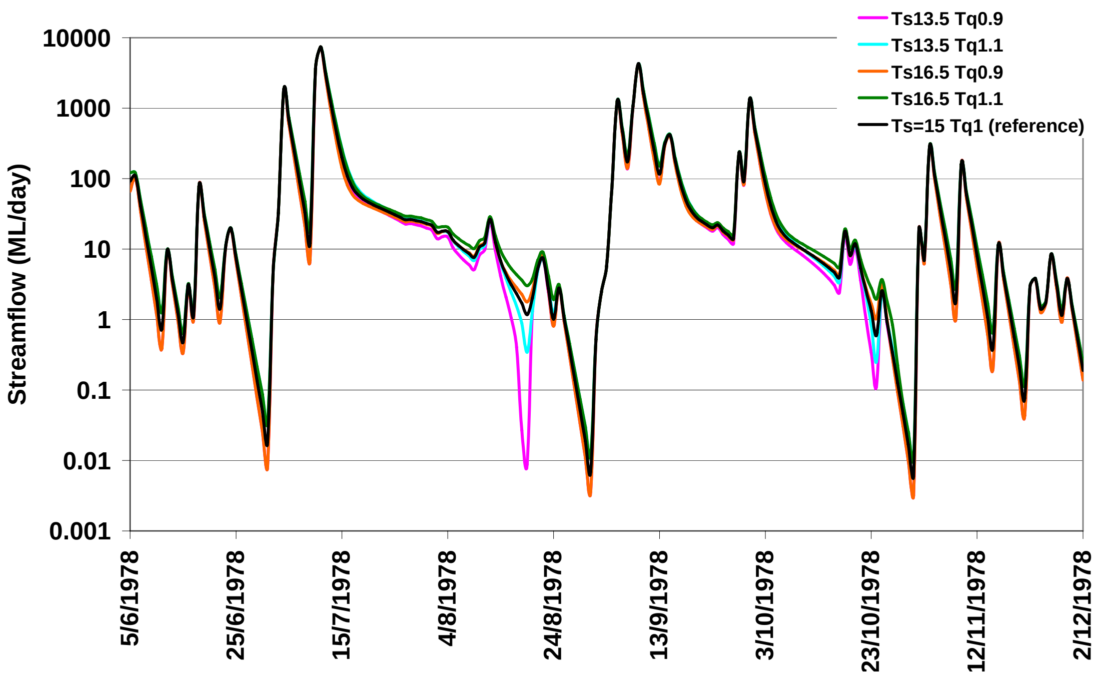


Figure 5-21 Modelled streamflow for perturbed τ_s and τ_q parameter values

The residual differences between modelled streamflows for the perturbed τ_q and τ_s parameter combinations relative to the reference parameter set are shown in Figure 5-22. This figure shows analogous processes to those seen in Figure 5-20 for the perturbed v_s and τ_q parameter combinations, where one can see the influence of the τ_q parameter throughout the modelled record. Upon comparing Figure 5-20 with Figure 5-22, it becomes clearer that the influence of the v_s parameter is predominantly on the volume of baseflow in modelled streamflows, as shown by the broader range of residual values over these periods indicating a greater sensitivity at those times. The influence of the $\tau_{s.}$ parameter is on the duration of the baseflow events, which is also evident in Figure 5-7.

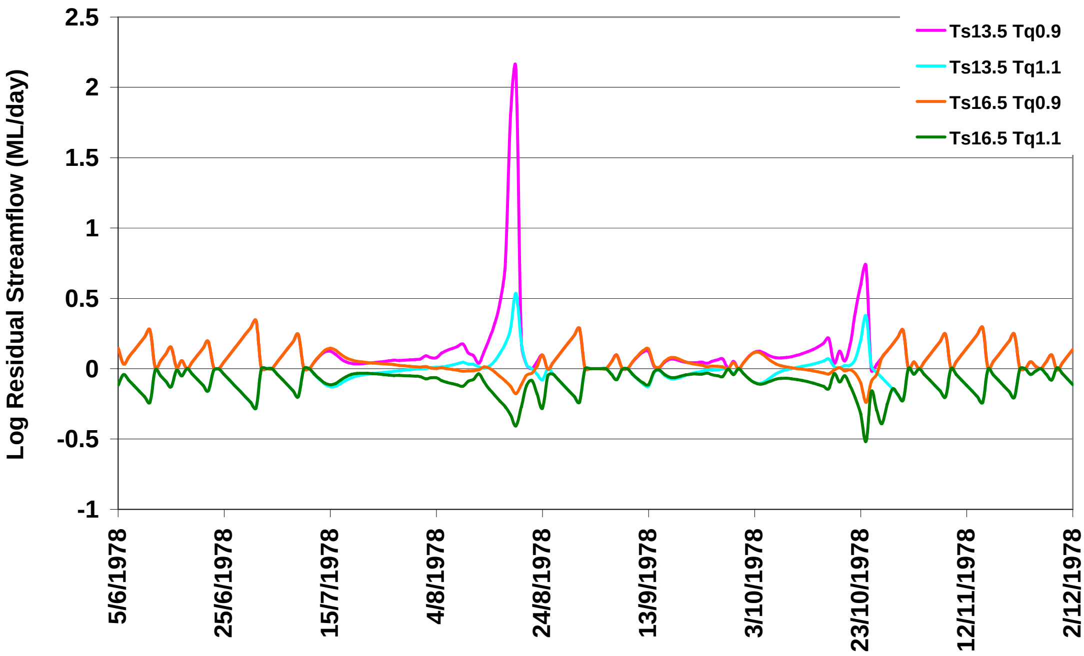


Figure 5-22 Residual difference between modelled streamflows using the reference parameter set and the perturbed τ_s and τ_q parameter combinations

5.7.3 Sensitivity Overview

One can see from the sensitivity analysis carried out for this model that calibration is somewhat complicated by the fact that the choice of parameter values influences the calculation of effective rainfall, which in turn affects the modelled streamflow and hence the selection of optimal parameter values. Because of the correlation between these parameter values as defined by the measure of sensitivity given by Equation 5-18 and shown in Table 5-2, an overestimation in one parameter can be compensated for by a decrease in another parameter. In particular, the τ_q has the largest influence on model output because the quick flow is currently being used to calculate effective rainfall. Hence the τ_q parameter is also influencing the behaviour of the τ_s and v_s parameters and consequently the baseflow/groundwater component module. This problem arises as a consequence of not being able to use a loss module as the non-linear loss module of IHACRES to generate effective rainfall. Nevertheless, the SA has shown that the residual differences for a 10% change in parameter value are evident, but not particularly large. Since in practice the model is calibrated to obtain a good fit to observed flows through a visual inspection, the errors would be relatively small, and most likely within the bounds of the -0.5 to +2.3 ML/day range shown in the modelled flow residuals for the 10% perturbations relative to the 'optimal' reference parameter set values.

The strong sensitivity of the model to the τ_q parameter suggests that this would be the first parameter to consider during a manual model calibration, followed by the v_s parameter and lastly the τ_s parameter. The fact that the model is the least sensitive to the τ_s parameter suggests that the relative uncertainty associated with this parameter may be the greatest.

The SA analysis showed that the τ_q parameter has a strong influence on the quick flow recessions as well as the tail end of baseflow recession periods, the v_s parameter influences the baseflow volumes and the τ_s parameter the duration of the baseflow recession. The information gained through this SA gives some insights into how the calibration process might be automated by determining objective functions whose fits are suited to individual parameters over selected portions of the stream hydrograph where their influence is greatest.

Ideally the use and behaviour of the IHACRES_GW model would be further assessed by undertaking a thorough SA using a non-linear loss module in a catchment where adequate coverage and quality of rainfall data is available. This was considered to be beyond the scope of this thesis. The sensitivity and interactions of model parameters were further assessed, however, by using an effective rainfall data series as model input to IHACRES_GW in order to gain insights into what types of parameter interactions occur in the absence of using streamflow data to generate effective rainfall. This is discussed in the following subsection.

5.7.4 Sensitivity Analysis using Effective Rainfall Data

The effective rainfall values were calculated using Equation 5-17 for the reference parameter set and subsequently used as model input to IHACRES_GW. Further model SA was conducted using OAT and TAT approaches to gain insights into how IHACRES_GW would perform using a non-linear loss module in comparison to its current configuration.

An OAT SA illustrates that the modelled streamflow values generated using the reference parameter effective rainfall series as model input to IHACRES_GW are very closely matched with modelled values generated by using observed streamflow data to calculate effective rainfall (compare Figures 5–23, 5-25 and 5-26 with Figures 5–4, 5–7 and 5–10). The relative difference (RD) between modelled streamflow generated using the reference parameter effective rainfall series and that generated by using observed streamflow to calculate effective rainfall were calculated as

$$RD = \frac{E_t}{S_t}$$

where E_t is the modelled streamflow at time, *t*,using the reference parameter effective rainfall data series as input to the model. S_t is the modelled streamflow at time, *t,* using the observed streamflow to calculate effective rainfall as model input.

The relative differences for the perturbed v_s and τ_q parameter values are shown in Figures 5-24 and 5-27. Their low values give assurance that the current configuration of IHACRES_GW, in which observed streamflow is used to derive effective rainfall, is not contributing greatly to any deviations in modelled output. The modelled streamflows for the τ_s parameters were identical regardless of whether the reference parameter effective rainfall data series or the streamflow-generated effective rainfall data was used as model input, and therefore the relative difference is not shown for this parameter.

The use of an effective rainfall series has altered the behaviour of the τ_q parameter, which now has little effect over baseflow recessions, and instead its influence is directed to quick flow recessions. The influence of the v_s parameter on quick flow events is lessened and the behaviour of the τ_s parameter has remained the same.

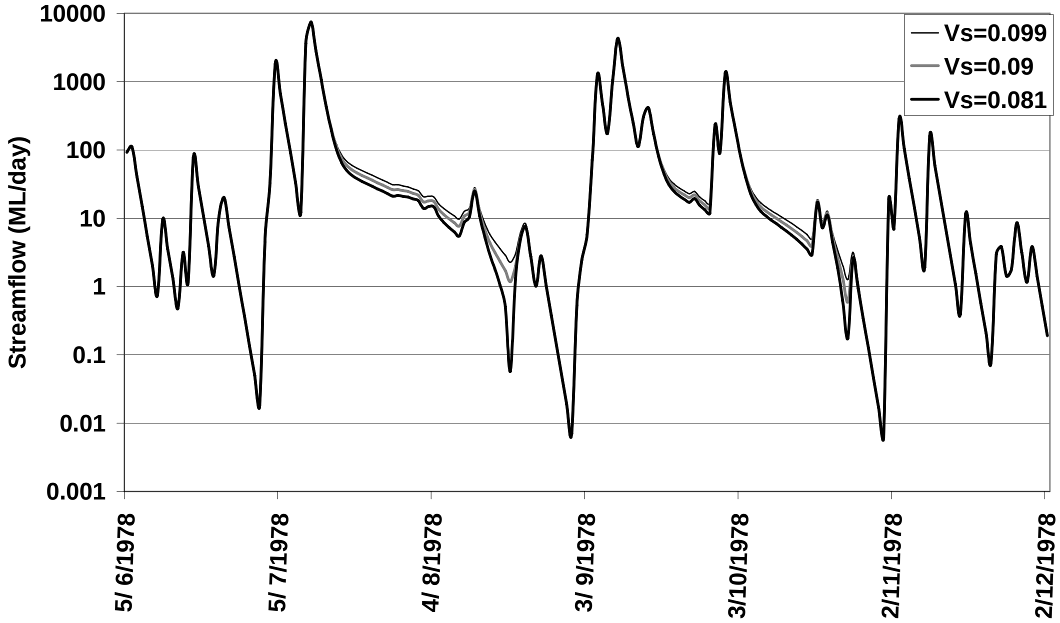


Figure 5-23 Modelled streamflow using reference parameter effective rainfall data series for varying slow flow volumes

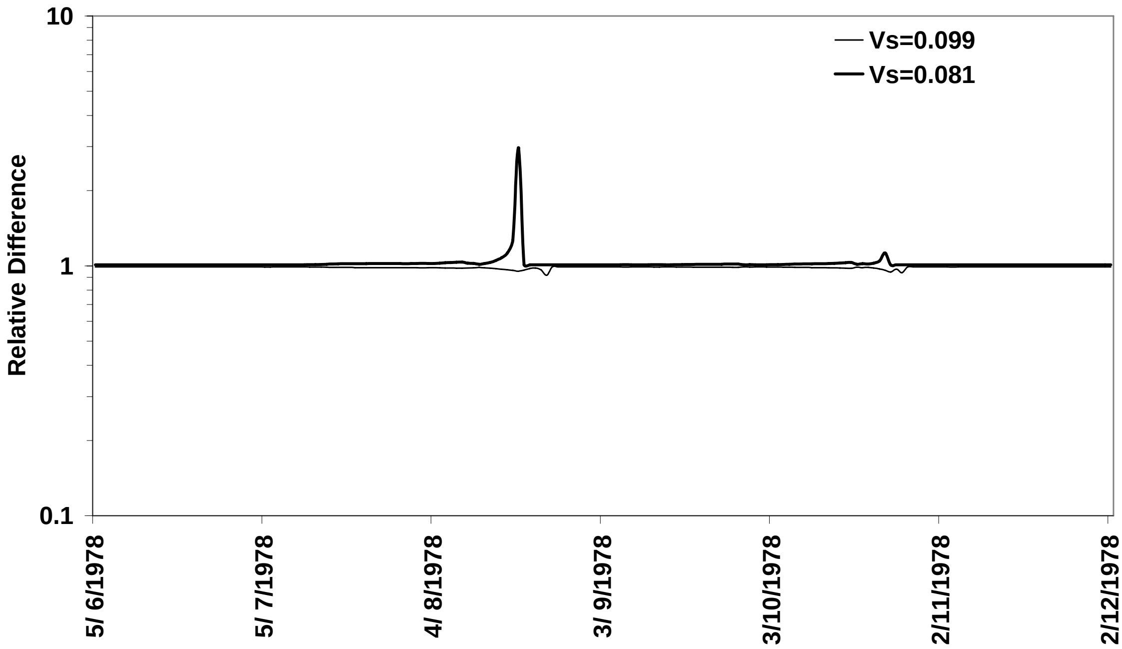


Figure 5-24 Relative difference in modelled streamflows using effective rainfall data series compared with effective rainfall calculated from observed streamflow as model input for varying slowflow volumes

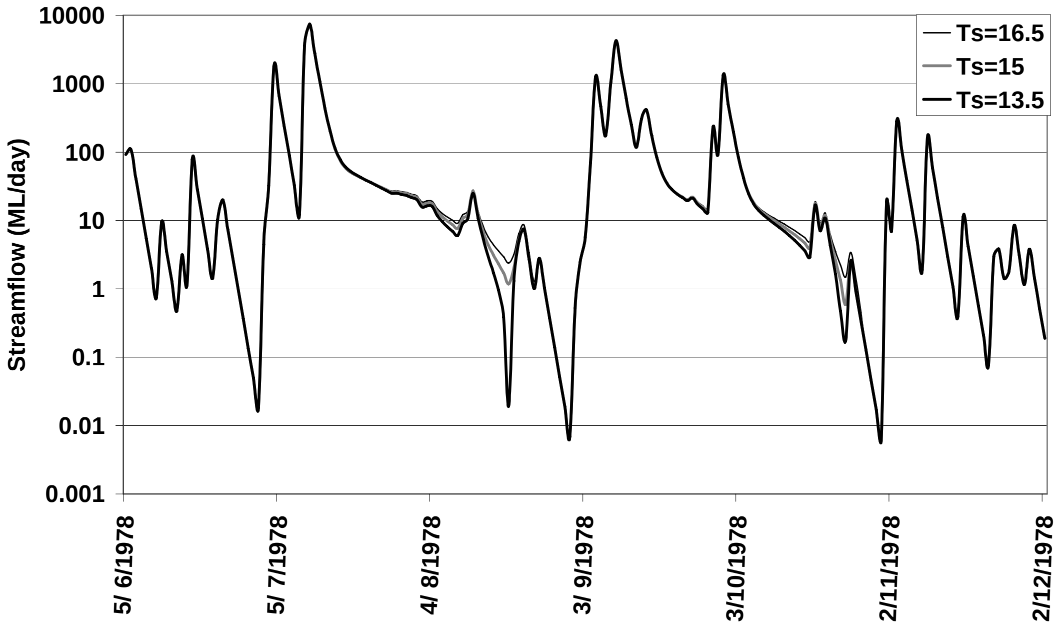


Figure 5-25 Modelled streamflow using reference parameter effective rainfall series for varying slow flow time constants

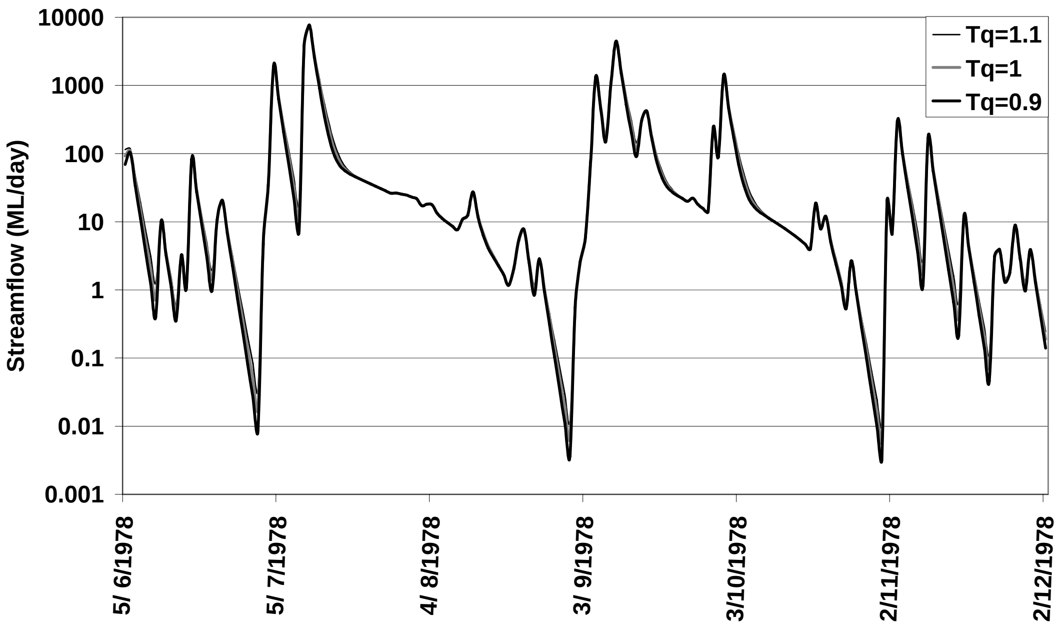


Figure 5-26 Modelled streamflow using reference parameter effective rainfall series for varying quick flow time constants

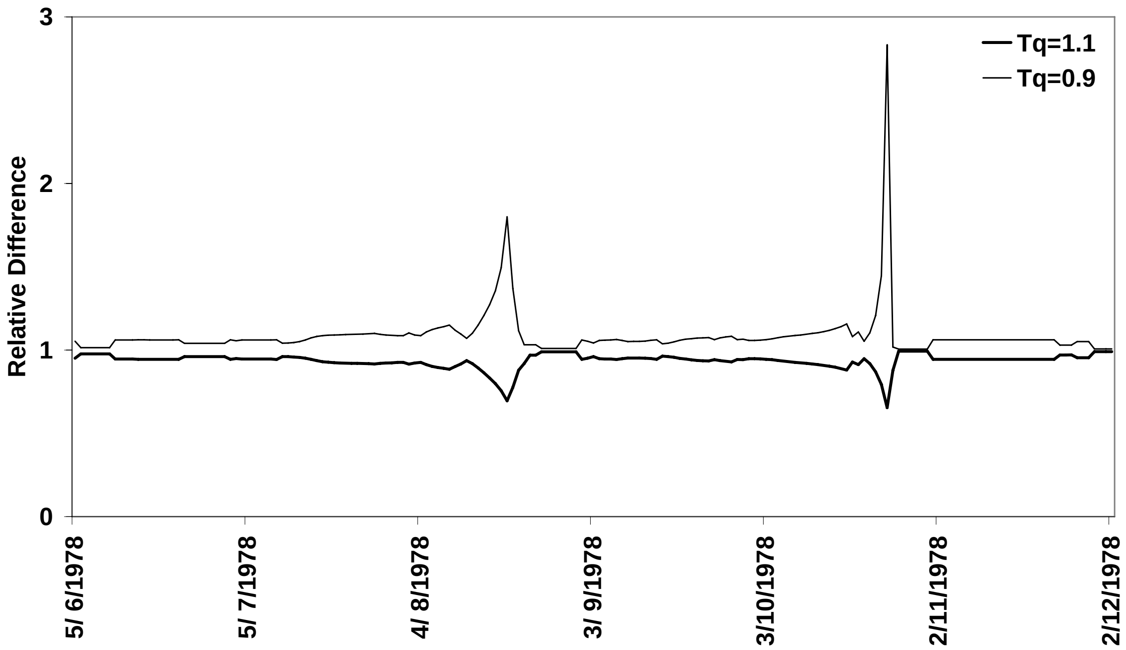


Figure 5-27 Relative difference in modelled streamflows using effective rainfall data series compared with effective rainfall calculated from observed streamflow as model input for varying quickflow volumes

The results from the TAT SA using Equation 5-18, are shown in Table 5-3. The results of the TAT SA indicate that by using the effective rainfall data file as model input to IHACRES_GW, the sensitivity of the model output to the τ_s parameter remains unaffected. However, the sensitivity of the τ_q parameter has been reduced by about 40%, and the v_s parameter by about 20% in comparison to the values shown in Table 5-2.

A reduction in sensitivity to the τ_q parameter is expected because there is no longer a reliance on the quick flow volume (influenced by the choice of τ_q parameter values) to generate effective rainfall data. Using an 'independent' effective rainfall dataset as model input to IHACRES_GW results in the v_s having the greatest influence on model output, with the τ_s and τ_q parameters having a similar magnitude of influence. The combination of τ_q and v_s has the greatest influence. The magnitude of the difference in sensitivity between individual parameters is not large though, and it appears that by using an independent effective rainfall series their influences have become more equally weighted.

Similar to the SA discussed in Section 5.7.2, the sensitivity to modelled streamflows is greatest when the parameter values are changed in the same direction. The highest sensitivity was found for a 10% reduction in both parameters from the reference value, with the second highest value determined for a 10% increase in both values. Using the effective rainfall data set as model input to IHACRES_GW has eliminated some of the cancelling effects between each of the parameters which occurred when using streamflow data to generate effective rainfall and suggests that model calibration may be somewhat easier with an independent effective rainfall data set. Nevertheless, the current configuration of IHACRES_GW, in which streamflow is used to generate effective rainfall, does not appear to be contributing greatly to any deviations in modelled output (based on the comparison of Figures 5–4, 5–7 and 5–10 with Figures 5–23, 5-25 and to 5–26 together with the relative differences shown in Figures 5-24 and 5-27). This configuration therefore seems appropriate for use in quick flow-dominated catchments where rainfall data is of poor quality and/or sparse.

Table 5-3 S values for Two-at-a-Time sensitivity analysis of modelled streamflow using reference parameter effective rainfall data set

v_s \ τ_s	**13.5**	**15**	**16.5**
0.081	-0.83	-0.49	-0.21
0.09	-0.36	–	0.18
0.099	0.09	0.32	0.52

v_s \ τ_q	**0.9**	**1**	**1.1**
0.081	-0.96	-0.49	-0.09
0.09	-0.45	–	0.38
0.099	-0.12	0.32	0.70

τ_s \ τ_q	**0.9**	**1**	**1.1**
13.5	-0.84	-0.36	0.04
15	-0.45	–	0.38
16.5	0.18	0.18	0.56

5.8 Chapter Summary

This chapter has described some of the modelling approaches commonly used in surface and subsurface hydrological studies. Groundwater models previously implemented in the Namoi River catchment were dismissed for this study in lieu of a simpler model. The development and use of a simple model was preferred for a number of reasons including: the requirement for subcatchment-scale water budget accounting in order to assess water sharing plans; the requirement to model streamflows, including baseflows, on a daily time step; the requirement for a model that could be later used in integrated assessments; the limited data pool and time with which to parameterise a complex model; and the uncertainties associated with validating models that are over-parameterised. The derivation of the simple, four-parameter, spatially lumped IHACRES_GW model was fully described, and a simple sensitivity analysis was carried out. The sensitivity analysis showed that the current configuration of IHACRES_GW, in which effective rainfall is generated using streamflow, does not appear to be contributing greatly to any deviations in modelled output and is thus suited to use in quick flow dominated catchments where rainfall data is of poor quality and/or sparse. The SA showed that the τ_q parameter has a strong influence on the quick flow recessions and the tail end of baseflow recession periods, the v_s parameter influences the baseflow volumes and the τ_s parameter the overall duration of the baseflow recession. The information gained through this SA gives some insights into how the calibration process might be automated in the future by determining objective functions whose fits are suited to individual parameters over selected portions of the stream hydrograph where their influence is seen.

In the following chapter the application of the IHACRES_GW model will be tested in the Cox's Creek subcatchment.

Chapter 6 Model Application

6.1 Introduction

A simple integrated aquifer-river model entitled IHACRES_GW was developed for use at the catchment scale in Chapter 5 in order to investigate the impacts of groundwater extraction on river flows in connected aquifer-river systems. The IHACRES_GW model includes a rainfall-runoff model combined with a simple bucket groundwater module that maintains a continuous water balance account of groundwater storage volumes for the upstream catchment area relative to the base of the stream, assumed to be the stream gauging station. In this chapter the application of the IHACRES_GW model is tested in the Cox's Creek subcatchment of the Namoi River catchment in order to assess its utility. A discussion of the model calibration, evaluation and performance criteria is provided within this chapter in order to assess the model.

6.2 Cox's Creek subcatchment

The IHACRES_GW model was applied to the Cox's Creek subcatchment using data from the Boggabri stream gauging station 419032 (see Figure 4-4 and Figure 6-1). The catchment area upstream of the gauge covers 4 040km^2. Cox's Creek was categorised in Chapter 4 as a variably connected-disconnected aquifer-river system that is variably gaining-losing (Figure 4-12). The river is an intermittent to ephemeral stream system with river flows measured 37% of the time at gauging station 419032. The average flow over the length of the streamflow record (1965-2003) is 254 ML/day, with a baseflow contribution over the whole length of the record that is approximately 9% of total average flows (Table 4-3). The Cox's Creek subcatchment is divided into two groundwater management zones. Zone 9 is located to the south of Mullaley and Zone 2 to the north. A narrowing of the valley at Mullaley separates the two zones. Groundwater is commonly used for growing cotton and other cropping options in Zone 9.

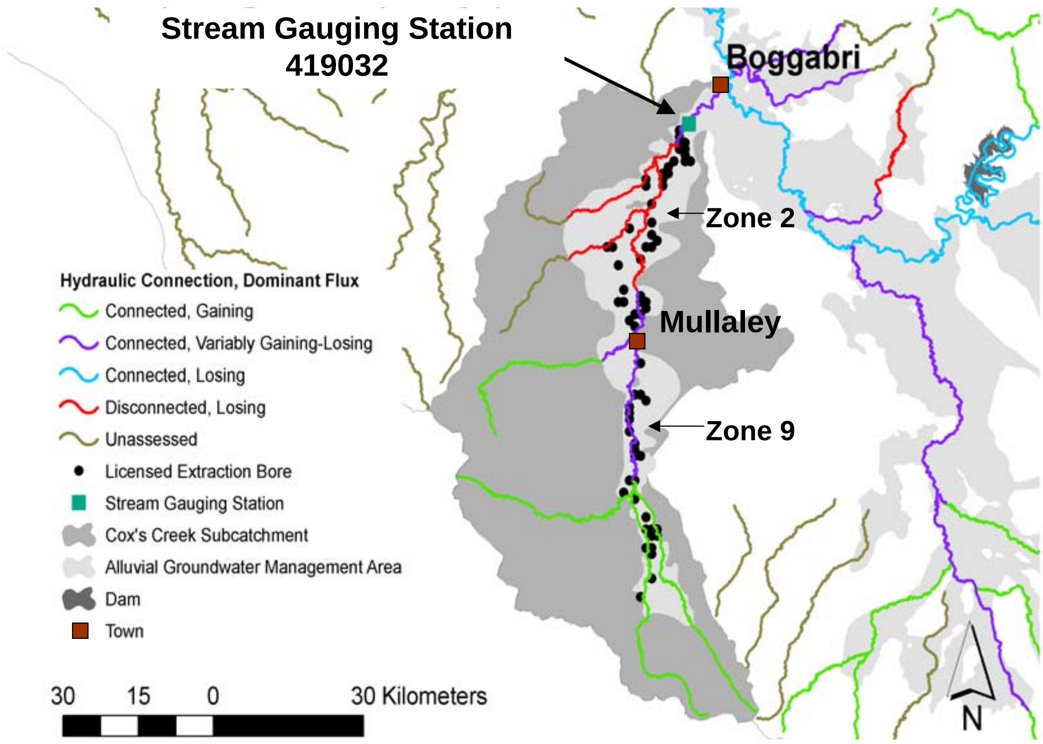


Figure 6-1 Location of Cox's Creek subcatchment, groundwater management Zones 9 and 2, extraction bores and gauging station 419032

6.3 Hydrogeology

The Cox's Creek alluvium is the largest aquifer type in the sub-catchment, sitting within a narrow alluvial valley that is about 20 km wide and 72 km in length. Although the valley is more than 20 km wide in places, the main high-yielding palaeochannel is less than 5km wide, flowing parallel to and on the western side of Cox's Creek (Brownbill, 2000). The maximum thickness of the alluvium is 140 m in the Boggabri area (Broughton, 1994a). The two main aquifers are divided into the upper Narrabri Formation and the lower Gunnedah Formation. The Gunnedah Formation contains gravels and sands, whilst the Narrabri Formation contains mostly clays and silts. Both aquifers are semi-confined, and the two formations are in vertical hydraulic contact throughout much of the subcatchment (recall Figure 4-15 and Figure 4-18). The alluvium has transmissivities ranging from 21 to 1300 m^2/day as a consequence of variations in hydraulic conductivity and thickness. Recharge to the Gunnedah Formation is at the southern, upstream end of the aquifer where extensive alluvial fans have been deposited by the upland creeks on the lower hillslopes of the ranges. Diffuse recharge and occasional flooding on the alluvial plain contributes recharge to the Narrabri Formation. Upward flow to the Narrabri Formation occurs through vertical leakage from the pressurised Gunnedah aquifer, which receives upward vertical leakage from the underlying Basalt bedrock aquifer (Dyce and Richardson, 1997). Groundwater flow is in a northerly direction towards the Namoi River.

6.3.1 Rainfall Record

Daily rainfall data for the Cox's Creek subcatchment were obtained from the Australian Bureau of Meteorology MetAccess Database and analysed for the period coinciding with available streamflow data (1/6/1965 – 9/12/2003). The mean monthly rainfall values ranged from a minimum of 38 mm in June to a maximum of 104 mm in January, with the greatest values for the October-February spring-summer period (Figure 6-2).

The average annual rainfall ranged from a minimum of 387mm in 1994 to a maximum value of 961 mm in 1998, with an average value of 679 mm (Figure 6-3). The low rainfall years of 1965, 1967, 1979/80, 1982, 1985/86, 1994 and 2003 are evident in this figure. These low rainfall periods and the drier transition periods around them are also clearly evident in the plot of the accumulative residual rainfall (ARR) (Figure 6-4). The ARR plot provides an overview of the fluctuations in monthly rainfall for each year relative to the average monthly rainfall for the period. The ARR is calculated by subtracting the actual monthly rainfall for a particular month from the average total monthly rainfall for that month over the period of the rainfall record being analysed. A positive slope indicates a cumulative period of above average monthly rainfall and a negative slope indicates below average monthly rainfall.

