



Australian Government
Land & Water Australia



The Impact of Groundwater Use on Australia's Rivers

Technical report



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**The Effects of Groundwater Pumping on Stream Flow in Australia.
Technical Report.**

Based on the Land & Water Australia Senior Research Fellowship Report
by Dr Richard Evans, Principal Hydrogeologist, Sinclair Knight Merz.

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Design Mariana Rollgejser
Print Union Offset Printing, April 2007
Product code PR071283

Contents

Acknowledgments	vii
About the Senior Research Fellowships	vii
Executive Summary	1
1. Aim and Scope	4
2. Fundamental Concepts	6
2.1 The Hydrologic Cycle	6
2.2 Aquifer Types	6
2.3 Gaining and Losing Streams	7
2.4 Recharge and Discharge Processes	8
2.4.1 Recharge Processes	8
2.4.2 Discharge Processes	9
2.5 The Water Balance	9
2.6 Impacts of Groundwater Pumping on Streams	10
3. Calculation of Stream Flow impacts	13
3.1 Review	13
3.2 Idealised Case	14
3.3 Idealised Case - Modified	19
3.4 Typical Case	20
3.5 Semi-confined Situation	21
3.6 Local Scale Heterogeneity	22
3.7 Regional Groundwater Processes	22
3.8 Numerical Modelling Approaches	23
3.9 Use of Chemical Methods to Determine Surface Water/Groundwater Interaction	25
4. Technical Challenges	27
4.1 Time Lags	27
4.2 Effects of Groundwater Pumping Far from a Stream on Reducing Stream Flow	30
4.2.1 Basic Hypothesis	30
4.2.2 Testing Basic Hypothesis	32
4.2.3 Application to Australia	34
4.3 Groundwater Discharge Component of Baseflow	37
4.4 Impact of Groundwater Pumping on Ephemeral Rivers	37
5. Baseflow – Where Groundwater and Surface Water Meet	38
5.1 Introduction	38
5.2 Components of Stream flow and Baseflow	38

5.3	The Baseflow Index	39
5.4	Baseflow Index Results	40
5.5	Trend Analysis of Baseflows	43
5.6	Overview	45
6.	Case Studies	46
6.1	USA	46
6.1.1	Eastern Snake River Plain Aquifer	46
6.1.2	Republican River Compact	49
6.2	China	53
6.3	Australia	53
7.	Implications for Australia	56
7.1	Comment on Water Resource Assessments in Australia	56
7.2	Estimate of Double Accounting in Australia	57
7.2.1	Methods of Water Resource Yield Assessment	57
7.2.2	Factors Influencing Impacts	58
7.2.3	Impacts in Surface Water Based Irrigation Areas	61
7.3	Evolving Understanding of Connectivity	62
7.4	National Surface Water Groundwater Interaction Assessment Methodology	64
8.	Possible Management Approaches	66
8.1	National Policy Development	66
8.2	Comment on Existing Management Approaches	66
8.3	Whole of Catchment Water Balances	66
8.4	Groundwater Sustainable Yield	68
8.5	Management Approaches, Tools and Options	69
8.5.1	Define Objectives	69
8.5.2	Water Resource Sustainability	71
8.5.3	Stream Management Plans	71
8.5.4	Transfers and Trading	76
9.	Conclusions and Overall Strategy for Australia	77
9.1	Overview	77
9.2	Technical	79
9.3	Management	80
9.4	Education	80
10.	Recommendations	81
10.1	Technical	81

10.2	Management	81
10.3	Education	82
Appendix A	Analytical Solution for Semi-confined Aquifers	83
Appendix B	Hypothetical Catchment Modelling	90
Appendix C	Baseflow Separation Analysis Methods	97
Appendix D	Whole of Catchment Water Balance	107
Appendix E	Management of Stream Depletion Effects from Environment Southland (2004)	109
11.	Bibilography	120

List of Figures

Figure 2-1 The Hydrologic Cycle (From Department of Land and Water Conservation [DLWC], 2000 p. 3)	6
Figure 2-2 Characterisation of Gaining (a) and Losing (b) Streams (after Winter et al. 2002)	8
Figure 2-3 Disconnected losing stream	8
Figure 2-4 Effect of groundwater pumping on a gaining stream (Note: induced stream leakage after 1,000 days is labelled as 'induced recharge')	11
Figure 3-1 Effect of induced recharge on drawdown in the pumped bore	16
Figure 3-2 Change in the rate of stream flow depletion as a percentage of the pumping rate after Jenkins, 1968 (i.e. change in the slope of the drawdown curve in Figure 3-1)	16
Figure 3-3 The delay before stream flow depletion commences at increasing distance between the bore and stream (with $T = 100 \text{ m}^2/\text{d}$ and $S = 0.1$)	17
Figure 3-4 The volume of stream flow depletion over time at increasing distance between the bore and the stream (with $T = 100 \text{ m}^2/\text{d}$, $S = 0.1$, and pumping rate = 200 ML/year) – log axes	17
Figure 3-5 The volume of stream flow depletion over time at increasing distance between the bore and the stream (with $T = 100 \text{ m}^2/\text{d}$, $S = 0.1$, and pumping rate = 200 ML/year) – linear axes	18
Figure 3-6 Effect of different ratios of pumping to recharge on stream impacts (modified after Cook and Lamontagne, 2002)	19
Figure 3-7 Typical hydrogeological situation of pumping from a semi- confined aquifer	21
Figure 3-8 Stream depletion rates for the base scenarios for a bore pumping 1,000 m^3/d for 5 years at varying distances from the river (From Braaten and Gates, 2004)	25
Figure 4-1 Effect of distributing groundwater extraction over a catchment (From Cook and Lamontagne, 2002)	28
Figure 4-2 Groundwater evaporation with depth (after Talsma, 1963) From SKM, (2005b) (Note: 1 ML/ha equals 100 mm)	32
Figure 4-3 Changes in mass balance caused by groundwater extraction – change in flux vs position of pumping bore. (Note: this is at steady state)	33
Figure 4-4 Groundwater discharge rate as a function of water table depth (From Cook et al. 2006). Error bars denote results of Ti Tree Basin Study, central Australia	35
Figure 5-1 Annual baseflow indices, 1990 to 1999, Murray-Darling Basin (From Neal et al. 2004)	42
Figure 6-1 Snake River, Idaho, USA	46
Figure 6-2 Republican River	50
Figure 8-1 Flow Chart of possible management approaches to control, mitigate or administer the impacts of surface water/groundwater interaction for new and existing water access entitlements	70
Figure 8-2 Proposed zonal concept for managing new water access entitlements	73
Figure 8-3 Indicative location of management zones	74
Figure 9-1 Surface water/groundwater interaction in Australia – a strategic approach	78
Figure A-1: Conceptual Model for Delayed Yield Solution Developed by Boulton (1973) for A Pumped Aquifer Bounded With an Aquitard Containing a Shallow Water table	83

Figure A-2: Impact of cyclical versus continual pumping on stream depletion. Example from Braaten and Gates (2004), Figure 1: a bore pumping at a constant rate of 1000 m ³ /day; and a bore pumping in a cyclical pattern of six months on at 2000 m ³ /day and six months off.	88
Figure B-1 Model Grid Layout and Features	91
Figure B-2 Topographic Contours of Model Top (values are in mAHD)	91
Figure B-3 Water Table Depth	92
Figure B-4 Locations of Pumping Bore	93
Figure B-5 Changes in Mass Balance Caused by Groundwater Extraction – Change in Flux vs Position of Pumping Bore.	94
Figure B-6 Bore Locations in Transient Models	95
Figure B-7 Changes in Water Balance Components – Bore Located at X=25 000m	95
Figure B-8 Changes in Water Balance Components – Bore Located at X=30 000m	96
Figure C-1: Baseflow separation hydrographs (Viessman et al. 1977)	101
Figure C-2: Baseflow separation hydrographs (Linsley et al. 1982)	101
Figure C-3: Examples of continuous baseflow separation using the smoothed minima technique (Nathan and McMahon, 1990)	104
Figure C-4: Examples of continuous baseflow separation using the Lyne and Hollick Filter (Nathan and McMahon, 1990)	106
Figure E-1 Typical stream depletion response for a bore having a direct hydraulic connection to a surface waterway (the dotted line represents the effect of stopping pumping after 75 days)	110
Figure E-2 The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a direct hydraulic connection	110
Figure E-3 Typical stream depletion response for a bore having a high degree of hydraulic connection to a surface waterway (the dotted line represents the effect of stopping pumping after 75 days)	111
Figure E-4 The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a high degree of hydraulic connection	112
Figure E-5 Typical stream depletion response for a bore having a moderate degree of hydraulic connection to a surface waterway (the dotted line represents the effect of stopping pumping after 75 days)	114
Figure E-6 The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a moderate degree of hydraulic connection.	114
Figure E-7 Typical stream depletion response for a bore having a low degree of hydraulic connection to a surface waterway (the dotted line represents the effect of stopping pumping after 75 days)	115
Figure E-8 The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a low degree of hydraulic connection	116
Figure D-9: The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a low degree of hydraulic connection	116

List of Tables

Table 3-1 Potential error of idealised case (after Sophocleous et al. 1995)	20
Table B-1 Model mass balance [ML/day]	92
Table E-1: Definition and management of proposed categories of hydraulic connection	118

Acknowledgments

The work presented in this report has been funded by the Land & Water Australia (LWA) Senior Research Fellowship. The foresight of the Board of LWA in creating the Fellowship and the encouragement and enthusiasm of Andrew Campbell and Nick Schofield is gratefully acknowledged.

The active and ongoing support of my employer, Sinclair Knight Merz, especially the time to contribute to this study, is greatly appreciated.

This report has benefited enormously from many discussions with colleagues and active input by many people, especially Mike Dudding, Brian Barnett, Greg Holland, Steve Parsons, Brad Neil, Rory Nathan and Bill Trehwella. Suggestions and helpful input from Peter Cook is especially acknowledged. The constructive comments from the reviewers of this report are also acknowledged; Tamie Weaver, University of Melbourne; Marios Sophocleous, University of Kansas and Peter Cook, CSIRO Land & Water.

About the Senior Research Fellowships

During the peak of a researcher's career their most precious commodity is time. Many of our best scientific brains spend too much of their time on activities other than research—administration, management, writing research proposals, wrestling with budgets and so on. In a new approach to funding science, the Land & Water Australia Fellowships are expressly designed to “free up” the time of a select few leading researchers each year, to give them some time and space free from the constraints of everyday work. The intent is to sponsor reflective, synthesis research by people at the top of their fields—in mid-career, rather than in retirement.

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Each year the Fellows are selected by the Land & Water Australia Board. The Fellowships are also made possible by the support of the Fellows' employers. Land & Water Australia thanks these organisations for their foresight and willingness to participate in this initiative.



Executive Summary

Many hydrologists and hydrogeologists have known since university that groundwater and surface water are commonly interconnected and interchangeable resources. For many involved at both a technical and management level this understanding has not been translated into a practical reality given that we manage our water resources in Australia as if they are separate entities. In times of abundance and low demand this has not often mattered. However, over the last few decades the significant increase in demand for water, combined with an extended period of low rainfall over most of Australia and the community desire for increased environmental flows, has contributed to a greater focus on the management of our water resources. In response, regulators have placed caps on many of our surface water resources but, failing to realise the common interconnection with groundwater, have continued to allocate additional groundwater licences. This has resulted in an unintended transfer of development pressure from surface water to groundwater resources.

The separate management of both resources has also meant that we have inadvertently double accounted the same water; once as groundwater and a second time as the baseflow of rivers. In some cases this has led to double allocation whereby we have allocated the same water twice. Double accounting has had the effect of reducing the security of supply to surface water users, and also resulted in reduced flow in rivers and even complete drying out of streams in some cases. We have not often recognised this double accounting because of the time lag between pumping groundwater and the reduced stream flow. This time lag varies greatly but in many cases can be decades.

This report presents the technical understanding of the effects of groundwater pumping on stream flow in Australia, identifies associated technical challenges, and then develops management approaches to address the issue. At a technical level, the basic hydraulic relationships defining surface water/groundwater interaction have been known since the 1950s. The idealised case that is presented clearly shows a 100% impact and time lags that can vary from only hours to centuries, depending on the distance of the bore to the river and other hydrologic properties. In this idealised case the steady state impact of groundwater pumping is identical regardless of the distance of the bore from the river. In reality, hydrogeological complexity of semi-confined aquifers and a myriad of other geological features results in a more complex environment where many different time and impact effects are experienced. Nonetheless, the basic idealised unconfined aquifer behaviour still often holds and frequently provides a realistic conceptual model for actual behaviour. The simple and more complex analysis methods are also presented.

Case studies predominantly from the USA, and also limited examples from China and Australia, are presented which show the need to address the issue of surface water/groundwater interaction. These case studies commonly show a 100% impact, albeit lagged by several decades. The magnitude and timing of double accounting of our surface water and groundwater resources in Australia has not been defined. The analysis of stream

flow records to deduce baseflow provides an especially useful tool to understand surface water/groundwater interaction. Baseflow appears to vary from typically 50% of the total stream flow in southern Australia to about 10% in northern Australia. Over the critical dry season low flow period groundwater discharge is commonly 100% of the stream flow. This data underscores the importance of groundwater discharge in maintaining the health of most streams and rivers in Australia.

Key technical challenges, in the Australian context of understanding surface water/groundwater interaction, are related to time lags and the effects of groundwater pumping when bores are located far from streams. The literature is generally devoid of discussion where bores are located far (e.g. tens of kilometres) from streams. It is postulated that groundwater evapotranspiration (ET) across typical Australian catchments can operate as a significant mitigating process to reduce the impact of groundwater pumping on streams. The critical significance of the location of bores relative to where ET is occurring and the streams is illustrated by a numerical model. Even though ET is clearly very important, there will still usually be an impact on the streams due to groundwater pumping virtually anywhere in a typical catchment.

It is suggested that, as groundwater pumping has commonly been underway actively in Australia for about 40 years and that often the bores are located relatively close to rivers, the effects of groundwater use in many catchments has already been felt in the rivers. Depending on the surface water resource assessment method, this impact may have already been factored into the (reduced) surface water yield. Defining typical impacts of groundwater pumping is difficult as the impacts can range from 0% to 100% depending on a broad range of hydrogeological factors. These factors (i.e. discharge to ET, to oceans, to another catchment, to deep groundwater systems, and disconnected streams) are discussed for Australia. These processes may be locally important, but regionally less important. Nonetheless, groundwater discharge to ET is usually a significant process. When bores are located close to streams, and assuming no complicating geological conditions, then the impacts will be 100%.

There is no common and agreed national approach on how to manage surface water/groundwater interaction. It is considered that the fundamental tool to assist management is a catchment water balance. This will firstly assist in identifying double accounting and then be able to lead into identifying double allocation. The current estimates of groundwater sustainable yields generally do not adequately allow for the need to maintain groundwater discharge to rivers, however there are some significant exceptions. This has led to the concept of connectivity, where a relatively simple categorisation of the impacts over a defined time period can be estimated based on simple stream and catchment characteristics. This can be used both as a risk based approach to prioritise investigations and also as a mechanism to introduce different management rules.

Somewhat different management approaches are required depending on whether the primary objective is total water resource sustainability or alternatively the maintenance of minimum environmental flows in rivers. Water resource sustainability is aided by

understanding the developed water balance, while minimum stream flows are strongly influenced by the time lags between groundwater pumping and impact at the stream. Possible approaches to address total water resource sustainability are presented, including 'capping' new licences, cancellation of existing licences and restricting pumping to particular volumes. The maintenance of environmental flows is aided by so called 'zonal' management which is presented in detail. This ultimately relies on different management approaches for different categories of groundwater users depending primarily on the distance from the river. Groundwater and surface water trading and transfers can be used to assist this approach.

The hypothesis that the impact of groundwater pumping on stream flow will usually be 100%, albeit commonly time lagged, except where a variety of other factors operate (of which it is believed that groundwater ET is often the most important) needs to be tested. Hence, it is recommended that more studies which 'close' the whole of catchment water balance are required. These include both field and modelling studies. This can then lead to a stronger technical foundation for a national assessment of the extent of double accounting of surface water and groundwater. The development of nationally agreed assessment methods and approaches for both technical and management purposes is also recommended.

The technical and management challenges to address the impact of groundwater pumping on stream flow are significant and a major effort by all water managers and users is required to address these challenges.

1. Aim and Scope

In much of Australia, groundwater and surface water are interconnected and interchangeable resources. This common physical reality is, however, not reflected in our water management systems whereby groundwater and surface water are generally managed as separate resources. The implications of this separate management are that the one resource is often allocated to both surface water users and to groundwater users. This 'double allocation' is not well understood and the extent of the problem throughout Australia is poorly quantified. More significantly the environment is the principal loser, as often the resulting effect is reduced flow in rivers and in some cases even complete drying out of some streams.

This report aims to provide the technical underpinning, and support the development of practical management approaches, to address the issue of stream aquifer interaction in Australia. It is aimed at water resource managers in Australia and related professionals who have an interest in how water resource decision making, and specifically groundwater allocations and management, impacts on the riverine environment, groundwater dependent ecosystems and water resource security.

The report is structured as follows:

Chapter 2 aims to explain the fundamental concepts of stream aquifer interaction.

Chapter 3 presents the various analysis methods which calculate the impacts of groundwater pumping on stream flows.

Chapter 4 considers some of the fundamental technical challenges faced in the understanding of surface water/groundwater interaction. The time lag between commencing groundwater pumping and significant stream response is discussed and the data which is available is presented. The significance of the time lag influences the management approach to be adopted. The link between the volume of groundwater pumped and the reduction in stream flow is assessed. The full catchment water balance (i.e. including groundwater) is considered for typical hydrogeological environments so that the impact of groundwater use on stream flow can be evaluated.

Chapter 5 discusses the nature of baseflow in streams in the context of this key component of the water balance. The different components of baseflow are assessed and their relative hydrogeological significance is evaluated. The various baseflow analysis methods are reviewed.

Chapter 6 presents relevant case studies on surface water/groundwater interaction from Australia, USA and China.

Chapter 7 discusses the implications for Australia of double accounting and focusses on the many factors which influence the extent of double accounting.

Chapter 8 presents possible management approaches. At the practical management level, the development of a range of options for different jurisdictional and hydrogeological environments is considered. Management action is required at two completely different scales; at the catchment scale and at the local scale. At the catchment level, surface water and groundwater allocation limits that allow for long term impacts need to be assessed. At the local scale, issues considered include appropriate triggers for restrictions, rostering methods and surface water/groundwater trading rules.

Chapter 9 develops key conclusions and presents an overall strategy for Australia.

Chapter 10 presents recommendations.