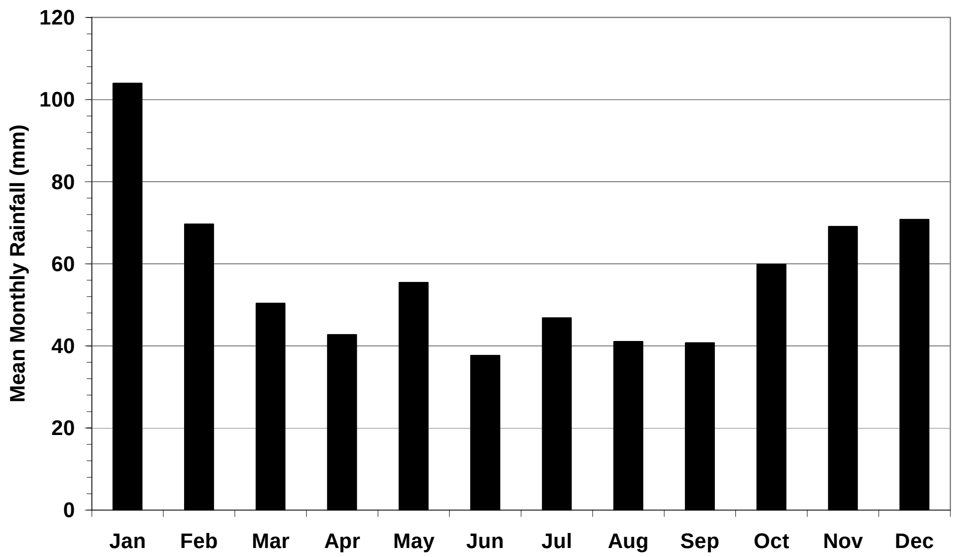


Figure 6-2 Mean monthly rainfall for the 1/6/1965 - 9/12/2003 period

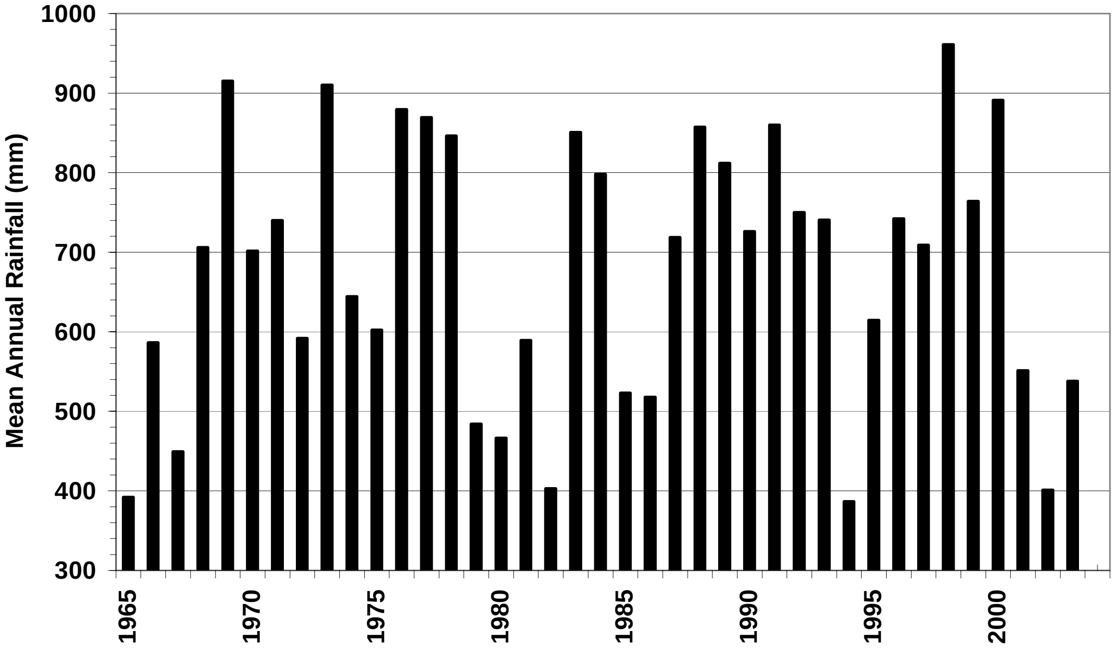


Figure 6-3 Mean annual rainfall for the 1/6/1965 - 9/12/2003 period

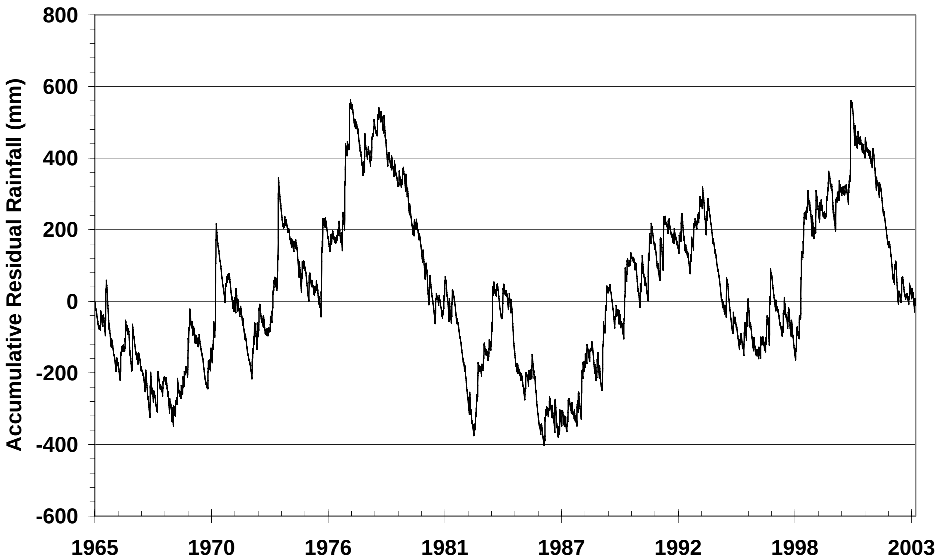


Figure 6-4 Accumulative residual rainfall for the 1/6/1965 - 9/12/2003 period

6.4 Model Performance Criteria

The key characteristics of streamflow that the IHACRES_GW model was intended to capture were:

1. the timing in the switch between baseflow periods and no-flow periods; and
2. the volume of baseflow contributed to streamflow on a daily basis.

The performance of the model over the calibration and simulation periods was principally assessed using visual inspection of the time series and flow duration of modelled streamflows compared to those from the observed data series. This pragmatism is required because of the difficulty in constructing objective functions that measure streamflow recession behaviour adequately for an ephemeral river system (where measured flows are commonly zero). This strategy was complemented, however, by assessment with five performance criteria, namely R^2, R^2_*Baseflow*, R^2_{inv}, Relative Bias (*RB*) and *RB_Baseflow*. In addition, confusion matrices were used to analyse the success of the model in estimating baseflow behaviour.

R^2 is the coefficient of efficiency described by Nash and Sutcliffe (1970) as

$$R^2 = 1 - \frac{\sum_{t=1}^{n} (O_t - M_t)^2}{\sum_{t=1}^{n} (O_t - O)^2}$$

where O_t is the observed value at time t, M_t is the predicted value at time t, O is the mean of the O_t and n is the number of daily time steps in the record being simulated. The coefficient of efficiency describes the degree of agreement between the observed and modelled values of a data series. The closer the R^2 value is to 1 the better the model reproduces the variance in the observed data set. The R^2 values were calculated for total streamflow and filtered baseflow (R^2_*slow*) using the minima filter described in Section 5.6. R^2 is biased towards reproducing high flows, not recession or baseflow behaviour, so it is of limited interest in terms of calibrating the model except to ensure the overall acceptability of model performance. The R^2_*slow*, however, is of particular interest because it gives an indication of how well the model captures the baseflow periods in the dataset.

A similar statistic to the coefficient of efficiency is the R^2_{inv} which is calculated as

$$R^2_{inv} = 1 - \frac{\sum_{t=1}^{n}\left(\frac{1}{1+O_t} - \frac{1}{1+M_t}\right)^2}{\sum_{t=1}^{n}\left(\frac{1}{1+O_t} - \frac{1}{1+\bar{O}}\right)^2} .$$

Like R^2, the R^2_{inv} measures the degree of association between individual observed and modelled values; however R^2_{inv} measures the fit to mostly low flows.

Relative Bias (*RB*) is a normalised measure of the average difference between the modelled and observed estimates of average flows for the length of the record. The closer the bias is to zero, the better the model fit. Relative Bias is given by

$$RB = \frac{\frac{1}{n}\sum_{t=1}^{n}(O_t - M_t)}{\bar{O}} .$$

RB measures are useful in assessing streamflow volumes over the length of the modelled period, but not on a daily time step. The RB was also calculated for the filtered streamflows (*RB_Baseflow*) using the minima filter described in Section 5.6

Confusion matrices were also analysed to assess the timing of the "switching on and off", and hence the recession behaviour of the model. These provide an indicator of the proportions of correctly and incorrectly classified flows for a qualifier, in this case the presence of baseflow.

6.5 Model Calibration

The IHACRES_GW model was calibrated to daily streamflow data from gauging station 419032 obtained from the Department of Natural Resources streamflow database (DIPNR, 2004). The period selected for calibration was 1/6/1965 to 30/6/1980, spanning a period of 5 508 days (or 15 years) with a continuous record of daily streamflow data which includes some periods of data-infilling undertaken by the Department of Natural Resources. The river flows during this period of time were considered to be representative of pre-groundwater extraction conditions. Annual groundwater extraction data is available from 1985 onwards, and it is understood that prior to around 1980 there were relatively small amounts of groundwater extraction taking place within the catchment.

The method of calibration used was one of trial and error where parameters were varied within a sensible range. This proved to be practicable, as well as valuable, because it facilitated parameter value selection by the inspection of visual behaviour of the model together with the use of multiple objective performance criteria (Section 6.4) in a flexible way. It also resolved the problem of how to weight different parts of the fit to the record e.g. where data were known to be in error due to infilling.

The calibration parameters providing the best model fit over the calibration period based on visual inspection to observed streamflows and flow duration curves are given in Table 6-1, along with the associated objective function fits.

Table 6-1 IHACRES_GW calibration period (1/6/1965 to 30/6/1980) parameter values and objective function fits

Parameter	Calibrated Value	Objective Function	Value
v_s	0.09	*R2*	0.89
τ_s	15 days	*R2_Baseflow*	0.62
τ_q	0.9 days	*R2inv*	0.79
Loss	6 ML/day	*RB*	0.28
		RB_Baseflow	0.48

The calibrated parameters listed in Table 6-1 resulted in derived values of α_q = -0.329 (Equation 5-4), α_s = -0.936 (Equation 5-5), v_q = 0.91 (Equation 5-6), β_q =0.61 (Equation 5-7), β_s =0.006 (Equation 5-8) and a = 0.07 (Equation 5-16).

The fits for R^2 and *RB* are good, as expected, because the effective rainfall was calculated using the quick flow signal in the observed streamflow data (refer to Section 5.6). Hence the fit biased towards higher flows is good. The R^2*_Baseflow* and R^2_{inv} , which are biased towards the low flows, suggest that the model is also capturing the recession volumes of baseflows rather well on a daily time step. The *RB_Baseflow* statistics, however, indicate that the overall volume of baseflow predicted over the 15-year calibration period is about half the volume "measured" in the filtered observed flow. This is in large part due to the fact that low flow events below 8 ML/day were not reliably recorded at the gauging station, resulting in either no data or data infilling over much of the early record. These low flow events were unreliably recorded due to the bias in the rating curve towards medium and high flows – which is not unexpected for an ephemeral river system- and because of the flat concrete causeway in the base of the river at the gauging station site making low flow readings difficult. The reader is referred to Sauer and Meyer (1992) for further discussion regarding uncertainty in stream discharge measurements. The implications of data-infilling on modelled streamflows are discussed in more detail later in this section.

A confusion matrix for the prediction of baseflows greater than 0.01 ML/day is shown below in Table 6-2. The data from this matrix indicates that the proportion of modelled flows with incorrect recession timings for each of the four possible combinations was 6.6% (4.5 plus 2.1%). The proportion of time where baseflow was "measured" (from the filtered observed streamflow using the minimum filter described in Chapter 5.6) but not modelled was 2.1%. These percentages suggest that the model is performing well in terms of capturing the baseflow switching behaviour within streamflow. By contrast, if no groundwater losses are included in the model run, as per the original IHACRES model formulation, 49% of the total proportion of flows is incorrectly modelled. This is because the exponential formulation does not allow for zero flows to occur. Hence, the IHACRES_GW model captured a substantial amount of baseflow recession behaviour not captured by the original IHACRES model.

Table 6-2 Confusion matrix for calibration period to assess performance of IHACRES_GW model

"Measured" Baseflow <0.01 ML/day Modelled Baseflow <0.01 ML/day	**"Measured" Baseflow <0.01 ML/day Modelled Baseflow >0.01 ML/day**
69.1%	4.5%
"Measured" Baseflow >0.01 ML/day Modelled Baseflow <0.01 ML/day	**"Measured" Baseflow >0.01 ML/day Modelled Baseflow >0.01 ML/day**
2.1%	24.3%

As indicated earlier, visual inspection of the observed versus the modelled streamflow data was a key component in the selection of appropriate parameter values over the calibration period. One can see from Figures 6-5 to 6-10 that the modelled streamflow output shows a good match to the observed streamflow record. Observed flows below 8 ML appear to have been unreliably recorded at the stream gauging station since these flows tend to be reported as zero flow values in the streamflow record. The general underprediction of modelled baseflows is also evident in the statistical measure of *RB_Baseflow,* with a value of 0.48. The largest residual differences between observed and modelled flows are associated with very high flow events, which are at times underpredicted by the model due to an overly rapid decay of modelled flows.

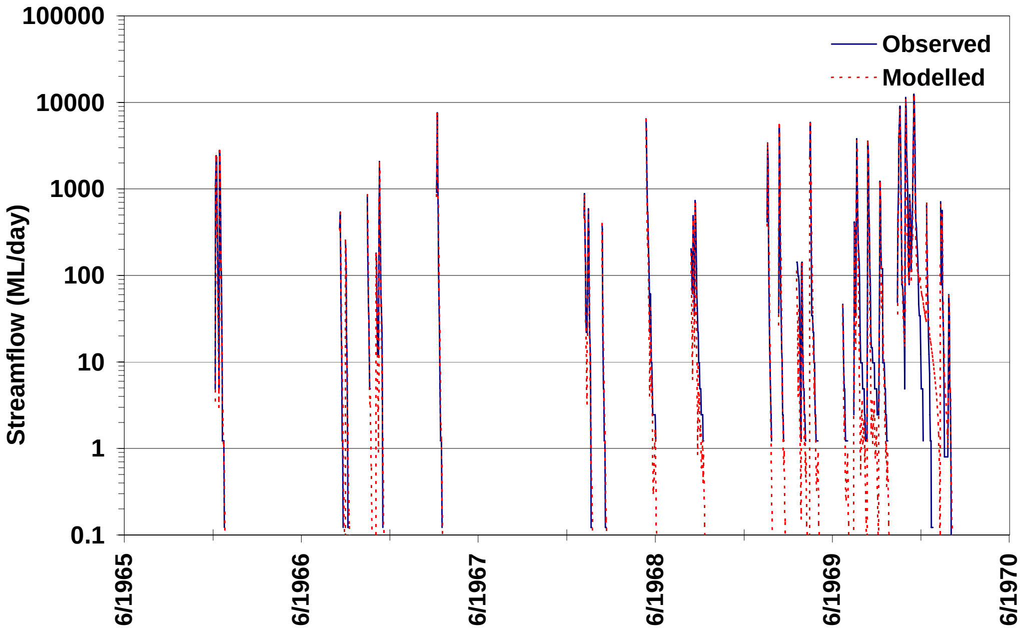


Figure 6-5 Observed and modelled streamflow at gauging station 419032, Cox's Creek at Boggabri, for the calibration period (1/6/1965 to 1/6/1970)

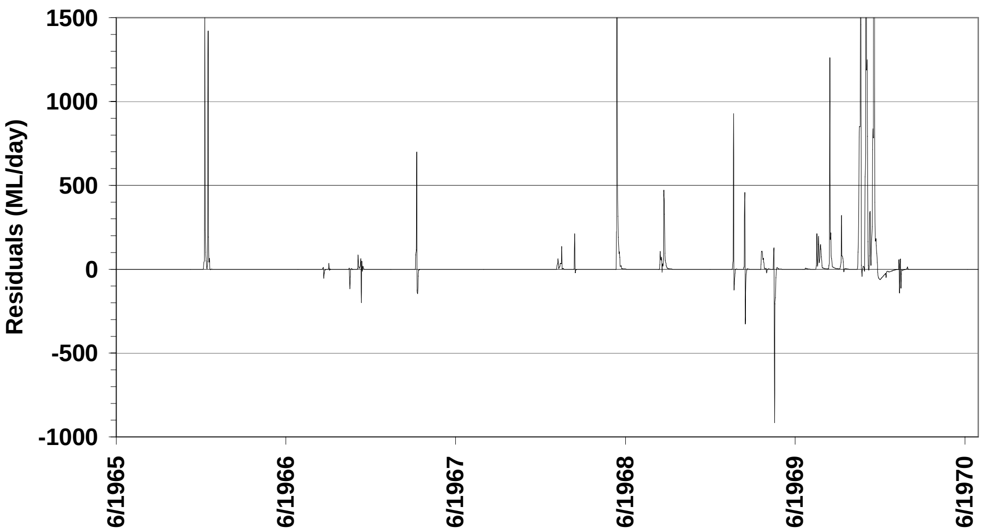


Figure 6-6 Residual difference between observed and modelled streamflow for the calibration period (1/6/1965 to 1/6/1970)

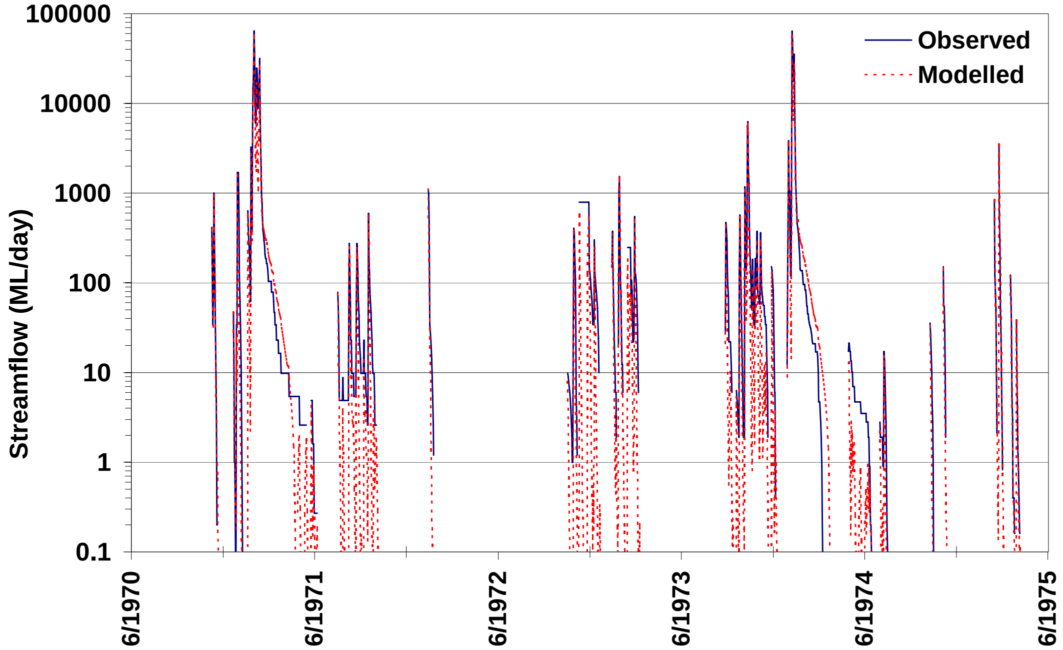


Figure 6-7 Observed and modelled streamflow at gauging station 419032, Cox's Creek at Boggabri, for the calibration period (1/6/1970 to 1/6/1975)

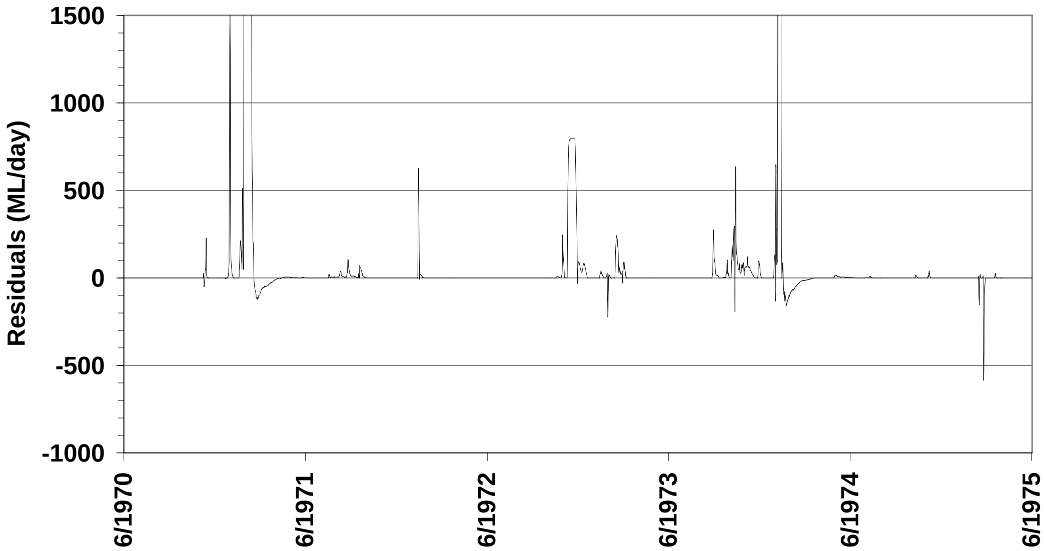


Figure 6-8 Residual difference between observed and modelled streamflow for the calibration period (1/6/1970 to 1/6/1975)

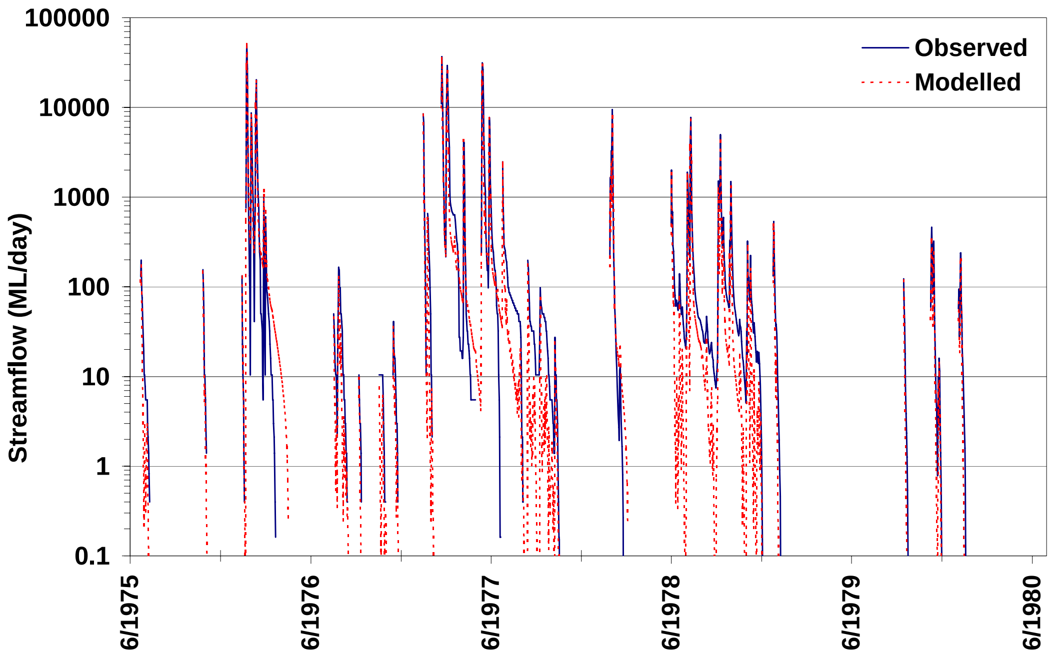


Figure 6-9 Observed and modelled streamflow at Gauging Station 419032, Cox's Creek at Boggabri, for the calibration period (1/6/1975 to 30/6/1980)

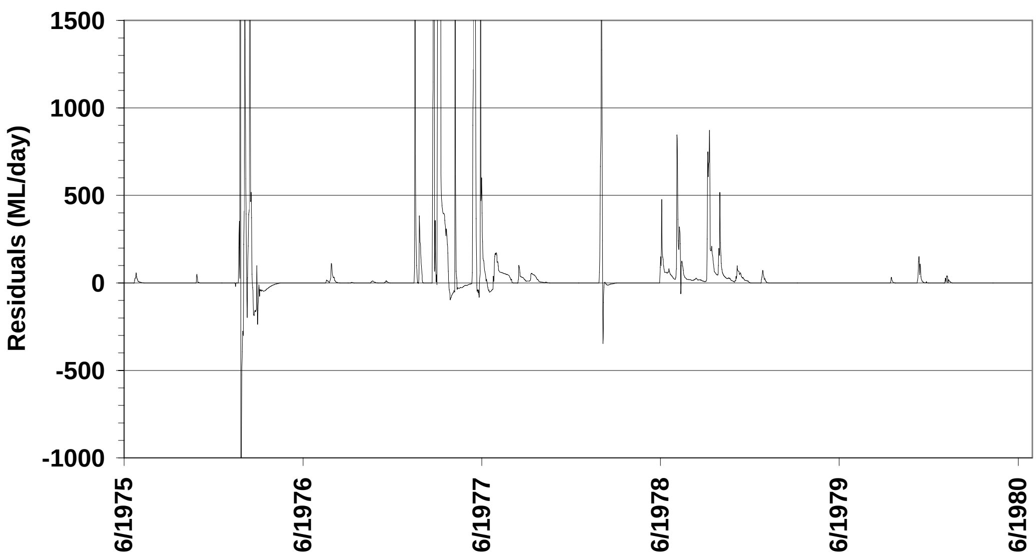


Figure 6-10 Residual difference between observed and modelled streamflow for the calibration period (1/6/1975 to 30/6/1980)

A more detailed portion of the calibration record has been plotted in order to better illustrate the performance of the modelled streamflow recession behaviour (Figure 6-11). From this figure it is evident that the modelled streamflow recessions are at times too rapid, too slow or about right. This suggests that the partitioning of effective rainfall into quick and slow flow components may not be a relationship that remains constant in time (an assumption in the IHACRES_GW linear module and IHACRES generally). For example, different sizes or intensities of rainfall events may result in variable volumes of groundwater recharge and so the partitioning of effective rainfall between the quick and slow pathways would also vary.

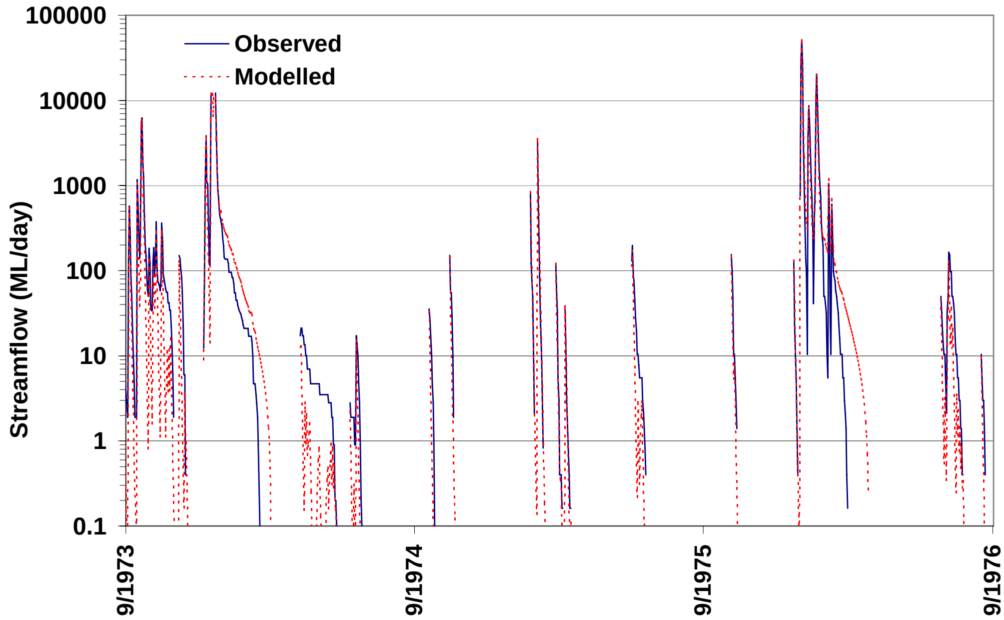


Figure 6-11 Detailed record of observed and modelled streamflows (22/9/1973-22/9/1976)

Because of missing data records, some infilling of data was undertaken by the data provider, the Department of Natural Resources. These periods are evident in the record when streamflow data remains constant for a period of time (e.g. up to several weeks or longer), which adds some difficulty in attempting to appropriately fit model parameters. The infilling becomes particularly apparent in the detailed plot of streamflow (Figure 6-12) and the flow duration curve (Figure 6-13) where sections of the observed data look blocky/angular. Because of the data infilling, the modelled flow exceedence percentages are less than those recorded as having been observed. The formulation for generation of effective rainfall (Equation 5-17) requires increasing streamflow volumes in order for effective rainfall to be generated (e.g. if streamflow values remain constant no effective rainfall is generated). Data infilling has resulted in constant streamflow values over large parts of the record, and consequently the effective rainfall contribution will have been calculated as zero over those periods of the data record. Without effective rainfall input to the model, the modelled streamflow will decline exponentially and result in modelled streamflows that are less than those recorded as having been 'observed'. Despite data infilling, the IHACRES_GW model applied to the calibration period has performed well in terms of both visual inspection and goodness of fit statistics over the calibration period. In particular, it has captured the switch between baseflow and no flow periods remarkably well.

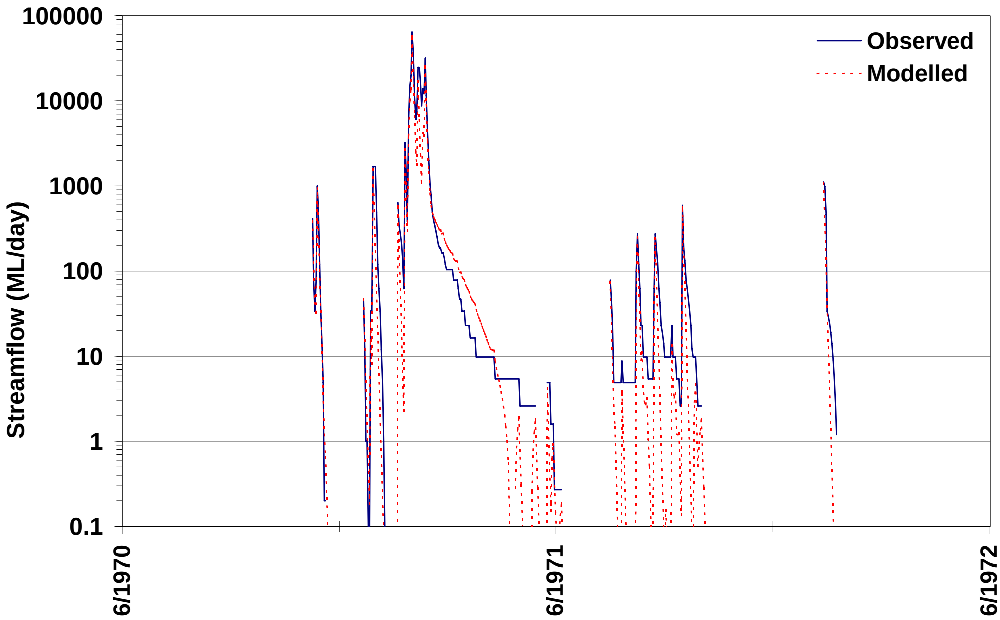


Figure 6-12 Examples of data infilling in observed streamflow record (1/6/1970-2/6/1972) at Gauging Station 419032, Cox's Creek at Boggabri

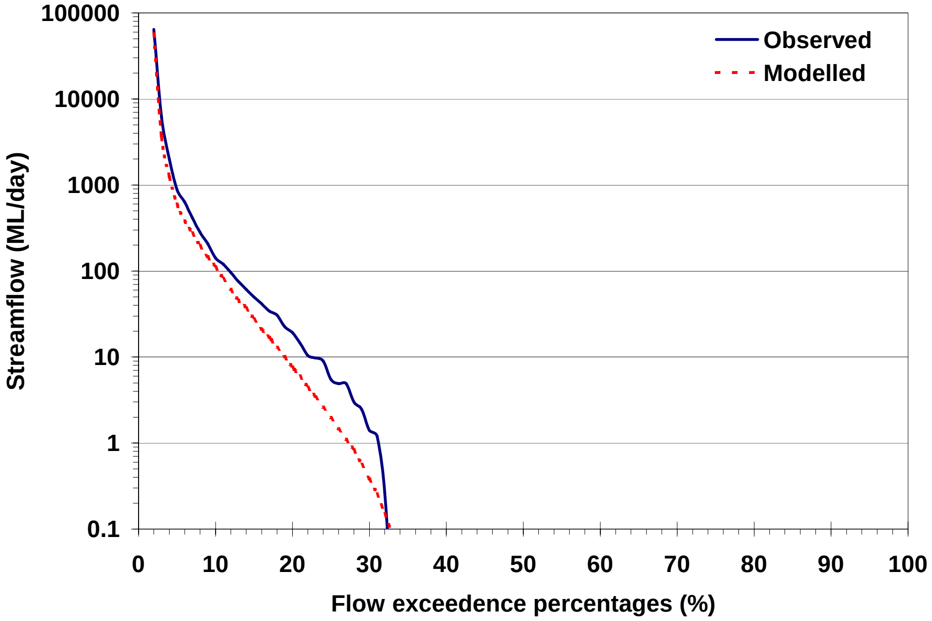


Figure 6-13 Flow exceedence percentages for observed and modelled streamflow for the 1/6/1965 to 30/6/1980 calibration period

6.6 Model Simulation

Model simulation consists of running the model forward with calibrated parameters using input data from a period that does not include any data from the calibration period. The period selected for model simulation using IHACRES_GW was 2/9/1988 to 9/12/2003, spanning 5 576 days (15.3 years). This period was selected because daily streamflow and yearly groundwater extraction data (converted to a daily average over the irrigation season) were available over the record. Simulations were run on a daily time step using the calibrated model parameters (Table 6-1). Groundwater extraction data was used as an additional loss from groundwater storage. The model was not calibrated to this period, so this simulation also serves as a test of the calibrated model.

6.6.1 Use of Groundwater Extraction Data

Annual extraction data from 1985 through to the present were available from the NSW Department of Natural Resources (DNR) groundwater database for each of the licensed extraction bores. The annual extraction volume at each bore was summed in order to determine the total volume of groundwater extracted from the alluvial aquifers within the Cox's Creek subcatchment above gauging station 419032 (note that very little groundwater extraction occurs within the subcatchment from either the volcanic or hard rock aquifers). The aggregated annual extraction volume within the subcatchment was subsequently divided by 212, the number of days in the groundwater irrigation season over 1 September – 31 March, in order to calculate a daily extraction rate (Figure 6-14). Outside the irrigation season groundwater extraction was set to zero, whilst the loss term (L_t) remained 6 ML/day as per the calibration period. It is notable that groundwater extraction volumes have increased considerably from 1994 onwards (Figure 6-14). Whilst some of the increase in groundwater pumping would be due to drought periods (e.g. 1994), even the wetter than average periods (e.g. 1998) still had double the volumes of groundwater extracted prior to 1994. This suggests that the implementation of the Murray Darling Basin Ministerial Cap in 1995 (refer to Section 3.4.1), which placed an upper limit on the volumes of surface water diversions permitted within each catchment of the basin, has led to an increase in the volumes of groundwater extracted. The Cap, in combination with an increase in cotton growing in the Cox's Creek subcatchment since the 1990's, appears to have resulted in the increased use of groundwater for irrigation.

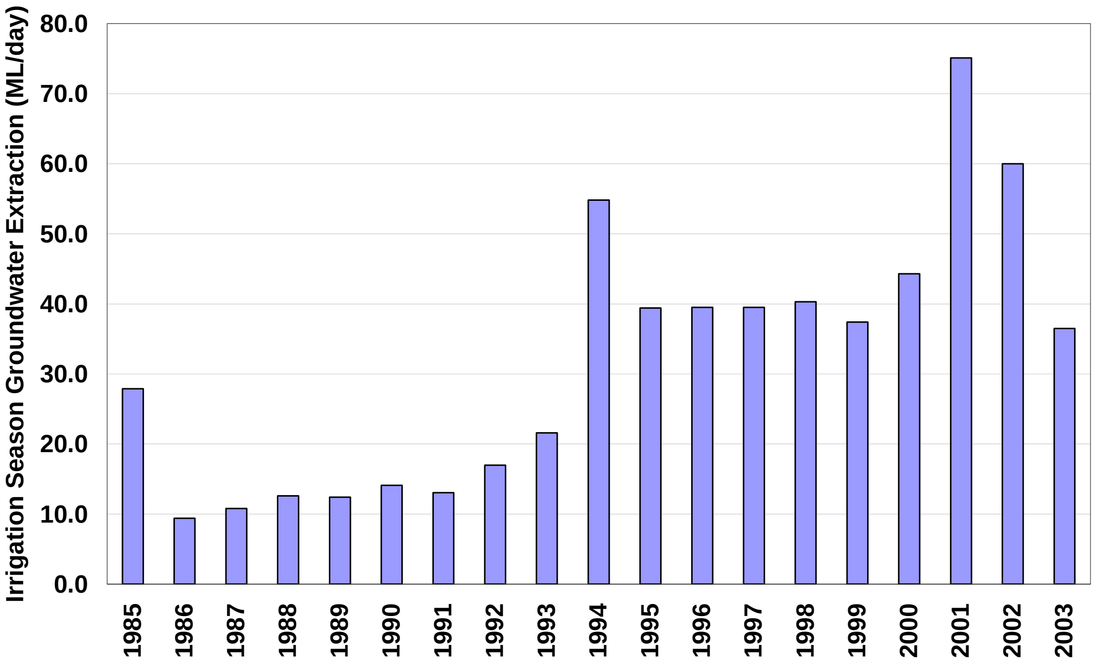


Figure 6-14 Daily volumes of groundwater extracted from the alluvial aquifers over the irrigation season for each water year (ML/day) in the Cox's Creek subcatchment for the area above gauging station 419032

6.6.2 Model Evaluation

Fits to the model, assessed by our five performance statistics for the simulation period, are provided in Table 6-3. An improvement in R^2, R^2*_Baseflow* , *RB,* and *RB_Baseflow* is evident together with a slight decrease in R^2_{inv} in comparison to the calibration period (refer to Table 6-1). The value of *RB_Baseflow* indicates that the baseflow volumes over the simulation period are approximately one-third of those measured in the filtered observed streamflow.

Table 6-3 IHACRES_GW simulation period objective function fits: 2/9/1988 to 9/12/2003

Objective Function	Value
R^2	0.96
R^2*_Baseflow*	0.75
R^2_{inv}	0.7
RB	0.1
RB_Baseflow	0.36

The confusion matrix (Table 6-4) gives the proportion of modelled flows with incorrect recession timings, for each of the four possible combinations outlined, as 7.4% (1.5 plus 5.9%). The proportion where baseflow was measured but not modelled was 5.9% (an increase from the 2.1% found for the calibration period).

Table 6-4 Confusion matrix for simulation period to assess performance of IHACRES_GW model

"Measured" Baseflow <0.01 ML/day Modelled Baseflow <0.01 ML/day	**"Measured" Baseflow <0.01 ML/day Modelled Baseflow >0.01 ML/day**
55.4%	1.5%
"Measured" Baseflow >0.01 ML/day Modelled Baseflow <0.01 ML/day	**"Measured" Baseflow >0.01 ML/day Modelled Baseflow >0.01 ML/day**
5.9%	37.2%

These figures indicate that the model is still performing well in terms of capturing the behaviour of the baseflow recessions, as well as the transitions from flow to no flow events (where streamflow volumes transition between greater and less than 0.01 ML/day) over the simulation period. This is despite the fact that the model was not calibrated to this period.

Plots of observed versus modelled streamflow for the simulation period and their residuals are shown in Figures 6-15 to 6-20. They demonstrate that the model is representing the overall streamflow recession behaviour reasonably well. However, it is also apparent that the modelled flows are underestimated for periods where observed flows last for a couple of months or longer, e.g. the baseflow-dominated periods, which is consistent with the value of the *RB_Baseflow* objective function fit of 0.36. The residual differences reflect an underestimation of very high flows and a too rapid decay of the baseflow recession.

The flow exceedence percentages for streamflows below 100 ML are underpredicted between 2 to 14% (Figure 6-21), i.e. the model underpredicts observed lower flows. Whilst a discrepancy of 2 to 14% in the model's capability to simulate flow durations is relatively small, it is a significant error because groundwater extraction appears to impact on river flows by a similar amount, as discussed in the next chapter (see Figure 7-5).

Despite the tendency of the model to underpredict low flows, one would expect that the differences between model outputs for a range of extraction scenarios, using the model as a basecase, would be much smaller than the uncertainties in the predictions themselves. This subject is discussed in more detail in Reichert and Borsuk (2005). It would be of interest to undertake a formal analysis of the predictive uncertainty of the model, though this was considered to be beyond the scope of this thesis. Some sources of uncertainty in model predictions include data quality issues, such as the streamflow and extraction data, which are used as model inputs, together with the natural variability that can exist within a system. Other sources of uncertainty arise from the way the model is structured, and these are assessed in the following subsection.

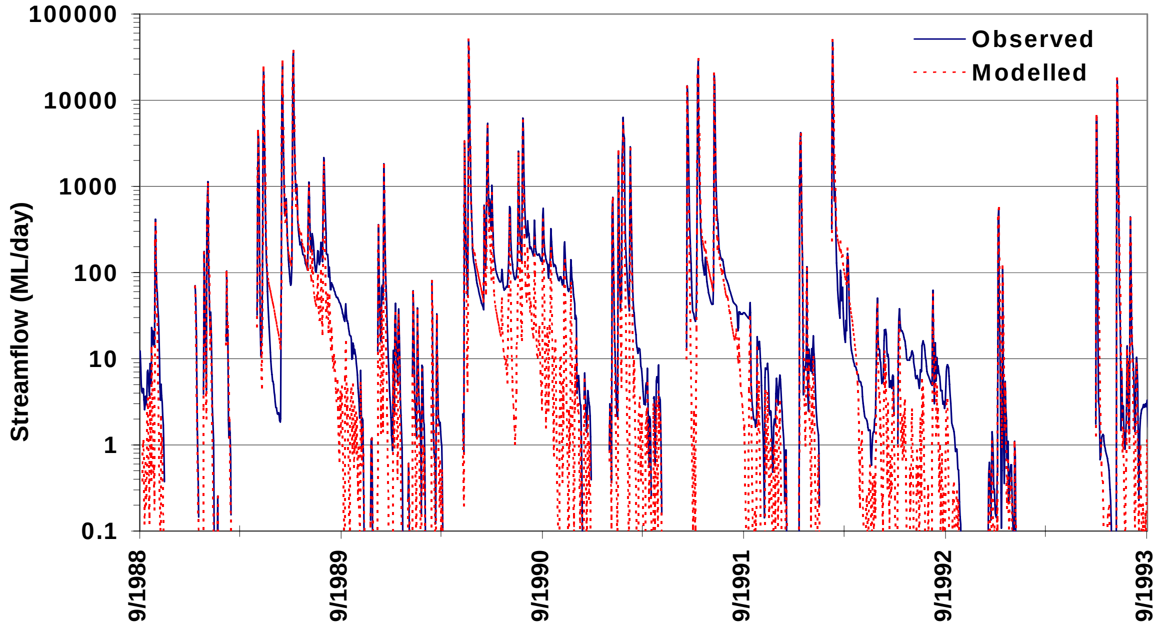


Figure 6-15 Observed and modelled streamflow at gauging station 419032, Cox's Creek at Boggabri, for the 2/9/1988 to 2/9/1993 simulation period

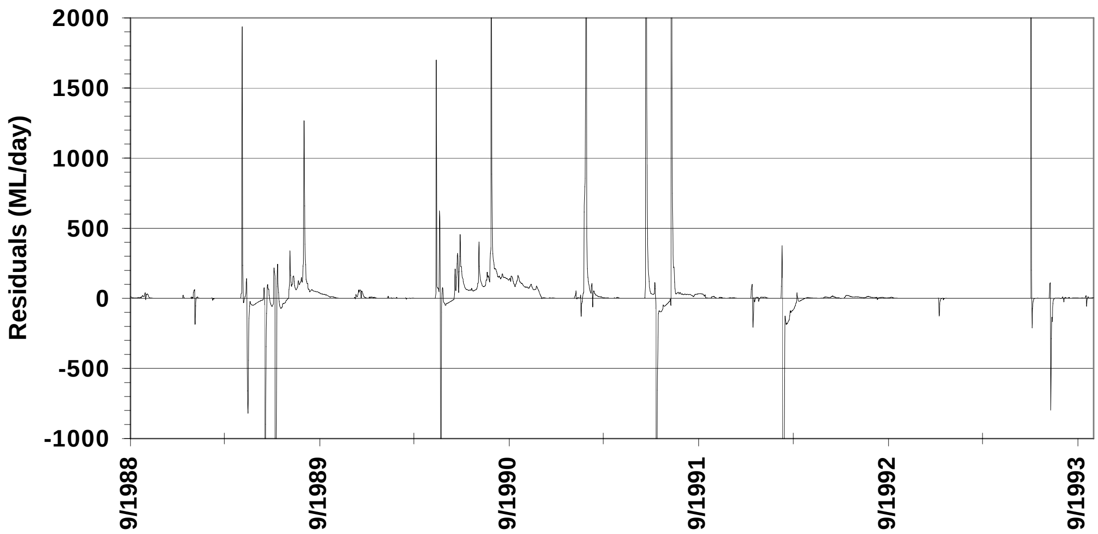


Figure 6-16 Residual difference between observed and modelled streamflow for the 2/9/1988 to 2/9/1993 simulation period

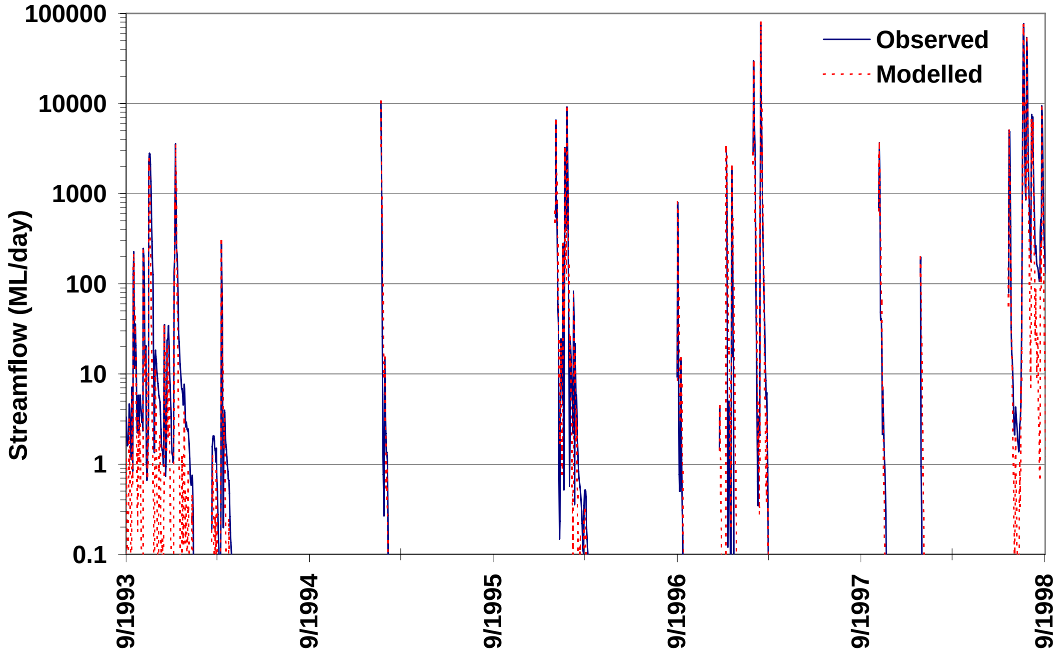


Figure 6-17 Observed and modelled streamflow at gauging station 419032, Cox's Creek at Boggabri, for the 2/9/1993 to 2/9/1998 simulation period

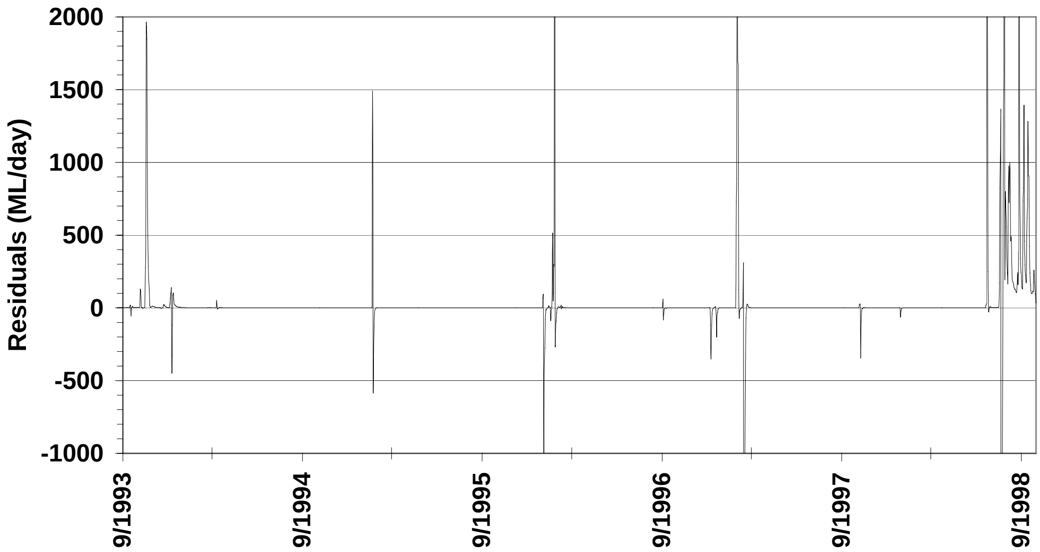


Figure 6-18 Residual difference between observed and modelled streamflow for the 2/9/1993 to 2/9/1998 simulation period

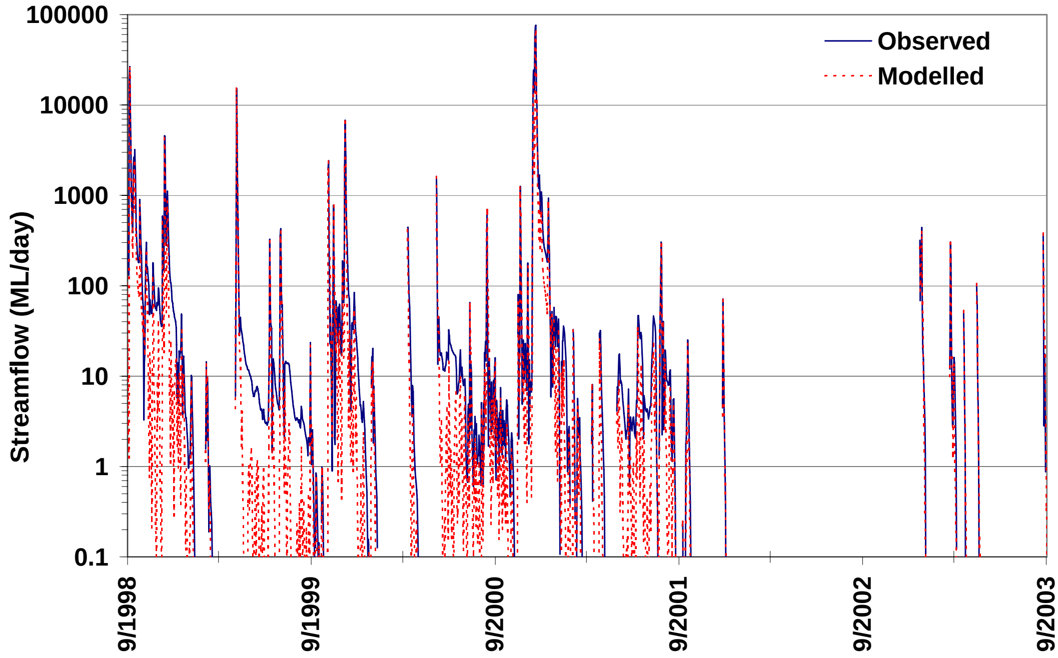


Figure 6-19 Observed and modelled streamflow at gauging station 419032, Cox's Creek at Boggabri, for the 2/9/1998 to 2/10/2003 simulation period

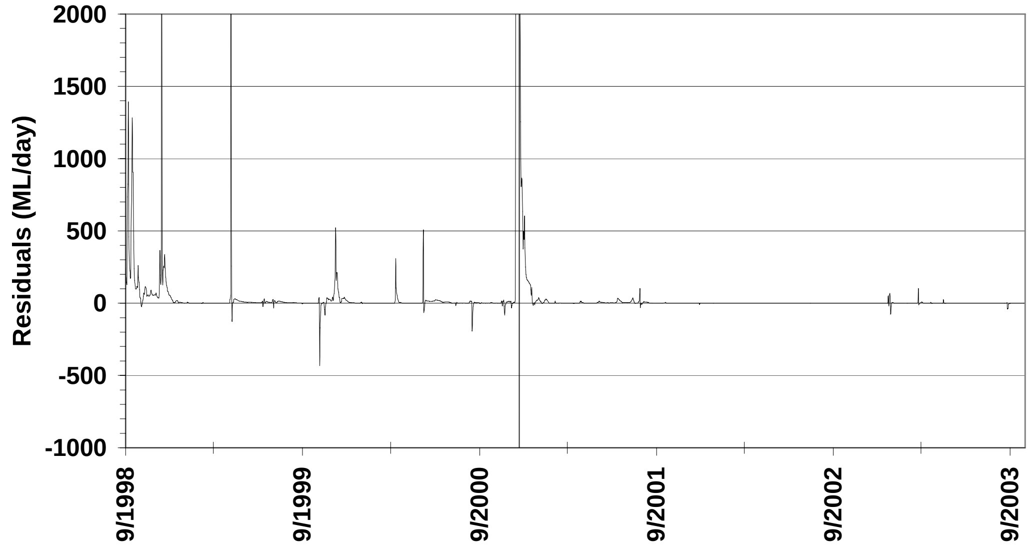


Figure 6-20 Residual difference between observed and modelled streamflow for the 2/9/1998 to 2/10/2003 simulation period

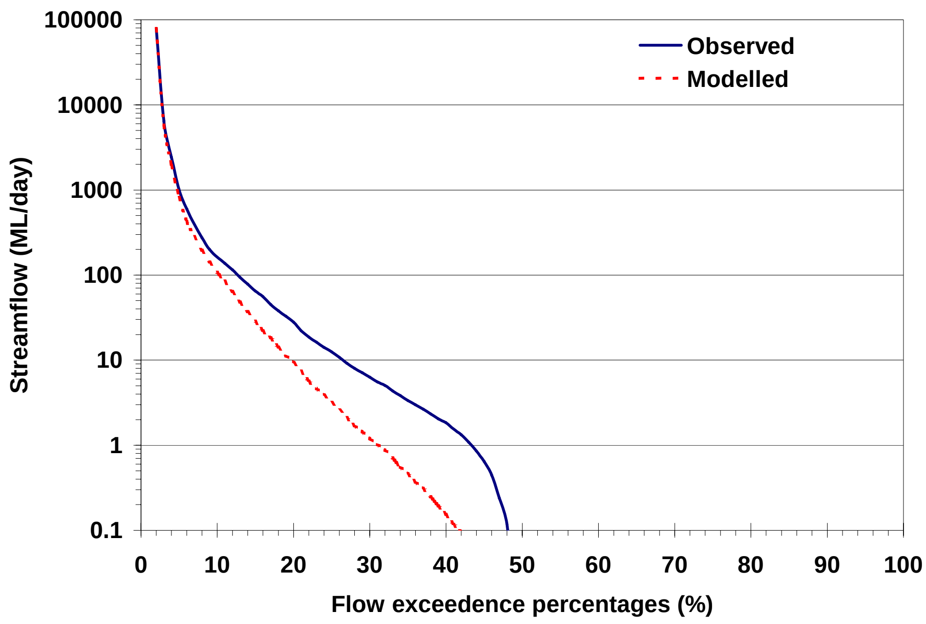


Figure 6-21 Flow exceedence percentages for observed and modelled streamflow for the 2/9/1998 to 2/10/2003 simulation period

6.6.3 Assessment of Factors Influencing Model Performance

There are a number of possible reasons why flows with a strong baseflow component are commonly underpredicted by the model. Some possibilities include:

- constant partitioning of quick and slow flow volumes in the model
- use of a constant loss term in the model
- changes between pre and post-development conditions
- variability in the timing and rates of groundwater extraction
- lumped approach to modelling
- method by which effective rainfall is calculated.

6.6.3.1 Constant Partitioning of Quick and Slow Flow Volumes

The fact that some of the modelled flows are overpredicted while others are underpredicted highlights the fact that the partitioning of effective rainfall between quick and slow flow pathways is not constant in time. Figure 6-22 shows a detailed portion of the modelled and observed streamflow record over the 1989 period in order to illustrate more clearly how modelled slow flows are both over and underpredicted, whilst the quick flows are nearly perfectly modelled.

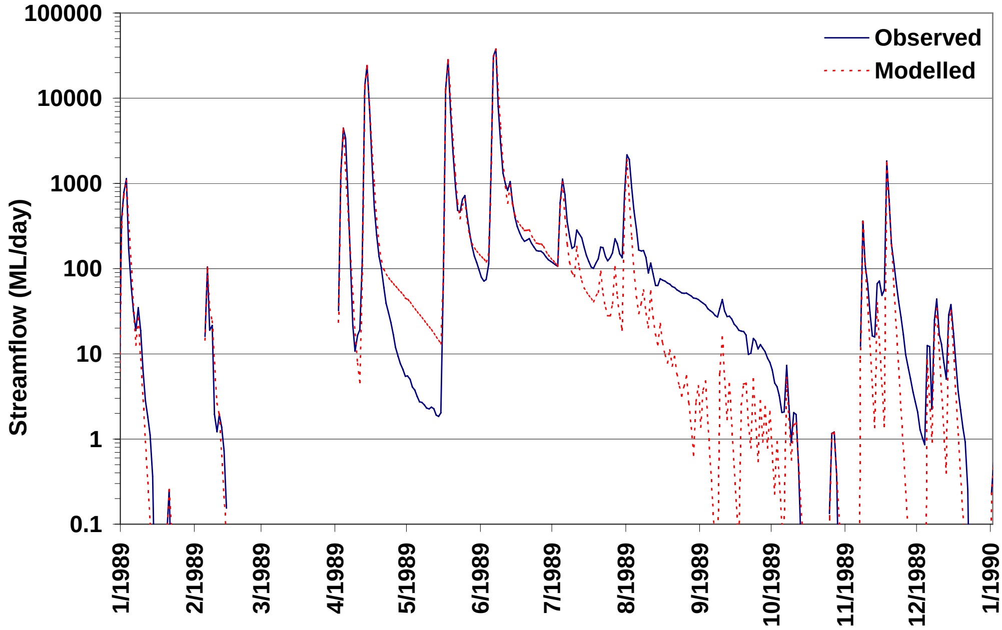


Figure 6-22 Detailed record of observed and modelled flows over the 1989 simulation period

Some of the hydrological factors that might influence the partitioning of effective rainfall to its quick and slow flow pathways include:

- changes in the depth to groundwater and the associated thickness of the unsaturated zone;
- variability in streamflow discharges and their influence on groundwater recharge volumes and bank storage effects; and
- variability in the volumes of groundwater recharge induced from the river in response to variable extraction rates.

A variable v_s parameter in the model would allow for the variable partitioning of effective rainfall to be considered, and hence varying rates of recharge to groundwater storage could be modelled. One can see that the modelled groundwater storage volumes over the 1989 period in Figure 6-23 are likely to have been too large over the mid-April to mid-May period, resulting in too much baseflow, which is evident in Figure 6-22 over this period, suggesting that the v_s parameter was too high for this period. The post-July period, conversely, is likely to have had insufficient groundwater storage volumes, resulting in the underestimation of baseflows and suggesting that the v_s parameter was too low over this period. This example highlights a difficulty with modelling baseflows accurately using a continuous groundwater storage water balance account when the partitioning of effective rainfall to quick and slow pathways is invariant. Modifying the IHACRES_GW model to allow for a varying v_s parameter would have the result of making model calibration a highly complex task, which may not significantly improve the model performance and utility.

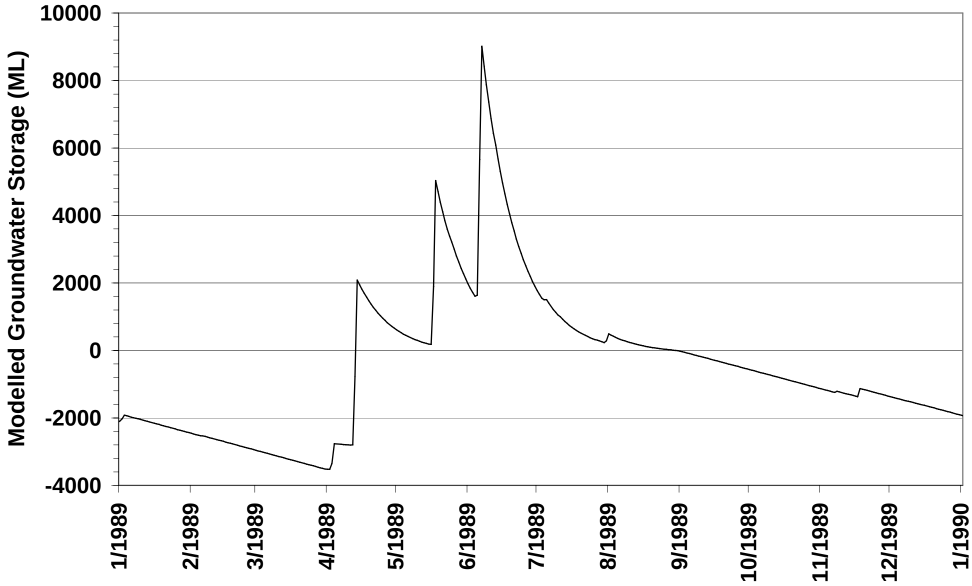


Figure 6-23 Modelled groundwater storage volumes over the 1989 simulation period

6.6.3.2 Use of a Constant Loss Term

An underestimation of baseflows could also arise when groundwater losses are too high or if they vary over time. The constant loss term of 6 ML/day was determined from the pre-extraction calibration period and applied to the simulation period. A constant loss of 6 ML/day when combined with the volumes of groundwater extracted over the simulation period appears to provide too much loss to groundwater storage (refer to Figure 6-24). This is because groundwater extraction results in captured and induced forms of groundwater recharge, which would reduce the impact of groundwater extraction losses on total groundwater storage volumes and would have the effect of reducing groundwater losses. (Note that the IHACRES_GW model does not explicitly distinguish between the various forms of groundwater loss/gains.) In addition, the deepening of groundwater levels as a consequence of pumping and other groundwater losses might influence the losses specifically arising as a result of evapotranspiration.