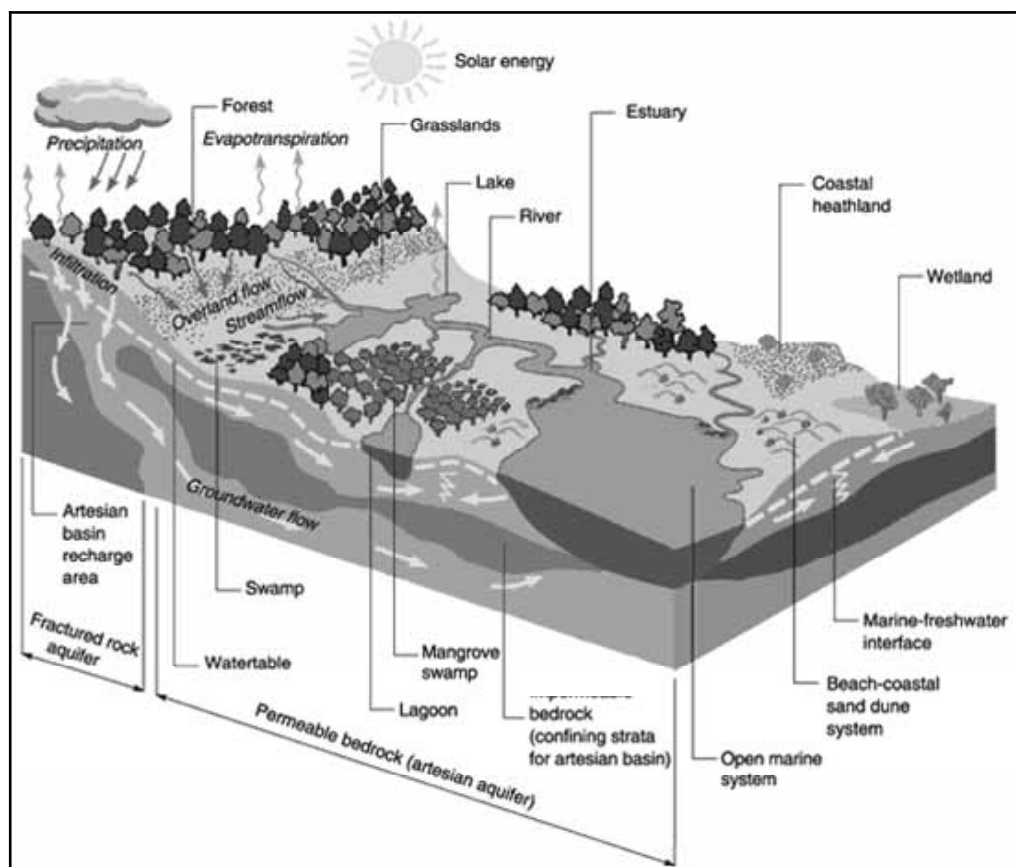
The focus of this report is on quantity, which is the magnitude and timing of the interaction between groundwater and surface water. It is however recognised that the quality aspects of interaction may be more important in some cases in Australia. This most important aspect is outside the scope of this current study.

2. Fundamental Concepts

2.1 The Hydrologic Cycle

The hydrologic cycle describes the continuous movement of water above, on, and below the surface of the earth (Winter et al. 2002). This fundamental concept is discussed in countless reports and is shown diagrammatically in Figure 2-1. The atmospheric component and the surface water component are relatively well understood, while the groundwater part of the hydrologic cycle is often not appreciated. Not surprisingly the interaction between surface water and groundwater is poorly grasped by the community. In a few relatively rare cases there is virtually no interaction between surface water and groundwater, while in the majority of cases there is substantial interaction, albeit highly temporally and spatially variable. Nonetheless, the hydrologic cycle is very real and to deny or ignore surface water/groundwater interaction is to ignore the hydrologic cycle itself! The fundamental concept of hydraulic continuity has been espoused by Toth (1990) and essentially promotes the idea that given sufficient time all geological units are hydraulically connected. The practical reality of this well proven theory is developed in this report.

- Figure 2-1 The Hydrologic Cycle (From Department of Land and Water Conservation [DLWC], 2000 p. 3)



2.2 Aquifer Types

Strong interactions between streams and the groundwater system are usually associated with shallow aquifers. The shallow aquifers are generally 'unconfined', but may sometimes

be 'semi-confined'. An 'unconfined' aquifer is one where the surface of the groundwater body (also known as the water table) is contained within the aquifer. In this case the groundwater pressure in the aquifer and the water table level are effectively the same. In the 'semi-confined' case the shallow aquifer is overlain by less permeable material (known as an aquitard), and the water table is contained within the aquitard or above it. Water can be transmitted up or down through the aquitard, but vertical movement is very limited compared with lateral movement in the aquifer. The water table level in the aquitard at any point can be significantly different from the groundwater pressure in the underlying aquifer if there is any significant vertical transmission of water to or from the aquifer at that point. A semi-confined aquifer is simply a confined aquifer that leaks significantly.

2.3 Gaining and Losing Streams

If the water table or groundwater level in an aquifer is higher than the running level in a stream, groundwater will flow or discharge to the stream. In this case, the stream is defined as a 'gaining stream', and the groundwater discharge is called 'baseflow'. If the water table or groundwater level is lower than the running level in a stream, water will flow from the stream and recharge the groundwater. In this case the stream is defined as a 'losing stream', and the recharge to the groundwater is called 'stream leakage'. Some parts of a stream may be gaining streams and others may be losing streams, and this may change over time.

A stream can be either 'disconnected' from or 'connected' to the groundwater body contained in the aquifer. The stream and the aquifer are considered to be 'connected' if there is no zone of unsaturated material between the stream and the water table. A 'connected' stream occurs when the water table level intersects the surface water body. (Although this may be generally true at the large scale, it is not strictly true at the local scale as there may be a 'seepage face' between the water table and stream level where the two encounter each other.) Under these conditions the surface water body can be affected by changes in the water table level and/or the groundwater level in the aquifer.

The stream and the aquifer are considered to be 'disconnected' if:

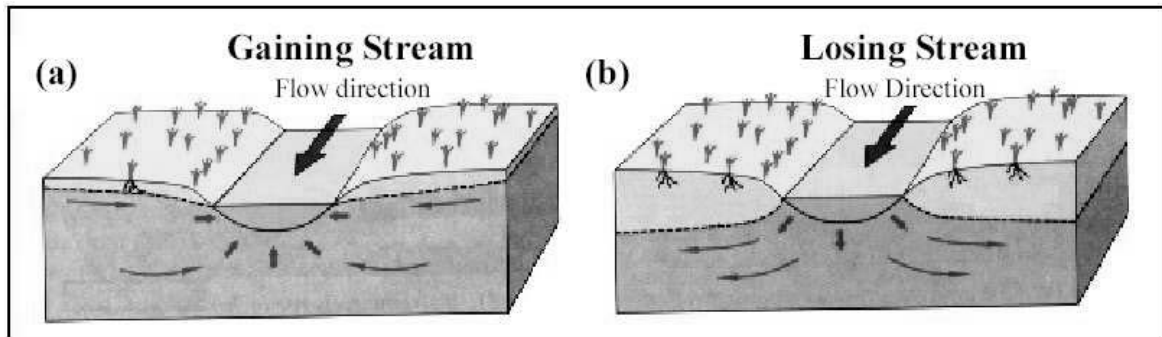
- The water table level is below the base of the surface water body (i.e. the water table level does not intersect the surface water body)
- A zone of unsaturated material exists between the surface water body and the water table.

In this case any changes in the water table level and/or the groundwater level in the aquifer will have little or no effect on the surface water body where the water table and water body are disconnected.

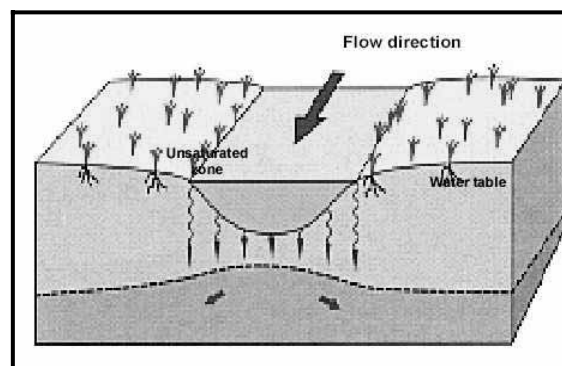
Figure 2-2(a) and (b), and Figure 2-3 show examples for a shallow unconfined aquifer of:

- gaining and losing streams where the aquifer and the stream are connected
- a losing stream where the aquifer and stream are disconnected.

- Figure 2-2 Characterisation of Gaining (a) and Losing (b) Streams (after Winter et al. 2002)



- Figure 2-3 Disconnected losing stream



Bouwer and Maddock (1997) discuss the nature of 'disconnected' losing streams. They conclude that when the thickness of the unsaturated zone beneath the stream is greater than about twice the stream width then the seepage rate becomes uniform. This case is where there is no clogging layer on the base of the stream. The important point to note is that there is no truly 'disconnected' stream, rather the seepage rate increases to that of unsaturated flow. The seepage rate from a disconnected stream will be greater than from an identical connected stream. As the groundwater level is reduced, a point is reached when the soil beneath the stream bed becomes unsaturated, and beyond that point reducing the groundwater level further does not increase the leakage further. This process is well defined in Fox and Durnford (2003). In the author's experience cases of disconnected streams are not common.

2.4 Recharge and Discharge Processes

Groundwater is stored in the aquifer (and any associated aquitard), and the volume available at any time is dependent on the volumes of water added to, or removed from, the aquifer over time. Processes that add water to groundwater storage are defined as recharge processes, and processes that remove water from storage are defined as discharge processes.

2.4.1 Recharge Processes

For any shallow aquifer recharge can occur by the following processes:

- recharge from rainfall and irrigation

- recharge from surface water bodies (stream leakage)
- recharge from underlying aquifers (upward leakage).

If a model deals with only part of the aquifer system, provision also needs to be made for recharge generated outside the model area. For analytical purposes this recharge is considered to be a groundwater inflow to the model area.

If a surface water body, such as a stream, is disconnected from the underlying aquifer the rate of stream leakage is determined by the water level in the water body, the wetted surface area, the effective combined permeability of the bed of the water body and the saturated layer immediately below the bed, and the thickness of the saturated layer.

If a surface water body is connected with the underlying aquifer the rate of stream leakage is also affected by the permeability of the stream bed sediments, the permeability of the aquifer, the saturated thickness of the aquifer, and the groundwater level adjacent to the water body. If the stream level is constant and above the groundwater level, and the groundwater level in the aquifer is lowered, the pressure gradient between the water body and the aquifer will be increased and the rate of stream leakage will also increase. If the stream level is constant and above the groundwater level, and the groundwater level in the aquifer is raised, the pressure gradient between the water body and the aquifer will be decreased and the rate of stream leakage will decrease.

2.4.2 Discharge Processes

Discharge from a shallow aquifer (and any aquitard) can occur by:

- discharge through the unsaturated zone above the water table (i.e. evapotranspiration)
- groundwater flow to a surface water body (baseflow)
- leakage to an underlying aquifer.

If a model deals with only part of the aquifer system, provision also needs to be made for discharge out of the model area. For analytical purposes this discharge is considered to be a groundwater outflow from the model area.

Baseflow will be generated in a stream reach or surface water body, if the water table is higher than the water level in the surface water body. The amount of baseflow generated is determined by the water level in the water body, the wetted surface area, the effective permeability and thickness of the bed of the water body, the permeability of the aquifer, the saturated thickness of the aquifer, and the groundwater level adjacent to the water body. If the stream level is constant and the groundwater level in the aquifer is lowered, the pressure gradient between the water body and the aquifer will decrease and less baseflow will be generated (i.e. there will be a decrease in stream flow). If the stream level is constant and the groundwater level in the aquifer is raised, the pressure gradient between the water body and the aquifer will increase and there will be more baseflow generated.

2.5 The Water Balance

Under consistent climatic conditions the groundwater in an aquifer will reach an equilibrium

(or steady state), where the volume of recharge to the aquifer over a significant time period will be equal to the volume of water discharged. At any point in time recharge may be different from discharge. Groundwater levels will generally rise in periods when recharge exceeds discharge, and fall when discharge exceeds recharge. However, under steady state conditions, groundwater levels will fluctuate seasonally around consistent levels.

If a significant new discharge process occurs, e.g. groundwater pumping, some groundwater will initially be removed from the groundwater storage, leading to some lowering of groundwater or water table levels. However, the groundwater levels will reach a new steady state over time if the pumping discharge continues. This will be achieved by either reducing some other discharge process (such as baseflow) or increasing recharge processes (such as stream leakage), or possibly both. While the groundwater is moving from one steady state to another it is considered to be in a transient state. The time period to reach the new steady state will depend on the size of the aquifer and the magnitude of the change in discharge.

2.6 Impacts of Groundwater Pumping on Streams

Groundwater pumping (or pumped discharge) will affect the rate of baseflow and/or stream leakage unless:

- the aquifer is disconnected from the stream (note that a perennial stream is unlikely to be disconnected from groundwater over its entire length)
- the amount of pumped discharge is offset by reduction in discharge to some other groundwater discharge point
- the amount of pumped discharge is offset by some additional (induced) recharge from another source such as a lake or wetland.

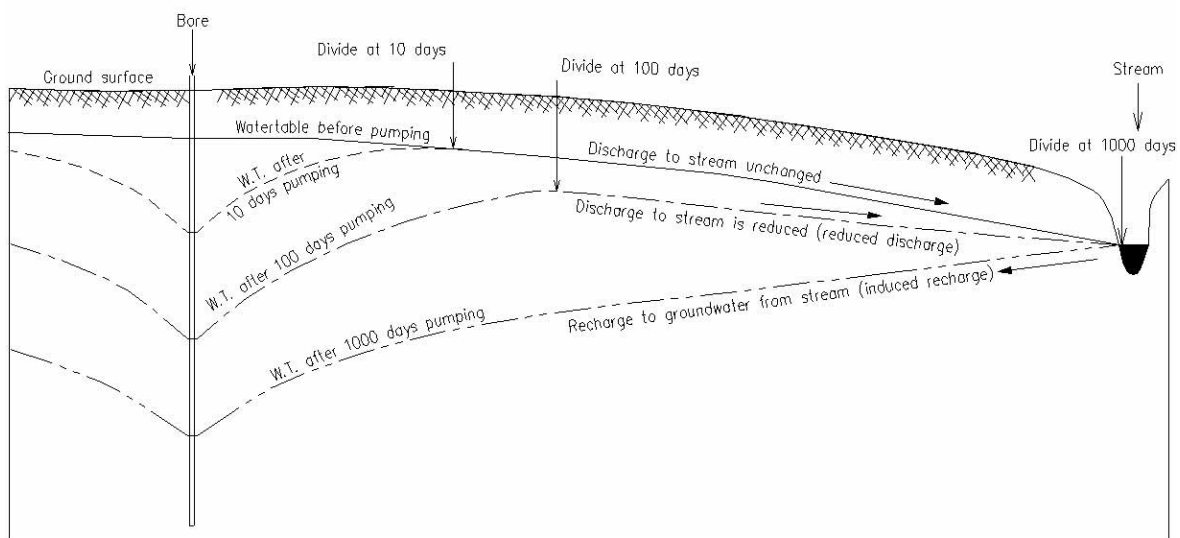
In the case of a losing stream, groundwater pumping will cause an increase in the rate of stream leakage (to offset the pumped discharge). The increased stream leakage is defined for this report as an '*induced stream leakage*'. The induced stream leakage will increase progressively as the water table or groundwater level adjacent to the stream falls, even if the water table level falls to a point where the aquifer is disconnected from the stream¹.

If the stream is a gaining stream the effect of pumping can be twofold. The initial effect will be to reduce the baseflow (so called 'reduced discharge') generated in that reach of the stream (e.g. after 100 days pumping in Figure 2-4). The baseflow will decrease progressively as the water table or groundwater level adjacent to the stream falls. The important point to note is that even though there is a groundwater divide located between the pumping bore and the stream, the hydraulic gradient to the stream is reduced and hence the amount of

¹ If the water table or groundwater level continues to fall after the aquifer has become disconnected from the stream there will not be any further increase in induced stream leakage along the disconnected stream reach. However, in order to maintain the water balance additional water will need to be accessed. Initially, this additional water will be derived from groundwater storage in the area where the water table has become disconnected from the stream (in much the same way groundwater is taken from storage when a bore starts pumping). This will cause the drawdown cone to expand at a greater rate which will increase the amount of induced stream leakage because there will be a greater length of stream intersected by the drawdown cone. As pumping continues the amount of additional water derived from storage will decrease in proportion to the volume derived from induced stream leakage. Ultimately 100% of the pumped discharge will be derived from induced stream leakage even though parts of the reach are disconnected from the aquifer.

groundwater flow to the stream is also reduced. If pumping is at a high enough rate and/or continues for long enough the water table or groundwater level adjacent to the stream may fall to the same level as the running level in the stream. At that point, baseflow will cease to be generated for that stream reach. If the water table or groundwater level continues to fall the stream becomes a losing stream with induced stream leakage (also called 'induced recharge', e.g. after 1,000 days pumping in Figure 2-4). The transition from a gaining stream to a losing stream is illustrated in Figure 2-4

- **Figure 2-4 Effect of groundwater pumping on a gaining stream (Note: induced stream leakage after 1,000 days is labelled as 'induced recharge')**



In summary, pumping from a bore reduces stream flow in two ways:

- 1) decreased recharge or baseflow (i.e. interception of groundwater before it can discharge to the stream)
- 2) increased recharge (i.e. leakage from the stream to groundwater).

Depending on the location of the bore, extent and depth of the cone of depression (i.e. pumping duration, transmissivity, storage co-efficient and pumping rate) there may be a considerable delay between the commencement of pumping and the decline in stream flow. In many instances the reduction in stream flow will be less than the pumped volume because there may be some increased recharge or decreased discharge from other sites. However, if we consider all streams across the entire catchment (including channel supply infrastructure within irrigation areas) then pumping will cause a net decrease in stream flow. The time delay is discussed further in Sections 3 and 4.

The above discussion has focussed on an idealised unconfined aquifer. In many catchments hydrogeological features may act to complicate the idealised case such that groundwater pumping may not have a 1:1 impact on reducing stream flow. Hydrogeological factors that

may reduce stream flow impacts are:

- discharge to evapotranspiration (ET). In this case the groundwater is 'used' by vegetation, wetlands, springs etc.
- discharge to oceans
- flow to another groundwater system (e.g. where the surface water catchment does not coincide with the groundwater 'catchment').
- recharge to deeper groundwater systems that are not hydraulically connected to streams and inter-aquifer flow
- disconnected streams.

These factors, as applied to Australia, are discussed further in Chapter 7.

3. Calculation of Stream Flow impacts

3.1 Review

Methods to calculate the impact of pumping on stream flow have been developed since Theis introduced his solution to transient groundwater flow. Following initial investigations by Theis (1940), Glover and Balmer (1954) developed an analytical solution for an idealised case where the stream fully penetrates the aquifer, the water table is flat (i.e. the stream is neither gaining nor losing), and the streambed is not clogged with low permeability sediments. A flat water table is used in the model because the Theis solution does not incorporate natural recharge or discharge (i.e. recharge or discharge can only be simulated using a bore). As a result, the stream flow depletion can only be represented by the model as increased recharge. However, the distinction between increased recharge and reduced discharge is unnecessary because the mechanism for these processes is the same (i.e. intersection of the stream by a drawdown cone). What is unknown is the proportion of stream flow depletion that is derived from reduced discharge and increased recharge respectively. Using this model these investigators showed the proportion of the pumped groundwater derived from stream flow (as either reduced discharge or increased recharge) to be a function of aquifer diffusivity (i.e. both aquifer transmissivity and storage co-efficient) and the square of the distance between the bore and the stream (i.e. a ten fold increase in distance causes a 100 fold time delay from the start of pumping till the commencement of reduced stream flow). From this simple model Jenkins (1968) and Glover (1974) developed an analytical solution for calculating stream flow depletion from a well discharging at a constant rate at a fixed distance from a stream.