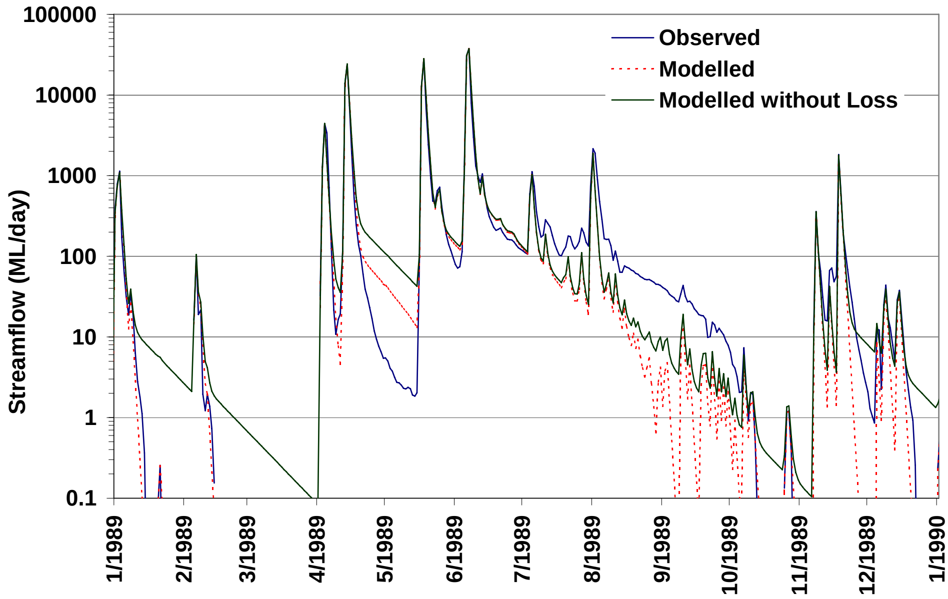


Figure 6-24 Detailed record of observed and modelled flows over the 1989 simulation period with loss parameter set to zero

These types of influences suggest that the loss term is most likely going to vary over time and not remain constant. Figure 6-24 shows how the modelled results for the 1989 period would appear if the loss term were set to zero (instead of 6 ML/day), and hence the only losses to groundwater storage are those arising from extractions over the September through to March irrigation season. One can see from Figure 6-24 that the modelling of baseflow-dominated flow events is somewhat improved, but at the cost of inadequate modelling of quick flow events especially in the absence of groundwater extraction as an additional loss (for those periods outside the irrigation season). However, calibrating the IHACRES_GW model for a variable loss term, given the lack of data, would be complex, and possibly not improve the model prediction capabilities of the model. A simple way to address a variable loss in the first instance might be to recode the model in such a way that, should the condition arise where groundwater extraction volumes exceed the pre-development calibrated loss parameter value, the loss parameter is not utilised for the model simulation since the extraction losses dominates. Another possibility might be to explore the functional relationship between loss and groundwater storage volumes, whereby the loss (*L*) at time *t* is a function of groundwater storage (*G*) or $L_t=f(G_t)$, and that as groundwater storage becomes increasingly depleted, the loss may also be reduced.

6.6.3.3 Pre-Development and Post-Development Conditions

A further reason for the underestimation of modelled baseflow volumes may be because the parameter values derived from the pre-groundwater development calibration period no longer apply to the developed period as a consequence of changed land use and associated land use practices. For instance, additional forms of groundwater recharge may be added to the system via irrigation deep drainage or other captured and induced forms of recharge, and hence the discharge dynamics might be different to those that occurred during pre-development conditions (see for example Bredehoeft, 2002). Groundwater extraction could also influence groundwater recharge processes by increasing the volumes of groundwater recharge if pumping were to take place in previously rejected recharge areas; for example where shallower water tables had resulted in greater volumes of surface runoff, by increasing drainage gradients to the aquifer or through allowing for increased upward vertical leakage from the underlying bedrock aquifer. These types of influences would potentially alter post-development model parameters. Calibration to a period of post-development data would provide some insights as to how the hydrology of the system has been altered. It is interesting to note that the model underpredicts streamflow by a similar magnitude to that of extraction (compare Figure 6-21 and Figure 7-5), which suggests that extraction may be capturing additional volumes of recharge water that are similar to the volumes extracted.

A recalibration of the 1988 to 2003 post-groundwater development period indicated an increase in the v_s, τ_s, and τ_q parameter values and a decrease in the loss parameter value (Table 6-5) compared to the calibration period (Table 6-1). The changes to the parameter values suggest that groundwater extraction and irrigation are resulting in increased recharge, most likely arising from deep drainage and induced and captured forms of recharge, as well as resulting in a slowing down of the runoff and baseflow recession rates. The objective function fits for the recalibration (Table 6-5), show an improvement relative to the simulation period (Table 6-3), as expected. The slightly negative values of *RB* and *RB_Baseflow* suggest that the modelled slow flow volumes are slightly overestimated for the whole model period. The confusion matrix (Table 6-6) does not indicate any improvement in capturing the switching behaviour of modelled streamflows through the use of the recalibrated parameters versus those determined from the pre-development calibration period (Table 6-4).

Table 6-5 IHACRES_GW calibrated parameter values for post-development period: 2/9/1988 to 9/12/2003

Parameter	Calibrated Value	Objective Function	Value
v_s	0.1	R^2	0.94
τ_s	25 days	R^2_*Baseflow*	0.72
τ_q	1.4 days	R^2_{inv}	0.79
Loss	3 ML/day	*RB*	-0.1
		RB_Baseflow	-0.2

Table 6-6 Confusion matrix for the calibration to post-development period

"Measured" Baseflow <0.01 ML/day Modelled Baseflow <0.01 ML/day	**"Measured" Baseflow <0.01 ML/day Modelled Baseflow >0.01 ML/day**
53.7%	3.3%
"Measured" Baseflow >0.01 ML/day Modelled Baseflow <0.01 ML/day	**"Measured" Baseflow >0.01 ML/day Modelled Baseflow >0.01 ML/day**
2.6%	40.4%

The fit to the flow duration curve is markedly improved using post-development calibration parameters (Figure 6-25), with the model now capturing the overall behaviour of flows as low as 10 ML/day. There is also an improvement in the model's capability to simulate the baseflow component of streamflow (compare Figure 6-26 to Figure 6-22). A problem still exists, however, where some of the modelled flows are overpredicted whilst many are underpredicted, as was previously discussed. The fact that the IHACRES_GW model was calibrated to pre-development data, and yet managed to predict the overall streamflow behaviour well in a post-development state outside of the calibration period, suggests a degree of robustness in the model structure. Furthermore, the switching behaviour of baseflow captured by the IHACRES_GW model was not improved by calibration to post-development parameters, suggesting that the timing of baseflow events is being adequately modelled through the use of pre-development parameters. Consequently and importantly, the IHACRES_GW model can be used with some confidence to run extraction scenarios for which the relative difference in modelled baseflows, using the modelled data as a base case, will provide a reliable measure of the relative impacts of extraction.

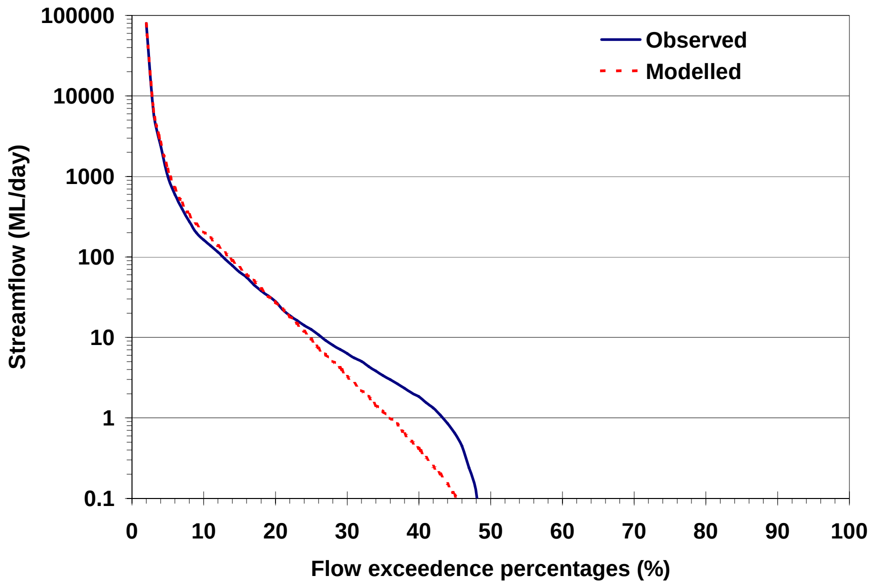


Figure 6-25 Flow exceedence percentages for observed and modelled streamflow using the post-development 2/9/1988 to 9/12/2003 calibration parameters

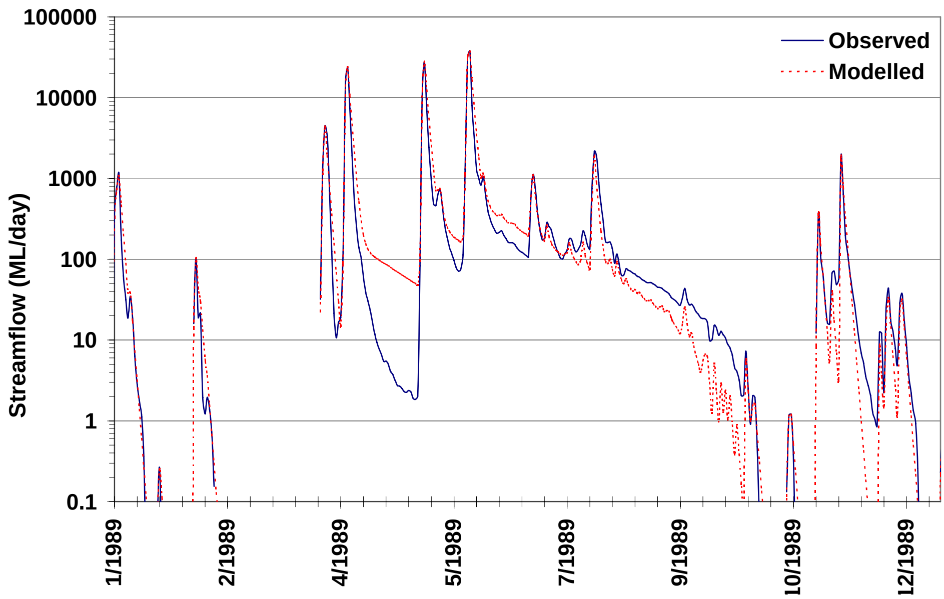


Figure 6-26 Detailed record of observed and modelled flows over the 1989 period using the post-development calibration parameters

6.6.3.4 Variability in Timing and Rates of Groundwater Extraction

Imprecision in the data for the timing and rates of groundwater extractions may account for some of the model output inaccuracies. The IHACRES_GW model has been run on a daily time-step, and the model assumes that groundwater extraction and other modelled losses to groundwater storage impact on riverflows during the same time step. However, the groundwater extraction data exists as annual extraction volumes that have been distributed uniformly (i.e. same amount per day) over a daily time step throughout the 1 September to 31 March irrigation season. In reality irrigation may occur outside of the irrigation season, for example during drier periods, and groundwater pumping may be taking place prior to the irrigation season in order to fill dams for use at a later time. The timing in irrigation returns to the shallow subsurface might also affect the timing/volume evident in the slow flow signal of streamflow. Moreover, the full influence of the volume of groundwater extracted may not be evident at the stream gauging station. For example, if groundwater extraction is occurring from a deeper aquifer then only a fraction of the volumes extracted may impact on the river. The collection and reporting of daily groundwater extraction volume data by state water management authorities would allow for increased confidence and improved modelling of these data, though this may be an unrealistic expectation of the agencies.

6.6.3.5 Spatially Lumped Approach to Modelling

The lumped approach to modelling using IHACRES_GW assumes that the volumes of groundwater extracted as per the data record will impact on groundwater storage volumes at the same time step, and hence that the impact to streamflow will also occur at the same time step if groundwater storage volume levels are above the gauging station reference point. This assumption seems valid given the fast response times of semi-confined, highly-connected aquifer systems to extraction in a narrow and bounded alluvial valley. However, the large spatial variability in catchment hydrogeology and groundwater extraction patterns may result in localised areas of groundwater drawdown that may not be evident within the baseflow signal obtained from the stream gauging station data. For example, a groundwater constriction in the alluvium at Boggabri downstream of gauging station 419032 has been documented (Dyce and Richardson, 1997; PPK Environment & Infrastructure, 2002), which has the effect of impeding groundwater flow and results in relatively higher water table elevations in the vicinity of the gauging station. These localised, more elevated water tables would influence flow characteristics around the stream gauging station and could at times result in greater ‘measured’ baseflow volumes compared to those predicted by the model, which represent an aggregated response for the upstream catchment area. This mechanism might confound model output interpretation. It would be useful to apply the IHACRES_GW model at each of the upstream gauging stations to better understand water balance processes along the length of the catchment and its rivers.

6.6.3.6 Groundwater Recharge in the Absence of Measured Streamflow

Another possible reason for insufficient modelled groundwater storage volumes is that recharge to the groundwater system could be taking place in the absence of measured streamflow. Recall that IHACRES_GW currently uses effective rainfall as model input, and that the effective rainfall is calculated from the filtered quickflow volumes of the observed streamflow data series (Section 5.6). Hence, with a reduction in streamflow (from induced recharge) or in the absence of measured streamflow, there would be less groundwater recharge added to the modelled groundwater storage volumes. In a large catchment such as Cox’s Creek, there could be sources of additional groundwater recharge such as from rain falling in the upper catchment and through river recharge upstream of the gauge when the river is losing water, even though there might not be any flow at the gauge itself. This would result in an underestimation of groundwater storage volumes, and hence result in an underestimation of baseflow volumes. In an intermittent/ephemeral stream, where for much of the record the river is dry, there may not be sufficient data in the streamflow record to allow a highly accurate account of groundwater storage volumes to be maintained throughout the periods with no measured flow at the stream gauging station. It would be informative to use the calibrated IHACRES_GW model parameters in conjunction with a non-linear loss model to generate effective rainfall in order to further explore some of these issues (recall that the poor raingauge network in the Cox’s Creek precluded the use of the non-linear loss module).

As an additional point about sources of model error, many of the aquifers in the Cox’s Creek subcatchment indicate a vertical, upward pressure from the deeper to the shallow aquifer that plays an important role in recharging the shallow aquifer. This type of aquifer recharge is not explicitly accounted for in this simple model, although the effect is partially accounted for via model calibration, and this may contribute to some degree of underestimation in modelled groundwater storage volumes.

6.6.4 Comparison of Model Output with Bore Data

The IHACRES_GW model was calibrated and evaluated on streamflow data alone, and consequently the simulated groundwater response remains "internal" to the model. Therefore, the possibility exists that model simulations of catchment processes inferred by streamflow data, such as the modelled groundwater storages in this study, may have little correspondence with real, observed subsurface responses. Some problems associated with validating conceptual models have been discussed by Mroczkowski *et al.* (1997). In order to assess the degree of credibility around how well the model was able to reproduce groundwater system behaviour, measurements of groundwater level data were compared to modelled groundwater storage data. Two caveats must, however, be borne in mind when comparing these two data sets. Firstly, the groundwater elevation data is obtained from observation bores that reflect local hydrogeological conditions. Secondly, and conversely, the modelled groundwater storages represent an aggregate hydrological response over the whole catchment area. Therefore it is perhaps not entirely appropriate to attempt to assess modelled groundwater storage values through such a comparison. Despite these differences, such a comparison may still be useful in assessing the performance of the model because the baseflow signal derived at the stream gauging station is often related to groundwater levels near the gauging station. Consequently, data representative of the shallow aquifers for six of the closest observation bore sites to stream gauging station 419032 were further inspected. Three of the observation bores were located downstream of the gauge at the catchment outlet (GW036602, GW036600, GW036565), and three were located upstream of the gauge (GW036434, GW036435, GW036440) (Figure 6-27). The observation bores were selected based on: 1) their proximity to the stream gauging station; 2) the availability of water level data that coincided with the dates of the gauged streamflow measurements; and 3) that they represented data for shallow aquifers less than 25 m deep. The data for the downstream (Figure 6-28) and upstream observation bores (Figure 6-29) were plotted together with modelled groundwater storage levels in order to assist with a visual comparison.

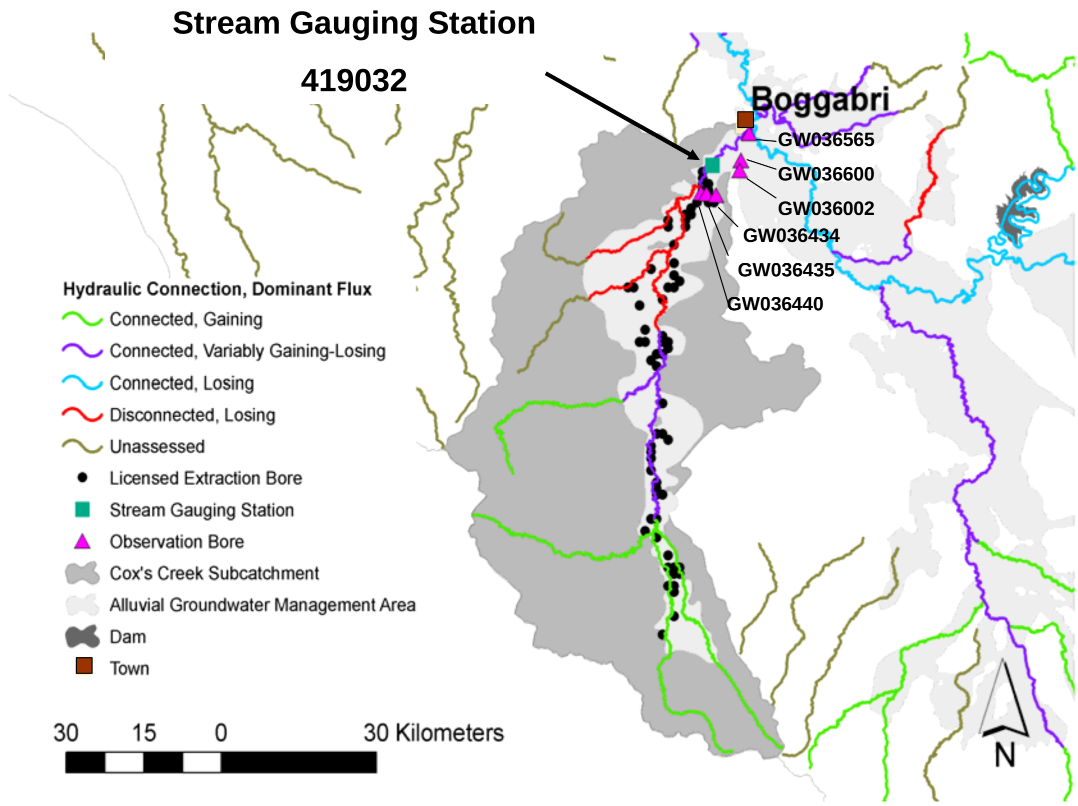


Figure 6-27 Location of shallow observation bores closest to catchment outlet at stream gauging station 419032

The modelled groundwater storage values appear to generally match the patterns found in the groundwater elevation data; e.g. where there is a relative rise or fall in groundwater storage volumes there is a corresponding rise or fall in groundwater elevation data in each observation bore, despite any differences in the magnitude of the changes observed. This correlation in patterns is surprisingly strong in the data for the downstream observation bores (Figure 6-28), especially for observation bore GW036565, which is the closest to the river of all six observation bores. Whilst the rise and fall patterns in groundwater storage and observational bore data also match the upstream bores, the groundwater elevation data themselves are less closely matched (Figure 6-29), reflecting local hydrogeological and groundwater extraction heterogeneities as well as the fact that the river becomes disconnected from the underlying aquifer system along this section.

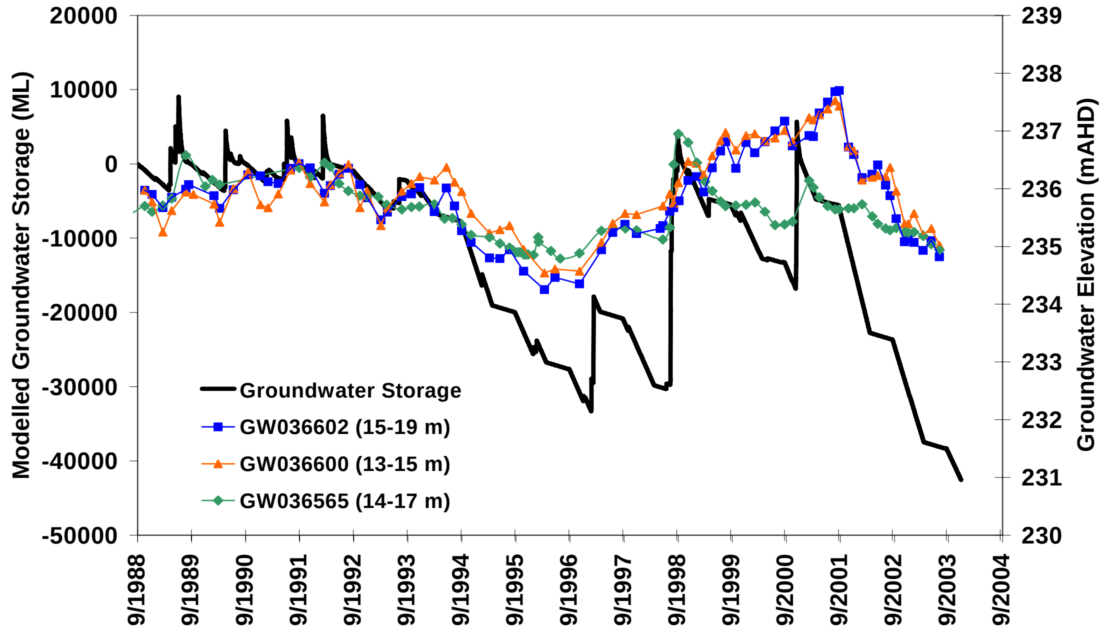


Figure 6-28 Modelled groundwater storage at stream gauging station 419032 and measured groundwater elevation in observation bores screening the shallow aquifers downstream of the gauging station

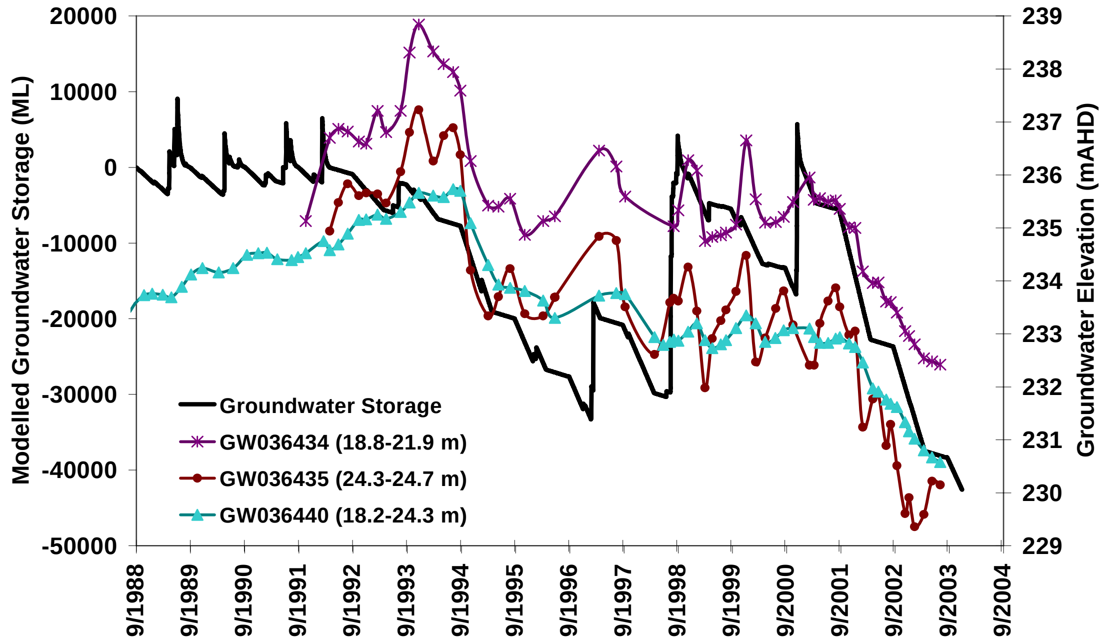


Figure 6-29 Modelled groundwater storage at stream gauging station 419032 and measured groundwater elevation in observation bores screening the shallow aquifers upstream of the gauging station

Overall, the modelled groundwater storage patterns are relatively spiky in comparison to the observed groundwater level data. This could be an artefact of a model assumption that the baseflow signal in the modelled streamflow equals groundwater discharge at the same time step, and that groundwater discharge equals groundwater recharge. The larger streamflow pulses will be associated with greater volumes of effective rainfall, and hence greater volumes of groundwater recharge will occur at that time step (NB one mm of effective rainfall over the 4040 km^2 catchment area is equivalent to 4040 ML). This has the effect of causing a rapid increase in groundwater storage volumes. Generally, one would expect a groundwater system to respond a bit more slowly to a recharge pulse.

Some slight timing delays between modelled groundwater storage fluctuations and those of the observed groundwater level data are apparent (by between 2 and 8 months) in Figure 6-28 and Figure 6-29. The delays in groundwater response may be associated with the timing of groundwater bore monitoring measurements and the interpolation of data values between measurements, as well as the strong possibility of dampened groundwater responses to recharge events and extraction. Additional confounding factors in assessing model performance include the possibility of poor quality records of groundwater extraction data and incorrect assumptions as to the timing of extraction (assumed to be evenly distributed over the irrigation season only) and insufficient lag time between groundwater pumping and its impact on the river. Of course the question remains as to whether the local observation bore data, despite being located towards the outlet of the catchment, can adequately represent the aggregated hydrological response over the whole of the catchment area that is captured by the model. Nonetheless, the model seems to provide a reasonable pattern of groundwater storage volumes, and suggests that the model is able to adequately capture general groundwater behaviour which gives the model a useful degree of credibility.

6.7 Chapter Summary

In this chapter the IHACRES_GW model developed in Chapter 5 was applied within the Cox's Creek subcatchment in order to test the capability of the model. A discussion of the model calibration, simulation and performance criteria was provided. The model demonstrated that it was able to effectively capture the timing in the switch between baseflow periods and no-flow periods within an intermittent river system. The model also demonstrated that baseflow volumes could be simulated on a daily time step, although, the model commonly underpredicted baseflow volumes. Reasons explaining why baseflows might be underpredicted by the model were given in Section 6.6.3 together with an analysis of the factors that could result in model performance deterioration. Modelled groundwater storage values were compared to independent observation bore data. The comparison of data sets suggested that the IHACRES_GW model provides a reasonable pattern of groundwater behaviour without calibration to these data, giving the model a useful degree of credibility. This chapter has demonstrated that a simple, conceptual model can be used to simulate the impact of groundwater extraction and other losses on river flows. In the following chapter the IHACRES_GW model will be used to simulate groundwater extraction scenarios in order to investigate the impacts of groundwater extraction on river flows and to inform water management policy.

Chapter 7 Extraction Impacts and Water Policy

7.1 Introduction

In the previous chapter, the application of IHACRES_GW to model streamflow and groundwater storage volumes in the Cox's Creek subcatchment established the credibility and utility of this conceptual, spatially-lumped modelling approach for use at (sub)catchment scales. In this chapter, the IHACRES_GW model is used as a tool to investigate the impacts of groundwater extraction on river flows in the Cox's Creek subcatchment and to consider the potential influence of water management policies developed to implement water reforms such as those of the National Water Initiative (NWI).

The history and development of water reforms was discussed in Section 3.4. Some of the broad water management questions for which answers are required in order to effectively implement appropriate water reform policies include:

- What have been the impacts of the historical rates of groundwater extraction on river flows?
- Can the impacts be quantified in order to appropriately consider risks to water security and riverine ecosystem health?
- How do the impacts vary with varying rates of groundwater extraction, and what is the implication for the Murray Darling Basin Ministerial Cap on surface water diversions?
- What role does climatic variability play in influencing the impacts observed?
- Are the groundwater allocation provisions in the water sharing plan sustainable?
- What insights can be gained from this study to better manage groundwater extraction in connected aquifer-river systems at catchment scales?

These questions will be addressed using the IHACRES_GW model in the sections that follow, demonstrating some utilities of the model.

7.2 The Impacts of Historical Rates of Groundwater Extraction

The IHACRES_GW model was used to simulate two scenarios in order to investigate the impacts of historical rates of groundwater extraction on river flows in the Cox's Creek subcatchment. One scenario utilised existing, historical groundwater extraction data (volumes shown in Figure 6-14) and the other scenario the absence of groundwater extraction. The period chosen for model simulation was from 2/9/1988 to 9/12/2003, (previously discussed in Section 6.6), using the calibrated model parameters (given in Table 6-1). The modelled groundwater storages for the two scenarios are shown in Figure 7-1 and the residual difference in the modelled baseflow volumes (i.e. the difference between the baseflow contributions to streamflow in the model simulations) is plotted in Figure 7-2.

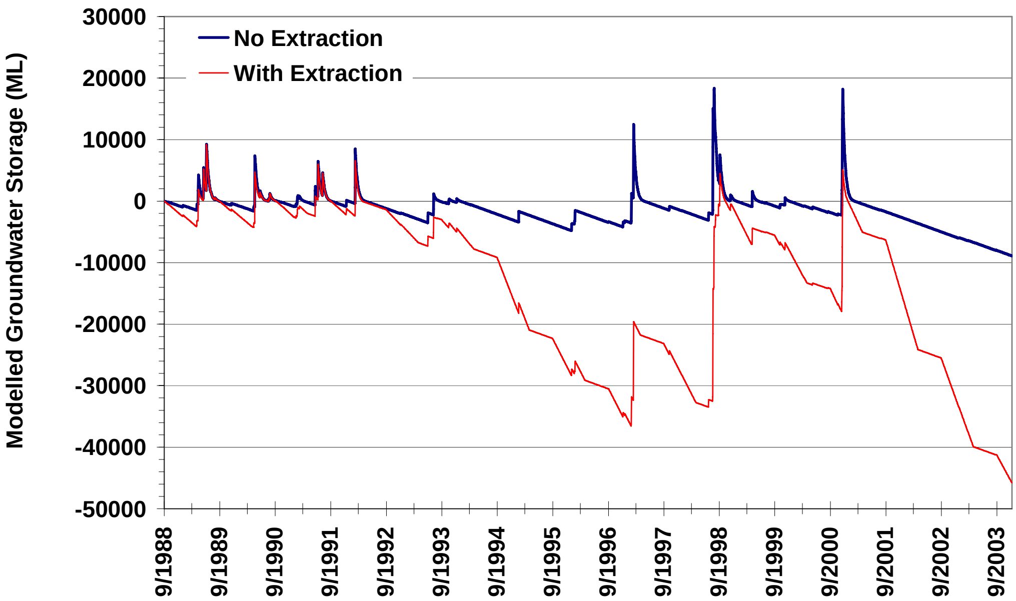


Figure 7-1 Modelled groundwater storages for simulation scenarios with and without groundwater extraction

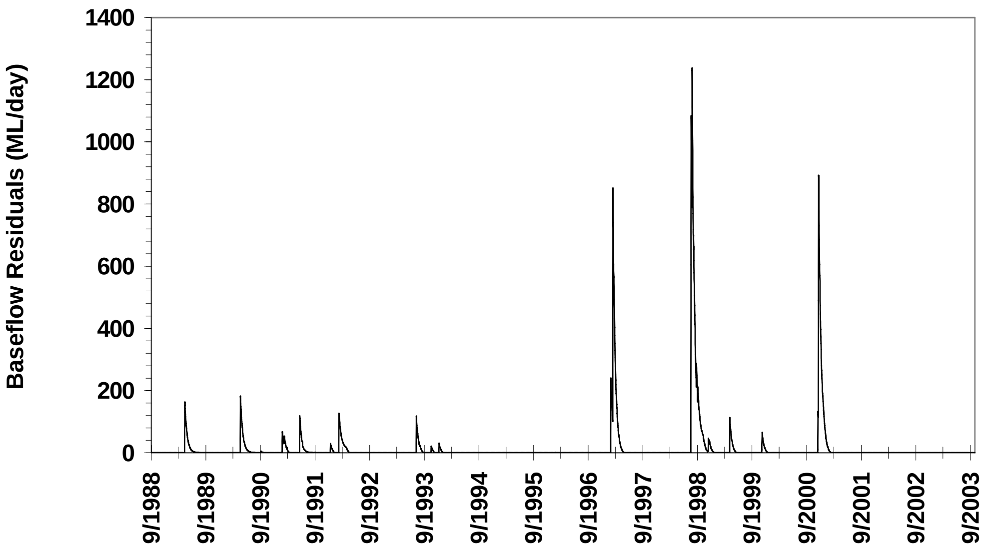


Figure 7-2 Residual baseflow volumes between simulation scenarios

The periods when groundwater storage volumes are above the zero reference point (Figure 7-1) coincide with streamflow periods that have a baseflow component. Two key impacts are seen in Figure 7-1: 1) a number of baseflow events, i.e. with positive groundwater storage values, would have occurred in the absence of groundwater extraction; and 2) in many instances the magnitude of the baseflow contribution has been reduced. The model simulations indicate that groundwater extraction has resulted in reduced baseflow contributions to flow ranging from zero to a maximum value of 1205 ML/day peak instantaneous flow (Figure 7-2), which is about five times the average annual streamflow measured at the gauging station. The modelled median reduction in baseflows, calculated for periods with baseflow, was 15 ML/day and the average reduction was 75 ML/day.