Many methods for assessing more typical² cases have been developed by various researchers. According to Baaker and Anderson (2003) the significance of streambed clogging on flow across a streambed (and hence on groundwater flow to the well) was identified by Kazmann (1948) and Walton (1963), who developed a method using extended flow lengths to simulate clogging. Hantush (1965) developed an analytical method that dealt with clogging more directly by assuming a thin layer of low hydraulic conductivity and no storage separates the aquifer from a fully penetrating stream. Analytical solutions for a partially penetrating stream have been developed by Hunt (1999), Zlotnik and Huang (1999), Butler et al. (2001), and Fox et al. (2002) using different assumptions regarding stream width and drawdown on the non-pumped side of the stream. The influence of other factors on stream flow depletion such as the direction of groundwater flow (towards or away from the stream), stream gradient (Baaker and Anderson, 2003), and intermittent pumping (Darama, 2001) have also been examined.

Due to the complexity and variability of the natural environment there is no single robust and technically simple tool for predicting the impact of groundwater pumping on stream flow. In the following sections the solution to the idealised case (i.e. the method by Glover and Balmer, 1954) is described and the errors introduced by factors such as streambed

² Where the stream is in a more typical situation, such as partially penetrating an aquifer or has a 'clogged' stream bed.

clogging and partial penetration are examined.

An excellent description of the available analysis methods is given in Environment Canterbury (2000). The work has an obvious New Zealand application and so is focussed on relatively high hydraulic conductivity and high hydraulic gradient applications which generally involve relatively short time intervals and short distances. Nonetheless, the descriptions of fundamental processes are excellent.

The analytical analysis method described below is based on the Theis analysis method, which strictly speaking is for confined aquifers. The use of this method to unconfined aquifers is common and considered to be valid provided that the limitations are appreciated. As the water table is drawn down the transmissivity will decrease and hence the Theis analysis is strictly speaking not valid. In practice, provided that the amount of drawdown is small relative to the thickness of the aquifer, then this error is usually small. Also in unconfined aquifers there could be delayed yield (see Kasenow, 1997) which acts to reduce the drawdown in the short term. Delayed yield can occur from hours to weeks when pumping commences. If this is the case then the analysis method will be slightly in error in the short term.

3.2 Idealised Case

Using the Theis solution Glover (1974) developed a model to calculate the volume of stream flow depletion due to pumping from a single bore. To use the Theis solution the model needed to incorporate a recharge source to ensure the water balance is maintained. To do this the model is constructed with an injection bore to simulate recharge and a pumping bore to simulate discharge. The stream is represented as an imaginary line located half way between the pumping bore and the injection bore. When the pumping (and injection) commences a cone of drawdown and a cone of impression form around the respective bores and the outer edge of each cone migrates towards the stream. The water balance is maintained because injection and pumping commence at the same time and operate at the same rate. After a period of pumping the two cones intersect at a point on the stream directly opposite the pumping and injection bores. When this occurs water from the cone of impression is diverted into the cone of depression slowing the rate of drawdown in the pumping bore (and slowing the rate of impression in the injection bore). It is important to note that the model calculates stream flow depletion using drawdown NOT groundwater level. As a consequence the model does not differentiate between the two forms of stream flow depletion; reduced baseflow and increased stream leakage.

As the two cones continue to expand the amount of water transferring from the injection bore to the pumping bore increases until 100% of the pumped water is derived from the injection bore (i.e. the stream). When this occurs the two cones cease to expand (i.e. the rate of stream flow depletion is equal to the rate of pumping). The rate at which stream flow depletion increases is proportional to the change in rate of drawdown in the pumped bore (Figure 3-1). The rate of stream flow depletion changes in a similar manner as the slope of the time drawdown curve in Figure 3-1 and follows the shape of the curve shown in Figure 3-2 (in a dimensionless form). The duration of pumping required before stream flow

depletion begins is dependent on the storage co-efficient, transmissivity and the location of the bore. The pumping rate does not influence the rate at which the drawdown cone spreads and as such does not influence the timing at which stream flow depletion commences. By keeping the transmissivity and storage co-efficient constant the curve in Figure 3-2 can be split into a series of curves which show the effect of distance between the bore and the stream on the duration of pumping before stream flow depletion begins (Figure 3-3). These curves can also be used to calculate the volume of stream flow depletion. For example, a bore located 500 m from a stream that has been pumped for 36 days (0.1 year) from an aquifer with a transmissivity of 100 m²/d and storage co-efficient of 0.1 will begin to deplete stream flow after 11 days pumping (0.03 years on Figure 3-3). The amount of stream flow depletion will increase as pumping continues, reaching 7% on day 36 (0.1 year). If the pumping rate is 550 m³/d (200 ML/year) the stream flow depletion rate, on day 36, will be 38.5 m³/d (Figure 3-3). Curves showing the total volume depleted can also be calculated (Figure 3-4 [log scale] and Figure 3-5 [linear scale]). After 36 days pumping the total volume depleted from stream flow is 0.386 ML or 1.9% of the total volume pumped (Figure 3-4).

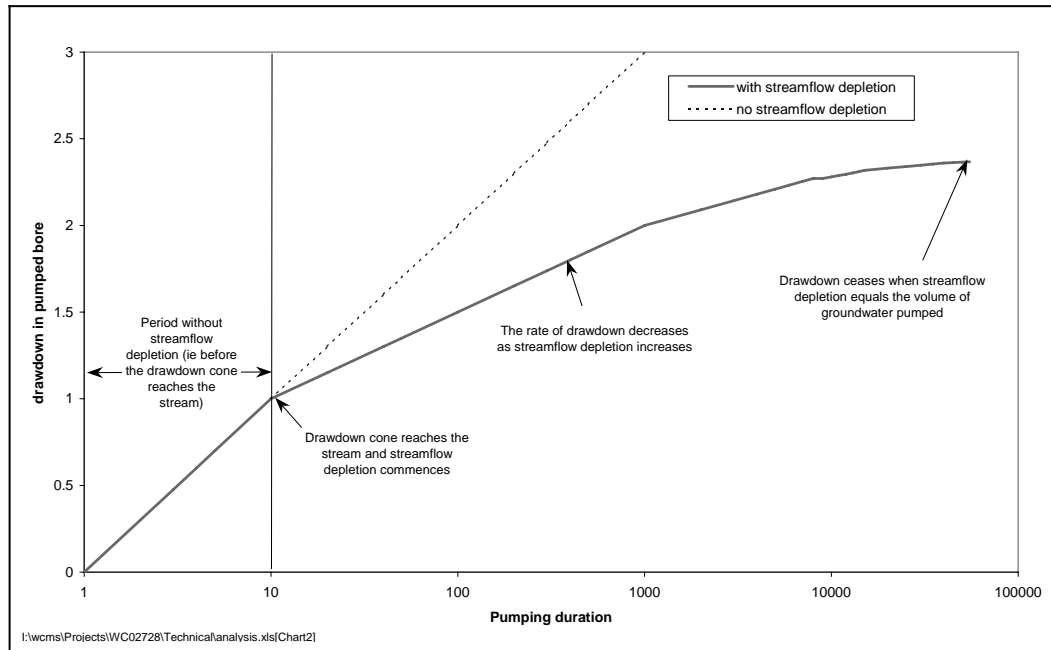
Another important issue is the volume of groundwater pumped before the drawdown cone intersects the stream. If pumping ceases before the cone reaches the stream the model will calculate zero stream flow depletion. This underestimate of stream flow depletion will be small when the bore is close to the stream and large when it is located at a large distance from the stream. It is possible to take this volume into account (including the timing of the stream flow depletion) by incorporating a non-pumping or recovery period into the analysis.

In summary the model for stream flow depletion is conceptualised in the following way:

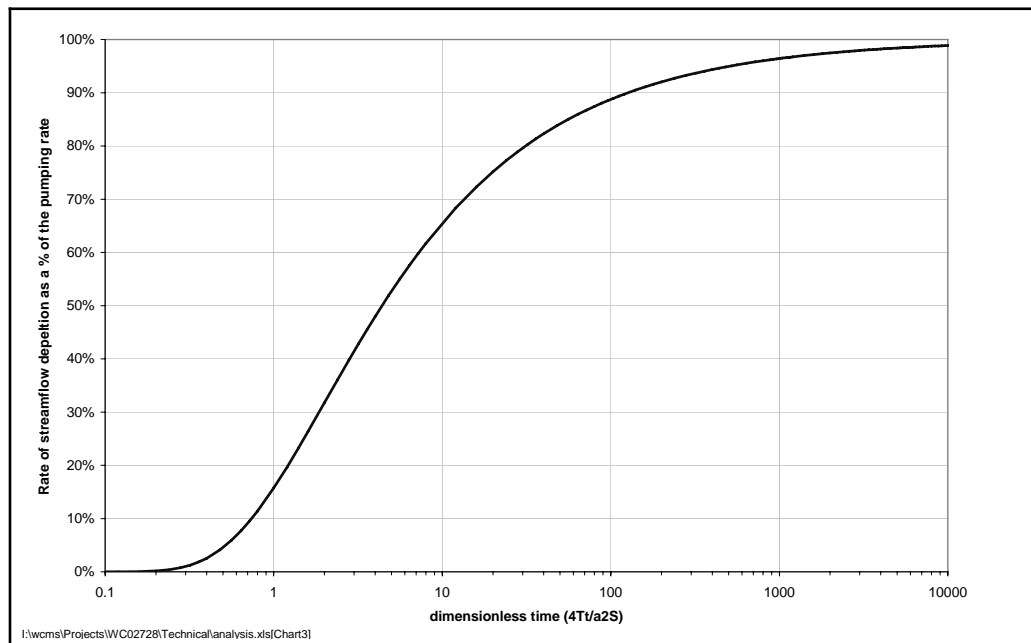
- Groundwater is extracted from a bore at a constant rate
- The stream is represented as a straight line at some distance from the pumped bore
- The source of increased recharge is represented as an image bore (i.e. an injection bore rather than the stream itself) located on the opposite side of the stream (equidistant from the stream as the pumped bore)
- The pumping bore and injection bore commence operating at the same time
- The injection rate is the same as the pumping rate
- The aquifer is isotropic and of infinite areal extent
- Prior to pumping the groundwater gradient is zero (i.e. there is no flow to or from the stream or within the aquifer)
- The only source of recharge is the stream (simulated by the injection bore)
- The stream fully penetrates the aquifer
- The stream bed is not clogged with low permeability sediments.

The most important feature demonstrated by these curves is that given sufficient time stream flow depletion will occur, and will eventually comprise 100% of the pumped volume for the assumed conditions.

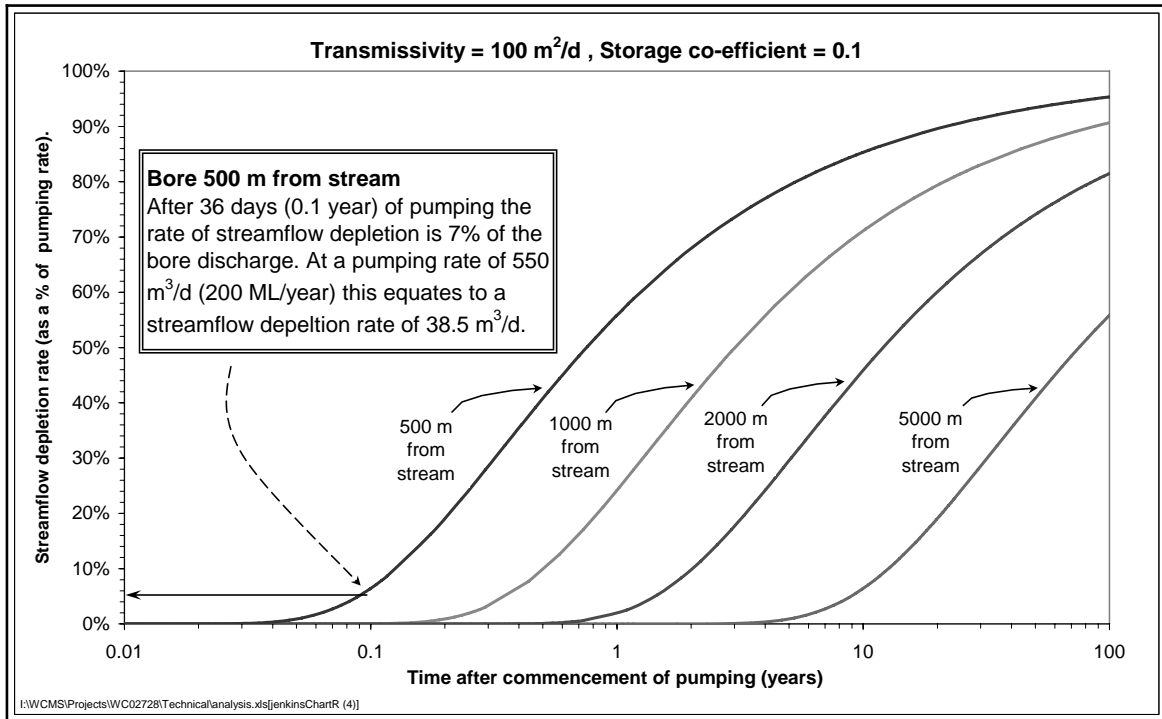
- Figure 3-1 Effect of induced recharge on drawdown in the pumped bore



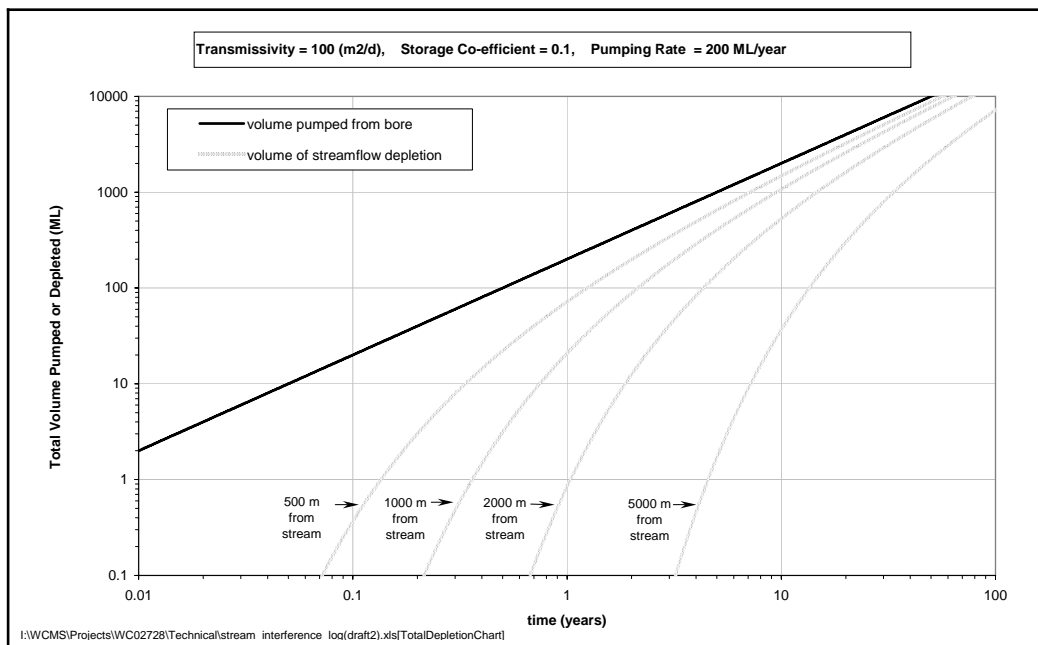
- Figure 3-2 Change in the rate of stream flow depletion as a percentage of the pumping rate after Jenkins, 1968 (i.e. change in the slope of the drawdown curve in Figure 3-1)



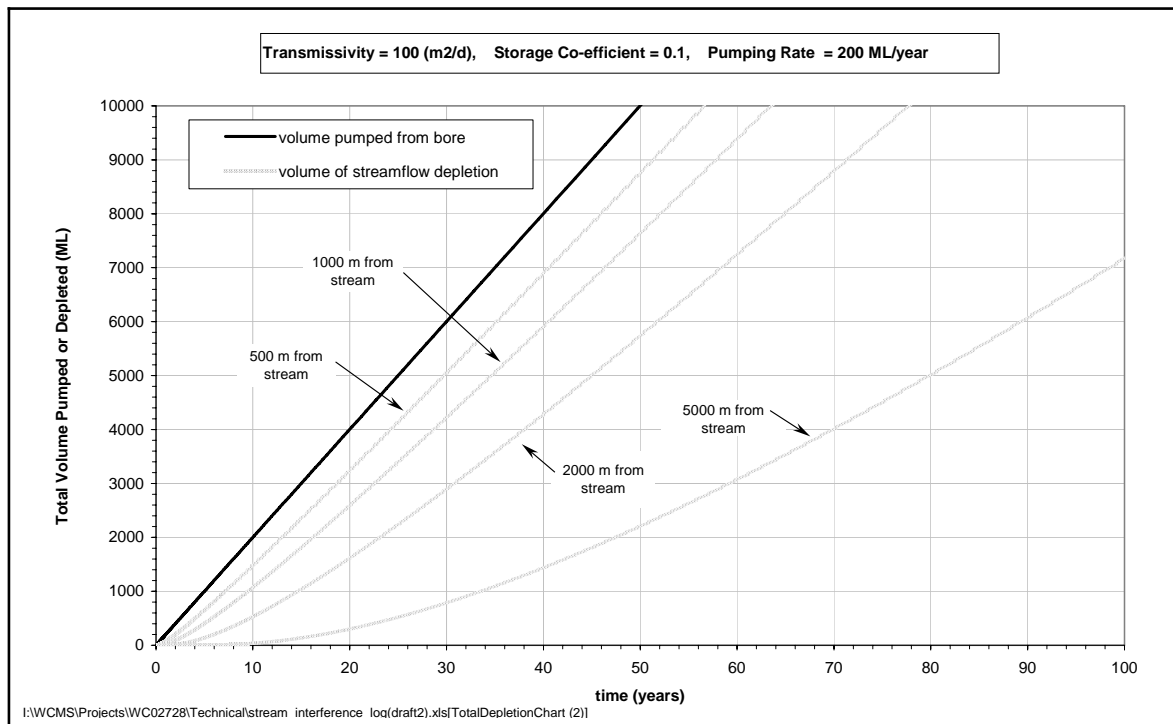
- Figure 3-3 The delay before stream flow depletion commences at increasing distance between the bore and stream (with $T = 100 \text{ m}^2/\text{d}$ and $S = 0.1$)



- Figure 3-4 The volume of stream flow depletion over time at increasing distance between the bore and the stream (with $T = 100 \text{ m}^2/\text{d}$, $S = 0.1$, and pumping rate = 200 ML/year) – log axes



- Figure 3-5 The volume of stream flow depletion over time at increasing distance between the bore and the stream (with $T = 100 \text{ m}^2/\text{d}$, $S = 0.1$, and pumping rate = 200 ML/year) – linear axes



Jenkins (1968) introduced the concept of the stream depletion factor (SDF) which is the time after the commencement of constant rate groundwater pumping that the stream depletion rate will be 50% of the groundwater pumping rate. The SDF is defined as:

$$\text{SDF} = d^2/S/T$$

where d is the distance between the extraction bore and the river, T is the transmissivity and S is the specific yield. The important point to note is that the time is a function of the distance squared. Hence, as the distance increases, the time increases at a much greater rate. At any time, the stream depletion rate (q) as a proportion of the groundwater extraction rate (Q) is:

$$q/Q = \text{erfc} (\text{SDF}/4t)^{1/2}$$

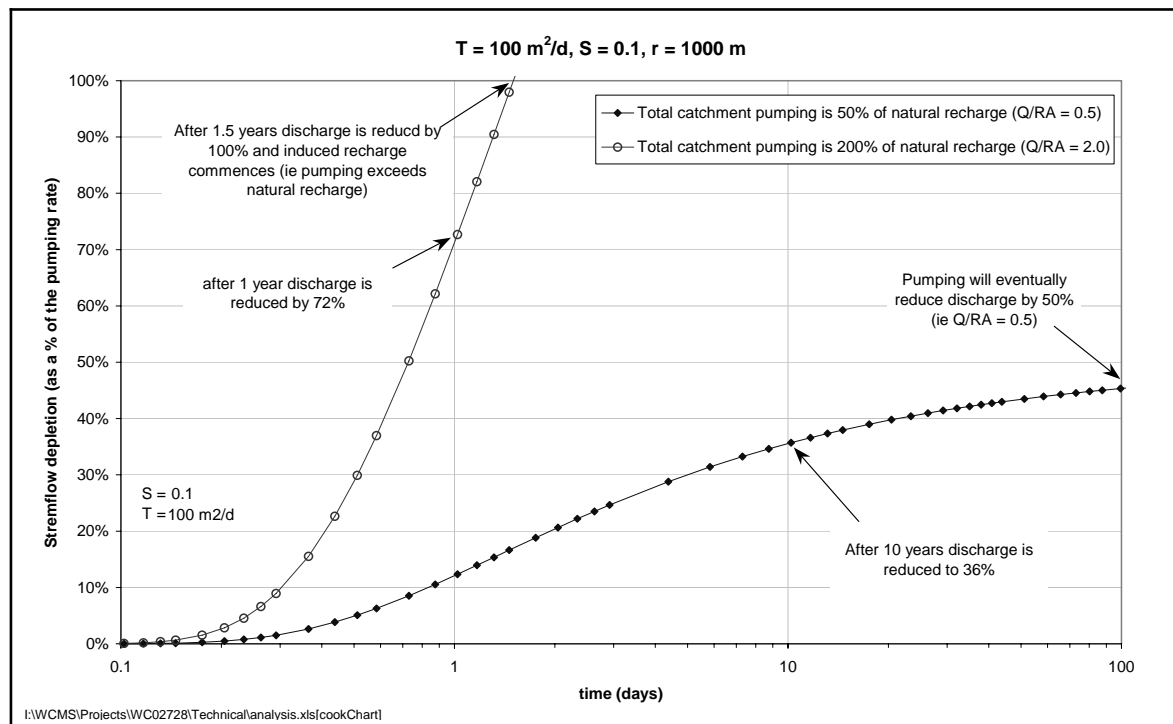
where erfc is the complimentary error function and t is the time since the start of pumping. This approach is useful in understanding basic concepts, but suffers from significant idealisation, including:

- an unconfined aquifer
- the river fully penetrates the aquifer
- no clogging of the river bed is allowed
- the aquifer is semi-infinite.