There are 14 'baseflow residual event peaks' shown in Figure 7-2 that represent periods with reduced baseflow in the streamflow record. A summary of the impacts on baseflow for each of these events is given in Table 7-1.

Table 7-1 Events during model simulation with reduced baseflow based on historical rates of extraction

Event	Start date	End date	Baseflow (ML) without extraction	Baseflow (ML) with extraction	Baseflow reduction (ML)	Baseflow reduction (%)	Impacts on timing
1	13/04/1989	30/08/1989	18 690	16 045	2 645	14	Onset of baseflow delayed by 1 day
2	21/04/1990	21/09/1990	9 585	6 730	2 855	30	Duration of baseflow event shortened by 15 days
3	24/01/1991	14/03/1991	1 240	0	1 240	100	Baseflow event lost
4	22/05/1991	4/09/1991	10 510	8 870	1 640	16	Baseflow event reduced by 6 days (3 days mid flow and shortened by 3 days)
5	14/12/1991	10/01/1992	310	0	310	100	Baseflow event lost
6	9/02/1992	18/04/1992	8 620	6 140	2 480	29	Duration of baseflow event shortened by 20 days
7	10/07/1993	27/08/1993	1 610	0	1 610	100	Baseflow event lost
8	17/10/1993	9/11/1993	200	0	200	100	Baseflow event lost
9	9/12/1993	5/01/1994	310	0	310	100	Baseflow event lost
10	31/01/1997	29/04/1997	14 900	0	14 900	100	Baseflow event lost
11	21/07/1998	22/12/1998	34 890	3 770	31 120	89	Onset of baseflow delayed by 46 days and shortened by a further 73 days
12	6/04/1999	20/05/1999	1 480	0	1 480	100	Baseflow event lost
13	7/11/1999	15/12/1999	810	0	810	100	Baseflow event lost
14	15/11/2000	11/02/2001	21 320	4 610	16 710	78	Onset of baseflow delayed by 6 days and shortened by a further 48 days
Total			124 475	46 165	78 310		

The largest reductions to baseflow were associated with long periods of relatively dry and/or drought events, such as occurred over the years 1993-1996 and post 2000, when greater than average volumes of groundwater were extracted (see Figure 7-3 for annual extraction rates and refer back to Figure 6-3 and Figure 6-4 for an overview of rainfall patterns). The combination of low rainfall conditions and intensive groundwater use has resulted in substantial drops in groundwater storage volumes, and hence the volumes of baseflow have also been reduced.

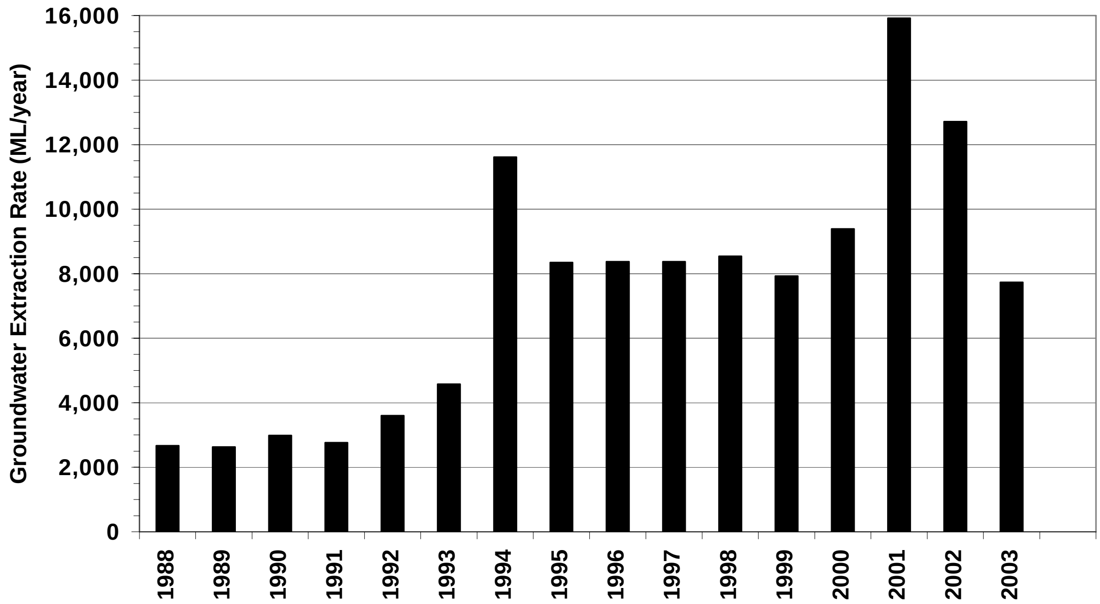


Figure 7-3 Reported annual groundwater extraction rates over the 1988-2003 simulation period (Department of Natural Resources Database)

Figure 7-4 plots modelled groundwater storage volumes and the residual difference in baseflow volumes in order to more clearly show the relationship between depleted groundwater storage volumes and reduced baseflow. The impact of groundwater extraction on groundwater storages over the 1993-96 dry/drought period is particularly striking (refer to Figure 7-4 and Table 7-1). During this period groundwater storage volumes were drawn down by as much as 36 270 ML. The impact of such a large decrease in groundwater storage volumes was to decrease baseflow contributions to streamflow over this period, as well as to reduce any future baseflow contributions to streamflow. For example, baseflow events number 7 (10/7/1993-27/8/1993), 8 (17/10/1993-9/11/1993), 9 (9/12/1993-5/1/1994) and 10 (31/1/1997-29/4/1997), listed in Table 7-1, were entirely lost because of the large volumes of groundwater extracted over the 1993-96 period.

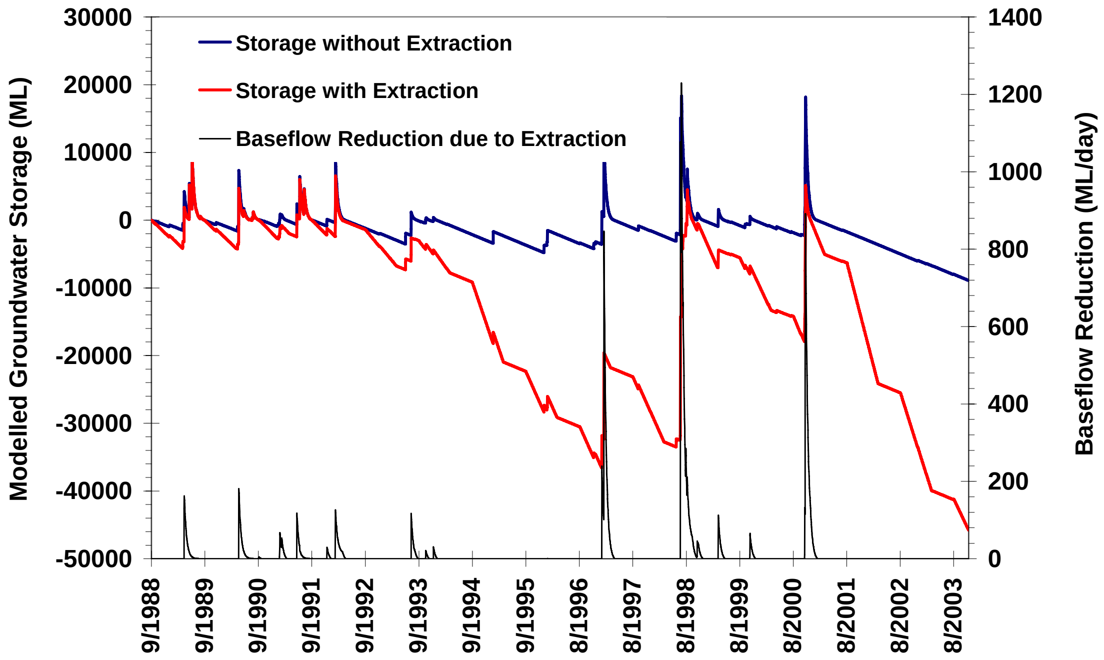


Figure 7-4 Modelled groundwater storage volumes and baseflow residuals

Despite the years 1997-98 being relatively wet, the impacts of previous groundwater extractions continued to affect baseflow discharges, as seen by baseflow event number 10 being lost (31/1/1997-29/04/1997), and with a large reduction in baseflow also evident for event number 11 (21/7/1998-22/12/1998). The model shows that the onset of event number 11 was delayed by 46 days and shortened by a further 73 days compared to the 'no extraction' scenario, resulting in a reduction of baseflow volumes by approximately 31 120 ML for this event alone. The modelled groundwater storages suggest that although recharge to groundwater storages can be significant during wetter periods, baseflow contributions continue to be affected by historical extraction usage patterns.

The consequences of the historical rates of extraction for overall groundwater storage volumes and associated baseflow discharges is a function of the net recharge to the exploited aquifer system versus loss as a consequence of extraction and other groundwater losses. It can take decades or longer to recharge aquifers to pre-drought storage levels if groundwater resources have been heavily and/or overly exploited.

Conversely, during wetter climatic periods associated with flooding and large amounts of recharge, groundwater storages can be replenished relatively quickly.

The total reduction in baseflow over the 15-year simulation period was 78.3 GL, representing 5% of the 1 643 GL modelled streamflow volumes in the absence of extraction (Table 7-1). This is equivalent to about 5 220 ML/year. There were 1 066 days that received reduced baseflow discharges in comparison to the 'no extraction' scenario. Baseflow contributions to streamflow as a result of groundwater extraction were reduced by between 14 and 100%, with an average reduction of 37% over the 15-year modelling period. The overall impact of groundwater extraction on the duration of streamflows has been to reduce the probability of flows lower than 100 ML/day by between 2 and 4% (Figure 7-5). The full impacts from the recent (post 2000) drought period remain to be seen and quantified.

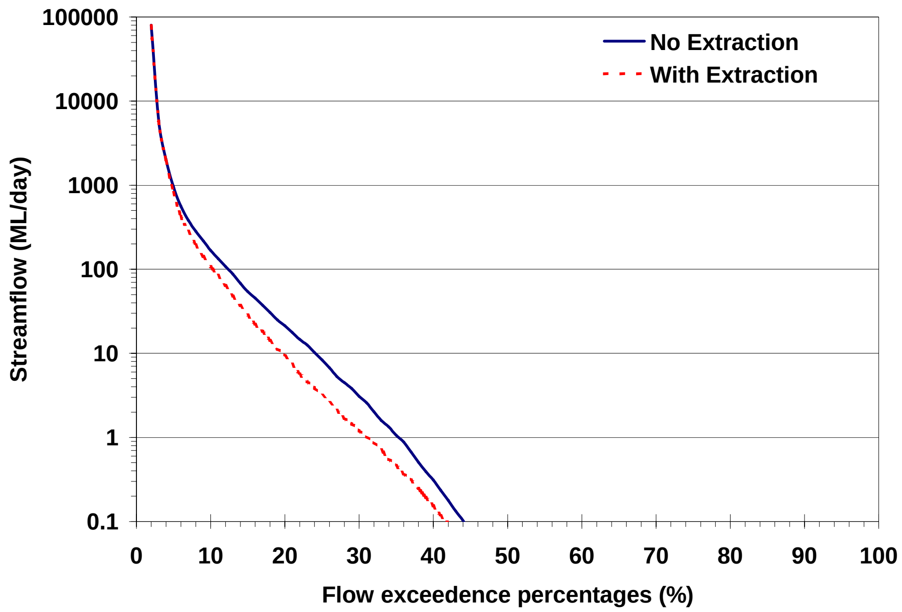


Figure 7-5 Flow exceedence percentages for streamflow simulation scenarios with and without groundwater extraction

The reductions in baseflow discharges that arise as a result of groundwater extraction, along with the increased length of time between baseflow events, can have significant detrimental impacts on groundwater dependent ecosystems. The particular characteristics of baseflow events are important considerations in the development of water sharing plans that give a priority to the environmental requirements of catchments over any other consumptive uses. Some indicators of hydrological alteration which are of relevance to ecosystem functioning include the magnitude, duration, timing and frequency of particular flow classes, and the rate and frequency of flow condition changes (Richter *et al.*, 1996). It is beyond the scope of this thesis to further explore ecological indicators, however, the IHACRES_GW model could be easily modified to include these types of statistical measures in order to assess the potential impacts of groundwater extraction on ecosystem function. To date, no riverine ecosystems have been identified within the Cox's Creek subcatchment for conservation.

7.3 Impacts of Varying Rates of Groundwater Extraction

In the previous section the impacts of historical rates of groundwater extraction on groundwater storages and baseflow discharges were assessed using the IHACRES_GW model. In this section the impacts of varying rates of groundwater extraction are assessed.

In order to provide insights into the impacts of varying rates of extraction on baseflow volumes, model simulations were performed using annual extraction rates ranging from 1 000 to 15 000 ML/year. To put these volumes in context, groundwater extraction rates in the Cox's Creek subcatchment over the 1988 to 2003 period ranged from a minimum of 2 630 ML/year in 1989 to a maximum of 15 920 ML/year in 2001 (Figure 7-3). The average extraction rate over this period was 7 390 ML/year. Model simulations for varying extraction rates were run using identical model parameters, with the exception of the irrigation season extraction rate, which was held at a constant rate for each model run. The modelled groundwater storage levels for varying (but each temporally uniform over the irrigation season) rates of extraction are shown in Figure 7-6.

One can see in Figure 7-6 that with increasing rates of extraction, groundwater storage volumes are increasingly reduced, as would be expected, with the overall groundwater storage mass balance reflecting the net difference between recharge and loss. Moreover, the losses to groundwater storages as a consequence of extraction are cumulative, i.e., storages continue to decline in the absence of sufficient recharge to storage to compensate for the losses (periods where storages increase). Thus it would be expected that climate variability would have an influence on groundwater storage volumes, and furthermore that changes in groundwater storage volumes as a consequence of extraction regimes may impact on baseflow discharges. It follows then that both the climate and rates of extraction need to be considered in baseflow assessments. The effects of climate and extraction on baseflow discharges are discussed in the following subsections.

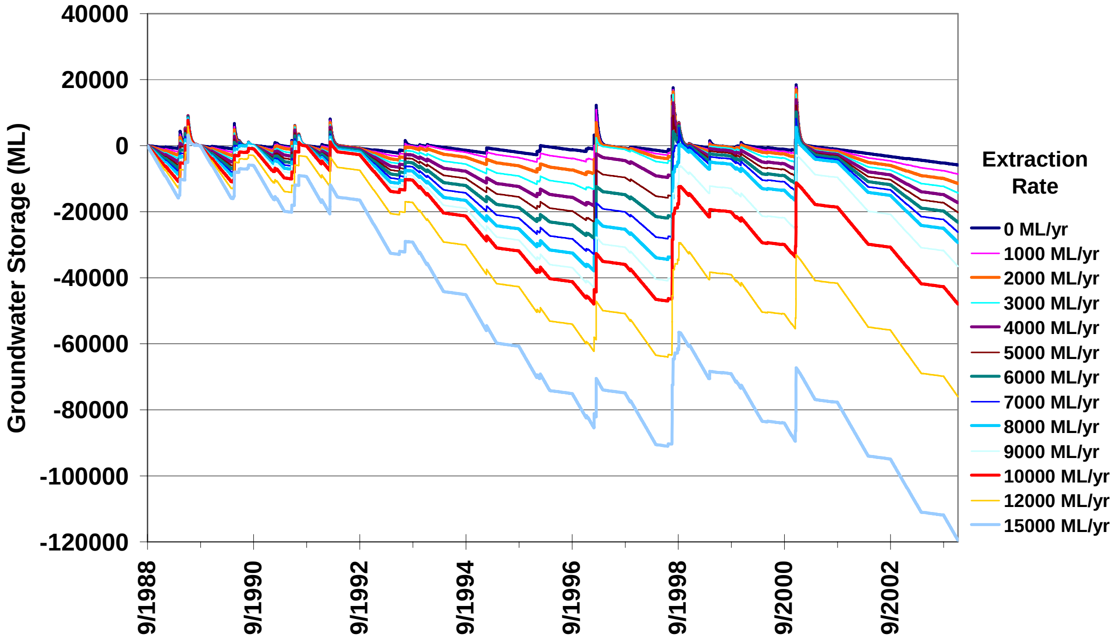


Figure 7-6 Modelled groundwater storage volumes for simulation scenarios using varying rates of constant groundwater extraction over the irrigation season in the 1988-2003 period

7.3.1 Climatic Influences on Model Outputs

The IHACRES_GW model uses effective rainfall estimates to produce modelled groundwater storages and streamflow, as was discussed in Chapter 5. In its current configuration, IHACRES_GW calculates effective rainfall from the streamflow data (Section 5.6), and the streamflow data reflect the climatic changes. Therefore, the model is well suited to study the effect of the climatic changes on groundwater recharge rates and the associated groundwater storage volumes over the 15-year modelled period. During wetter climatic periods, for example, there will be more frequent streamflow events and greater volumes of water transported within the catchment. This equates to larger volumes of effective rainfall available to be partitioned to groundwater storage through increased volumes of groundwater recharge. Conversely, during drier periods there will be less frequent streamflow events and thus less effective rainfall, and hence there will be less water available for groundwater recharge. The effective rainfall volumes calculated for use as model input based on streamflow records at gauging station 419032 over the 15-year simulation period are shown in Figure 7-7.

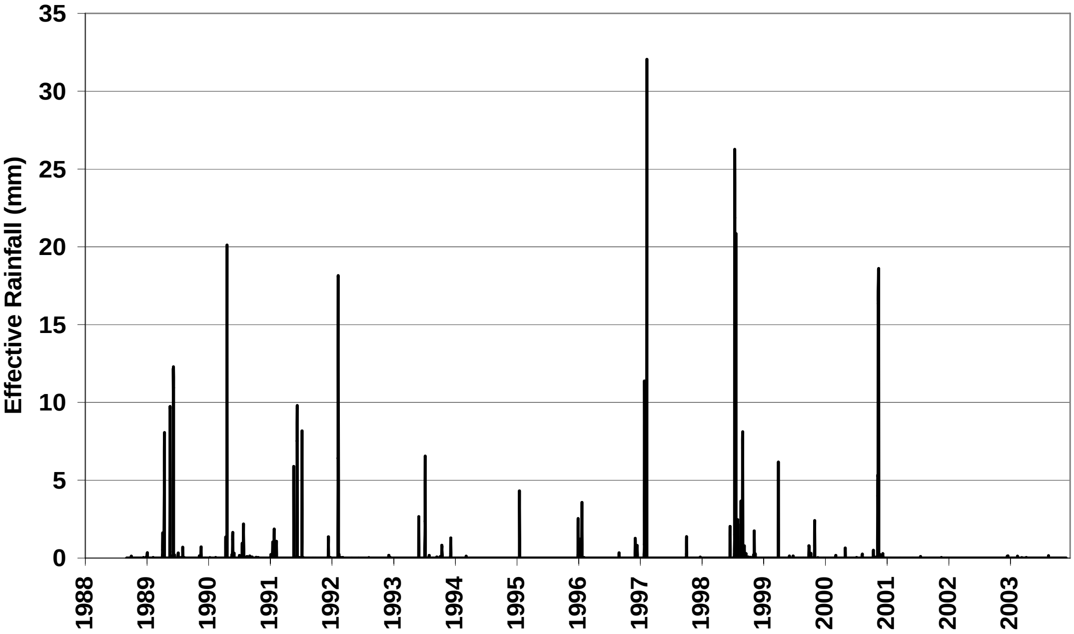


Figure 7-7 Effective rainfall estimations based on streamflow data measured at gauging station 419032 over the 1988-2003 simulation period

One can see from Figure 7-6 that during wetter climatic periods, such as over the 1989-1992 period which was wetter than average (see Figure 7-7 and recall climatic data presented in Figure 6-3 and Figure 6-4), that relatively large volumes of groundwater – up to 9 000 ML/year – can be extracted without resulting in the loss of baseflow events, although, of course, the magnitude of the baseflow events would be reduced. This is because during wetter periods the volumes of groundwater recharge are larger, and as a consequence there is also an increase in groundwater storage volumes. In contrast, during drier climatic periods, such as over the 1993-1995 period, relatively small amounts of groundwater extraction, as little as 2 000 to 3 000 ML/year, can result in the complete loss of baseflow events through the depletion of groundwater storages.

It is during the drier periods that the demands for groundwater resources are the greatest. Yet it is at these times that groundwater extraction rates would need to be curtailed to maintain groundwater storage volumes above a certain level in order to ensure that the resumption and duration of baseflow events at the onset of wetter cycles are not delayed. This may be particularly important where, and if, groundwater (i.e.

baseflow) dependent ecosystems are identified for protection. One can see that on resumption of a wetter period in 1997 and late 1998, significant recharge occurs to groundwater storages. But the recharge is insufficiently high to compensate for the prolonged antecedent dry period coupled with elevated extraction rates.

Without good groundwater recharge estimates, the interactions between groundwater and river systems may not be accurately modelled as has been discussed by Devlin and Sophocleous (2005). In this thesis the IHACRES_GW model has estimated groundwater recharge based on the partitioning of 9% of the volume of effective rainfall to groundwater storage, determined in the calibration of the ν_s parameter in Chapter 6 (Table 6-1), which has allowed for appropriate consideration of groundwater recharge on a daily timestep. The variability in groundwater storage volumes as a consequence of climate variability and associated groundwater recharge rates is critical to determining sustainable pumping rates and sustainable groundwater allocation.

The significance of baseflows to riverine ecosystems requires further study and consideration within the Namoi River catchment, though this is beyond the scope of this thesis. Storage declines have been clearly shown to impact upon baseflow discharges, and declines in storage may equate to lower groundwater levels, which might also have an impact on vegetation and other ecosystems reliant on shallow groundwater systems.

7.3.1.1 A Comment on Conjunctive Water Use

The surface water entitlement for the Cox's Creek subcatchment is currently of the order of 2 600 ML/year, which is relatively low compared to the volumes of groundwater extracted within the subcatchment. Groundwater is of course a more reliable source of water during dry periods, compared to the intermittent/ephemeral nature of the Cox's Creek, and provides a more secure water supply for irrigation and other uses at these times. Nevertheless, even during the 1993/94 drought there was a total 40 475 ML of streamflow generated through runoff events, whilst groundwater extraction was of the order of 16 195 ML over these years. If groundwater extraction allocations were to be limited during droughts in order to protect defined groundwater (or baseflow) dependant ecosystems, then some of the shortfall of the water allocation could be augmented through greater access to surface water during these periods – depending of course on the water management objectives for the catchment. It is beyond the scope of this PhD to assess these trade-offs in any detail. Nevertheless, the conjunctive use of surface water and groundwater, coupled with allocations that vary according to climatic factors, would make for an important study. These modelling results suggest the potential for considering variable water allocation volumes with variable climatic regimes.

7.3.2 Quantifying Baseflow Reductions for Varying Rates of Extraction

The IHACRES_GW model was used to model the impacts of varying rates of extraction on groundwater storage volumes (Figure 7-6) and the consequent reductions in baseflow discharges. The modelled reductions in baseflow for varying extraction rates over the 15-year simulation period have been tabulated in Table 7-2.

Table 7-2 Modelled reductions in baseflow with varying rates of groundwater extraction over the 2/9/1988 to 9/12/2003 simulation period

Extraction rate (ML/year)	Minimum reduction (ML/day)	Maximum reduction (ML/day)	Median reduction (ML/day)*	Average reduction (ML/day)*	Total reduction (GL)	Yearly reduction (ML/year)
1 000	0	215	5	12	12.6	830
2 000	0	360	9	24	25.2	1 650
3 000	0	675	14	36	37.8	2 470
4 000	0	840	18	48	50.6	3 310
5 000	0	860	20	59	63.1	4 120
6 000	0	1 040	22	71	75.5	4 940
7 000	0	1 205	24	83	87.9	5 750
8 000	0	1 205	27	94	100.2	6 550
9 000	0	1 270	29	102	108.7	7 110
10 000	0	1 270	32	106	112.1	7 330
12 000	0	1 270	35	109	115.6	7 550
15 000	0	1 270	36	112	118.5	7 750

*calculated for days with baseflow only

Figure 7-8 (after Ivkovic *et al.*(2005b) demonstrates that the relationship between the rate of groundwater extraction and the resultant decline in baseflow is highly linear (y= 0.82x) up to an extraction rate of about 9 000 ML/year, indicating that baseflow reduction has been in the order of 82% of the extraction volume over the 15-year modelling period. These data suggest that the Cap on surface water diversions is also going to be eroded as a consequence of groundwater extraction given that baseflow discharges to Cox's Creek appear to be reduced by about 82% of the rate of extraction.

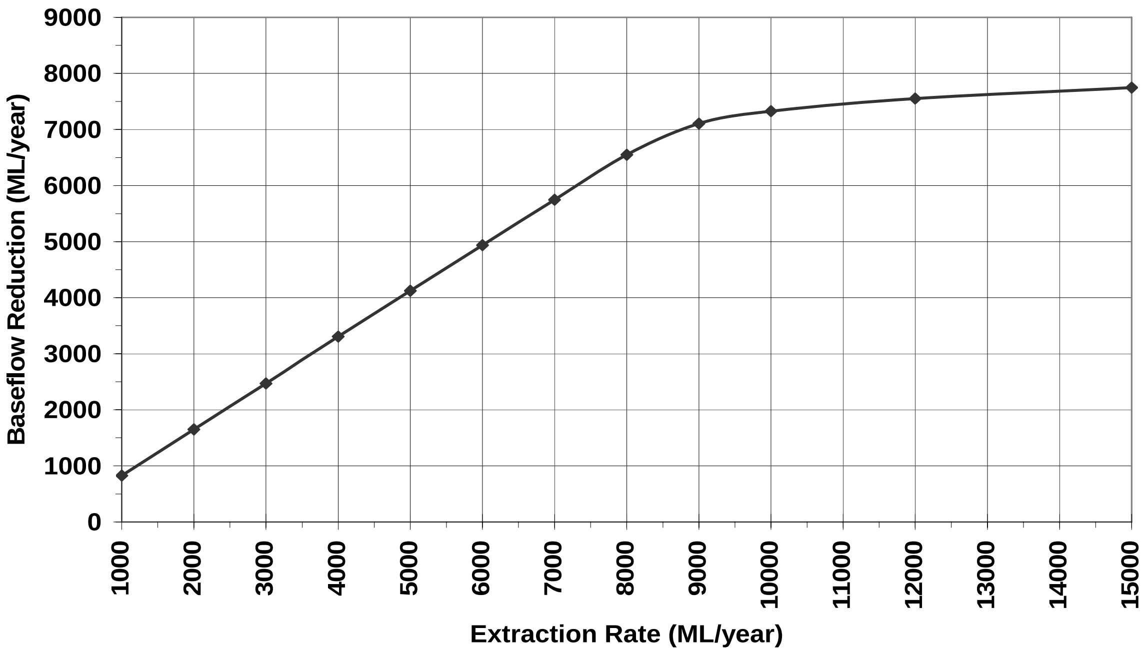


Figure 7-8 Modelled reductions in baseflow for varying rates of groundwater extraction over the 2/9/1988 to 9/12/2003 simulation period

At extraction rates above 9 000 ML/year, the reductions in baseflow start to level off because groundwater storage levels decline to such an extent that disconnection increasingly occurs between the groundwater and river systems, as is evident in Figure 7-6 hence the flattening of the slope at this point in Figure 7-8. If long term pumping rates were to exceed 9 000 ML/year, then this would eventually result in the river reach becoming a disconnected-losing system. Despite the fact that the reductions in baseflow at extraction rates greater than 9 000 ML/year start to level off, extractions from disconnected aquifer-river systems will still result in captured groundwater discharges, and these volumes of water will no longer have the potential to discharge further down the catchment. This might eventually impact upon the river system down-gradient in areas where the exploited aquifer and river system eventually become connected.

The potential impacts of groundwater extraction have yet to be quantified in any policy attempts to meet river flow targets, although the potential impacts have been acknowledged by the water reform agenda of the National Water Initiative. The use of the IHACRES_GW model has allowed for the impacts of groundwater extraction rates on baseflows to be simulated and quantified for the range of climatic regimes having existed over the 15-year modelling period. The modelling results suggest that groundwater extraction in the Cox's Creek catchment will have the effect of reducing baseflow discharges in the order of 82% of the volume of groundwater extracted (for rates up to 9 000 ML/year), though the impacts might be greater or lesser than this figure depending on the particular climatic period. The remaining 18% of the total volume of groundwater extraction is assumed to be impacting on the available volumes of subsurface throughflow below the level of the gauging station. The magnitude in the reduction of baseflows will need to be considered in light of the objectives of the Cap on surface water diversions, as well as in water account budgets and in water allocation plans more generally.

Assuming that the climatic regimes experienced within the Cox's Creek subcatchment over the last 15 years are reasonably representative of future climatic patterns, particularly since there have been considerable dry/drought events over the modelled period and the projections are for increased dry spells within this part of NSW, then these modelling results can be used to guide policy directed towards more sustainable groundwater extraction in light of the expected reductions in baseflows. If the IHACRES_GW model were to be tested and found valid for use with a non-linear loss module, then a range of future climatic scenarios could also be simulated more directly to better understand how different climate regimes might impact on water resources.

7.4 Assessment of Water Sharing Plans

The water reform process has resulted in decreased water entitlements for water users in the Cox's Catchment in order to promote resource security and sustainability. The water sharing plan for the Upper and Lower Namoi Groundwater Sources 2003 under the Water Management Act 2000 specify that the Upper Namoi Zone 2 (between the towns of Mullaley and Boggabri) in the Cox's Creek subcatchment shall have groundwater entitlements reduced by 70% (from 23 801 ML/yr) in order to meet the Estimated Average Annual Recharge (EAAR) of 7 200 ML/year (Table 3-1). No reductions were specified for Zone 9 (upstream of Mullaley), which currently has a relatively low usage of around 690 ML/year and had a maximum historical usage of 2 320 ML during the 1994/94 drought (Brownbill, 2000). The EAAR for Zone 9 is 11 400 ML/year, and this Zone has a large number of inactive licenses with potential to grow in the future. No groundwater-dependent ecosystems have been identified by the NSW Department of Natural Resources for the Cox's Creek subcatchment.

Simulations using the IHACRES_GW model suggest that for an annual extraction rate of 7 000 ML/year, over the whole of the Cox's Creek subcatchment (including both Zones 2 and 9), baseflow volumes would be reduced by approximately 5 750 ML/year or a total of 87.9 GL over the 15-year model simulation period (refer to Table 7-2). Furthermore several baseflow events would be entirely missed during the drier 1993/96 periods, thus decreasing the frequency, magnitude and duration of baseflow events. The 1993/96 period, overall, was particularly dry and consequently any extraction rate greater than 3 000 ML/year would have resulted in a loss of baseflow events (Figure 7-6).

If the total calculated EAAR volume of 18 600 ML/year (for both Zones 2 and 9) were to be extracted as stipulated within the water sharing plans, the modelling results suggest that the groundwater and river systems will become permanently disconnected, as inferred from the simulation data presented in Figure 7-8. Although the volumes of groundwater extracted in Zone 9 are currently well below the EAAR of 11 400 ML/year, any future increases in groundwater extraction within this zone will impact down gradient and affect Zone 2 by reducing the volumes of groundwater available as throughflow as a consequence of captured discharge. This would exacerbate the water security of an already over allocated Zone 2. The IHACRES_GW model simulations suggest that the extraction limits within the current water sharing plans are set too high, and that a limit of between 7 000 and 8 000 ML/year might be more appropriate over the whole subcatchment i.e. including **both** Zone 2 and Zone 9. This would allow for replenishment of groundwater stores within a couple of large events, such as occurred in March 1997 and July 1998, as demonstrated by Figure 7-6 where large accessions to storage are seen during these flood events.

Terms and concepts used in the water sharing plans include the "sustainable yield", defined as the EAAR, or the "ecologically sustainable yield", defined as the sustainable yield minus the requirements of groundwater-dependent ecosystems (or 70% of the EAAR). It is important that water managers keep in mind that these terms do not recognise that the available groundwater storage volumes and associated baseflow responses will vary over time in response to changing recharge conditions, for example in response to climatic variability (as previously discussed in Section 7.3.1). Furthermore, if the annual groundwater pumping rates are equal to the EAAR, then the groundwater discharges down gradient will be reduced, and could result in the drying up of a river system as discussed by Sophocleous (1997; 2000).

According to Devlin and Sophocleous (2005), the concepts of sustainable groundwater resources development and sustainable pumping are easily confused. They state that there are two important distinctions that characterise sustainable groundwater resources development. The first is that sustainable development is concerned with ecology, water quality and human and environmental welfare. The second is that although groundwater recharge rates are not required for estimating sustainable pumping rates, they are critical for an accurate assessment of sustainability.

The sustainable yields referred to in the water sharing plans would be more appropriately called sustainable pumping rates because their management objective is primarily focused on ensuring that the aquifers within the catchment are not de-watered. In contrast, the sustainable development of groundwater resources needs to consider the impacts of extraction on river flows, in particular on the timing and magnitude of baseflow events required for ecosystem function, cultural values and water security more generally within the catchment.

7.5 Managing Groundwater Extraction in Connected Aquifer-River Systems at Catchment Scales

The research findings from this thesis can be used to provide some insights into better managing the impacts of groundwater extraction in connected aquifer-river systems. Some logical and relatively broad steps are suggested.

Step 1 – Establish presence of hydraulic connection

In the first instance, the presence of hydraulic connection between an aquifer and river system needs to be established. There is a range of techniques that can be employed to assess hydraulic connection, some of which were discussed in Chapter 4. Establishing the dominant direction of flux between an aquifer and river system may be helpful in terms of conceptualising the nature of the interactions. Catchments having connected reaches can then become the focus of study for future aquifer-river interaction studies.

Step 2 – Assess potential for groundwater extraction to impact on river flows

The potential for groundwater extraction to impact on river flows needs to be assessed for the connected reaches, whilst bearing in mind that extraction in disconnected aquifer-river reaches will have impacts down-gradient where aquifer and river systems eventually become connected, or at other groundwater discharge sites. Plotting the locations of extraction bores relative to river systems and collating groundwater extraction data for catchments and groundwater management areas is an important step in prioritising the regions where the volumetric impacts of extraction may be greatest. Extraction patterns and projected growth in the use of groundwater will also be important considerations.

The vertical connectivity between the shallow aquifers in connection with a river system, and any deeper aquifers from which groundwater extraction occurs, needs to be established. Extraction from deeper confined units may not impact directly on river flows, whilst extraction from unconfined and semi-confined aquifers potentially has a direct impact.

Step 3 – Develop conceptual, water balance models

The use of simple, but dynamic, conceptual models, such as the IHACRES_GW model, can be a useful tool for assessing the overall water balance of a catchment and the impacts of extraction on river flows, particularly because of their simplicity. The model simulations can be used to calculate the impact of current extraction rates and/or reported sustainable yields for an aquifer system on the frequency, magnitude and timing of baseflows, and assist with meeting river flow targets such as the Murray Darling Basin Ministerial Cap. The requirements of ecosystems may be an important consideration in assessing river flow targets.

Step 4 – Conduct Integrated Assessments

The results of the simple, dynamic water balance modelling can be used to assess the ability of a catchment to respond to any proposed alterations to water allocation policy. Existing water sharing plans can be revised in light of the model findings if required, after community consultation and integrated assessments are conducted that consider socio-economic factors together with the biophysical. The role of water markets and trading has the potential to play an important role in water volumetric adjustments of both river and groundwater entitlements in order to meet river flow targets or ecosystem requirements.

Step 5 – Develop Fully Integrated Groundwater-River Models in Priority Regions

It would be appropriate to manage water as a single resource through fully integrated, groundwater-river models within high priority catchments so that the spatial aspects of water management can be better addressed. This is still an area of technical development and debate, with considerable computational and financial costs involved depending on the available data pool and the spatial and time scales used in the model. Nonetheless, it would be reasonable to expect that fully-integrated models will become more commonplace tools for allocating water conjunctively in the near future.

7.5.1 Data Requirements

Whilst the five broad steps listed above are relatively simple in concept, they assume that a basic pool of data is readily available. The Namoi River catchment is one of the better-studied catchments in Australia, and consequently there were considerable data sets available with which to undertake aquifer-river interaction analysis and model development/application.

Some key datasets used in this study include: stream gauging data (1965 onwards); piezometer data (late 1960's onwards); yearly extraction data (1985 onwards); climatic data (rain and temperature data); driller logs; existing hydrogeological studies, including quantity and quality/hydrochemical assessments; and previous hydrogeological mapping and hydrogeological modelling. The relatively lengthy data series, e.g. 20 years of pre-development and 15 years of post-development data, greatly assisted with model calibration and validation, and was useful in distinguishing pre-development from post-development conditions.

Despite the relatively good data pool, there were some shortcomings in the data sets. Firstly the stream gauging stations were surveyed relative to an arbitrary datum rather than relative to the Australian height datum, and so river stages could not be compared with groundwater elevation. (It was beyond the resources available for this research to survey the local datum relative to the Australian height datum, but this could be easily achieved by government departments responsible for these data.) Secondly, few piezometers were located adjacent to the river, or better still, transected the river at a gauging station. This made establishing the flow direction between the river and aquifer systems difficult, and as a result the direction of flux was inferred primarily from flow duration and stream hydrograph data, as was discussed in Chapter 4. Thirdly, the timing of data collection complicated an assessment of the temporal nature of groundwater river interactions. For example, streamflow data is collected on a daily time step, at minimum, but observation bores are read at most quarterly with manual readings in rapid decline to the extent that water level readings for a large number of observation bores are no longer measured. Fourthly, extraction data was available as a yearly volume. Ideally each of the data sets would be available on a daily or monthly time step, and automated forms of data collection and logging would be routinely undertaken. Fifthly, the use of IHACRES_GW with a non-linear loss module that could generate effective rainfall was hampered by the relatively poor spatial coverage of rain gauging stations in the Cox's Creek subcatchment, and the associated uncertainties in areal catchment rainfall volumes. Andréassian *et al.* (2001), Croke *et al.* (2006) and Hansen *et al.* (1996) provide a more detailed discussion of the subject of rainfall data quality and rainfall-runoff modelling. A broader network of climate stations in catchments exhibiting spatial rainfall heterogeneities would improve prediction of streamflow using rainfall-runoff models.

An audit of data availability would ideally be conducted for each catchment, with data gaps identified and addressed for priority regions, so that the series of steps discussed above could be initiated with a view to managing the impacts of extraction on river flows.

7.5.2 Consideration of Time Lags

Groundwater extraction from a connected aquifer-river system will eventually impact on the river. A commonly-asked question by water managers is: how long does it take for the impacts on a river system to become evident once pumping commences and, conversely, how quickly are groundwater storages replenished?

The primary role of the IHACRES_GW model is to represent the time lag present in groundwater storage depletion and replenishment, which will be driven by the net rate of groundwater extraction and other storage losses relative to the recharge rates. This catchment-scale perspective considers the aggregated water balance response within the catchment on a river system, and does not consider the response of an individual bore.

The main objective of this research, was to develop a (sub)catchment scale understanding of the impacts of groundwater extraction on river flows through the application of a simple, dynamic and spatially-lumped model. Consequently, the spatial aspects associated with the extractions of individual bores are not directly considered. This type of modelling approach particularly lends itself to integrated assessments of water allocation options in which hydrological, ecological and socio-economic data sets are combined, and where data is commonly aggregated upwards to a larger scale of interest to meet policy requirements.

The time lag associated with groundwater extraction, in particular the spatial impacts of individual bores on river systems and associated groundwater-dependent ecosystems, is a subject that requires further research. The key factors that drive the response times of extraction within different types of aquifer systems are not well understood. Braaten and Gates (2004) explored a range of factors through a sensitivity analysis using MODFLOW. They found that whether an aquifer was semi-confined or unconfined, the aquifer width and its boundary conditions strongly influenced the time lag response. Their study suggested that connected aquifer-river systems would ideally be classified according to the driving factors influencing time lags with a view to further developing extraction management zones within a catchment based on response times.

The IHACRES_GW model was trialled in the Cox's Creek catchment, which is a narrow, semi-confined alluvial valley. This type of system was found by Braaten and Gates (2004) to show no lags in response times between the onset of pumping and impact on a river system. It would be interesting to trial the IHACRES_GW model in other types of catchment settings in order to assess lag time issues associated with spatially-lumped catchment scale models in comparison with other types of models, and to further assess the performance of IHACRES_GW.

7.6 Chapter Summary

The IHACRES_GW model was used to simulate a range of extraction scenarios, which has allowed for the impacts of groundwater extractions on river flows to be assessed. The impacts arising from the historical rates of groundwater extraction on baseflow events were quantified over the 15-year (1988-2003) simulation period. The relationship between the rate of extraction and associated baseflow reduction was calculated, providing insight into the degree to which the Murray Darling Basin Ministerial Cap is undermined by groundwater extractions. The influences of variable climate on net groundwater storage volumes were also explored.

The IHACRES_GW model was subsequently used to assess the sustainability of the water allocation provisions in the water sharing plans. While there are a number of limitations to a conceptual style of modelling approach in the management of water resources (e.g. due to the lack of spatial considerations), this type of modelling approach can be useful in gaining a better understanding of large-scale water management issues such as assessing the impacts of water allocation and groundwater extraction on river flows at the catchment scale and informing water sharing plans. This type of modelling approach particularly lends itself to integrated assessments of water allocation options in which hydrological, ecological and socio-economic data sets are combined, and where data is commonly aggregated upwards to a larger scale of interest to meet policy requirements. The research findings from this thesis were used to provide some insights into how to better manage the impacts of groundwater extraction in connected aquifer-river systems.

Chapter 8 Conclusions

8.1 Introduction

Developing an understanding of the interactions that occur between groundwater and river systems is critical for the effective management and allocation of water resources. This thesis has considered the theme of groundwater-river interactions using the Namoi River catchment as a case study area. The first part of the thesis focused on characterisation of the groundwater-river interaction processes and the second part addressed the development, application and testing of the IHACRES_GW model, which allows for groundwater-river interaction behaviour at the catchment scale to be simulated. The IHACRES_GW model developed within this thesis has been used to investigate the impacts of groundwater extraction on river flows in the Cox's Creek subcatchment and to provide recommendations which can be used to inform water management policy. The conclusions from these two over-arching thesis research components, that is characterisation of river reaches and model development and application, follow.

8.2 Characterisation of River Reaches

The gauged river reaches in the Namoi River catchment were characterised according to three levels of information: 1) presence of hydraulic connection between aquifer-river systems; 2) dominant direction of aquifer-river flux; and 3) the potential for groundwater extraction to impact on river flows. The methods used to characterise the river reaches included the following analyses: 1) a comparison of groundwater and river channel base elevations using a GIS/Database; 2) stream hydrographs and the application of a baseflow separation filter; 3) flow duration curves and the percentage of time a river flows; 4) vertical aquifer connectivity from nested piezometer sites and 5) paired stream and groundwater hydrographs.

A map was prepared for river reaches in the catchment that indicates aquifer-river connectivity and dominant direction of flux (refer to Figure 4-12). Much of the Upper Namoi catchment was assessed as having connected aquifer-river systems, with groundwater extraction bores located in close proximity to the rivers. Thus the potential for groundwater extraction to impact on river flows was considered to be high in this area (refer to Figure 4-13). In the connected aquifer-river reaches it is important to quantify the impacts of groundwater extraction on river flows arising as a consequence of captured discharge and induced recharge. The Lower Namoi catchment was assessed as having mostly disconnected aquifer-river systems. In these reaches groundwater extraction will not directly impact on river flows – but the impacts of captured discharge will become evident down gradient as reduced volumes of throughflow, as well as impact on downstream rivers if and where the exploited aquifer and river systems become connected.

8.3 Development and Application of IHACRES_GW

In order to assess the impacts of groundwater extraction on river flows and to inform water management policy, a simple integrated aquifer-river model, IHACRES_GW, was developed for use at the (sub)catchment scale. The IHACRES_GW model was derived from the IHACRES rainfall-runoff model and its derivation has been fully described in Chapter 5. The IHACRES_GW model includes a simple groundwater model component that maintains a continuous water balance account of groundwater storage volumes for the upstream catchment area relative to the reference point at which groundwater contributes to streamflow (as observed at the stream gauging station). The groundwater storage module allows for the impact of groundwater extraction and other groundwater losses on streamflows to be modelled. Furthermore, the groundwater storage module allows for improved rainfall-runoff model performance in intermittent types of river systems because, in these systems, a continuous water balance account of the changes in groundwater storage during periods of zero flow is required in order to correctly simulate the onset of baseflow periods.

A top-down, spatially-lumped, but still dynamic, approach to modelling was selected for use in this thesis for several reasons including: the requirement for catchment-scale water budget accounting in order to assess water sharing plans; the need to model streamflows, including baseflows, on a daily time step; the preference for a relatively simple model that could be later used in integrated assessments; the limited data pool and time with which to parameterise a complex model; and the uncertainties associated with models that are physically over-parameterised (see Chapter 5 for a discussion on model approaches and selection).

IHACRES_GW was tested in the Cox's Creek subcatchment. Some aspects of the IHACRES_GW model functionality and findings are reviewed below in order to assess whether the model development and application met the original model objectives set out in Section 5.4.1, with the ultimate purpose of addressing the thesis research aims described in Section 1.2.

8.3.1 Has IHACRES_GW Met Its Objectives?

The IHACRES_GW model was developed for use in this thesis with the aim of achieving four main objectives, namely: 1) to consider how existing water allocation models could be improved upon through modelling groundwater-river interactions; 2) to quantify the impacts of groundwater extraction on river flows within the connected aquifer-river systems; 3) to inform water policy on groundwater extraction; and 4) to be able to utilise the model in future integrated assessment of water allocations options at the catchment scale. The extents to which these model objectives have been achieved are discussed in more detail below. Section 8.3.2 suggests some further developments of IHACRES_GW.

8.3.1.1 Improving Water Allocation Models

Groundwater and river resources are currently managed and allocated separately in Australia. Surface water is often allocated through the use of rainfall-runoff models and/or monitoring of upstream flows. Groundwater is allocated based on a calculation of the "sustainable yield", determined from estimates of the long-term average annual recharge to an aquifer system. The separate allocation of surface water and groundwater has resulted in double accounting of water resources, which when considered together with the impacts of extraction that arise from the processes of induced recharge and captured discharge, has resulted in reduced river flows. The IHACRES_GW model permits both river and groundwater resources to be modelled conjunctively on a daily time step, and hence the dynamic interactions between the two systems are captured at the catchment scale.

The IHACRES_GW model also quantifies the impacts of the historical rates of groundwater extraction on river flows (Section 7.2 and Table 7.1). The integrated simulation of both groundwater and river water resources provides greater understanding of the implications of groundwater allocation on river flows. The model shows an example of how a simple, spatially-lumped model can be used to better simulate and predict the effects of water allocation at catchment scales.

The application of the IHACRES_GW model demonstrated that groundwater extraction affects the frequency, timing and magnitude of baseflow events, and that the impacts vary not only as a consequence of the extraction rates and other losses to groundwater storage, but also according to the groundwater recharge rates (Section 7.3). The importance of good groundwater recharge estimates for adequately modelling aquifer-river interactions has been highlighted in this research. The legacy that historical rates of extraction have on overall groundwater storage volumes and associated baseflow discharges is a function of the net recharge to the exploited aquifer system versus loss as a consequence of extraction and other groundwater losses. It can take decades or longer to recharge aquifers to pre-drought storage levels if groundwater resources have been heavily and/or overly exploited. Conversely, during wetter climatic periods, particularly when associated with flooding and increased groundwater recharge, groundwater storages may be replenished within a relatively short time. Although groundwater recharge rates are not required for estimating sustainable pumping rates, they are critical for an accurate assessment of groundwater-river interactions and sustainability assessments.

There are of course limitations to a simple, spatially-lumped model. Most notably the spatial aspects of the surface and groundwater system are lacking, which would ultimately be required for the conjunctive management of water resources within a catchment. It is suggested that a rainfall-runoff model such as IHACRES eventually be integrated (coupled or loosely coupled) with a spatially distributed groundwater model such as MODFLOW in order to manage the spatial aspects associated with groundwater allocation, e.g. time lags, groundwater levels etc. Such an integrated model would also provide a cross-validation of the IHACRES_GW model and yield insights into the different types of information that simple versus complex models can generate along with the associated model uncertainties.

The IHACRES_GW model is an advance in considering water allocation at the larger, (sub)catchment scale. Now that the IHACRES_GW model has been developed and tested for use within the Cox's Creek subcatchment (see Chapter 6), this simple model has the potential to be easily transported for use in either developed or undeveloped catchments in order to explore any of the historical or potential future impacts of groundwater extraction on river flows. The data required to run the model consists of daily streamflow data and annual extraction data. A shorter time step for the extraction data would be more appropriate where available.

The IHACRES_GW model was developed for use in areas where the error in the catchment rainfall data is high as a consequence of the poor spatial coverage of rain-gauging stations and non-uniform rainfall patterns, such as is the case for the Cox's Creek subcatchment (refer to Section 5.6). In these areas the errors in deriving catchment average rainfall data combined with the uncertainty associated with the non-linear loss module tend to mask out the signal from the influence of groundwater extraction within the linear module. In particular, there can be significant uncertainty around modelling the timing and volume of baseflows, and because of this the streamflow data in the current configuration of IHACRES_GW has been used to calculate effective rainfall. This model configuration allows for the model to focus on assessing the groundwater extraction impacts on streamflows with greater certainty in runoff-dominated catchments characterised by intermittent to ephemeral rivers. The current model configuration would not be appropriate for groundwater-dominated river systems. In groundwater-dominated catchments, however, the perennial nature of the river systems with their lengthier record of low magnitude streamflows maintained by baseflows would make model calibration of baseflows more straightforward. As a result, the groundwater-dominated catchments might be easier to model with a rainfall-runoff model (that includes a non-linear module).

Further testing of IHACRES_GW with a non-linear loss module that is used to generate effective rainfall is an important future step required for this model to become a fully functioning water allocation model. This would allow for the effects of climate variability and groundwater extraction in groundwater-dominated river systems (rather than mainly runoff-dominated catchments as in its current configuration) to be simulated. The IHACRES_GW model is well suited to modelling unregulated and gauged river systems in narrow, semi-confined as well as narrow, shallow, unconfined alluvial valleys that have strong aquifer-river connectivity and where groundwater extraction predominantly occurs upstream of a stream gauging station located at the catchment outlet. The Upper Namoi River catchment, as well as many other upper catchments within the Murray Darling Basin, is commonly characterised by these types of aquifer systems. The IHACRES_GW model was developed for use in an unregulated river system, and is not appropriate for use in a regulated system without additional model development.

8.3.1.2 Quantifying the Impacts of Groundwater Extraction on River Flows

The IHACRES_GW model explicitly accounts for captured discharge through the use of a daily extraction rate (derived from yearly extraction data), whilst induced recharge is implicitly considered over calibration periods by the use of the slow flow volume/recharge parameter (v_s). The IHACRES_GW model has allowed for the impact of historical extraction rates on the timing, frequency and magnitude of baseflows to be quantified (Table 7-1). The model results indicate that streamflow volumes have been reduced by 5% over the 15-year modelling period (2/9/1988 to 9/12/2003) as a result of groundwater development, over which time extraction rates varied between 2 630 ML/year and 15 920 ML/year, with an average extraction rate of 7 390 ML/year. The modelled median reduction in baseflows (calculated for periods with baseflow only) was 15 ML/day and the average reduction was 73 ML/day. The largest reductions in baseflows were associated with drought periods that were characterised by greater than average volumes of groundwater extraction resulting in significant declines in groundwater storage volumes. The total reduction in baseflow over the whole 15-year simulation period was approximately 78.3 GL (Table 7-1). The analysis shows that the overall impact of groundwater extraction on the duration of streamflows has been to reduce the probability of flows lower than 100 ML/day by between 2 and 4% (Figure 7-5).

The model has also been used to run scenarios in order to quantify the impacts on baseflows for varying rates of groundwater extraction (see Figure 7-8 and Table 7-2). IHACRES_GW suggests that baseflow discharges are reduced by 82% of the volume of groundwater extracted to a maximum rate of 9 000 ML/year for the range of climatic conditions encountered over the 15-year simulation period. In other words, 82% of the volume of groundwater extracted would have otherwise become river water, with the remaining 18% of the total volume of groundwater extraction assumed to be impacting on the available volumes of subsurface throughflow below the level of the gauging station. Extraction rates above 9 000 ML/year resulted in disconnected groundwater and river systems. The modelling results also suggest that groundwater extraction has resulted in increased groundwater recharge (from both induced and captured recharge sources) approximating the volumes of groundwater extracted (refer to Section 6.6.3.3).

8.3.1.3 Informing Water Policy on Groundwater Extraction

The IHACRES_GW model has been used to assess the impacts of the currently reported "sustainable yield" in the existing water sharing plans for the Upper Namoi (refer to Section 7.4). The model simulations suggest that the reported rate of 7 200 ML/year for Zone 2 of the Cox's Creek would reduce baseflow discharges by approximately 6 000 ML/year. The reported sustainable yields of 18 600 ML/year for Zones 2 and 9 could adversely impact upon river flows given that the modelling results suggest that, for extraction rates above 9 000 ML/year, the groundwater and river systems would become permanently disconnected. The IHACRES_GW model simulations suggest that the extraction limits within the current water sharing plans are set too high, and that a limit of between 7 000 and 8 000 ML/year might be more appropriate over the whole subcatchment i.e. including **both** Zone 2 and Zone 9. This would allow for replenishment of groundwater stores over a few large events, such as occurred in March 1997 and July 1998 (Figure 7-6), and hence maintain connection between the groundwater and river systems upon resumption of wetter climatic periods. Based on these modelling results, it is suggested that the "sustainable yield" calculations for the subcatchment be revised.

The sustainable yield estimates laid out in the water sharing plans currently do not consider the impact of extraction on the frequency, timing and magnitude of the baseflow events and, should ecosystem water requirements be defined, then these figures may need to be reviewed. The possibility of implementing variable water allocations for variable climatic regimes (i.e. moving away from the paradigm of using a fixed 'sustainable yield' calculation in water sharing plans) is suggested as an area of further research in order to better consider sustainable water resources development.

The IHACRES_GW model simulations have indicated that with a groundwater extraction rate of 7 200 ML/year, river flows in Cox's Creek would be reduced by about 6 000 ML/year (Figure 7-8). Consequently, for the integrity of the Murray Darling

Basin Ministerial Cap to be maintained, and to ensure that river flow targets are met, surface water entitlements may need to be reduced by similar amounts, or alternatively groundwater extraction rates may need to be further revised. Ideally, conjunctive management approaches to water allocation would be considered that would provide greater flexibility in terms of how water is allocated to meet any defined baseflow targets.

Simulations of varying rates of extraction have highlighted that the impacts of groundwater extraction on baseflow discharges will vary over different climatic regimes, such that larger volumes of groundwater can be extracted during wetter periods and less during drier periods (refer to Section 7.3). Whilst groundwater use is preferred by irrigators during drought periods because of its greater reliability as a water supply, extraction during drought periods can deplete groundwater storage volumes which in turn will impact upon the timing, frequency and magnitude of baseflow events even after the end of a drought period. If groundwater extraction allocations were to be reduced during dry/drought periods in order to protect defined groundwater-dependent ecosystems, then the shortfall in water could be made up through increased surface water allocations during periods of high flows, for example, in order to fill surface water storages for use during drier periods (noting that even during drought periods there may be sufficient surface runoff dominated events to be exploited). Water trading between surface and groundwater license users may assist with managing the shortfalls of reduced baseflows arising as a consequence of groundwater extraction. The potential to use groundwater and river water resources conjunctively has been highlighted as a policy option that requires further study.

8.3.1.4 Integrated Assessments of Water Allocation Options

In order for water resources allocation to be sustainable, allocation must consider a range of issues including ecosystem health, water quality, water security, socio-economic factors and other catchment values. One of the objectives of the National Water Initiative water reforms is for catchments to be managed using integrated assessment approaches, whereby the broader community is involved in defining catchment values and assessing the associated trade-offs that must be considered when water is allocated. The IHACRES_GW model has the potential to be highly useful in the water allocation debate because this conceptual style of model can easily be integrated with other models and data sets, especially where data needs to be aggregated upwards to a larger catchment-policy scale.

Aside from climatic variations and water use regulation, a major factor influencing groundwater extraction patterns is the economics associated with the irrigation of high-value commodities and the financial returns to the community. The water reform process will result in changes to the availability and use of water, with reduced water allocations potentially impacting adversely upon catchment communities reliant on irrigation water. Integrated assessments will allow for the exploration of the interactions between regulation and market forces, as well as the socio-economic drivers of how water is both managed and used, and may assist with facilitating sustainable outcomes for the catchment. The IHACRES_GW model is currently being tested for use in an integrated assessment of water allocation options in the Namoi River catchment (Letcher *et al.*, 2004). The outcomes of this trial could significantly improve decision-making process by contributing to a better understanding of the complex interplay of factors which determine the overall sustainability of resources and livelihoods within a catchment community.

8.3.2 Further Development of IHACRES_GW

Over the course of this research the potential for further development of IHACRES_GW was identified. Some possibilities for additional model research and development are outlined below.

8.3.2.1 Improved Model Performance of Baseflow Dominated Events

An evaluation of IHACRES_GW model performance over the simulation period (described in Section 6.6) has indicated that the model captures the timing in the switch between baseflow and non-baseflow periods well, despite the fact that the model was not calibrated to this period. Consequently, the model simulations that compare extraction with non-extraction baseflow volumes (as undertaken in Chapter 7) using the model are expected to provide robust estimates of the relative impacts of groundwater extraction on river flows. However, the IHACRES_GW model tends to underpredict baseflows during baseflow-dominated periods (Section 6.6.2). Whilst this does not affect the usefulness of the model in terms of assessing the relative impacts of groundwater extraction on river flows, it does affect the capability of the model to reproduce 'observed' baseflow volumes. Some key factors to explore to improve upon model performance over baseflow-dominated periods include further assessment of the factors influencing net groundwater storage volumes (refer to Section 6.3.3).

The current formulation of IHACRES_GW uses a constant daily loss factor determined during model calibration. However, captured and induced forms of recharge and increased groundwater depths as a consequence of extraction, and the associated influences on evapotranspiration rates, will influence the calibrated loss factor. There is likely to be a minimum groundwater storage volume below which additional losses to storage are no longer measurable, therefore a constant daily loss factor may be too high thus contributing to an underestimation in baseflow volumes. The relationships that potentially exist between the loss parameter and modelled groundwater storage volumes require further exploration.

In an intermittent/ephemeral stream, where for much of the record the river is dry, there may be insufficient data in the streamflow record to allow for a highly accurate account of groundwater storage volumes to be maintained throughout the periods with no measured flow at the stream gauging station. This also could potentially be impacting upon the ability of IHACRES_GW to simulate baseflow-dominated events. The use of a non-linear loss module to generate effective rainfall might allow for a more accurate account of groundwater recharge and groundwater storage volumes to be maintained throughout periods when no flows are measured at the stream gauging station (e.g. when rainfall occurs in the upper catchment yet no streamflow is measured at the downstream catchment outlet). If the IHACRES_GW model were to be tested and found valid for use with a non-linear loss module, this would have the added benefit of allowing the model to more directly simulate a range of climatic scenarios in order to better assess how different climate regimes and extraction rates might impact on water resources. Alternatively, in the absence of fully coupling IHACRES_GW with a non-linear loss module, an effective rainfall input file from other rainfall loss models could be used as input into IHACRES_GW.

Finally, it would be informative to run the IHACRES_GW model for each of the upstream gauging stations to better understand water balance processes along the length of the Cox's Creek subcatchment. In this thesis the water balance has been assessed at the outlet of the Cox's Creek subcatchment, with the water balance reflecting an aggregate response of upstream catchment processes. There may be important groundwater-river water balance interaction processes occurring upstream that might be more clearly identified through a smaller-scale assessment using the IHACRES_GW model. These processes might yield insights into longitudinal groundwater storage and baseflow water balances, perhaps allowing for improved model performance during baseflow-dominated periods.

8.3.2.2 Increased Functionality

This research has demonstrated that groundwater extraction in connected aquifer-river systems impacts on baseflow events. Additional functionality could be added to the IHACRES_GW model that would allow for indicators of hydrological alteration relevant to ecosystem functioning to be calculated. These include the magnitude, duration, timing, and frequency of particular flow classes, and the rate and frequency of flow condition changes. These types of statistical measures would facilitate more comprehensive assessments of the potential impacts of groundwater extraction on river flows and ecosystem function.

This thesis has focussed on volumetric water exchanges, and yet water quality exchanges are also important considerations in groundwater-river interaction studies as well as water allocation management more generally. The relationship between water quality indicators, such as salinity for example, and changes in water quality parameters as a consequence of varying baseflow discharge volumes and groundwater extraction rates, could be further investigated using an IHACRES_GW type model. Further research in this area might ultimately provide additional functionality to river water quality and quantity assessment tools.

8.3.2.3 Translation to Different Catchment Settings

The IHACRES_GW model has been tested within the Cox's Creek subcatchment, which is a long, narrow semi-confined alluvial valley constrained by bedrock. A comparison of model performance within both wide and narrow, as well as in semi-confined and unconfined alluvial valleys, would provide insights into the wider applicability of the model (within the constraints of the model assumptions listed in Section 5.5.3). This type of research would provide insights into the potential use of IHACRES_GW in other catchment settings and perhaps also provide greater insights into time lag issues within these different catchment settings (recall Section 7.5.2). It is expected that IHACRES_GW will be further applied in catchment settings similar to that of the Cox's Creek subcatchment in order to further demonstrate the many utilities of this modelling approach.

8.4 Chapter Summary

This research has made a number of contributions to the topic of groundwater-river interactions using the Namoi River catchment in New South Wales as a case study area.

The broad-scale spatio-temporal interactions occurring between aquifer and river systems have been identified within the Namoi River catchment using a range of research methods. The data-driven approaches used in this research to map aquifer-river connectivity and dominant direction of flux included the use of a GIS/database, bore and stream hydrograph data analysis, as well as baseflow filtering and flow duration analysis. Maps of aquifer-river connectivity/dominant direction of flux and vertical aquifer connectivity are two important thesis outputs that will be fundamental to any future integrated hydrological studies in the catchment.

A parsimonious, integrated aquifer-river model, IHACRES_GW, that considers the interactions between groundwater and river systems was developed for use at the (sub)catchment scale. Model testing of IHACRES_GW in the Cox's Creek subcatchment has shown that a simple, dynamic water allocation model can be used to better simulate and predict the effects of water allocation at the catchment scale.

The model was used to assess the historical impacts of extraction on river flows and to inform water management policy development. A number of associated recommendations pertaining to water sharing plans, water allocation and the management of groundwater extraction more generally have been made for connected aquifer-river systems.

References

Anderson, E.I., 2003. An analytical solution representing groundwater-surface water interaction. Water Resources Research, 39(3): Art. No.-1071.

Anderson, M.G. and Bates, P.D. (Editors), 2001. Model validation: Perspectives in hydrological science. John Wiley & Sons Ltd, Baffins Lane, Chichester.

Andréassian, V., Perrin, C., Michel, C., Usart-Sanchez, I. and Lavabre, J., 2001. Impact of imperfect rainfall knowledge on the efficiency and the parameters of watershed models. Journal of Hydrology, 250: 206-223.

ARMCANZ, 1996. Allocation and use of groundwater - a national framework for improved groundwater management in Australia. Occasional Paper Number 2.

Beven, K.J., 1993. Prophecy, reality and uncertainty in distributed hydrological modeling. Advances in Water Resources, 16: 41-51.

Beven, K.J., 2000a. Rainfall-runoff modelling: The primer. John Wiley & Sons Ltd., Chichester, England.

Beven, K.J., 2000b. Uniqueness of place and process representations in hydrological modelling. Hydrology and Earth System Sciences, 4: 203-213.

Beven, K.J., 2001. How far can we go in distributed modeling? Hydrology and Earth System Sciences, 5: 1-12.

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H. and Valett, H.M., 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecological Systems, 29: 59-81.