3.3 Idealised Case - Modified

In the idealised case by Glover (1974) the model assumes there is no natural recharge. Invoking a sloping water table onto the Jenkins (1968) model implies that there is a source of recharge (to sustain the water table slope in the absence of pumping). Using research by Knight et al. (2002), Cook and Lamontange (2002) have incorporated natural recharge (i.e. recharge from rainfall) into the idealised case (i.e. all of the assumptions of the Jenkins (1968) model remain except for the 'flat water table'). By incorporating natural recharge Cook and Lamontange (2002) have shown that the total pumped volume must exceed the total 'natural' recharge volume before there is a net induced recharge from the entire river system (Figure 3-6). Induced stream leakage only occurs if the pumping rate exceeds the total 'natural' recharge to the catchment (Figure 3-6). Note – the model also shows reduced baseflow occurring in the same manner as in the Jenkins (1968) model. This model provides a means for assessing the stress status of an entire catchment. However, the Cook and Lamontange (2002) model cannot be used for assessing the impact of pumping on a specific reach. Cook and Lamontange (2002) have also shown that the distribution of bores within a catchment can have a significant impact on the timing of reduced discharge and induced stream leakage. Hence, in simple terms, for most hydrogeological situations the greater the distance the extraction bore from the river the longer the time for the effect to be felt at the river, i.e. distance equals time. The timeframes may be many years. For example the 'drying' of the upper parts of many catchments in the United States took many decades, as per the discussion in Section 4.

■ Figure 3-6 Effect of different ratios of pumping to recharge on stream impacts (modified after Cook and Lamontange, 2002)



1. 'r' represents the distance all pumping occurs from the river (all bores are located at this distance)

There are also situations where groundwater pumping can increase the groundwater recharge rate. This is normally associated with a reduced water table as a result of groundwater pumping. Several different processes may operate, including an increase in river recharge from a losing stream and an increase in diffuse recharge due to a reduction in rejected recharge. In both cases the groundwater pumping causes a reduction in river flow, directly or indirectly, through a reduction in surface runoff.

3.4 Typical Case

As described in the review, streams and aquifers are not typically configured in the manner described for the idealised case. As a result the predictions using the idealised case may be in significant error. An evaluation by Sophocleous et al. (1995) identified the range of discrepancy between the idealised case without recharge (Jenkins, 1968) and simplified typical cases. A summary of these results are presented in Table 3-1. The features that introduced the most significant error (>10% error in the predicted stream flow depletion) were streambed clogging, partial penetration of the aquifer, and aquifer heterogeneity. In each instance, except transverse aquifer heterogeneity, the idealised case overestimated the stream depletion. On the basis of the assessment by Sophocleous et al. (1995) it could be concluded that more sophisticated solutions should be used to evaluate stream depletion. However, the evaluation by Sophocleous et al. (1995) was undertaken using a stream/bore configuration that achieved 95% stream depletion over a 2 month period (i.e. a bore very close to the stream). If, however, the modelling was conducted over a longer period of time and/or at greater distances from the stream it is likely that the level of error would be lower, and if the distance and/or time were sufficiently long then the difference between the models would be negligible (i.e. at steady state the volume pumped equals the volume recharged irrespective of the source of the recharge). Aside from stream and aquifer configuration, Sophocleous et al. (1995) have also identified a key issue regarding the assessment of stream depletion which is:

Should transient or steady state conditions be used to assess the impact of stream depletion, and if transient conditions are to be used what period of time is representative of a typical pumping period?

■ Table 3-1 Potential error of idealised case (after Sophocleous et al. 1995)

Typical case feature ¹	Discrepancy with idealised case
Variable stage stream (in equilibrium)	2 – 8% Overestimate by idealised case
Gaining or losing stream (± 1 m head)	5 – 8% Overestimate by idealised case
Clogged streambed	($k_{sb}/k_{aq}=0.01$) 58 – 71% Overestimate by idealised case ($k_{sb}/k_{aq}=0.1$) 9 – 29% Overestimate by idealised case
Storage co-efficient (0.1 to 0.3)	1 – 8% Overestimate by idealised case
Hydraulic conductivity (50 to 86 m/day)	1 – 8% Overestimate by idealised case
10% partial penetration by the stream	10 – 61% Overestimate by idealised case
Aquifer heterogeneity (layered)	7 – 26% Overestimate by idealised case
Aquifer heterogeneity (transverse)	4 – 38% Underestimate by idealised case

1. only one feature was evaluated at a time

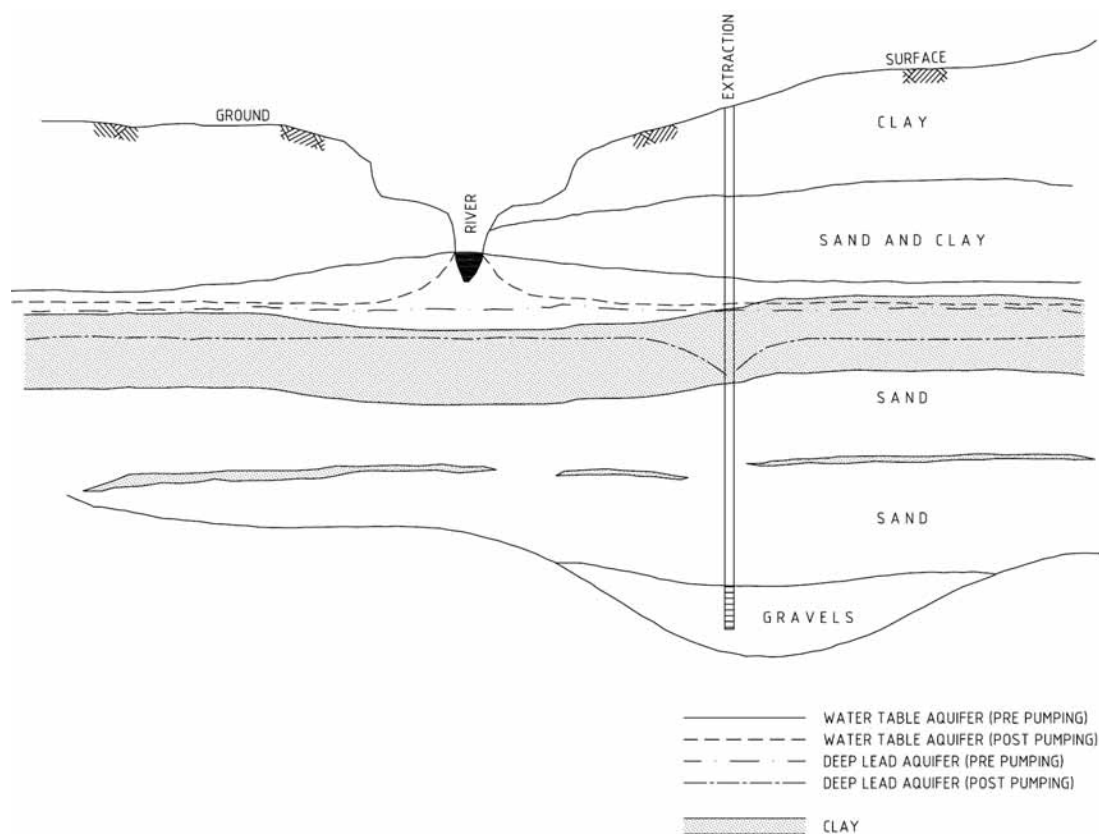
It is clear that there are many issues that require further examination to determine whether the idealised case is appropriate. For example, is the level of error using the idealised case acceptable?

The case of partially penetrating streams is discussed by Butler et al. (2001). They arrived at similar conclusions to Sophocleous et al. (1995). However, they also noted that when the pumping wells are at large distances from the stream the overestimation was usually of no practical significance.

3.5 Semi-confined Situation

In many typical situations in Australia, the river may be located in a shallow unconfined aquifer, while pumping may occur from a deeper semi-confined aquifer. This is shown diagrammatically in Figure 3-7. In this case downward leakage is induced due to deep aquifer pumping. This also results in reduced stream flows, albeit typically over a longer time period than the unconfined case.

■ Figure 3-7 Typical hydrogeological situation of pumping from a semi-confined aquifer



The previous analytical analysis methods have generally covered the case of the unconfined aquifer. Even though the unconfined aquifer case is typical, there are many situations

throughout Australia where groundwater pumping occurs from a deeper semi-confined aquifer and the stream is incised into an aquitard. Hunt (2003b) has developed an analytical analysis method for this case. It is included as Appendix A as it represents a valuable and poorly known tool for the analysis of this common case. The use of this analysis method in typical situations in Australia shows that the same fundamental processes as described above still occur. However, as expected, the time lags are just increased, depending on the hydraulic properties of the specific situation. The time lags can typically be decades or even centuries. Also, as shown by Braaten and Gates (2004), the distance between a pumping bore and the river becomes less important in determining the time lags.

3.6 Local Scale Heterogeneity

The scale generally adopted in this report is the catchment scale. It is important to emphasise that at the local scale many hydrogeological processes operate which can influence the (local) impacts. In addition to the (very common) semi-confining layer case, at varying depths, (as discussed in the previous section) examples of local scale heterogeneity include stream beds with low hydraulic conductivity lining, aquifer heterogeneity, faults, preferential pathways and aquifer boundaries. For example, beneath rivers, clay and silt lenses that may be predominantly parallel to the river can be important in transferring flow down stream, either beneath the river bed or even parallel to the river. Low permeability clay and silt layers in the stream bed or the flood plain can result in a significant reduction in the connectivity between the river and the flood plain sediments. The numerous types of local scale heterogeneity act to produce effects which are locally different from the idealised cases analysed in sections 3.3 and 3.4.

Understanding these local scale processes are critically important for the interpretation of data from individual sites and stream reaches, individual bores and local scale in-river chemistry data. As local scale heterogeneity is almost always present, individual local data will often present a complex picture and care in interpretation and analysis is always needed. Nonetheless, the local scale processes should not disguise the broad regional processes. At the catchment scale, a water balance must be achieved. However, it is recognised that locally there may not be closure of the water balance.

3.7 Regional Groundwater Processes

Groundwater flow longitudinally within catchments can also be significant. For example, if there is a significant down valley flow in high permeability sediments that may underlie the river (e.g. in 'deep leads'), the catchment is not closed with respect to groundwater and there may be a significant amount of groundwater exporting the catchment. In coastal catchments, discharge to the ocean may be a major part of the catchment water balance. Submarine groundwater discharge may be important in controlling the health of estuarine or marine groundwater dependent ecosystems. In other cases, the groundwater flow may not be coincident with the surface water catchment and hence significant input or output from the surface water catchment may occur via groundwater.

If a catchment has a groundwater export component (which in reality is very common), then this must act to modify the catchment scale water balance. These regional groundwater processes can be readily considered in the water balance and so the validity of applying the idealised analytical analysis methods as described in previous sections must be considered. Nonetheless, it is appreciated that in many cases it is difficult to accurately quantify the magnitude of these regional processes.

3.8 Numerical Modelling Approaches

Numerical modelling approaches are comparatively more sophisticated than analytical modelling approaches, and necessary for understanding many 'real world' cases. As emphasised by many authors, for example Bouwer and Maddock (1997), many of the assumptions underpinning the analytical approaches are often invalid (e.g. the common lack of completely penetrating streams) which leads to the analytical approaches overestimating the stream losses due to groundwater pumping. Numerical modelling has major advantages over the simple analytical approaches, especially in the ability to predict transient impacts. Also complex real world cases frequently need a numerical model to predict the effect of, for example, stream bed clogging, narrow valleys and semi-confined conditions. However, numerical models are much more expensive than analytical models. Consequently, a common approach is to use an analytical model first and then consider if it is necessary to undertake a numerical model.

Most numerical models that are commercially available have routines which allow surface water/ groundwater interaction to be modelled. The most commonly used is MODFLOW (McDonald and Harbaugh, 1988) which has a specific River Package which is used to simulate the influence of a surface water body on the groundwater regime. The package can simulate the interaction via a seepage layer which separates the surface water body from the groundwater system.

Over the last 20 years various attempts have been made to link surface water models with groundwater models. These have had mixed success, largely because of the hugely varying time periods of the analysis between surface water models and groundwater models and also because of the different scales of the analysis. A three dimensional finite element based Integrated Groundwater Surface Water Model (IGSM) was developed in California (Montgomery Watson, 1993) and extensively used. A review of the model by LaBolle et al. (2003) identified some major computational issues which may produce significant errors. Recently a new version of MODFLOW, called MODHMS (Hydrogeologic, Inc. 2003) has been introduced which adds a one dimensional channel flow model to MODFLOW. This fully implicit coupling of the surface water and groundwater models in MODHMS provides an integrated assessment of stream aquifer interaction. This is however very computationally intensive. Werner et al. (2005) used MODHMS to understand the groundwater interaction with Sandy Creek in the Pioneer Valley, Queensland. The model generally produced a good calibration with observed stream flow, except at very low flows. However, the comparison with manual and automated baseflow separation techniques was poor. Nonetheless, the use of the MODHMS model provided valuable insights into the temporal and spatial variability of

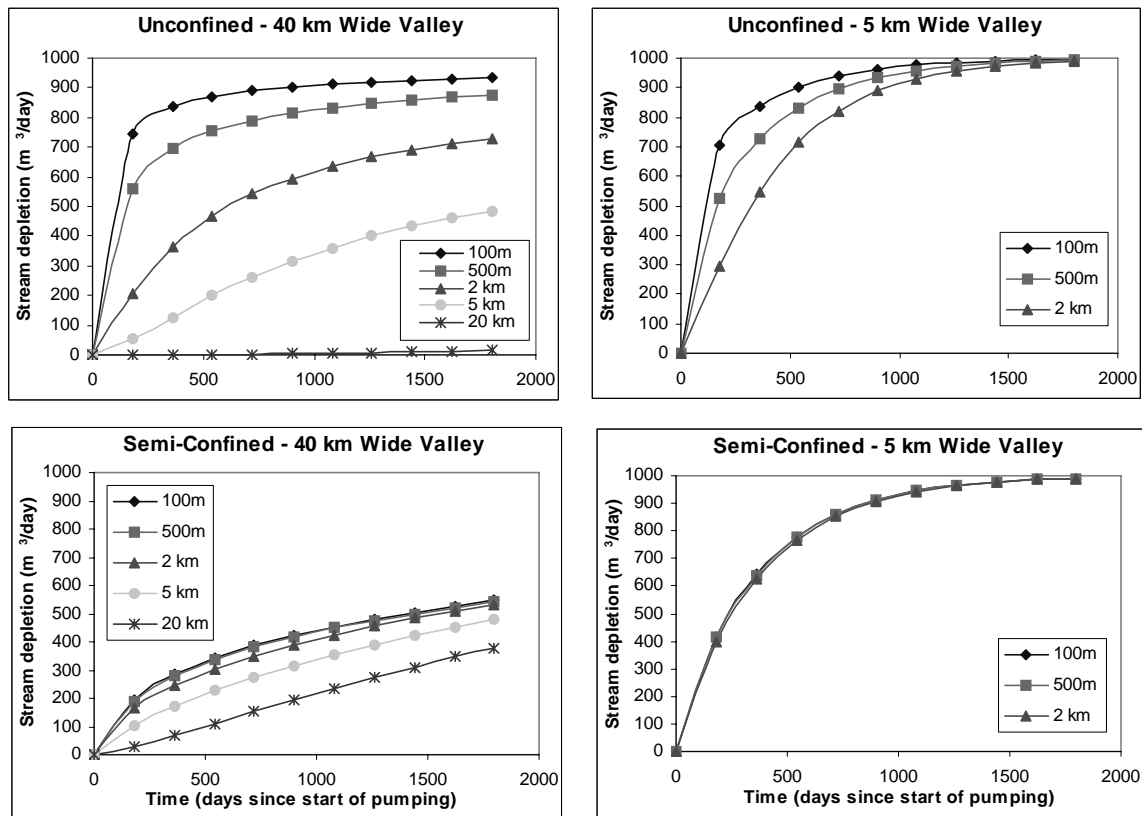
the exchange rates. Choosing the 'right' model for each situation requires considerable judgement. Lin and Medina (2003) undertook integrated stream aquifer modelling with a specific focus on modelling solute transport in both the aquifer and the stream. Transient storage phenomena for the stream was shown to be important. Also stream aquifer interaction was shown to be a very significant in influencing solute transport in streams.

Braaten and Gates (2004) used MODFLOW to assess the sensitivity of the time lag response function to a range of aquifer parameters and configurations. In order to explore how groundwater pumping affects river losses in non-ideal systems a sensitivity analysis was also undertaken. Four hypothetical base scenarios were developed in the model:

- a wide unconfined aquifer
- a narrow unconfined aquifer
- a wide semi-confined aquifer
- a narrow semi-confined aquifer.