Boulton, N.S., 1942. The steady flow of groundwater to a pumped well in the vicinity of a river. Philos. Mag., 7: 34-50.

Boussinesq, J., 1877. Essai sûr la théorie des eaux courantes. Mémoires présentes par divers savants à l'Academie des Sciences de l'Institute National de France, 23: 1-680.

Bouwer, H. and Maddock, T., 1997. Making sense of the interactions between groundwater and streamflow: Lessons for water masters and adjudicators. Rivers, 6(1): 19-31.

Braaten, R. and Gates, G., 2002. Groundwater - surface water interaction in NSW: A discussion paper, DLWC.

Braaten, R. and Gates, G., 2003. Groundwater - surface water interaction in inland New South Wales: A scoping study. Water Science and Technology, 48(7): 215-224.

Braaten, R. and Gates, G., 2004. Lagging behind: Exploring the time lag in river-aquifer interaction, 9th Murray Darling Basin Groundwater Workshop, Bendigo.

Bredehoeft, J., 2004. The conceptualization model problem - surprise. Hydrogeology Journal, 13: 37-46.

Bredehoeft, J.D., 2002. The water budget myth revisited: Why hydrogeologists model. Ground Water, 40(4): 340-345.

Broughton, A., 1994a. Coxs Creek catchment hydrogeological investigation and dryland salinity studies, volumes 1 & 2. TS94.082, Department of Water Resources, Barwon Region.

Broughton, A., 1994b. Mooki River catchment hydrogeological investigation and dryland salinity studies, Liverpool Plains, New South Wales (volumes 1 and 2). TS94.026, Department of Water Resources, Barwon Region.

Brownbill, R., 2000. Upper Namoi Valley groundwater status report 1999, DLWC, Barwon Region.

Brunke, M. and Gonser, T., 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology, 37:1-33.

Camp, Dresser & McKee Inc., 2001. Evaluation of integrated surface water and groundwater modelling tools.

Carr, R., 1987. Sam3 - stream aquifer model users guide, Lawson and Treloar Pty. Ltd.

Chapman, T., 1999. A comparison of algorithms for stream flow recession and baseflow separation. Hydrological Processes, 13: 701-714.

Chapman, T.G., 1991. Comment on "evaluation of automated techniques for base flow and recession analyses" by R.J. Nathan and T.A. McMahon. Water Resources Research, 27(7): 1783-1784.

Chapman, T.G., 2003. Modelling stream recession flows. Environmental Modelling and Software, 18: 683-692.

Chen, J.S., He, D.W. and Cui, S.B., 2003. The response of river water quality and quantity to the development of irrigated agriculture in the last 4 decades in the Yellow River Basin, China - Art. No. 1047. Water Resources Research, 39(3): 1047-1047.

Chow, V.T., 1964. Handbook of applied hydrology. McGraw-Hill Inc., New York.

CMA, 2004. Annual report for the combined catchment management authorities.

COAG, 1994. Communiqué, report of the working group on water resource policy, Council of Australian Governments.

COAG, 2003. National Water Initiative communiqué, Council of Australian Governments.

Connell, D., Dovers, S. and Grafton, R.Q., 2004. Property rights and water management: A critical analysis of the National Water Initiative, 7th International River Symposium, 31 August-3 September, Brisbane.

Coram, J. and Jaycock, J., 2003. Groundwater recharge in the Mooki River catchment, northern New South Wales, draft report, Bureau of Rural Sciences.

Coutagne, A., 1948. Les variations débit en période non influencée par les précipitations. La Houille Blanche, 3: 416-436.

Croke, B.F.W., Cleridou, N., Kolovos, A., Vardavas, I. and Papamastorakis, J., 2000. Water resources in the desertification-threatened Messara Valley of Crete: Estimation of the annual water budget using a rainfall-runoff model. Environmental Modelling & Software, 15: 387-402.

Croke, B.F.W., Evans, W.R., Schreider, S.Y. and Buller, C., 2001a. Recharge estimation for Jerrabomberra Creek Catchment, the Australian capital territory, MODSIM 2001. Modelling and Simulation Society of Australia and New Zealand, The Australian National University Canberra, Australia.

Croke, B.F.W., Gilmour, J.K. and Newham, L.T.H., 2001b. A comparison of rainfall estimation techniques, Proceedings of the 3rd Australian Stream Management Conference, Brisbane.

Croke, B.F.W. and Jakeman, A.J., 2004. A catchment moisture deficit module for the IHACRES rainfall-runoff model. Environmental Modelling and Software, 19: 1-5.

Croke, B.F.W., Letcher, R.A. and Jakeman, A.J., 2006. Development of a distributed flow model for underpinning assessment of water allocation options in the Namoi River Basin, Australia. Journal of Hydrology, 319: 51-71.

Dawes, W.R., Gilfedder, M., Walker, G.R. and Evans, W.R., 2004. Biophysical modelling of catchment-scale surface water and groundwater response to land-use change. Mathematics and Computers in Simulation, 64(1): 3-12.

Dawes, W.R., Walker, G.R. and Stauffacher, M., 2001. Practical modelling for management in data-limited catchments. Mathematical and Computer Modelling, 33(6-7): 625-633.

Debashish P., Demetriou C. and Punthakey J.F., 1996. Gunnedah groundwater model in the Upper Namoi Valley, NSW. TS96.019, DLWC.

Devlin, J.F. and Sophocleous, M., 2005. The persistence of the water budget myth and its relationship to sustainability. Hydrogeology Journal, 13(4): 549-554.

Dietrich, C.R., Jakeman, A.J. and Thomas, G.A., 1989. Solute transport in a stream-aquifer system .1. Derivation of a dynamic-model. Water Resources Research, 25(10): 2171-2176.

DIPNR, 2004. Pinneena 8, NSW water data archive.

DLWC, 1997. The NSW state groundwater policy framework document.

DLWC, 1998. Building a more secure future for the Namoi, Namoi River Management Committee.

DLWC, 1999. Water sharing in NSW - access and use, a discussion paper.

DLWC, 2000. Status report for the alluvial groundwater resources of the Lower Namoi Valley NSW, draft report, Barwon Region.

DLWC, 2001. Water Management Act 2000 what it means for NSW.

DLWC, 2002. Water sharing plan for the Upper and Lower Namoi groundwater sources 2003 order.

DPMS, 1996. Namoi community catchment plan situation statement, Donaldson Planning and Management Services for the Namoi Catchment Planning Taskforce.

Dunn, S.M., 1999. Imposing constraints on parameter values of a conceptual hydrological model using baseflow response. Hydrology and Earth System Sciences, 3(2): 271-284.

Dyce, P. and Richardson, P., 1997. Characterisation of subcatchment aquifers in the Liverpool Plains for the purpose of groundwater modelling. Technical Report 16/97, CSIRO Land and Water.

Dye, P.J. and Croke, B.F.W., 2003. Evaluation of streamflow predictions by the IHACRES rainfall-runoff model in two South African catchments. Environmental Modelling & Software, 18: 705-712.

EPA, 1994. Preliminary regional environment improvement plan: Northern tablelands, NSW Environment Protection Authority, Sydney.

EPA, 1995. Report on three water quality surveys in the Namoi River Valley (December 1987, February 1988, June 1988), NSW Environment Protection Authority.

EPA, 1997. Proposed interim environmental objectives for NSW waters: Namoi catchment, NSW Environment Protection Agency, Sydney.

European Communities, 2000. Directive 200/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Official Journal of the European Communities, L372(43): 1-73.

Evans, J.P. and Jakeman, A.J., 1998. Development of a simple, catchment-scale, rainfall-evapotranspiration-runoff model. Environmental Modelling and Software, 13: 385-393.

Fox, G.A., DuChateau, P. and Durnford, D.S., 2002. Analytical model for aquifer response incorporating distributed stream leakage. Ground Water, 40(4): 378-384.

Gates, G., 1980. The hydrogeology of the unconsolidated sediments in the Mooki River Valley, NSW. MSc Thesis, University of New South Wales, Sydney.

Glennon, R.J., 2002. Water follies, groundwater pumping and the fate of America's fresh water. Island Publisher, Washington D.C.

Glover, R.E. and Balmer, C.G., 1954. River depletion resulting from pumping a well near a river. Eos Transactions, AGU, 35: 468-470.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J. and Nathan, R.J., 2004. Stream hydrology an introduction for ecologists. John Wiley & Sons, Ltd, Chichester.

Grayson, R.B., Argent, R.M., Nathan, R.J., McMahon, T.A. and Mein, R.G., 1996. Hydrological recipes. Estimation techniques in Australian hydrology. CRC for Catchment Hydrology, Dept of Civil Engineering, Monash University.

Gustard, A., Bullock, A. and Dixon, J., 1992. Low flow estimation in the United Kingdom, Institute of Hydrology report 108, Institute of Hydrology, UK.

Halford, J.K. and Mayer, G.C., 2000. Problems associated with estimating ground water discharge and recharge from stream-discharge records. Ground Water, 38(3): 331-342.

Hall, F.R., 1968. Base flow recessions - a review. Water Resources Research, 4(5): 973-983.

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(1-3): 193-202.

Hantush, M.S., 1965. River depletion resulting from pumping a well near a river. American Geophysical Union Transactions, 35(3): 468-470.

Heath, R.C., 1987. Basic ground-water hydrology. U.S. Geological Survey Water-Supply Paper 2220, U.S. Geological Survey, Denver.

Horton, R.E., 1933. The role of infiltration in the hydrologic cycle. Transactions, American Geophysical Union, 14: 446-460.

Ivkovic, K.M., Croke, B.F.W., Letcher, R. and Evans, W.R., 2005a. The development of a simple model to investigate the impact of groundwater extraction on river flows in the Namoi catchment, NSW Australia, "Where Waters Meet" NZHS-IAH-NSSSS Conference, 28 November - 2 December 2005, Auckland, New Zealand.

Ivkovic, K.M., Letcher, R. and Croke, B.F.W., 2005b. Investigating the impact of groundwater extraction on river flows in the Namoi catchment, NSW Australia, International Workshop, From Data Gathering and Groundwater Modelling to Integrated Management, 4-8 October 2005. International Association of Hydrogeologists, Alicante Spain.

Ivkovic, K.M., Letcher, R., Croke, B.F.W., Evans, W.R. and Stauffacher, M., 2005c. A framework for characterising groundwater and river water interactions: A case study for the Namoi catchment, NSW., Water Capital: 29th Hydrology and Water Resources Symposium, 21-23 February 2005, Canberra ACT.

Ivkovic, K.M., Letcher, R.A. and Croke, B.F.W., 2004. Groundwater-river interactions in the Namoi catchment and their implications for water allocation, 9th Murray-Darling Basin Groundwater Workshop 2004, Bendigo.

Jakeman, A.J., Dietrich, C.R. and Thomas, G.A., 1989. Solute transport in a stream-aquifer system .2. Application of model identification to the River Murray. Water Resources Research, 25(10): 2177-2185.

Jakeman, A.J. and Hornberger, G.M., 1993. How much complexity is warranted in a rainfall-runoff model? Water Resources Research, 29: 2637-2649.

Jakeman, A.J., Littlewood, I.G. and Whitehead, P.G., 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 Balquhidder catchments. Journal of Hydrology, 145: 337-355.

Jenkins, C.T., 1968. Techniques for computing rate and volume of stream depletion by wells. Ground Water, 6: 37-46.

Kalf and Associates Pty. Ltd. and National Centre for Groundwater Management, 2000. Groundwater management model for zone 8 of the GWMA004 Mooki Valley. Consultancy report for Department of Land and Water Conservation.

Kingham, R., 1998. Geology of the Murray-Darling Basin - simplified lithostratigraphic groupings, AGSO Record 1998/21, Australian Geological Survey Organisation.

Kirk, S. and Herbert, A.W., 2002. Assessing the impact of groundwater abstractions on river flows. In: K.M. Hiscock, M.O. Rivett and R.M. Davison (Editors), Sustainable groundwater development. Geological Society, London Special Publications, pp. 211-233.

Klemeš, V., 1983. Conceptualization and scale in hydrology. Journal of Hydrology, 65: 1-23.

Knight, J.H., Gilfedder, M. and Walker, G.R., 2005. Impacts of irrigation and dryland development on groundwater discharge to rivers - a unit response approach to cumulative impacts analysis. Journal of Hydrology, 303(1-4): 79-91.

Koivusalo, H. and Kokkonen, T., 2003. Modelling runoff generation in a forested catchment in southern Finland. Hydrological Processes, 17(2): 313-328.

Kokkonen, T., Koivusalo, H. and Karvonen, T., 2001. A semi-distributed approach to rainfall-runoff modelling - a case study in a snow affected catchment. Environmental Modelling & Software, 16(5): 481-493.

Kokkonen, T.S., Jakeman, A.J., Young, P.C. and Koivusalo, H.J., 2003. Predicting daily flows in ungauged catchments: Model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. Hydrological Processes, 17(11): 2219-2238.

Konikow, L.F. and Bredehoeft, J.D., 1992. Groundwater models cannot be validated. Advances in Water Resources, 15(1): 75-83.

Lacey, G.C. and Grayson, R.B., 1998. Relating baseflow to catchment properties in south-eastern Australia. Journal of Hydrology, 204(1-4): 231-250.

Larkin, R.G. and Sharp, J.M., 1992. On the relationship between river-basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvial aquifers. Geological Society of America Bulletin, 104: 1608-1620.

Lavitt, N., 1999. Integrated approach to geology, hydrogeology and hydrochemistry in the lower Mooki River catchment. PhD Thesis, University of New South Wales, Sydney, 388 pp.

Lawson and Treloar Pty. Ltd., 1988. Upper Namoi Valley groundwater model. Report No. 1222, Prepared for the New South Wales Department of Water Resources, Sydney.

Letcher, R., 2002. Issues in integrated assessment and modelling for catchment management. PhD Thesis, Australian National University, Canberra, 314 pp.

Letcher, R.A. and Giupponi, C., 2005. Policies and tools for sustainable water management in the European Union. Environmental Modelling & Software, 20: 93-98.

Letcher, R.A., Jakeman, A.J. and Croke, B.F.W., 2004. Model development for integrated assessment of water allocation options. Water Resources Research, 40(W05502).

Littlewood, I., Croke, B.F.W., Jakeman, A.J. and Sivapalan, M., 2003. The role of "top-down" modelling for prediction in ungauged basins (PUB). Journal of Hydrology, 17: 1673-1679.

Littlewood, I.G., 2002. Improved unit hydrograph characterisation of the daily flow regime (including low flows) for the River Teifi, Wales: Towards better rainfall-streamflow models for regionalisation. Hydrology and Earth System Sciences, 6(5): 899-911.

Littlewood, I.G. and Jakeman, A.J., 1994. A new method of rainfall-runoff modelling and its applications in catchment hydrology, in: Environmental modelling, vol. 2. Computational Mechanics Publications, Southhampton, UK.

Lyne, V. and Hollick, M., 1979. Stochastic time variable rainfall-runoff modelling., Institution of Engineers Australia, I.E. Aust. Natl. Conf. Publ. 79/10, pp. 89-93.

Maillet, E., 1905. Essais d'hydraulique souterraine et fluviale. Hermann, Paris, 218 pp.

McDonald, M.G. and Harbaugh, A.W., 1988. A modular three-dimensional finite-difference ground-water flow model, US Geological Survey, techniques of water resources investigations Book 6, Chapter A1, pp. 586.

McLean, W.A., 2003. Hydrogeochemical evolution and variability in a stressed alluvial aquifer system: Lower Namoi River catchment, NSW. PhD Thesis, University of New South Wales, Sydney.

Merrick, N.P., 1989. Lower Namoi groundwater model, Heritage Computing Report for Department of Water Resources, New South Wales.

Merrick, N.P., 1998a. Lower Namoi groundwater flow model: Calibration 1987-1994, Insearch Limited Report for Department of Land and Water Conservation, Project No. C94/44/005.

Merrick, N.P., 1998b. Lower Namoi groundwater flow model: Post audit 1987-1990, Insearch Limited Report for Department of Land and Water Conservation, Project No. C94/44/005.

Merrick, N.P., 1998c. Lower Namoi groundwater flow model: Scenario modelling 1994-1997, Insearch Limited Report for Department of Land and Water Conservation, Project No. C94/44/005a.

Merrick, N.P., 1999. Lower Namoi groundwater budgets: Simulation 1980-1994, Insearch Limited Report for Department of Land and Water Conservation (Tamworth), Project No. C94/44/008.

Merrick, N.P., 2000. Lower Namoi groundwater flow model: Hydrographic verification 1980-1994 and conceptualisation scenarios, Insearch Limited Report for Department of Land and Water Conservation, Project No. C99/44/001, Sydney.

Merrick, N.P., 2001a. Groundwater simulation using the minimum dissipation principle. In: K.P. Seiler and S. Wohnlich (Editors), New approaches characterising groundwater flow, Proceedings of the XXXI IAH Congress, 10-14 September, 2001. Balkema, Rotterdam, Lisse, Munich, Germany, pp. 371-374.

Merrick, N.P., 2001b. Lower Namoi groundwater flow model: Calibration 1980-1998, Insearch Limited Report for NSW Department of Land and Water Conservation. Project No. C99/44/001.

Merrick, N.P., 2001c. Upper Namoi zone 8 groundwater flow model: Calibration 1979-2000, Insearch Limited Report for Department of Land and Water Conservation, Project No. C99/44/001.

Merrick, N.P., 2003a. Optimising groundwater usage to mitigate native vegetation decline in the Namoi Valley, NSW. Milestone report no. 3 phase 2: Management model. LWA Project No. NDW23, Institute for Water and Environmental Resource Management - National Centre for Groundwater Management, University of Technology, Sydney.

Merrick, N.P., 2003b. The regional groundwater flow model of the Lower Namoi Valley, Abstract for the Northern Murray Darling Basin Water Balance and Deep Drainage Group Workshop, Narrabri.

Merrick, N.P., 2006. National Centre for Groundwater Management, University of Technology Sydney.

Merritt, W.S., Letcher, R.A. and Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environment Modelling & Software, 18: 761-799.

Moore, R.J. and Bell, V.A., 2002. Incorporation of groundwater losses and well level data in rainfall-runoff models illustrated using the PDM. Hydrology and Earth System Sciences, 6(1): 25-38.

Mroczkowski, M., Raper, G.P. and Kuczera, G., 1997. The quest for more powerful validation of conceptual catchment models. Water Resources Research, 33(10): 2325-2335.

Mulligan, M. and Wainwright, J., 2004. Modelling and model building. In: M. Mulligan and J. Wainwright (Editors), Environmental modelling: Finding simplicity in complexity. John Wiley & Sons, Ltd, Chichester.

Murray Darling Basin Commission, 1999. The Cap.

Namoi CMA, 2005. Namoi CMA annual report 2004-2005. Landscapes for the future, Namoi Catchment Management Authority.

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, part 1-a discussion of principles. Journal of Hydrology, 10: 282-290.

Nathan and McMahon, T.A., 1990. Evaluation of automated techniques for baseflow and recession analysis. Water Resources Research, 26(7): 1465-1473.

NGERP, 1999. Report of the Namoi groundwater expert reference panel on the groundwater allocation adjustment process in the Namoi Valley, NSW.

NWI, 2004. Intergovernmental agreement on a National Water Initiative. Council of Australian Governments http://www.coag.gov.au/meetings/250604/index.htm#water_initiative).

PPK Environment & Infrastructure, 2002. Regional groundwater data review - central Namoi Valley, prepared for the Boggabri irrigators and the Department of Land and Water Conservation, Sydney.

Pulido-Velazquez, M.A., Sahuquillo-Herraiz, A., Ochoa-Rivera, J.C. and Pulido-Velazques, D., 2005. Modeling of stream-aquifer interaction: The embedded multireservoir model. Journal of Hydrology, 313: 166-181.

Reichert, P. and Borsuk, M.E., 2005. Does high forecast uncertainty preclude effective decision support? Environmental Modelling & Software, 20: 991-1001.

REM, 2002. Watermark: Sustainable groundwater use within irrigated regions. Project 2: Conjunctive resource management, Milestone 2 final report. A review of stream-aquifer interaction assessment methods, Resource & Environmental Management, Prepared for the Murray-Darling Basin Commission.

Richter, B.D., Baumgartner, J.V., Powell, J. and Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology, 10(4): 1163-1174.

Ringrose-Voase, A. and Cresswell, H., 2000. Measurement and prediction of deep drainage under current and alternative farming practice. Final Report to the Land and Water Resources Research and Development Corporation Project CDS16, CSIRO Land and Water.

Rodríguez, L.B., Cello, P.A. and Vionnet, C.A., 2006. Modeling stream-aquifer interactions in a shallow aquifer, Choele Choel Island, Patagonia, Argentina. Hydrogeology Journal, 14(4): 591-602.

Salotti, D., 1997. Borambil Creek groundwater model, DLWC.

Saltelli, A., Chan, K. and Scott, M., 2000. Sensitivity analysis. John Wiley & Sons, Chichester.

Sauer, V.B. and Meyer, R.W., 1992. Determination of error in individual discharge measurements, U.S. Geological Survey Open File Report 92-144, Norcross, Georgia.

Seibert, J. and McDonnell, J.J., 2002. On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multicriteria model calibration. Water Resources Research, 38(11): Art. no.-1241.

Shaw, E.M., 1983. Hydrology in practice. Van Nostrand Reinhold (UK) Co. Ltd., Molly Millars Lane, Wokingham, Berkshire, England.

Sivapalan, M., Bloschl, G., Zhang, L. and Vertessy, R., 2003. Downward approach to hydrological prediction. Hydrological Processes, 17(11): 2101-2111.

SKM, 2002. Survey of baseflows in unregulated catchments in the Murray-Darling Basin. Murray-Darling Basin Commission Project R2005, Sinclair Knight Merz Pty Limited.

SKM, 2003. Projections of groundwater extraction rates and implications for future demand and competition for surface water. Murray Darling Basin Commission Publication 04/03, Sinclair Knight Merz.

Smakhtin, V.U., 2001. Low flow hydrology: A review. Journal of Hydrology, 240: 147-186.

Smith, S., 2000. New water management legislation in NSW: A review. Briefing Paper No 8/2000, NSW Parliamentary Library Research Service.

Sophocleous, M., 1997. Managing water resources systems: Why "safe yield" is not sustainable. Ground Water, 35(4): 561.

Sophocleous, M., 2000. From safe yield to sustainable development of water resources - the Kansas experience. Journal of Hydrology, 235: 27-43.

Sophocleous, M., 2002. Interactions between groundwater and surface water: The state of the science. Hydrogeology Journal, 10: 52-67.

Sophocleous, M., Koussis, A., Martin, J.L. and Perkins, S.P., 1998. Calibrated models as management tools for stream-aquifer systems: The case of central Kansas, USA. Journal of Hydrology, 152: 31-56.

Sophocleous, M. and Perkins, S.P., 2000. Methodology and application of combined watershed and ground- water models in Kansas. Journal of Hydrology, 236(3-4): 185-201.

Stauffacher, M., Walker, G.R. and Evans, W.R., 1997. Salt and water movement in the Liverpool Plains - what's going on?, Land and Water Resources Research and Development Corporation Occasional Paper No. 14/97, Canberra.

Stauffacher, M., Walker, G., Dawes, W., Zhang, L. and Dyce, P., 2003. Can simple catchment-scale models provide reliable answers? An Australian case study. CSIRO Land and Water technical report 27/03, Murray-Darling Basin Commission and CSIRO.

Tallaksen, L.M., 1995. A review of baseflow recession analysis. Journal of Hydrology, 165: 349-370.

Tan, P., 2002. An historical introduction to water reform in NSW - 1975 to 1994. Environmental and Planning Law Journal, 19(6): 445-460.

Theis, C.V., 1941. The effect of a well on the flow of a nearby stream. American Geophysical Union Transactions, 22(3): 734-738.

Turányi, T. and Rabitz, H., 2000. Local methods. In: A. Saltelli, K. Chan and M. Scott (Editors), Sensitivity analysis. John Wiley & Sons, Ltd., Chichester.

U.S. Army Corps of Engineers, 1999. Engineering and design groundwater hydrology. Engineer Manual 1110-2-1421, Department of the Army, Washington, D.C.

Uhlenbrook, S. and Siebert, A., 2005. On the value of experimental data to reduce the prediction uncertainty of a process-oriented catchment model. Environmental Modelling & Software, 20(1): 19-32.

Ward, R.C., 1975. Principles of hydrology 2nd edition. McGraw Hill Book Company (UK) Limited, 367 pp.

Wheater, H.S., Jakeman, A.J. and Beven, K.J., 1993. Progress and directions in rainfall-runoff modelling. In: A.J. Jakeman, M.B. Beck and M.J. McAleer (Editors), Modelling change in environmental systems. John Wiley & Sons, Chichester, pp. 101-132.

Whitehead, P.G. and Young, P.C., 1975. A recursive approach to time series analysis for multivariable systems. In: G.C. Vansteenkiste (Editor), Modeling and simulation of water resources systems, North Holland, Amsterdam, pp. 39-58.

Williams, R.M., 1985. Hydrogeology and hydrochemistry of natural induced recharge of the unconsolidated sediments of the Lower Namoi Valley with references to the effects of artificial recharge, 21st IAHR Congress, Melbourne, Australia.

Williams, R.M., 1997. The Cainozoic geology, hydrogeology and hydrochemistry of the unconsolidated sediments associated with the Namoi river in the Lower Namoi Valley, NSW. CNR 97.093, Centre for Natural Resources.

Winter, T.C., 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journal, 7(1): 28-45.

Winter, T.C., Judson, W.H., Franke, O.L. and Alley, W.M., 1998. Ground water and surface water a single resource. Circular 1139, U.S. Geological Survey, Denver.

Wittenberg, H. and Sivapalan, M., 1999. Watershed groundwater balance estimation using streamflow recession analysis and baseflow separation. Journal of Hydrology, 219: 20-33.

Woessner, W.W., 2000. Stream and fluvial plain groundwater interactions: Rescaling hydrogeological thought. Ground Water, 38(3): 423-429.

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, P., 2003. Top-down and data-based mechanistic modelling of rainfall-flow dynamics at the catchment scale. Hydrological Processes, 17: 2195-2217.

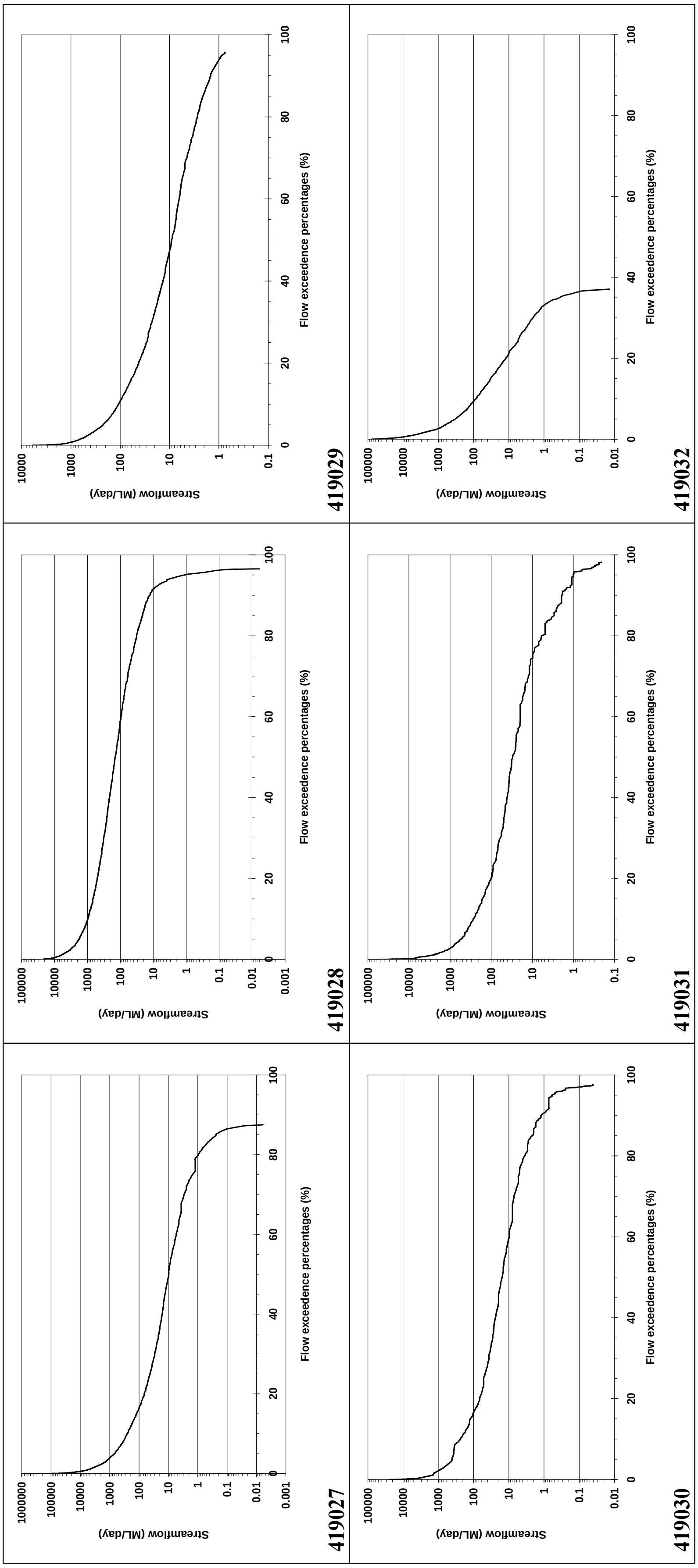
Young, P.C., 1974. Recursive approaches to time series analysis. Bulletin of the Institute of Mathematics and its Applications, 10: 209-224.