To test the effect of the different base scenarios, a pumping bore was placed at the mid-point of the valley at varying distances from the river, pumping at 1,000 m³/day for five years in half yearly time steps. The key results are presented in Figure 3-8. The numerical modelling results demonstrated that the response function linking groundwater pumping and stream depletion is complex, with a wide range of time lags depending on the characteristics of the aquifer system. The study concluded that a numerical modelling approach is able to provide more insight than an analytical model, indicating in particular, that multiple layers and flow boundaries can have a significant effect, not just on the time lag, but on the factors that drive the time lag. For example, while distance between a pumping bore and the river is generally considered to be one of the principal drivers of the time lag, the modelling exercise demonstrated that distance had no effect in a narrow semi-confined valley. Importantly, the Braaten and Gates study indicated that a 'one size fits all' approach to managing connected systems is not appropriate. The authors recommended that the classification of systems for management must take into account whether the aquifer is unconfined or semi-confined, wide or narrow, whether the river is regulated or unregulated and whether it flows reliably or intermittently.

- Figure 3-8 Stream depletion rates for the base scenarios for a bore pumping 1,000 m³/d for 5 years at varying distances from the river (From Braaten and Gates, 2004)



3.9 Use of Chemical Methods to Determine Surface Water/Groundwater Interaction

The effective use of the above analytical and numerical methods to calculate the amount of groundwater discharge/recharge to/from a stream is dependent on the availability of the aquifer hydraulic properties and a reasonable understanding of other physical processes. The common lack of this hydraulic information has driven many researchers, over the last decade, to use chemical methods to understand and, in some cases, quantify the amount of surface water/groundwater interaction. The methods are often much less expensive than hydraulically based approaches and offer the distinct advantage of 'integrating' processes over a stream reach, rather than giving 'point' data. Most techniques rely on the differing properties of groundwater and surface water. The methods can be considered to fall into three groups:

- Use of physical properties of water, principally total dissolved solids, temperature, dissolved oxygen and pH. Lamontagne et al. (2003) demonstrated an effective use of these properties in the Wollombi Brook in NSW. Stonestrom and Constantz (2003) have produced a comprehensive report on the use of heat to study the movement of groundwater near streams. Baskaran et al. (2005) use temperature to understand interaction processes in the Border Rivers and Lower Richmond Catchments. This approach is not usually quantitative.

- Use of chemical properties of water, principally major ions, stable isotopes and radon. For example, Cook et al. (2003) used a broad range of techniques to define the groundwater inflow rates to the Daly River in the Northern Territory.
- Use of introduced tracers, principally dyes (e.g. rhodamine) and bromide.

These techniques usually require some hydraulic data to aid interpretation and consequently they are usually undertaken in conjunction with traditional hydraulic analysis methods. Their use within Australia is still limited, but is sure to increase.

The measurement of groundwater and surface water chemical parameters, albeit for determining hydraulic relationships, also has the added benefit of being able to be used to define the water quality implications for both groundwater and surface water of the interaction. In some cases the quality implications may be more important than the quantity issues. For example, the growth of toxic blue green algae has been postulated as being linked to groundwater discharge. Also, most river systems in Australia are nitrogen limited, i.e. their ecological health is controlled by the availability of nutrients. Surface water is typically nutrient poor while groundwater may often be nutrient rich. Hence, the discharge of groundwater into rivers is often crucial in controlling the health of their ecology.

4. Technical Challenges

4.1 Time Lags

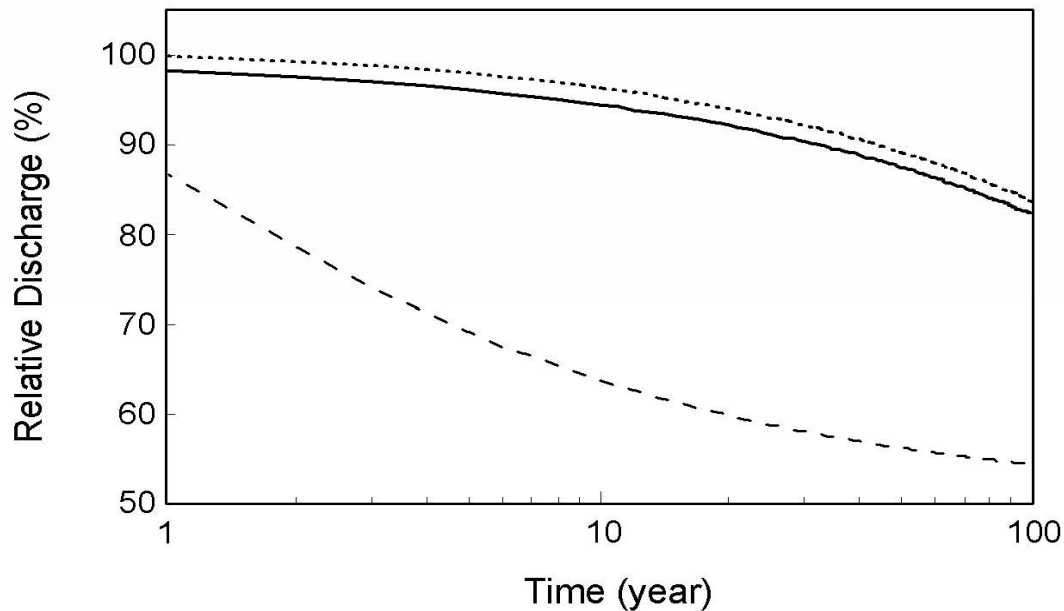
An important concept to understand in surface water/groundwater interaction studies is the effect of time. The time lag between starting pumping groundwater and the resulting effect on a stream can vary greatly, from only hours to many centuries. The analysis undertaken in Chapter 3, and shown in Figure 3-3, describes the idealised case and the factors which influence the time lag.

The Jenkins (1968) analysis method does not include recharge in the catchment. The time lag between extraction and a reduction in discharge to a stream depends on the groundwater extraction rate relative to the natural recharge and discharge rates. Cook and Lamontagne (2002) have developed models to predict changes in flow to rivers as a result of changes in recharge or discharge. They showed that if an aquifer has only one source of natural discharge, then the relative rate of natural discharge following groundwater extraction from a single bore can be calculated as:

$$\frac{\Delta q(t)}{q_0} = \frac{Q}{RA} \operatorname{erfc} \left[\frac{a}{2} \sqrt{\frac{S}{Tt}} \right]$$

where T is the aquifer transmissivity, S is the specific yield, a is the distance of the groundwater extraction from the river, Q is the pumping rate (ML/yr), t is time, R is the aquifer recharge rate (mm/yr), A is the total area of the basin, and RA is the total aquifer recharge (ML/yr). Note that this is actually the same equation as at the end of section 3.2, except that it explicitly assumes that groundwater discharge was originally equal to recharge ($q_0 = RA$). Figure 4-1 from Cook and Lamontagne (2002) shows the effect of changing the location of the groundwater extraction points within the catchment.

- Figure 4-1 Effect of distributing groundwater extraction over a catchment (From Cook and Lamontagne, 2002)



All simulations are for $Q/RA = 0.5$, $T/S = 10^5$. The solid line shows the effect of distributing groundwater extraction evenly over the entire catchment (which is 10 km in length). The broken lines both contain a 500 m buffer zone adjacent to the river. The dotted line has groundwater extraction evenly distributed in the rest of the catchment, whereas the dashed line has all groundwater extraction located on the edge of the buffer zone.

This work illustrated the critical importance of the location of the groundwater pumping relative to the river and hence the very long time lags which may exist in some cases. Nonetheless, they all ultimately have the same impact, albeit over significantly different timeframes.

For large groundwater basins with relatively low recharge fluxes, the time lag between groundwater extraction and reduced stream flows may be hundreds of years, as shown for example by Sophocleous (2005). (Obviously however where the extraction is relatively close and the aquifers are highly transmissive then the time lag can be very short.) Even when pumping is stopped, the adverse impacts on river flow may continue for a variable time. Hubbell et al. (1997) showed for the Snake River in Idaho USA, that the maximum effect of groundwater pumping in the catchment was not felt until approximately 20 years after the pumping was stopped. Also the effect continued for many more decades. In the Snake River catchment the effects of groundwater pumping produced different time varying responses, ranging from only a few years to centuries, depending on location and aquifer properties. Braaten and Gates (2004) clearly showed that for NSW aquifers, time lags can vary from only days up to decades depending on the hydrogeological environment.

Johnson and Cosgrove (1999) introduce two concepts to help our understanding of time lags. They describe response ratios and response functions. Response ratios express cause and effect relationships at a single point in time. Response functions describe the relationships including the temporal variation. Both describe stream depletion at one point in the system resulting from a unit stress at a second point. The functions can be calculated using either analytical or numerical models. A response function is essentially composed of a series of response ratios representing different time periods. In practice the response ratio and the response function is applied at a point in the stream (e.g. at a stream gauge) which represents a stream reach and describes the impact of groundwater pumping over a region of the catchment where there is a relatively uniform impact on the stream reach. For example, assume the relationship between ten years of continuous pumping and stream depletion at a given pair of locations is represented by a response ratio of 0.3. Then after ten years of pumping at a rate of 10 ML/day, the stream reach is depleted by 3 ML/day. If the stress is doubled to 20 ML/day, the response ratio would still be 0.3, but the depletion after ten years would be 6 ML/day. Johnson and Cosgrove (1999) define response ratios and functions over all of the Snake River catchment using a MODFLOW model. This approach is helpful in management for identifying like regions in the catchment where similar management approaches may be applied to control impacts of groundwater pumping.

In circumstances where the bores are located relatively close to rivers the time lag can be used to advantage in the development of management approaches. For example, Holland et al. (2005) propose to use the relatively small time lag in the narrow Ovens Valley in Victoria to assist in the development of restrictions on groundwater users to maintain minimum environmental low flows.

When time lags are short and impacts are large, stream flow monitoring, if it exists, will usually be able to measure the actual impact of groundwater pumping. However, this is often not the case. Bores located far from streams will have long time lags and if the bore yield is low (e.g. stock and domestic bores) the impacts will not readily be able to be measured. The natural variability in stream flow combined with other catchment processes (e.g. land use change) means that groundwater use impacts on stream flow can only effectively be predicted using modelling. The challenge is to develop enough well documented case studies to give the community confidence in the modelled predictions.

It is important to emphasise in the above discussion of time lags that strictly speaking the time lag before any impact may be small, but in many situations the effect is not significant until after a long period of time. Also, in cases where groundwater pumping has been underway for many years, albeit seasonal for say irrigation purposes, the effect felt at any time on the river will be due to pumping from previous years (or decades) and is not related to the current pumping.

Across Australia there is an almost infinite variety of situations with widely varying time lags. Nonetheless, at the broadest of scales, there are two common situations:

- High transmissivity alluvial aquifers associated with river systems where the bores are often relatively close to the rivers. In these cases the time lags associated with

groundwater pumping affecting river flows would be relatively short (in the order of days to months) and hence there is effectively no time lag.

- Broad plains of varying geology where the bores are far from any streams. In this case the time lags can be very long, in the order of years to decades.

Hence, the challenge for much of Australia is to characterise the time effects of the current (i.e. historical) pumping. In addition, long term monitoring of stream flow and associated groundwater pumping, to provide good case studies to illustrate the time lags, is also required.

4.2 Effects of Groundwater Pumping Far from a Stream on Reducing Stream Flow

4.2.1 Basic Hypothesis

Virtually all published literature on the impacts of groundwater pumping on stream flow deals with the case of bores located relatively close to a stream, i.e. within several kilometres, and most of these cases deal with bores that are within tens of metres of the stream. Where groundwater pumping is located far from a stream, e.g. tens of kilometres away, the effects of pumping on reducing stream flow are theoretically identical, albeit there may be very long time lags, e.g. decades or centuries. The groundwater drawdown emanating from the extracting bore will ultimately have the effect of reducing stream flow. This is shown in Figure 4-2. However, in the typical catchments in Australia, which are often relatively flat and with very low hydraulic gradients, the water table may come relatively close to the ground surface at many locations throughout the catchment. Therefore, evapotranspiration (ET) from the water table may be significant. This is referred to as ET_{gw} . ET_{gw} will potentially occur through many mechanisms: through deep rooted vegetation where the water table is within about 10 m of the surface; through wetlands scattered throughout the catchment where ET_{gw} may be large, and most importantly on the river flood plain where groundwater use by riparian vegetation and ET_{gw} from the typically shallow water table could be significant. The ET referred to here is ET from the groundwater table, which is usually much less (e.g. 5 – 10%) than the actual ET as described in the Climatic Atlas of Australia – Evapotranspiration (Wang et al. 2001). The actual ET includes ET from the land surface and the unsaturated zone. Only in exceptional cases of, for example, a very shallow water table, good groundwater quality and a forested catchment would the ET derived from groundwater approach the actual ET values in Wang et al. (2001).

When there is a steeply incised stream and a deep water table (e.g. greater than 10 m depth) over all of the catchment the amount of ET_{gw} from the water table would be almost nil. In this case it is expected that the impact of groundwater pumping on reducing stream flow would be virtually 100%, (albeit often with a long time lag). However, where water tables are between 0 m and about 10 m in depth there would be significant ET over the catchment. In this common case the impact of groundwater pumping on reducing stream flow would be less than 100%. It is important to note in this case that although there would be less than a 1:1 impact on reduced stream flow, the impact of groundwater pumping would also be reduced ET over the catchment and this would have a direct effect on the

health of groundwater dependent ecosystems (principally terrestrial vegetation and wetlands). A working hypothesis is that the actual impact would be a function of the water table depth. (This approach is only applicable to unconfined aquifers and does not consider groundwater discharge to deep aquifers, the ocean, outside the surface water catchment and other common hydrogeological complexities. Also this approach is for the steady state, which usually means over a long timeframe.)

Consider the groundwater component of the steady state water balance over an idealised catchment:

$$R = D \text{ where } R = \text{Recharge, } D = \text{Discharge}$$

As emphasised in Devlin and Sophocleous (2005), this over simplification can lead to erroneous conclusions, but for the purposes of this discussion is helpful.

For our idealised catchment and with a gaining stream D can be considered to comprise two components, discharge to ET and discharge to streams, hence:

$$R = D_{et} + D_{st}$$

The relative significance of discharge by ET and discharge to streams in a catchment will vary greatly depending on the depth of the water table and the morphology of the catchment. In catchments with deep water tables the ET will be nearly nil and all discharge occurs to streams. Conversely, where there are large areas of shallow water table, the amount of discharge to ET will be equal to the recharge and there will be no discharge to streams. It is important to note that when the water table is shallow the capillary fringe may almost intersect the land surface and consequently the amount of D_{et} may be very large. The importance of the capillary fringe is discussed by Gillham (1984).

When groundwater pumping commences the discharge component can be expanded:

$$R = D_{et} + D_{st} + D_b$$

where D_b is discharge via a bore.

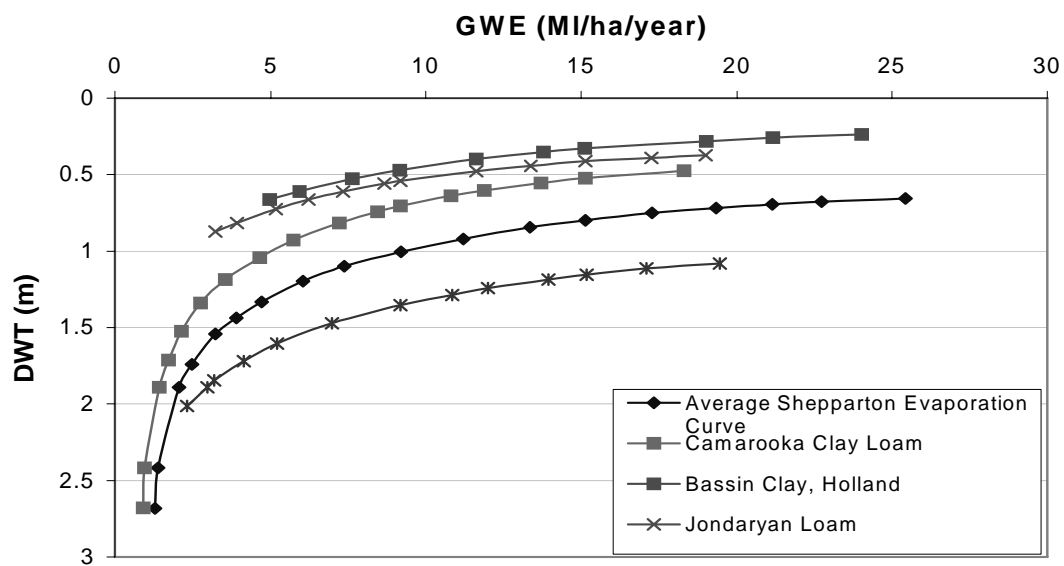
As groundwater pumping commences the groundwater level decreases and volume of D_b is matched by a reduction in D_{et} and D_{st} . (In reality water is taken from groundwater storage in the short term and so the above equation strictly only applies to the steady state case, e.g. the long term.) Depending on the location of the bore relative to the D_{et} (e.g. a wetland) there may initially be a greater impact on D_{et} rather than D_{st} . As groundwater levels fall the amount of ET decreases. But in virtually all catchments the level of the base of the stream is lower than other features in the catchment where ET is occurring, e.g. wetlands and vegetation using groundwater. Hence, gradually over time as the groundwater level falls, the D_{et} decreases at a greater rate than D_{st} and ultimately (at steady state) all of D_b may be derived from D_{st} . In this case D_{et} is already zero and cannot decrease any further. Clearly, if there is only a modest decrease in groundwater level due to groundwater pumping then both D_{et} and D_{st} will supply D_b . However, if there is a significant decrease in groundwater level such that the groundwater level is below the extinction depth for ET, then all the D_b

will be derived from D_{st} . D_{et} is effectively 'switched off', leaving only D_{st} to supply D_b . What this means in practice is that the impact on groundwater dependent ecosystems may be very significant and also that in the long term the impact of groundwater pumping on stream flow will tend to be 100% of the volume of groundwater pumped, i.e. a 1: 1 impact.

An important qualification to the above hypothesis exists. The above discussion deals with the case of a gaining stream. If the stream is a losing stream or the stream becomes a losing stream due to groundwater level decline then the above equations do not hold, as an additional 'recharge' term needs to be included. This does not alter the primary hypothesis.

It has long been known that the change in ET with depth is not linear but rather is highly nonlinear, (see for instance Talsma, 1963). This is shown in Figure 4-2. As the water table decreases due to groundwater pumping, the ET decreases at a proportionately greater rate, such that the effect described above of shifting the impact more and more to D_{st} , is actually increased even more due to the nonlinear nature of the ET with depth relationship.

- **Figure 4-2 Groundwater evaporation with depth (after Talsma, 1963)**
From SKM, (2005b) (Note: 1 ML/ha equals 100 mm)

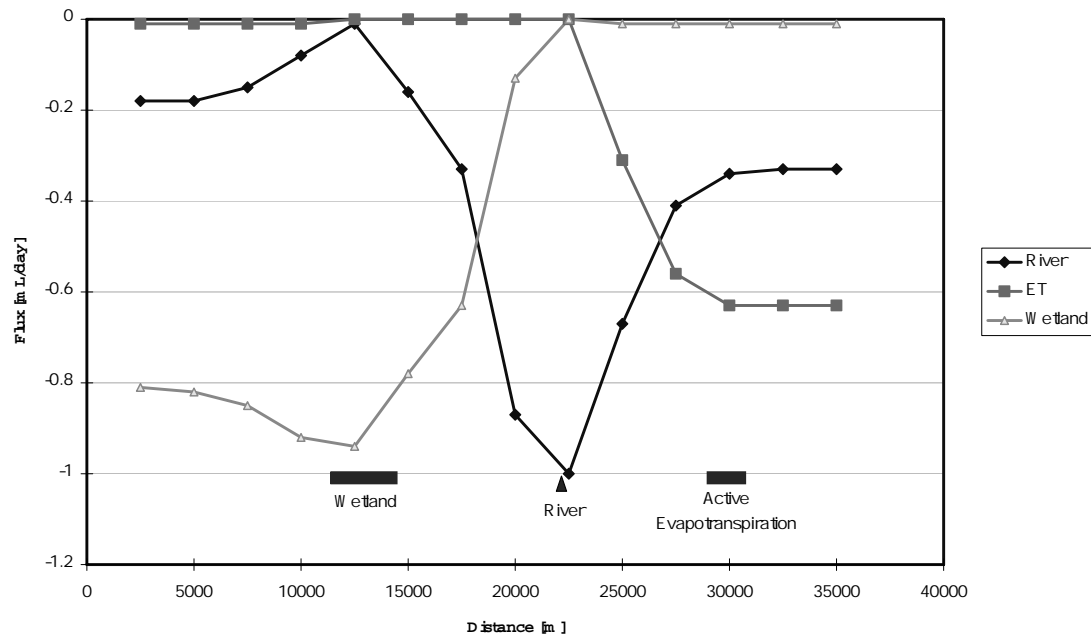


4.2.2 Testing Basic Hypothesis

The above hypothesis, that in time there is a tendency for a greater proportion of the effect of groundwater pumping to be derived from stream flow, is tested using a simple numerical model for a hypothetical catchment. Details of the model and its results are presented in Appendix B.