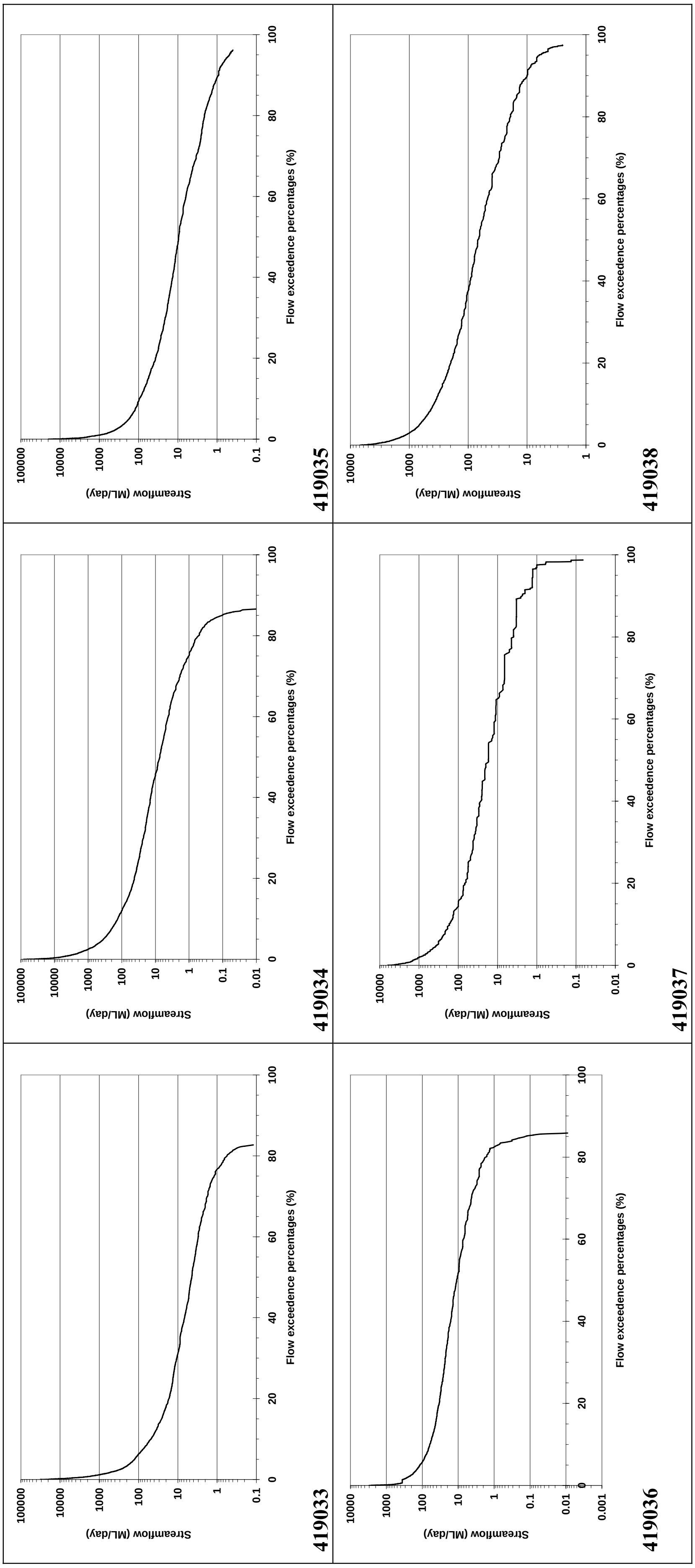
Appendices

Introduction

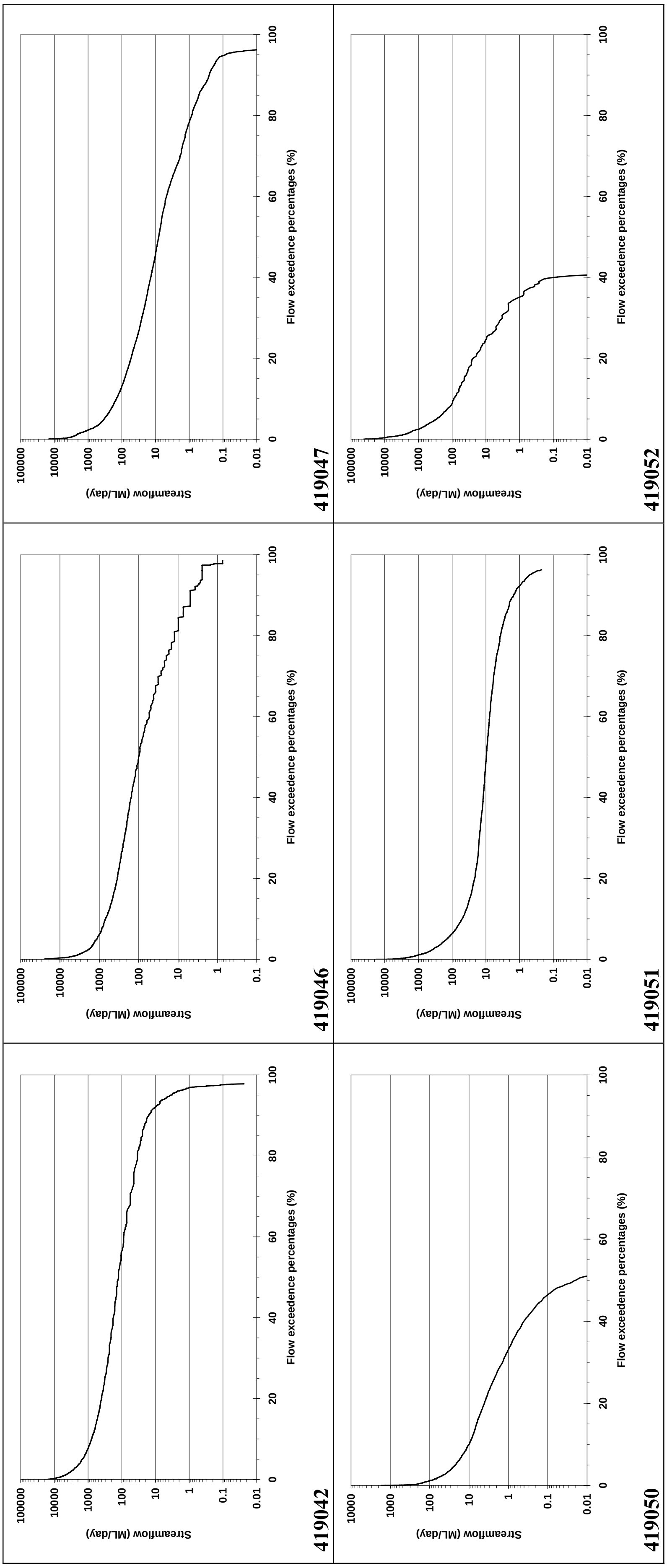
Appendices A, B and C follow in the subsections that follow. Appendix A includes flow duration curve plots for the gauged, unregulated river systems of the Namoi River catchment (refer to Table 4-2 for river gauging station details). Appendices B and C provide summary tables of the nested piezometer vertical connectivity (refer to Section 4.6.1) and paired stream and bore hydrograph interaction (refer to Section 4.6.2) assessments discussed in Chapter 4. The raw data is not included in this thesis due to data confidentiality issues.

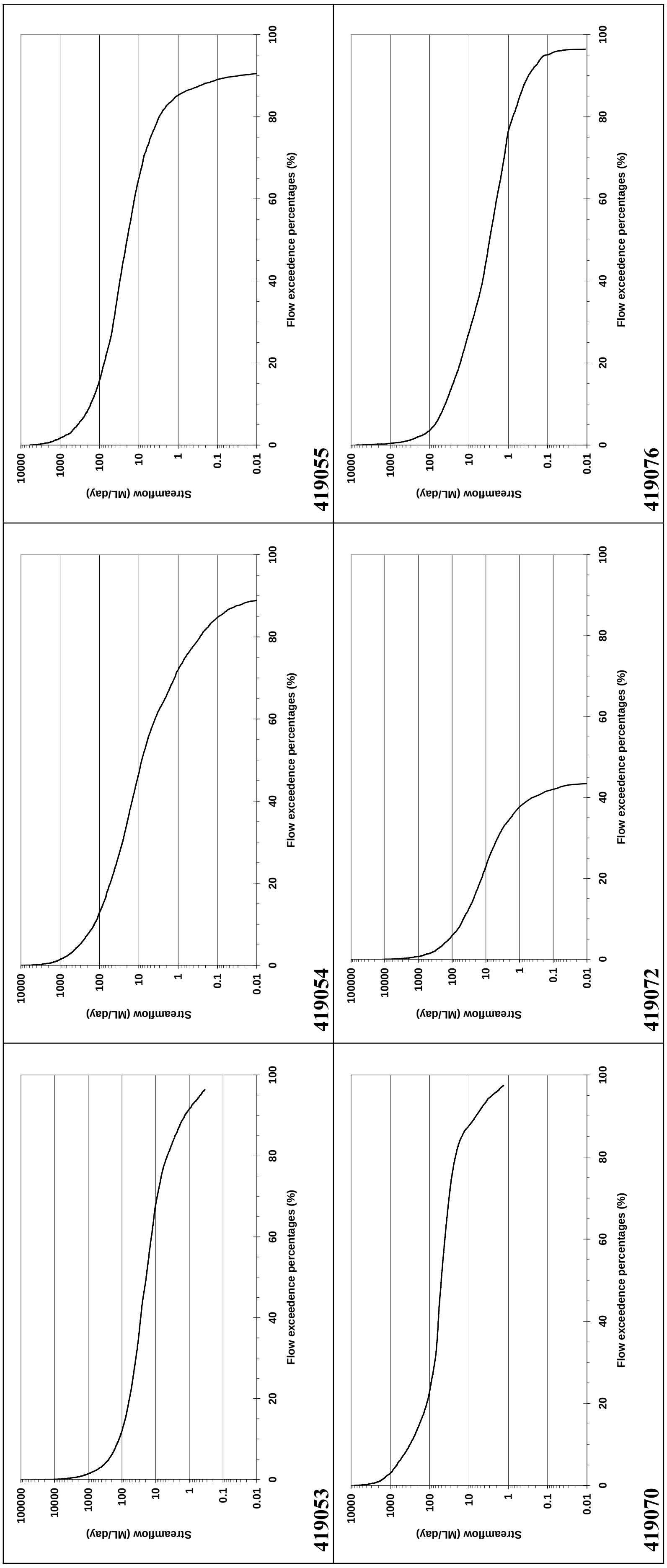
Appendix A Flow Duration Curves

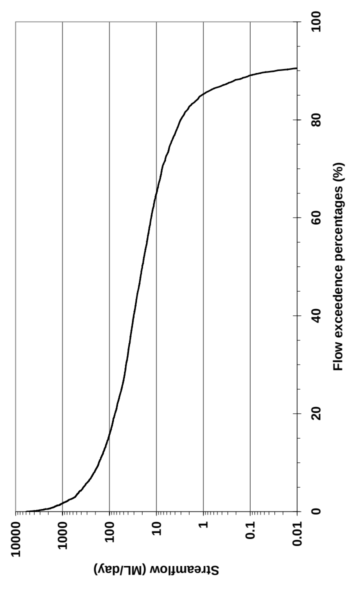




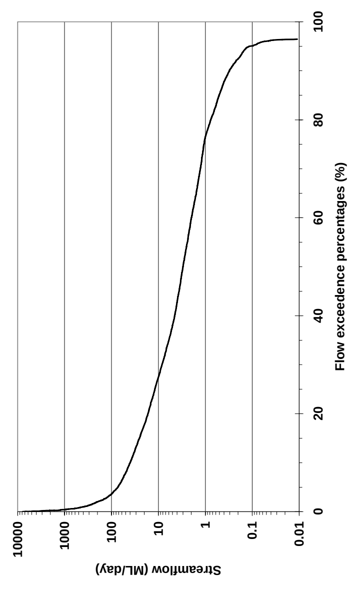
419035
419034
419033
419038
419037
419036
Streamflow (ML/day)
Flow exceedence percentages (%)
Flow exceedance percentages (%)


419047
419046
419042
419052
419051
419050
Streamflow (ML/day)
Flow exceedence percentages (%)

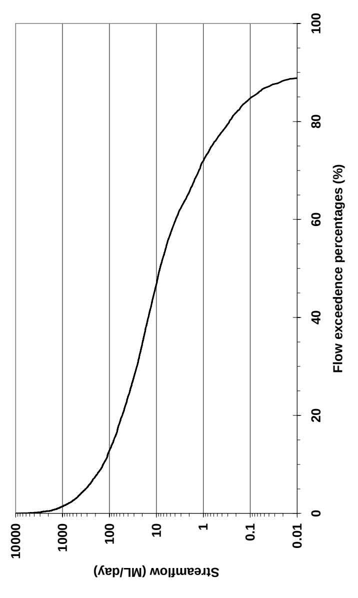

419055
419054
419053
419076
419072
419070
Streamflow (ML/day)
Flow exceedence percentages (%)



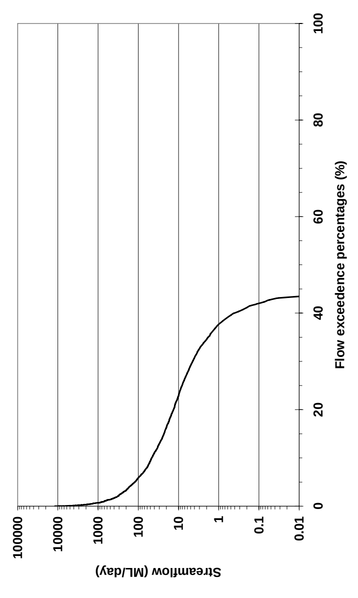
419055



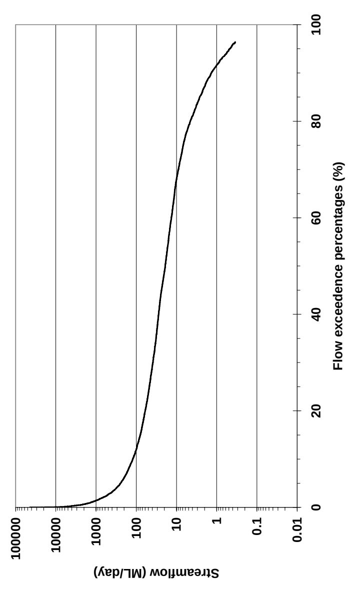
419076



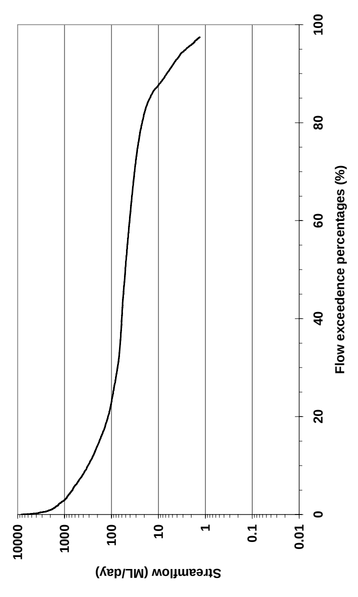
419054



419072



419053



419070

Appendix B Nested Piezometer Vertical Connectivity

Nested Piezometer Site	Latitude	Longitude	Vertical Connection
GW021088	-30.93750000000	150.26000000000	Good
GW021092	-30.91944444000	150.30083330000	Good
GW021093	-30.91555556000	150.31166670000	Good
GW021263	-30.20972222000	149.59138890000	Good
GW021266	-30.16527778000	149.59916670000	Poor
GW021412	-30.22611111000	149.60000000000	Good
GW021435	-30.28861111000	149.58694440000	Good
GW021436	-30.30444444000	149.58416670000	Good
GW021479	-30.22254044000	149.43673140000	Poor
GW025012	-30.30833333000	149.41222220000	Good
GW025044	-30.18027778000	149.45194440000	Poor
GW025047	-30.13666667000	149.45916670000	Poor
GW025049	-30.10916667000	149.46500000000	Poor
GW025055	-30.02444444000	149.48027780000	Strong
GW025137	-30.17416667000	149.30611110000	Good
GW025144	-30.07444444000	149.31138890000	Poor
GW025146	-30.04750000000	149.31611110000	Good
GW025219	-30.26833333000	149.67333330000	Strong
GW025220	-30.28250000000	149.67055560000	Strong
GW025221	-30.29555556000	149.66777780000	Good
GW025222	-30.31138889000	149.65888890000	Poor
GW025244	-29.99416667000	149.31222220000	Poor
GW025245	-29.97916667000	149.31500000000	Poor
GW025248	-29.93388889000	149.32138890000	Poor
GW025321	-30.08166667000	149.56305560000	Poor
GW025324	-30.12444444000	149.55611110000	Poor
GW025325	-30.13888889000	149.55333330000	Good
GW025326	-30.15472222000	149.55055560000	Strong
GW025327	-30.16833333000	149.54833330000	Poor
GW025328	-30.17722222000	149.54694440000	Poor

Nested Piezometer Site	Latitude	Longitude	Vertical Connection
GW025332	-30.21000000000	149.53805560000	Good
GW025333	-30.21194444000	149.53750000000	Good
GW025334	-30.22611111000	149.53416670000	Good
GW025336	-30.22277778000	149.49055560000	Good
GW025337	-30.23666667000	149.48750000000	Good
GW025338	-30.25583333000	149.49166670000	Good
GW025339	-30.26805556000	149.48333330000	Good
GW025340	-30.28472222000	149.48000000000	Strong
GW025341	-30.29833333000	149.47722220000	Poor
GW025342	-30.31277778000	149.47555560000	Good
GW025419	-30.21722222000	149.53555560000	Good
GW030006	-31.27972222000	150.47777780000	Good
GW030007	-31.29361111000	150.46555560000	Good
GW030008	-31.30583333000	150.46333330000	Good
GW030009	-31.32000000000	150.46027780000	Good
GW030011	-31.34694444000	150.45500000000	Poor
GW030016	-31.33055556000	150.50472220000	Good
GW030024	-31.52138889000	150.65138890000	Strong
GW030049	-30.70361111000	150.10277780000	Poor
GW030050	-30.70527778000	150.11638890000	Strong
GW030054	-30.19833333000	149.54250000000	Good
GW030064	-31.45138889000	150.57416670000	Good
GW030070	-30.20138889000	149.59277780000	Good
GW030071	-30.18888889000	149.59500000000	Good
GW030088	-31.46750000000	150.60555560000	Good
GW030098	-30.17722222000	149.57583330000	Good
GW030099	-30.19916667000	149.56000000000	Good
GW030100	-30.20194444000	149.57833330000	Good
GW030101	-30.22111111000	149.62361110000	Good
GW030116	-30.25166667000	149.68666670000	Good
GW030117	-30.27305556000	149.72888890000	Good

Nested Piezometer Site	Latitude	Longitude	Vertical Connection
GW030120	-30.30888889000	149.78805560000	Poor
GW030121	-30.30916667000	149.77111110000	Good
GW030122	-30.31666667000	149.75888890000	Good
GW030180	-31.48333333000	150.55638890000	Poor
GW030188	-30.18666667000	149.45805560000	Good
GW030226	-30.38500000000	149.88611110000	Good
GW030232	-30.45972222000	149.96305560000	Good
GW030233	-30.46194444000	149.97916670000	Good
GW030242	-30.31000000000	149.79500000000	Poor
GW030243	-29.96333333000	149.50027780000	Strong
GW030260	-30.13027778000	149.46027780000	Strong
GW030265	-30.11638889000	149.46277780000	Poor
GW030266	-30.15388889000	149.52194440000	Good
GW030275	-31.45305556000	150.53611110000	Strong
GW030280	-30.19416667000	149.47666670000	Good
GW030281	-30.19361111000	149.51388890000	Poor
GW030298	-30.98166667000	150.31222220000	Good
GW030299	-30.98027778000	150.33027780000	Good
GW030303	-30.99833333000	150.39277780000	Good
GW030304	-30.99916667000	150.40722220000	Good
GW030306	-30.98890339000	150.44103400000	Good
GW030308	-30.39027778000	149.88527780000	Strong
GW030309	-30.27472222000	149.67250000000	Good
GW030329	-30.26472222000	149.67250000000	Good
GW030344	-30.91472222000	150.29333330000	Good
GW030358	-30.32666667000	149.76194440000	Good
GW030378	-31.39027778000	150.46527780000	Good
GW030379	-31.39000000000	150.45722220000	Strong
GW030399	-30.38972222000	149.86722220000	Strong
GW030419	-31.34527778000	150.44666670000	Strong
GW030430	-31.14527778000	150.39777780000	Good

Nested Piezometer Site	Latitude	Longitude	Vertical Connection
GW030431	-31.14083333000	150.43361110000	Poor
GW030432	-31.14361111000	150.45083330000	Good
GW030433	-31.14583333000	150.46638890000	Poor
GW030434	-31.14833333000	150.48361110000	Poor
GW030445	-30.27638889000	149.59416670000	Good
GW030450	-30.26388889000	149.59305560000	Poor
GW030451	-30.24888889000	149.59611110000	Poor
GW030471	-30.65111111000	150.07138890000	Strong
GW030472	-30.67916667000	150.13000000000	Poor
GW030476	-31.15055556000	150.49777780000	Poor
GW030477	-31.15305556000	150.51500000000	Poor
GW030478	-30.34444444000	149.82083330000	Good
GW030481	-30.29694444000	149.58527780000	Good
GW036007	-30.63277778000	150.03777780000	Good
GW036011	-31.15027778000	150.53944440000	Poor
GW036016	-30.59805556000	150.03916670000	Good
GW036022	-30.20833333000	149.36611110000	Good
GW036038	-31.19083333000	150.47611110000	Good
GW036045	-29.94222222000	149.31944440000	Good
GW036047	-30.26888889000	149.70000000000	Good
GW036055	-30.57888889000	149.99972220000	Good
GW036060	-30.17694444000	149.39638890000	Good
GW036061	-30.16277778000	149.38388890000	Poor
GW036071	-31.21361111000	150.47444440000	Strong
GW036093	-30.54638889000	150.00361110000	Good
GW036094	-30.49305556000	149.98194440000	Good
GW036101	-31.34777778000	150.46361110000	Strong
GW036149	-31.07972222000	150.40944440000	Good
GW036152	-31.23166667000	150.46194440000	Poor
GW036166	-31.04777778000	150.43416670000	Good
GW036189	-31.16611111000	150.42361110000	Poor

Nested Piezometer Site	Latitude	Longitude	Vertical Connection
GW036190	-31.21111111000	150.44861110000	Good
GW036193	-31.00888889000	150.46611110000	Good
GW036196	-31.12638889000	150.38194440000	Good
GW036197	-31.10722222000	150.36444440000	Good
GW036200	-31.10138889000	150.49277780000	Poor
GW036210	-31.08027778000	150.36055560000	Good
GW036213	-31.07250000000	150.37305560000	Poor
GW036215	-31.02527778000	150.40916670000	Good
GW036217	-30.06111111000	149.14916670000	Poor
GW036225	-29.82555556000	149.15277780000	Poor
GW036227	-29.79055556000	149.15333330000	Poor
GW036238	-30.95916667000	150.32666670000	Poor
GW036239	-30.95055556000	150.29777780000	Good
GW036251	-29.97305556000	148.95722220000	Good
GW036252	-29.93777778000	148.96527780000	Good
GW036255	-29.83416667000	148.98944440000	Good
GW036266	-31.04138889000	150.36138890000	Good
GW036272	-31.00305556000	150.31694440000	Good
GW036280	-29.96888889000	148.74944440000	Good
GW036287	-29.80527778000	148.99111110000	Poor
GW036289	-30.99611111000	150.29472220000	Good
GW036308	-30.88694444000	150.30750000000	Good
GW036314	-29.92166667000	148.75805560000	Poor
GW036320	-29.98944444000	148.74083330000	Good
GW036322	-30.82472222000	150.34750000000	Good
GW036325	-29.85388889000	149.06750000000	Poor
GW036340	-29.92500000000	148.79194440000	Good
GW036341	-29.79111111000	148.93944440000	Poor
GW036346	-29.83694444000	149.14972220000	Good
GW036361	-29.81750000000	148.95194440000	Poor
GW036363	-29.87555556000	148.90944440000	Poor

Nested Piezometer Site	Latitude	Longitude	Vertical Connection
GW036364	-29.93333333000	148.82361110000	Good
GW036365	-30.01583333000	148.65472220000	Good
GW036383	-30.83083333000	150.38972220000	Good
GW036387	-30.00000000000	148.61277780000	Good
GW036388	-30.02916667000	148.60833330000	Poor
GW036415	-30.77805556000	150.37666670000	Strong
GW036418	-30.82916667000	150.37861110000	Good
GW036435	-30.81750000000	149.97555560000	Good
GW036436	-30.81833333000	149.98194440000	Good
GW036441	-30.85083333000	149.95333330000	Good
GW036457	-30.82888889000	150.14666670000	Good
GW036463	-30.85888889000	150.25638890000	Good
GW036476	-30.87027778000	150.25694440000	Poor
GW036499	-30.94833333000	149.90083330000	Poor
GW036506	-31.07777778000	149.89527780000	Good
GW036515	-31.01277778000	149.85916670000	Poor
GW036541	-30.04138889000	148.40527777800	Good
GW036544	-30.94888889000	149.90722220000	Poor
GW036546	-30.85111111000	149.91416670000	Poor
GW036548	-30.75000000000	150.10472220000	Good
GW036549	-30.85611111000	149.92861110000	Poor
GW036568	-30.74527778000	150.04944440000	Good
GW036598	-30.75888889000	150.04583330000	Good
GW036600	-30.76277778000	150.03555560000	Good
GW036602	-30.77944444000	150.03305560000	Good
GW036656	-30.85027778000	149.90250000000	Poor
GW036660	-30.89444444000	149.85444440000	Poor
GW965576	-31.39757006000	150.34135460000	Good
GW965576	-31.39757006000	150.34135456900	Good

Appendix C Paired Stream and Bore Hydrograph Interaction

Gauging Station	Latitude	Longitude	Monitoring Bore	Latitude	Longitude	Evidence of Interaction
419001	-30.96155686	150.253105	GW021085	-30.96512789	150.2563269	Yes
			GW021086	-30.95611111	150.2569444	Yes
			GW021087	-30.9475	150.2583333	Yes
			GW021088	-30.9375	150.26	Yes
			GW021089	-30.93027778	150.2613889	Yes
			GW030297	-30.97722222	150.2802778	Yes
			GW030343	-30.96529408	150.2562272	Yes
			GW036239	-30.95055556	150.2977778	Yes
			GW039338	-30.95222222	150.3036111	Yes
419002	-30.32785111	149.7814425	GW021346	-30.33833333	149.7969444	Yes
			GW030120	-30.30888889	149.7880556	Yes
			GW030121	-30.30916667	149.7711111	Yes
			GW030122	-30.31666667	149.7588889	Yes
			GW030123	-30.33222222	149.7444444	Yes
			GW030242	-30.31	149.795	Yes
			GW030358	-30.32666667	149.7619444	Yes
			GW030441	-30.35083333	149.8138889	Yes
			GW030478	-30.34444444	149.8208333	Yes
419009	-31.0920948	150.9265171	GW030140	-31.08611111	150.9741667	Yes
419012	-30.66972222	150.0687026	GW030048	-30.70111111	150.0830556	Yes
419012	-30.66972222	150.0687026	GW030049	-30.70361111	150.1027778	Yes
			GW030468	-30.67027778	150.0530556	Yes
			GW030469	-30.66611111	150.0622222	Yes
			GW030470	-30.66027778	150.0663889	Yes
			GW030535	-30.70361111	150.1027778	Yes
			GW036008	-30.63305556	150.0422222	Yes
			GW036092	-30.66805556	150.0602778	Yes
419019	-30.20171729	149.5119392	GW025328	-30.17722222	149.5469444	Yes
			GW025329	-30.19111111	149.5436111	Yes
419019	-30.20171729	149.5119392	GW025330	-30.20333333	149.5413889	Yes

Gauging Station	Latitude	Longitude	Monitoring Bore	Latitude	Longitude	Evidence of Interaction
			GW025332	-30.21	149.5380556	Yes
			GW025333	-30.21194444	149.5375	Yes
			GW025334	-30.22611111	149.5341667	Yes
			GW025335	-30.24027778	149.5333333	Yes
			GW025336	-30.22277778	149.4905556	Yes
			GW025337	-30.23666667	149.4875	Yes
			GW025419	-30.21722222	149.5355556	Yes
			GW030054	-30.19833333	149.5425	Yes
			GW030099	-30.19916667	149.56	Yes
419023	-30.45125525	149.9473558	GW030230	-30.43361111	149.9030556	No
			GW030231	-30.45444444	149.9475	No
			GW030232	-30.45972222	149.9630556	Yes
			GW030233	-30.46194444	149.9791667	Yes
			GW030234	-30.46388889	149.9955556	Yes
419027	-31.2738595	150.4587406	GW028395	-31.30833333	150.4908333	Yes
			GW030000	-31.25694444	150.4736111	Yes
			GW030001	-31.25611111	150.4808333	Yes
			GW030002	-31.25421111	150.4885528	Yes
			GW030005	-31.26694444	150.4738889	Yes
			GW030006	-31.27972222	150.4777778	Yes
			GW030007	-31.29361111	150.4655556	Yes
			GW030008	-31.30583333	150.4633333	Yes
			GW030019	-31.29694444	150.4933333	Yes
			GW030072	-31.30305556	150.4638889	Yes
			GW036124	-31.25555556	150.4769444	Yes
			GW036125	-31.25222222	150.4961111	Yes
			GW036131	-31.25444444	150.4875	Yes
			GW036152	-31.23166667	150.4619444	Yes
			GW036305	-31.28055556	150.4836111	Yes
			GW093105	-31.28085556	150.4168722	Yes
419032	-30.77098192	149.9848708	GW031920	-30.74055556	150.0219444	Yes

Gauging Station	Latitude	Longitude	Monitoring Bore	Latitude	Longitude	Evidence of Interaction
			GW036433	-30.80861111	149.9633333	Yes
			GW036600	-30.76277778	150.0355556	Yes
			GW036602	-30.77944444	150.0330556	Yes
419033	-31.35000853	149.8887628	GW008969	-31.35027778	149.8816667	Yes
			GW015676	-31.32805556	149.8988889	Yes
			GW036599	-31.34222222	149.9027778	Yes
			GW036601	-31.33916667	149.8847222	Yes
419034	-31.41034438	150.4362719	GW017277	-31.36833333	150.4402778	Yes
			GW026742	-31.41888889	150.4691667	Yes
			GW029617	-31.40305556	150.4502778	Yes
			GW030013	-31.37333333	150.4516667	Yes
			GW030078	-31.39138889	150.4477778	Yes
			GW030079	-31.40194444	150.4352778	Yes
			GW030080	-31.40361111	150.4475	Yes
			GW030081	-31.40833333	150.4586111	Yes
			GW030082	-31.41527778	150.4705556	Yes
			GW030083	-31.42333333	150.4861111	Yes
			GW030152	-31.45194444	150.4427778	Yes
			GW030378	-31.39027778	150.4652778	Yes
			GW030379	-31.39	150.4572222	Yes
			GW030380	-31.38916667	150.4480556	Yes
			GW030381	-31.39555556	150.4419444	Yes
			GW040266	-31.38527778	150.4536111	Yes
419039	-30.25781947	149.6847877	GW025215	-30.23277778	149.6916667	No
			GW025216	-30.24861111	149.6947222	Yes
			GW025217	-30.25805556	149.6811111	Yes
			GW025218	-30.25972222	149.6786111	Yes
			GW025219	-30.26833333	149.6733333	Yes
			GW025220	-30.2825	149.6705556	Yes
			GW025221	-30.29555556	149.6677778	Yes
419039	-30.25781947	149.6847877	GW030116	-30.25166667	149.6866667	Yes

Gauging Station	Latitude	Longitude	Monitoring Bore	Latitude	Longitude	Evidence of Interaction
			GW030117	-30.27305556	149.7288889	Yes
			GW030309	-30.27472222	149.6725	Yes
			GW030329	-30.26472222	149.6725	Yes
			GW036047	-30.26888889	149.7	Yes
			GW040245	-30.23555556	149.6891667	Yes
			GW040248	-30.22555556	149.6883333	Yes
419051	-30.49706589	150.081806	GW030129	-30.52388889	150.0511111	Yes
			GW030130	-30.51583333	150.0541667	Yes
			GW030131	-30.50527778	150.055	Yes
			GW030132	-30.48666667	150.0541667	Yes
			GW030133	-30.47305556	150.0602778	Yes
			GW030134	-30.46694444	150.0613889	Yes
			GW030237	-30.47111111	150.0463889	Yes
419052	-31.10083333	149.9011111	GW007929	-31.10194444	149.8975	No
			GW035565	-31.07694444	149.8611111	No
			GW035568	-31.0875	149.8733333	No
			GW035834	-31.07472222	149.9	No
419059	-30.19397498	149.4332685	GW021479	-30.22254044	149.4367314	Yes
			GW021480	-30.23555556	149.4272222	Yes
			GW025044	-30.18027778	149.4519444	Yes
			GW025045	-30.165	149.4544444	Yes
			GW030188	-30.18666667	149.4580556	Yes
			GW030189	-30.1725	149.4530556	Yes
			GW030190	-30.15666667	149.4555556	Yes
			GW030288	-30.20722222	149.4386111	Yes
			GW036059	-30.19611111	149.3930556	Yes
			GW036060	-30.17694444	149.3963889	Yes
419063	-30.20157341	149.2886656	GW025136	-30.18638889	149.2986111	No
			GW025137	-30.17416667	149.3061111	No
			GW036036	-30.18305556	149.3	No
419063	-30.20157341	149.2886656	GW036066	-30.21083333	149.2602778	No

Gauging Station	Latitude	Longitude	Monitoring Bore	Latitude	Longitude	Evidence of Interaction
			GW036067	-30.19527778	149.2736111	No
419064	-30.09166667	149.0666667	GW036232	-30.10055556	149.0783333	Yes
			GW036233	-30.10472222	149.045	Yes
419079	-30.2919766	149.2883609	GW036062	-30.30027778	149.2469444	No
			GW036063	-30.27111111	149.2486111	No
419084	-31.03547256	150.3341238	GW036203	-31.06527778	150.3255556	Yes
			GW036260	-31.02111111	150.3763889	Yes
			GW036266	-31.04138889	150.3613889	Yes
419087	-31.57980556	150.5306944	GW030060	-31.55833333	150.5163889	Yes
419088	-30.16666667	149.1333333	GW036153	-30.14083333	149.1344444	No
			GW036154	-30.17583333	149.1258333	No
			GW036155	-30.20722222	149.1113889	No
419089	-29.91123455	148.7420956	GW036314	-29.92166667	148.7580556	No
4190002	-31.065167	151.054333	GW093036	-31.07	151.0580556	Yes
			GW093037	-31.06805556	151.0566667	Yes
			GW093038	-31.06611111	151.055	Yes
			GW093040	-31.06305556	151.0525	Yes