The hypothetical catchment considered in the model is typical of semi-arid areas of Australia. The catchment is approximately 35 km by 25 km with a hydraulic conductivity of 2 m/d. There is a river flowing through the middle of the catchment and a significant wetland. Over the whole catchment ET_{gw} represents 5% of the water balance. The model was initially run in steady state with the location of an extraction bore varying across the model. The key results of the model are summarised in Figure 4-3.

- Figure 4-3 Changes in mass balance caused by groundwater extraction – change in flux vs position of pumping bore. (Note: this is at steady state)



The key conclusions from this hypothetical modelling are:

- The recharge rate over the model does not stabilise the cone of depression and hence the impact is not prevented from reaching the river.
- The location of the pumping bore has a major influence on the relative impact on ET and discharge to the river.
- When the bore is introduced, the water comes from the river and ET. Depending on the location of the bore, the impact on reducing river flows will be greater over time than the impact on reducing ET.
- Even when the bore is located directly in the middle of the active ET_{gw} zone (i.e. at 8 km from the river), there is still significant impact of groundwater pumping on the river. Obviously when the bore is close to the river the impact on reduced stream flow is approaching 100%.
- The long time to reach steady state is because of the very flat hydraulic gradient (0.0005) and the low hydraulic conductivity (2 m/d).

This model deals with the case of a pumping bore being introduced into a 'virgin' catchment. The pumping lowers the water table and ET is extinguished over part of the model. If additional bores were introduced into the model then virtually all the impact of pumping would be felt by greater reduction in river flow.

The modelling suggests that the basic hypothesis espoused in 4.2.1 is correct. However, in reality it is likely to be more complicated and the relative significance of impact will be

critically location specific.

4.2.3 Application to Australia

The lack of detailed field studies where the full water balance is 'closed' is noted. The Australian literature contains examples of surface water focussed studies where, for example, runoff and ET are measured but groundwater is ignored. Conversely groundwater focussed studies may measure groundwater recharge and even runoff, but ET is ignored. Hence, frequently the water balance is almost never 'closed' and major assumptions are made about key components of it. Also, an important distinction needs to be drawn between the natural catchment water balance (albeit often with cleared native vegetation) and the developed catchment water balance with significant groundwater pumping underway. Greater confidence in the fundamental hypothesis of this report will be achieved only by better quality total catchment water balances.

Depth to water table maps are gradually being prepared for many catchments throughout Australia. For example, the Australian Dryland Salinity Assessment (2000) produced a depth to water table map for all of Victoria. Since then depth to water table maps have been produced in many other catchments. These typically have contour intervals of <2 m, 2 – 5 m, 5 – 10 m and >10 m. These contour intervals are suitable for considering the effects of ET in a catchment.

In areas where the water table is between 1 and 2 m, the average groundwater ET would be large; in the order typically of 100 to 1,000 mm/yr. Where the water table is between 2 and 5 m the ET would typically be 10 to 100 mm/yr. The change in ET with depth depends on many factors, especially soil type. It is assumed for the purposes of this approach that if the water table is >10 m then the ET is almost zero.

Many catchments in Australia are very flat with commonly large areas of relatively shallow water tables. Obviously this generalisation varies greatly and there are as many exceptions as there are 'rules'. Nonetheless, in Australia there are large areas of shallow water table where the amount of discharge to ET will be equal to the recharge and there will be no discharge to streams. The fact that many of our streams in Australia have significant baseflow suggests that in many catchments across Australia the ET volume is comparable to the groundwater volume discharging to streams.

Whilst there are very few full water balances undertaken for catchments in Australia, the limited available literature (e.g. Jolly, 2001) suggests that ET from groundwater for typical catchments in Australia may be significant relative to the amount of groundwater discharge to streams. This is the 'natural' case. However with the introduction of groundwater pumping in a catchment (the 'developed' case) the postulated mechanism above of D_{et} decreasing and D_{st} decreasing at a much slower rate will occur, and in the cases where the groundwater level is significantly lowered the impact of groundwater pumping on reducing stream flow will be approaching 1:1. This has very significant implications.

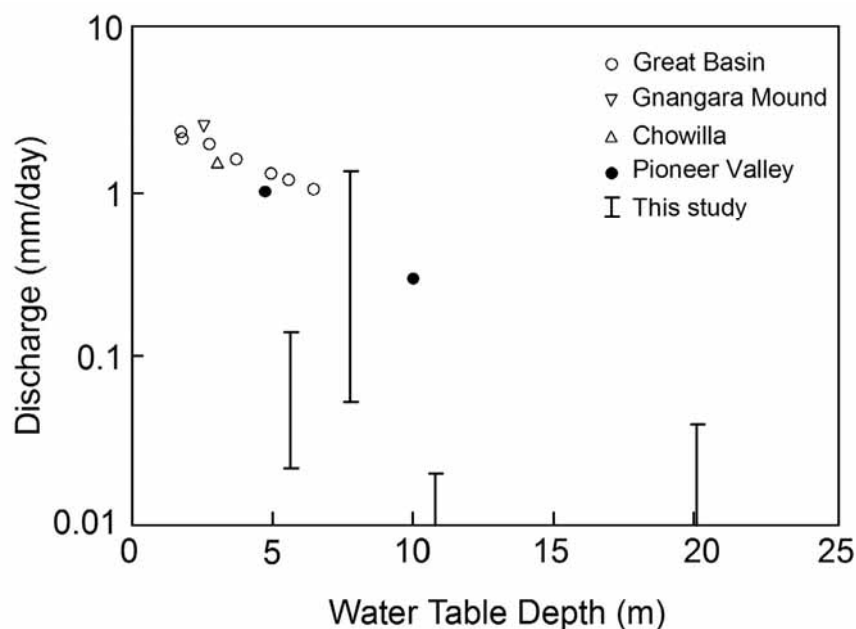
There are several important qualifications to this hypothesis:

- This only applies to the unconfined aquifer case where there is a gaining stream
- This would usually only occur over the very long term, i.e. decades or even centuries
- The location of the pumping bores with respect to the discharge sites is very important
- Groundwater ET will usually not be completely 'switched off'.

Nonetheless, the hypothesis that the effects of groundwater pumping will often ultimately be felt at the streams is considered to be the general case. The time for this to occur in many typical catchments in Australia will often be many decades.

There are some measurements of ET from groundwater in Australia (e.g. O'Grady et al. 2006) and these are summarised in Cook et al. (2006). These results are shown in Figure 4-4. This indicates that with a typical water table depth of say 5 m the ET_{gw} is in the order of 1 mm/day. As there are many areas across Australia with water table depths of this magnitude, this suggests that ET_{gw} is a significant process.

- **Figure 4-4 Groundwater discharge rate as a function of water table depth (From Cook et al. 2006). Error bars denote results of Ti Tree Basin Study, central Australia**



Actual ET and therefore actual water use by the environment accounts for 65% of the water use on average across the world. There is reasonable evidence to suggest that for Australia it is higher and in the order of 85%. As ET is clearly the major part of the water balance (other than rainfall), our challenge is to understand ET better. Actual ET by vegetation is the major water use component. This has only been measured at the field scale for agricultural crops and limited native vegetation. Over the last 15 years major research has been underway to measure the actual ET using remote sensing linked to the Surface Energy

Balance Algorithm for Land (SEBAL). The methodology is described by Bastiaanssen et al. (2005). The significant technical advance provided by this approach is the spatially and temporally distributed nature of the ET measurement at a reasonable cost. SEBAL was originally developed to estimate evaporation from shallow groundwater tables in the Western Desert in Egypt. In recent times SEBAL has been used to estimate net groundwater use across large irrigation areas (see Ahmad et al. 2005).

The above discussion concluded that the principal components of the water balance which are relevant to understanding surface water/groundwater interaction are often groundwater ET and discharge to rivers. To gain a greater understanding of the relative significance of the change in groundwater ET and groundwater discharge to rivers it is desirable to estimate groundwater ET. The direct measurement of the groundwater component of the total ET is possible and various field methods are available (see Cook et al. 2006). However these isolated 'point' measurements cannot readily define the spatial and temporal variability. It is considered possible to use SEBAL combined with other spatially distributed data to estimate groundwater ET. A knowledge of land use, rooting depth of vegetation, depth to water table (as discussed above) and surface water supply information (if the region also has surface water supply), groundwater pumping data and rainfall could be used with SEBAL output to spatially estimate groundwater ET. For typical situations:

- $ET = ET_{gw} + ET_{unsat}$
- $ET_{gw} = VegET_{gw} + E_{gw}$
- $ET_{unsat} = VegET_{unsat} + E_{unsat}$
- where
- ET_{gw} = Evapotranspiration of groundwater
- ET_{unsat} = Evapotranspiration of the unsaturated zone
- E_{gw} = Evaporation from the water table
- E_{unsat} = Evaporation from the unsaturated zone
- $VegET_{unsat}$ = Evapotranspiration from the unsaturated zone
- $VegET_{gw}$ = Transpiration primarily from deep rooted vegetation, but after rainfall it will include evaporation directly from the soil surface
- In practice it is hard to distinguish between evaporation (E) and transpiration (T) in vegetated areas. Hence, for land covered by vegetation SEBAL will give a composite of E and T: ET. In areas without vegetation ET is primarily direct evaporation from the water stored in the soil and water that reaches the surface through capillary rise. Several important assumptions would need to be made, such as where vegetation sources its water for typical rooting depths. There is considered to be sufficient information available to justify these assumptions. Hence, it is considered that it is feasible to estimate a spatially distributed groundwater ET. It is however recognised that as typically ET_{gw} is a small component of

total ET the estimate of ET_{gw} may have significant error bands. Nonetheless, this can then be used to assist in estimating the relative significance of groundwater ET to groundwater discharge to rivers across typical catchments in Australia.

- The hypothesis presented in this section needs to be tested by detailed water balance focussed catchment studies.

4.3 Groundwater Discharge Component of Baseflow

Chapter 5 discusses the issues associated with baseflow analysis. The emphasis in this report on baseflow is driven by the belief that this is a relatively cheap and largely underused data source which is able to provide useful groundwater data. Of most importance is the ability for river baseflow data to be a key input to a whole of catchment water balance. Nonetheless, there remains a significant technical challenge in the interpretation of the groundwater component of the baseflow. The five main components of baseflow are discussed in Chapter 5. What is currently required are more detailed case examples linked to field measurement where the different components of baseflow are assessed and greater confidence in understanding the groundwater component is obtained. The groundwater component is almost always less than the total baseflow. One can envisage hydrogeological situations where it may be only, say, half of the baseflow. For example, where there are large floodplains with significant bank storage, through to cases where the groundwater component is almost all groundwater, as would occur in steep fractured rock undeveloped catchments. The influence of climate across Australia on baseflow also needs to be assessed.

4.4 Impact of Groundwater Pumping on Ephemeral Rivers

Most of the above discussion has been on perennial rivers. However, there are large areas of Australia where the rivers are ephemeral. In this case the argument has been put that groundwater pumping will have no impact on river flow as the river is a 'disconnected' losing stream (see Figure 2-3). The development of a conceptual model for the ephemeral river case is critically dependent on the temporal and spatial scale. It has been shown above that groundwater pumping will often lower the groundwater level beneath the river. This means that the thickness of the unsaturated zone will increase. Therefore, when the wet season rains occur and the quick flow in the river recharges the aquifer, the time taken to fill the unsaturated zone increases. Thus the length of time that the river is ephemeral also increases. Also, stream reaches which are ephemeral also expand in length due to groundwater pumping. Thus over the short term and over small spatial scales groundwater pumping will appear to have no affect on ephemeral streams. However, over longer timeframes and over greater river reaches, the ephemeral nature of streams will definitely increase due to groundwater pumping. What is required for Australia is a greater number of well monitored case studies to better understand and prove these processes.

5. Baseflow – Where Groundwater and Surface Water Meet

5.1 Introduction

Baseflow analysis provides a very useful tool for hydrogeologists to understand groundwater discharge to streams and hence surface water/groundwater interaction. This section seeks to explain the strengths and weaknesses of the techniques for separating baseflow from recorded stream flow data. It then leads on to provide typical examples of baseflow indices for several regions and rivers in Australia. Methods to analyse the trends in baseflow over time are also presented. This approach allows for a detailed analysis of the impacts of groundwater pumping in a catchment on surface water flows. These underused techniques provide valuable insights to groundwater processes and especially the relative and absolute magnitude of surface water/ groundwater interaction. The 'integrating' process between groundwater and surface water is baseflow. The hydrologic focus of this section is not intended to underemphasise the importance of alternative methods of baseflow separation, such as chemical and isotopic techniques, as illustrated, for example, by Cook et al. (2003).

5.2 Components of Stream flow and Baseflow

Stream flow can be thought of as consisting of quick flow, sourced from surface runoff and baseflow, sourced predominantly from groundwater. Most estimates of baseflow consist of:

- groundwater discharge
- interflow, which represents the discharge of water to streams through the unsaturated soil profile and not sourced from unconfined aquifers
- bank storage
- delayed surface water (e.g. from lakes and wetlands)
- delayed groundwater (e.g. from perched aquifers).

The boundary between each of these sources of water is difficult to distinguish in practice. It is well accepted that generally the major source of baseflow is groundwater discharge, although in certain circumstances some of the other components of baseflow may be significant, e.g. after major floods in high specific yield aquifers bank storage may be important. Whiting and Pomeranets (1997) develop an analysis method to predict the bank storage component to stream flow, and show that it can be significant in certain circumstances. Chen et al. (2006) analyse the importance of bank storage in baseflow separation studies and conclude that it must be included in any analysis. River channel precipitation and ET also occurs, but is generally small and indistinguishable from other components of stream flow. It is important to emphasise that in practice groundwater discharge will usually be less than baseflow. Thus, a baseflow analysis usually provides an upper bound for groundwater discharge.

Some workers, for example Halford and Mayer (2000) have identified significant problems

with the use of hydrograph separation techniques for estimating groundwater discharge and recharge. They consider that the components of baseflow identified above (plus snow melt) may be a significant component of the stream discharge record and also decrease exponentially during the recession period. Consequently the results may be ambiguous. Other workers, for example Wittenberg and Sivapalan (1999) believe that the key underlying components of the groundwater balance can be identified from baseflow separation. Interestingly, they identify that depletion of groundwater by ET loss through the water uptake by trees near the groundwater discharge into the stream, was found to influence the recession curve in the case example considered.

Surface water/groundwater interaction can occur from the stream to groundwater, vice versa or in both directions at different times, depending on river and groundwater levels and hydrogeological conditions. Baseflow separated from stream flow data at a gauging station location represents the estimate of baseflow from all of the catchment upstream of that gauging station. In practice, only part of the upstream river reaches may be receiving baseflow, whilst other reaches may be losing water to groundwater. The baseflow observed at the stream flow gauge represents the net effect of these upstream processes.

In cases where the water table is shallow and the capillary zone extends to virtually the land surface, Gillham (1984) and Abdul and Gillham (1989) showed that a rapid increase in groundwater discharge to streams occurs following rainfall. This has been proved to be due to the effect of the partially saturated capillary zone wetting up rapidly with rainfall and causing rapid discharge to streams. This process may affect the baseflow separation interpretation considerably.

In cases where there are deep water tables, and ET is effectively nil, it could be argued that baseflow equals recharge over the catchment. Many studies have attempted to prove this relationship. In most cases ET is significant and hence baseflow is usually less than recharge. Other components of baseflow, as identified above, may also be significant. Hence, in many catchments the baseflow volume cannot be used as a surrogate for recharge.

The techniques available to undertake a baseflow analysis and the assumptions used are presented in Appendix C, as are the points which need to be considered in preparing stream flow data. Solutions for baseflow separation based on analytical solutions of the Boussinesq equation, and using graphical analysis of individual recession events, are presented in Szilagyi and Parlange (1998).

5.3 The Baseflow Index

After baseflows have been separated from recorded stream flow data, the statistical properties of the data can be examined. In addition to the specific statistics on the absolute value of baseflows, such as average annual baseflows, seasonal average baseflows and baseflow exceedance curves, an additional variable that can be extracted from the data is the baseflow index (BFI).

The long-term average BFI is defined as the baseflow divided by the total stream flow over a

concurrent period. It represents the relative contribution of baseflow to total stream flow on a standardised basis for comparison between sites along a river with different upstream catchment areas and in different catchments.

The BFI is generally regarded as an indicator of the hydrogeological conditions in a particular catchment. The Institute of Hydrology (1980) presents typical baseflow index ranges for particular rock types. SKM (2003b) developed a prediction equation to estimate baseflow index in ungauged catchments in Victoria using catchment characteristics. These characteristics included vegetation cover and rainfall (indicators of input water into groundwater and surface water), stream frequency (an indicator of potential connectivity of groundwater to surface water drainage lines) and soil permeability rating (an indicator of hydraulic conductivity and transmissivity). This enables baseflow properties to be estimated in catchments with no stream flow gauging information or with stream flow conditions not amenable to a baseflow separation.

Whilst long-term average baseflow index is generally regarded as an indicator of hydrogeologic conditions, it is important to remember that baseflow index is a measure relative to total stream flow. Over short time intervals, baseflow index will generally reflect fluctuations in surface runoff rather than changes in baseflow. During extended dry periods the baseflow index will be equal to 1.0, whilst during flood events, the baseflow index will be close to zero.

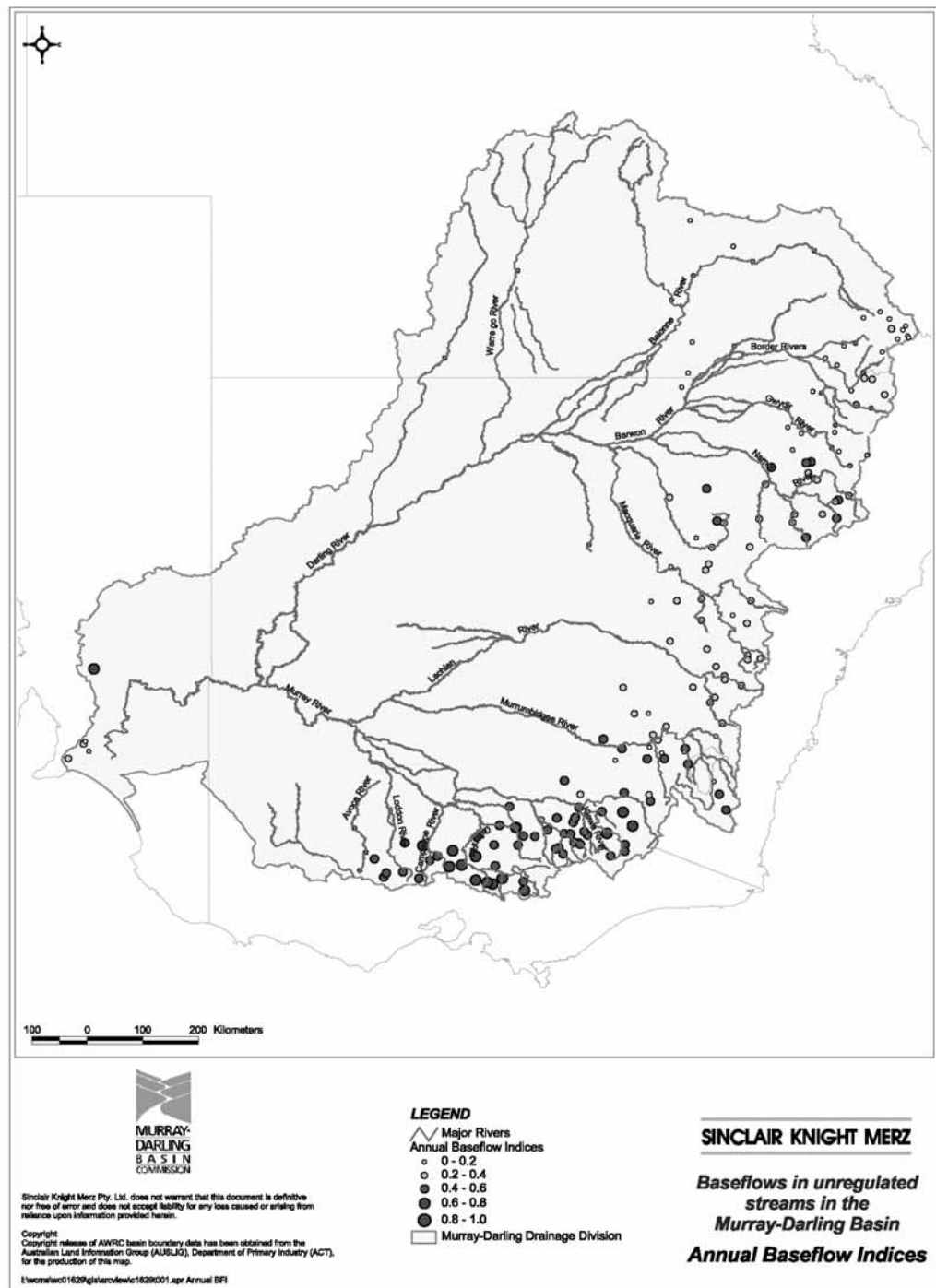
5.4 Baseflow Index Results

Annual baseflow index results indicate the annual average baseflow contribution to stream flow. Annual BFIs are useful for regional and long term studies, but they tend to disguise the marked seasonal variation in many rivers, especially in northern Australia. Hence for most studies it is considered that monthly, or at most seasonal, BFIs are required for meaningful analysis.

Winter et al. (2002) analysed the BFI of 54 streams in the U.S.A. over a 30 year period and found that the annual average BFI was 0.52. No comparable analysis has been undertaken for Australia. An analysis of 178 unregulated streams in the Murray-Darling Basin by Neal et al. (2004) over a ten year period from 1990 to 1999 revealed significant spatial variations, as shown in Figure 5-1. Baseflows were separated from surface runoff using a recursive digital filter. (A recursive digital filter is a mathematical function used to smooth the noise within time series data. In baseflow separation, it smoothes hydrograph peaks from surface runoff to reveal the underlying baseflow time series.) As only unregulated streams were used, most of the catchments were in the fractured rocks of the highlands. The annual BFIs ranged from 0.04 (almost no baseflow contribution) to 0.76 (around three quarters of the total flow is baseflow), with much higher BFIs during summer and autumn when total flow is lowest. Baseflow indices tended to be higher at the Victorian sites (median baseflow index 0.58) than New South Wales (median baseflow index 0.23) and

Queensland (median baseflow index 0.11) sites. There were too few sites to draw statewide conclusions about the South Australian data. There is a clear gradient in baseflow index from the southern Murray-Darling Basin in Victoria to the northern Murray-Darling Basin in Queensland, which is potentially attributable to the prevalence of either summer dominant or winter dominant rainfall regimes in these different parts of eastern Australia. The likely influence of the climate regime on baseflow index is supported by the statistical significance of rainfall in the regional prediction equation for baseflow index developed in SKM (2003b). There was also, as expected, significant variation between the seasons.

- Figure 5-1 Annual baseflow indices, 1990 to 1999, Murray-Darling Basin (From Neal et al. 2004)



The Daly River is one of the few Northern Territory rivers that maintains significant flow throughout the dry season. A report by Jolly (2001) provides a valuable water balance to indicate the significance of baseflow. This example is included as it is one of the few complete water balances for an Australian catchment. The mean groundwater outflow is calculated at 13 mm, while the mean annual stream flow is 146 mm/yr (volume = 6,821,775

ML/yr). This indicates that the baseflow index is 9%. During the dry season, typically from April to November, the BFI is 1. The interesting point of the analysis is that the variability in flow from year to year is very large and consequently the recharge rate varies from 0 to 300 mm/yr (mean = 90 mm/yr), using a water balance approach. The large difference in the recharge rate and the baseflow is due to the large component of ET from creeks, rivers, wetlands and riparian zone vegetation. Furthermore, the large variation in rainfall from one year to the next results in large groundwater level variation and hence large variation in ET.

Variations in BFI are controlled by several factors, the most important being climate, hydrogeology and land use. Too few baseflow analyses have been undertaken to date to show clear differences between southern (temperate) and northern (tropical) Australia. However, the variation in BFI suggests that the differences between the tropics and the rest of Australia are dominated by:

- greater fluctuations in water tables (e.g. a 10 m range is common)
- greater variability in recharge (especially if there are cyclones)
- the possibility of less total stream baseflow due in part to an increase in runoff volume
- less dry season baseflow (but this is critically dependent on the local hydrogeology).

Variations in hydrogeology across a catchment influence the amount of baseflow in streams. These hydrogeological variations are linked to the total catchment water balance. For example, high hydraulic conductivity sediments will have both high recharge and high discharge rates. In practice the usual complex hydrogeological variation within a catchment makes these simple statements often invalid. As almost all of the sites analysed by Neal et al. (2004) are in fractured rocks, the hydrogeological variability is mostly eliminated in this analysis.

5.5 Trend Analysis of Baseflows

A wide variety of land and water management actions can influence stream flow behaviour. Due to the complexity of interactions between these actions and stream flow response, catchment managers generally rely on catchment and water models to isolate and estimate likely stream flow response. This approach can be problematic as it is based on inferring a response under modelled conditions rather than directly measuring the response in the river under historical conditions. Consequently confidence in this approach is heavily dependent on how well the model is able to reproduce the historic behaviour.

Trend analysis can be used to examine historical stream flow response to land and water management actions. Nathan et al. (2000), for example, utilised trend analysis to successfully detect and estimate the magnitude of the reduction in stream flow caused by farm dam development in the Marne River catchment in South Australia. Such an outcome provides confidence to both modellers and catchment managers that stream flow behaviour is well understood and that management actions (or absence thereof) to date have resulted in a known, quantifiable and statistically detectable change in actual stream flow behaviour.

The same approach can be applied to the analysis of baseflows in order to better understand the effect of land and water management actions on them. Particular issues include the effect of groundwater pumping and large-scale land use change, such as agro-forestry and urbanisation, on stream flows.

There are various trend analysis techniques available (Helsel and Hirsch, 1992). Techniques which lend themselves to the trend analysis of baseflows are those that can accommodate missing data and can adequately account for the effect of exogenous variables such as climate. An example of such a technique is the use of a Generalised Additive Model (GAM), which addresses the issue of the influence of exogenous variables (Nathan et al. 1999). The GAM technique has been tested over a wide range of practical hydrologic applications in Australia since the late 1990s.

Regardless of the technique used, the first step in the trend analysis is the model formulation, which will depend on both the nature of the hypothesis that the trend analysis is attempting to address and the availability of time series data to support the test.

An example would be the effect of groundwater pumping on groundwater discharge to streams. The equation chosen to fit observed baseflow data may consist of some function of time, quick flow and season, as shown by the equation below:

$$\text{Baseflow} = C_1 + C_2.\text{fn}\{\text{time}\} + C_3.\text{fn}\{\text{season}\} + C_4.\text{fn}\{\text{quick flow}\} + \text{AR}$$

where c_x is a constant and AR is an auto-regressive term, used to remove the time dependency of residuals.

In order to achieve the best fit of the model to the observed data, the function used to fit each independent variable is determined by the user, and can be either linear, polynomial or spline. The spline function is often able to provide the best fit to the data as, by definition, this function includes both a linear and non-linear component. Variables are transformed as required to ensure that modelling assumptions required to make statistical inferences were not violated. The model assumptions relate to the independence, constant variance, and normality of model residuals.

There are myriad of factors to consider when selecting variables for inclusion in a trend analysis of baseflows. The final model adopted will be governed by the statistical significance of independent variables and the suitability of the model fit with respect to model assumptions, particularly for parametric models such as GAM. For example, the pumped volume time series selected will depend on the estimated lag between individual groundwater production bores and stream flow response and the vertical connectivity to the river of aquifers being pumped at different depths. Similarly, the selection of appropriate climate variables will depend on local conditions, but could include combinations of current rainfall, lagged or accumulated rainfall (either a simple lag or accumulation or the adoption of an antecedent precipitation index), quick flow or regional groundwater levels in aquifers unaffected by pumping. In systems where irrigation takes place, an allowance must also be made for the effect of irrigation on aquifer behaviour and stream flow response.

Trend analysis does not lend itself well to the inclusion of discretised variables, because accounting for exogenous variables usually requires the development of a continuous functional relationship between that variable and the dependent variable. This has implications for detecting the effect of groundwater pumping on baseflows, because an individual groundwater pump is typically either on or off. This creates a range of baseflows for effectively only two values of pumped groundwater volume, which is difficult to accommodate with parametric trend analysis techniques. This can be overcome through the analysis of stream flows affected by a greater number of groundwater pumps (particularly if they operate independently) or analysis is at a longer time step. Systems that exhibit a discretised response under pumping and no pumping conditions may be better suited to alternative techniques, such as paired t-tests on data sets during periods with and without pumping.

Analysis of trends in baseflow is in its infancy and has not been widely applied to date. An example can be found in SKM (2005a), which examined the effect of declining groundwater levels on baseflow in a catchment in South Gippsland in Southern Victoria. The Tarra River Catchment has experienced declining groundwater levels since the 1970s. GAM analysis of baseflow between the late 1960s and present combined with analytical calculations indicates a baseflow decline of about 40% over the critical low flow months of February and March from about 12 ML/d to 8 ML/d. This study detected significant reductions in baseflow in an area with regionally declining groundwater levels. However, due to data constraints the analysis was not conclusive and warranted further data collection.

5.6 Overview

The wealth of stream flow data throughout Australia has only infrequently been analysed from the point of view of understanding groundwater processes. Baseflow analysis usually provides an upper bound for groundwater discharge. Depending on the hydrogeological conceptual model for the catchment, the baseflow estimate should be factored down to provide the estimated groundwater discharge component. Nonetheless, baseflow analysis provides a valuable and relatively accurate source of information on groundwater processes. Stream baseflow data can be used to help deduce a whole of catchment water balance. This in turn will be a key to understanding the influence of groundwater pumping on reducing stream flows.

6. Case Studies

6.1 USA

6.1.1 Eastern Snake River Plain Aquifer

Background

The Eastern Snake River Plain Aquifer (ESPA) is a massive, largely unconfined, basalt aquifer in southern Idaho, USA. It is Idaho's principal aquifer and is roughly 80 km wide and 270 km long and is several hundred meters thick. In broad terms the aquifer is recharged over the Eastern Snake River Plain and discharges into the Snake River over parts of its length. The Snake River is shown in Figure 6-1. There is intensive water use of both groundwater and surface water for irrigated agriculture, hydropower and aquaculture. For example, 75% of the world production of rainbow trout comes from aquaculture in this area. Conflict between 'junior' groundwater pumpers (there are approximately 50,000 wells) and 'senior' surface water users has emerged over the last decade as a major water resource planning issue for Idaho.

■ Figure 6-1 Snake River, Idaho, USA



History of Development

A rise in groundwater levels over the Snake River Plain, during the first half of the 20th century, occurred due to leakage from irrigation delivery channels. Consequently the historical discharge of groundwater into the Snake River increased accordingly. Since then significantly increased groundwater usage during the 1960s and 1970s has caused a 20% decrease in groundwater discharge to the Snake River over the period 1950 to 1990 and beyond. The declining spring discharge to the Snake River has resulted in major conflict among competing users. Many surface water users have senior priority water rights and argue that groundwater pumping has reduced spring flow. Numerous law suits between the power companies and aquaculture interests against the groundwater users have resulted (Hubbell et al. 1997).

Idaho State Water Plan

The Idaho State Water Plan states:

It is the policy of Idaho to seek to maintain spring flows in the American Falls and Thousand Springs reaches of the Snake River which will sustain beneficial uses of surface and groundwater supplies in accordance with state law. Spring discharges in the American Falls and Thousand Springs reaches of the Snake River are vital to the Snake River Basin and Idaho economy. The springs near American Falls provide an important part of Snake River flow appropriated by Magic Valley irrigators. In the Thousand Springs reach, spring flow is the only practical source of water for many of the State's aquaculture facilities. During portions of low-water years, river flows downstream from Milner Dam to the Murphy gauging station consist almost entirely of groundwater discharge from the Thousand Springs reach. Maintaining this discharge should be the goal of water managers. Managed recharge of the aquifers and continued efforts to efficiently use groundwater are two strategies for maintaining spring discharges in these reaches.³

As groundwater levels have declined, the spring discharges have also decreased. Not only has the volume of groundwater discharging to the Snake River decreased, but there is also an increasing emphasis on water quality and arguments of how water quality is to be included as part of the water right. For example, fish hatcheries require specific temperatures and decreased groundwater of uniform temperature is seen as affecting senior right holders.

Aquifer Management Agreement

Water law in Idaho, as in much of the western United States, is based on the principle of Prior Appropriation. Groundwater and surface water have historically been managed separately. Thus new groundwater development has been allowed until very recently, even though surface water was fully capped in the 1920s. The recognition of the inter-connected nature of the groundwater and surface water has resulted in the regulation of groundwater

³ From Idaho Comprehensive State Water Plan, www.idwr.state.id.us 2005, p19.

and surface water as a single resource. Extensive analysis (see, for example, Hubbell et al. 1997) has shown that groundwater pumping anywhere on the vast Snake River Plain results in a 1:1 reduction in groundwater discharge to the Snake River, albeit this relationship can be significantly time lagged.

In March 2004 the State of Idaho and the water users reached agreement on dealing with the conflict, described as 'The Eastern Snake Plain Aquifer Mitigation, Recovery, Restoration Agreement for 2004'. This was only a one year agreement and provided for the spring water users (the senior surface water users) to not make claims against the groundwater users in exchange for the implementation of a range of short term measures and a commitment by the state to provide a forum to develop long term solutions. A broad range of options are being canvassed including artificial recharge, retirement of groundwater pumping, greater use of poorer quality waste water, compensation provisions to pump less groundwater and retirement of surface water users. It was estimated that it would cost in the order of US\$100 million to buy back groundwater licences.

A MODFLOW groundwater model was developed in the 1980s and has provided the backbone for analysis of the situation. As part of the 2004 agreement it was recognised that greater accuracy in the joint management of surface water and groundwater was required. To achieve this, it is planned to link the MODFLOW model to a Mike Basin surface water model. The modelling undertaken to date has shown that pumping anywhere on the plain will impact spring flows, albeit lagged. Furthermore, even when groundwater pumping ceases, the impacts of the pumping may persist for decades.

Lessons Learnt from an Australian Perspective

- A major program of surface water and groundwater licence retirement is likely.
- The economic consequences of the loss of agricultural production is the key issue.
- Even if the impacts are very small (i.e. from one bore) there is still a requirement for a mitigation plan.
- Regardless of the distance of the bore from the stream, the impact on the stream is the same.
- The Eastern Snake Plains Aquifer Plan provides more certainty to both senior water right holders and junior water right holders.
- Groundwater modelling is used as the key tool to assess impacts of mitigation options.
- There is a need for an enhanced monitoring and compliance program.
- There is a need for a clear domestic use policy given that the collective impact of the huge number of small users is very significant.
- A groundwater management plan must have a long term planning timeframe – i.e. at least 50 years.
- There must be agreement at a high policy level that all water users should be treated equally.

6.1.2 Republican River Compact

Background

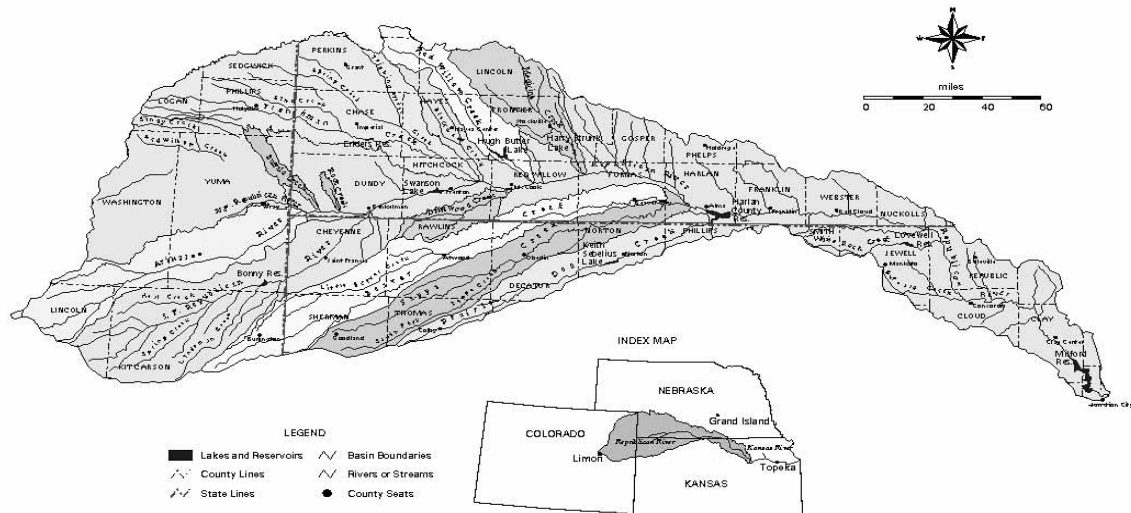
Interstate River Compacts are used in the United States as a legal instrument to equitably distribute water within a multi-state river system (Knox, 2004). There are forty five Interstate River Compacts in the United States, which aim to resolve interstate controversy and minimise litigation, and focus on the distribution of water supplies. Of these, to date, only six include groundwater within the distribution system. This is despite the fact that groundwater use in virtually all river basins in the United States is very significant and is usually the dominant source of water supply. There is significant pressure to include groundwater in all the river compacts allocation systems. The Republican River Compact (RRC) is an interesting case study of the evolution in thinking involving the historical ignorance of groundwater processes, the gradual consideration of impacts, deferral, and then the ultimate inclusion of groundwater within the interstate river compact allocation system.

The Republican River Basin

The tributaries at the headwaters of the Republican River rise in the high plains of Colorado and western Kansas and Nebraska, as shown in Figure 6-2. The river flows for 720 km and joins the Kansas River at Kansas. The predominant source of groundwater in the Republican River Basin is the shallow Quaternary alluvium and underlying Tertiary aged Ogallala Formation which collectively form the High Plains Aquifer. This is mostly an unconfined aquifer, although at some locations it is confined. The saturated thickness of the High Plains aquifer ranges from zero in the outcrop areas in Colorado to about 300 m in Nebraska.

Groundwater pumping for irrigation was limited prior to World War 2, but progressed rapidly in the 1960s and 1970s. Across the three states, there are now approximately 26,000 wells. New groundwater development was halted in the upper State, Colorado, in 1976 where about 4,000 wells exist. Up to 2001, the groundwater level declined by up to 26 m. The reduction in groundwater level caused a decrease in baseflow in the upper tributaries and a complete drying up of streams in some cases. A halt in new groundwater wells was introduced in Colorado and Kansas in 1976 and 1980 respectively. Impacts of reduced stream baseflows were sometimes not felt for several decades later.

■ Figure 6-2 Republican River



The Republican River Compact

The Republican River Compact is an agreement between Colorado, Nebraska and Kansas to share the surface water resources of the Republican River. This was based on the legal system of prior appropriation whereby senior (i.e. prior) surface water users have rights over junior groundwater users. The following analysis of the Compact is from <http://water.state.co.us/wateradmin/RepublicanRiver.asp>

In 1998 the State of Kansas filed a complaint to the United States Supreme Court that claimed the State of Nebraska had violated the Republican River Compact by allowing the unimpeded development of thousands of wells in hydraulic connection with the Republican River and its tributaries. The State of Colorado was joined in the lawsuit because the headwaters of the Republican River rise within that state and it is a party to the Republican River Compact.

The State of Nebraska denied Kansas' allegations and filed a Motion to Dismiss the case upon their premise that the Republican River Compact did not specifically mention groundwater, therefore groundwater could not be restricted or included in the allocation or consumptive use computations. The State of Kansas argued the opposite and asserted all forms of groundwater should be included within the computation of virgin water supply and consumptive use. The State of Colorado offered an intermediate position and claimed the compact and historic practice of the Republican River Compact justified the inclusion of alluvial groundwater, but did not include wells located on the tablelands that pump from the Ogallala aquifer. In 2000, the judge denied Nebraska's Motion to Dismiss and concluded groundwater was to be included within the allocation and consumptive use computations in the Republican River Compact. As to the alleged ambiguity of inclusion of groundwater within the Republican River Compact allocation system because the compact is silent on the

term 'groundwater', the judge found:

Nebraska's assertion that the Compact does not restrict ground water pumping because it never mentions ground water misses a critical fact: Although the Compact never uses the word "ground water", stream flow, which the Compact fully allocates, comes from both surface runoff and ground water discharge. Interception of either of those stream flow sources can cause a State to receive more than its Compact allocation and violate the Compact. Thus, the comprehensive definition of virgin water supply, even without use of the express term "ground water", requires a conclusion that, as a matter of law, a State can violate the Compact through excessive pumping of ground water hydraulically connected to the Republican River and its tributaries.

The final settlement reached in 2002 stipulated many conditions including:

- Groundwater modelling. The States agreed to form a committee composed of representatives from each state to construct a comprehensive groundwater model to determine the amount, timing, and location of depletions from groundwater pumping that accrue to the Republican River and its tributaries.
- Moratorium on the construction of new wells. This imposed a moratorium on the construction of new groundwater wells in Nebraska to match the de facto moratorium in Colorado and Kansas which had been in place for 30 years.
- Mechanisms for future Compact administration. The Final Settlement Stipulation contained numerous clarifications and accounting improvements that will assist the Republican River Compact Agreement (RRCA) in administration of the Compact. The clarifications and improvements include: revised water accounting procedures and formulas; use of a five-year running average for computing virgin water supply and consumptive use; extensive information and data sharing requirements; and commitments by each state to take specific water administrative actions during water-short years.
- Dispute resolution system. The Republican River Compact is silent on enforcement matters and the Final Settlement Stipulation contains specific procedures to encourage the resolution of disputes, including binding arbitration.

The Supreme Court approved the Final Settlement Stipulation in May 2003. In Colorado, for example, the Colorado State Engineer is working with the local water users to create an administrative body that will be used to identify and fund compact compliance measures to ensure Colorado meets the terms of the Republican River Compact and the Final Settlement Stipulation.

Groundwater Model

A key aspect of the final settlement was an agreement to jointly develop a groundwater model which would allow all groundwater pumping impacts (amount, location and timing) on the river and its tributaries to be defined. The MODFLOW based model was calibrated for the period 1918 to 2000. It helped define the zones from the river where impacts were short term and longer term. A key aspect of the calibration approach was the use of 65

stream reaches which were used for baseflow analysis. An output of the model was baseflow at selected stream cells for a variety of pumping scenarios. The model was used to identify the causes of falling groundwater levels: drought, groundwater pumping and land use change. It was shown that groundwater pumping caused about 70% of the groundwater level decline.

Implementation

In Colorado, for example, in late 2004 the community based groundwater management group decided that in effect there would be two zones. Zone 1 would be those wells (about 30) close to the river which would have an impact in less than one year, and Zone 2 which covers the rest of the catchment. The model was used to define the size of Zone 1 and in practice it means those wells within about 3 km of the river. The aim in the first few years was to focus on Zone 1 wells. The community group, in a monumental decision, voted to impose a levy on all groundwater users in the catchment (approximately 4,000 users) in proportion to the size of their licence. This levy, to begin operating in 2005, would raise US\$3.4 million per year and would fund:

- temporary retirement of surface water licences: US\$140,000
- temporary retirement of groundwater licences: US\$1,342,000
- permanent retirement of surface water licences: US\$100,000
- permanent Retirement of groundwater licences: US\$1,780,000

The intention is that this would be a permanent levy as it is expected to take many years to achieve the objectives of the Compact. The management of the compensation scheme is to be undertaken by the community group. This would be a voluntary program initially and the effectiveness in reducing baseflow impacts would be assessed after a few years.

Lessons Learnt from an Australian Perspective

- We must reach agreement on the scientific method to be used (in this case the MODFLOW modelling) in an open and transparent manner involving all relevant technical people and without any lawyers present.
- The model predicted the long term impacts and there was a good appreciation in the community of these long term impacts.
- The scientific basis must be complete before the management plan is developed.
- There must be flexibility in the management plan/approach to accommodate a broad range of conditions and to allow changes over time.
- The key driver in this case was the need to meet downstream and interstate river flow requirements. The Republican River Compact (not unlike the Murray-Darling Basin Agreement) was set up many years ago and did not include any consideration of groundwater impacts.
- The principle of prior appropriation (where by senior surface water users have right over groundwater users) is NOT appropriate for Australia.
- The use of the two zone concept effectively allowed the development of a targeted

approach of dealing with high impact users first.

6.2 China

There are no published reports on surface water groundwater interaction for China in English to the author's knowledge. Hence the example described below represents inference from various sources of information.

The North China Plain in NE China is underlain by a vast Quaternary alluvial aquifer. This aquifer supplies approximately 70% of the water resources of the plain and is home to approximately 300 million people. The serious nature of the falling groundwater levels across this massive plain has been documented in many reports, for example Foster et al. (2004). Groundwater level declines of up to 40 m in the shallow aquifers and 70 m in the deep aquifers have been observed beneath the Yellow River and across vast areas of the plain. Groundwater usage for irrigation is especially intense across the broad plains around the Yellow River. This high usage has been recently identified by remotely sensed ET data. Surface water flows in the Yellow River are known to decrease significantly when the river emerges from the mountains and flows across the plain (see, for example, World Bank, 2001). The problem has become so serious over the last decade that the Yellow River now ceases to flow across the plains every year for at least several months, sometimes up to six months. As the plain is approximately 300 km wide the social and economic impacts are huge. With the well documented large declines in groundwater levels beneath the Yellow River, it is postulated that at least part of the reason (if not the whole reason) for the major reduction in flow is that the river has become a serious losing river over its entire length on the plain due to groundwater pumping. This pumping may be many tens of kilometres away and has been underway since the 1960s.

6.3 Australia

There has been no Australia wide review of the extent of surface water/groundwater interaction undertaken. Apart from several Murray-Darling Basin reviews, all other projects are either site specific or over a region or catchment. Consequently this section attempts to review a selection of literature, while the next chapter aims to draw out the national implications. The author is aware of many projects currently underway which provide valuable insights, however these are not yet published.

SKM (2003) provides a summary of reports on surface water/groundwater interaction in the Murray-Darling Basin up to 2000. This report estimated that the total growth in groundwater usage from water table aquifers since the surface water cap was introduced in 1993/94 until 1999/2000 has been 310 GL/yr. Adopting 60% as an estimate of the amount of double accounting results in an estimate of 186 GL/yr of stream flow being captured. This represents about 2% of the total surface water cap of roughly 10,000 GL/yr. Assuming that groundwater use will increase up to the estimated groundwater sustainable yield levels, then this river loss will increase to 711 GL/yr by 2050 or about 7% of the cap volume. These estimates do not allow for the effects of groundwater allocations made prior to 1993/94, which may partially not have been felt. The total groundwater allocation in 1999/2000 in

Groundwater Management Units in the Murray-Darling Basin was 2,861 GL/yr.

Braaten and Gates (2002) undertook a scoping study of the significance of surface water/groundwater interaction in the Murray-Darling Basin portion in New South Wales. They postulate a clear relationship between basin geomorphology and regions of high connection between groundwater and surface water. They find that stream losses in the mid-sections of the major rivers with well developed yet narrow and constricted alluvial systems and shallow groundwater systems, are strongly related to groundwater levels, and quote that "there is a high likelihood of stream depletion due to groundwater pumping within a relatively short timeframe." (2002 p.10). They conclude that high stream losses may be indicative of groundwater recharge from the rivers in the lower valleys of the Murray-Darling Basin. Large scale irrigation bore development is common across many of the floodplains of the major rivers. They also conclude that about one third of the total groundwater extraction in NSW occurs in these areas, most of it within a few hundred meters of the rivers. Groundwater pumping is expected to impact stream flow to a large degree and within a relatively short timeframe in systems such as the Upper Murray, Billabong Creek, Mid Murrumbidgee, portions of the Upper Lachlan, Upper Namoi and Peel and several tributaries of the Macquarie.

Hardie and White (2004) quote estimates of the impact of groundwater pumping in the Murray- Darling Basin from 2000/01 over the following 20 years of 330 GL/yr. This is based on capping groundwater extractions at the estimated sustainable yield. They quote an uncertainty of from 275 to 550 GL/yr. This range is based on the uncertainty on the level of connection between groundwater and surface water. REM (2004) expand on the basis for the above estimate. The difference in the volume between the 2000/01 use and the estimated sustainable yield for connected systems is 550 GL/yr. Taking a range of 50% to 100% for the amount of groundwater coming from stream flow, this results in the stream flow being reduced by between 275 and 550 GL/yr. REM also identify high risk areas as including the eastern Groundwater Management Units in Queensland (e.g .the Condamine), Lower Gwydir, Upper Namoi, Upper Macquarie, Upper Lachlan, Murrumbidgee in NSW and the upper Groundwater Management Units in Victoria.

Kalf and Woolley (1977) investigated the Gumly Gumly bore scheme near Wagga Wagga. They predicted that within about five years, 88% of the water pumped from the borefield would directly deplete the river.

In a rare example of the use of long term monitoring data Sinclair et al. (2005) report on the drying out of Maules Creek over a 20 year timeframe. Maules Creek is a tributary of the Namoi River in Northern NSW and is an unregulated ephemeral stream. The long term surface water flow and groundwater level monitoring has shown how extractions from the gravel alluvium of Maules Creek directly impacts on surface water flows and also that baseflow is declining over time.

Another example of the short term impact of groundwater pumping on stream flow is from the Barwon Downs bore field, which provides Geelong's water supply. The development of

the bore field in the early 1980s resulted in the drying up of Boundary Creek which is located 5 km from the borefield. The time lag between groundwater pumping and drying up of the stream was approximately 1 year (SKM, 2002). This effect was predicted to occur.

A major investigation has been underway for several years in South West Western Australia to support a licence application from the Water Commission to extract 45 GL/yr from the South West Yarragadee aquifer within the Blackwood Groundwater Area to supply Perth (Strategen, 2004). The Yarragadee aquifer outcrops under part of the Blackwood River and discharges about 15 GL of fresh water into the river annually. These discharges may be important in providing fresh water refugia in the lower sections of fresh tributaries. They are also important in maintaining lower salinities in main stem river pools during summer months, than would possibly be the case without such discharges. The Yarragadee aquifer may also support wetlands, vegetation and stygofauna communities in outcrop areas where it forms a water table aquifer. There is also significant discharge from the aquifer into the Blackwood River where it incises into the aquifer downstream of Darradup. For a period of several weeks at the end of dry summers, stream flow in the Blackwood River at Hut Pool and Darradup remains almost constant while inflow from upstream at Nannup and from tributaries is zero. Excluding five years when the summer flow did not recede to a summer minimum, the average discharge for the catchment between Hut Pool and Darradup from 1980 to 2002 was about 33 GL/yr (4.7% of rainfall on the surface catchment). This value is effectively a lower bound for a recharge estimate. Consideration of the application has also required extensive economic and social research.

The Daly River is one of the few Northern Territory rivers that maintains a significant contribution of flow throughout the dry season. A report by Jolly (2001) provides a valuable water balance which indicates the significance of baseflow, with the mean groundwater outflow calculated at 13 mm/yr, while the mean annual stream flow is 146 mm/yr (equivalent to 6,821,775 ML/yr), which indicates a baseflow index of 9%. Consideration of the implications of possible new groundwater based irrigation developments in the catchment is underway.

The above selected site specific case studies, and the few Murray-Darling Basin wide studies, have generally focussed on highly connected systems where the response time to groundwater pumping affecting stream flow is relatively short. There are many other studies throughout Australia where a similar story can be told. The challenge is for where the bores are far from the rivers and/or when the hydraulic conductivity of the aquifers is low. The obviously much slower response times and possibly reduced impact calls for long term monitoring and a better understanding of fundamental processes.

7. Implications for Australia

7.1 Comment on Water Resource Assessments in Australia

The history of groundwater development in Australia is not well documented. Various reports, e.g. Inland Water Theme of the State of the Environment Advisory Council (1996) and Australian Water Resources Assessment (AWRA) (2000) discuss groundwater in the context of total water resource development. Evans (2001) identifies the extent of overdeveloped aquifers in Australia. Many other detailed papers exist on specific regions.

In the context of this report, the key factors which have driven groundwater development in Australia are:

- Even though groundwater use started in the 1890s (mostly in the Great Artesian Basin), groundwater use only became significant in the 1960s and 70s
- The growth in use has been steadily increasing over the last 40 years
- Major growth in use occurred during the key droughts – 1967/68, 1982/83 and 2002/03
- Licensing does not yet exist in all of Australia and only effectively began in some of Australia in the 1970s
- Groundwater licensing, until very recently, has been completely separate from surface water licensing
- Groundwater resource assessments have traditionally been based on assessed recharge rates.

The 1985 Review of Australia's Water Resources estimated total groundwater use in 1983/84 as 2,634 GL. By 1996/76 it had increased 58% to 4,171 GL (AWRA, 2000). The AWRA quotes surface water use in 1996/97 at 19,100 GL. Thus groundwater use represented approximately 18% of total water use. No national use data is currently available, however in view of the sustained drought over the last five years and the serious imposition of caps on surface water use in many regions it is estimated that current groundwater use is likely to be in the order of 6,000 to 8,000 GL/yr.

Review '85 assessed the groundwater resources of Australia completely separately from the surface water resources. Similarly the AWRA (2000) undertook separate resource assessments for surface water and groundwater, although in a few (very limited) cases the interaction between groundwater and surface water was specifically considered and the available resources adjusted accordingly. Therefore, it would appear that in large measure the AWRA (2000) double accounts surface water and groundwater resources. Double accounting refers to where the interaction between groundwater and surface water is not considered and separate resource assessments of groundwater and surface water do not allow for this interaction. It has the effect of overestimating the total water resource, because the same parcel of water is counted twice, once as surface water and a second time as groundwater. Detailed studies are required to identify the extent of this double accounting. However, an approximate estimate is undertaken below.

7.2 Estimate of Double Accounting in Australia

7.2.1 Methods of Water Resource Yield Assessment

Double accounting is a water resource planning issue, but does not in itself create any problem. However, it may have the effect of leading to double allocation, where the same parcel of water is allocated to both groundwater and surface water users. What in effect happens is that the security of supply of surface water users decreases and also the environmental flows in rivers decrease. In some cases it can lead to the complete drying out of rivers. The extent of double allocation is completely unknown in Australia. Any assessment of the extent of double accounting for all of Australia must be very approximate and cannot be assumed to be accurate. This is because the way in which surface water resource assessments are undertaken is completely different from groundwater resource assessments.

Surface water resources can be derived by applying one of the following methods:

- Analysing gauge data: Transposition of a time series of natural flows (derived at the furthest downstream gauge) to the catchment outlet by applying a factor derived from a regional area-flow relationship, and calculating mean annual flow. Natural flows are derived by adding estimated historic upstream impacts (demands, catchment dams, etc) to gauged flow data.
- Using time series un-impacted inflow data in a water resources model: The flows used as inputs to these models are representative of or close to natural flows., and so the total mean annual flow at the site of interest can be calculated by summing the relevant inflows.

It is important to note that due to the variability of flows from year to year, this calculation of surface water availability is heavily influenced by the period of record over which it is calculated. Also, this calculation assesses all the surface water in the catchment, and makes no allowance for volumes that may need to be set aside for environmental flow requirements, nor does it allow for historic changes of yield that may have occurred due to land use change.

Many rivers in Australia have dams constructed on them where it is common practice to assess the yield of the dam. This is often related to the location of the available stream gauges. If the possible reduction in river flow due to groundwater pumping occurs above the dam, then the yield of the dam (as assessed at a stream gauge located close to the dam) would be decreased as the effect of groundwater use is equivalent to an increasing drought. However, if the groundwater use is below the dam, then the groundwater use would act to reduce environmental flows in the river.

In Australia, most groundwater use is located on broad alluvial plains below any dams. The previous discussion ignores the effect of time lags between groundwater pumping and a reduction in stream flow. If there is a significant time lag then the effects of existing groundwater pumping would not be felt at the stream gauge and hence the available surface water resource will be overestimated.

There is no agreed method in Australia for determining the groundwater sustainable yield. However, the traditional approach of considering the recharge rate as the available resource does not consider the discharge component. Therefore, in many cases the available resource is overestimated. It is important to note that in very recent times many water resource departments in Australia have been considering the discharge component of the groundwater balance. Nonetheless, most currently published 'sustainable yield' estimates use the traditional approach.

7.2.2 Factors Influencing Impacts

Chapter 2 presents the idealised unconfined aquifer case where groundwater pumping anywhere in the catchment has a 1:1 impact on reducing stream flow (albeit often time lagged). The hydrogeological factors that may reduce stream flow impacts are:

- discharge to evapotranspiration (ET). In this case the groundwater is 'used' by vegetation, wetlands, springs etc.
- discharge to oceans
- flow to another groundwater system (e.g. where the surface water catchment does not coincide with the groundwater 'catchment')
- recharge to deeper groundwater systems that are not hydraulically connected to streams and inter-aquifer flow
- disconnected streams.

These factors are discussed in turn for Australia:

Discharge to evapotranspiration

Section 4.2 postulates that in many typical catchments in Australia ET from groundwater can be a significant component of the water balance. What this means is that in these catchments groundwater pumping will lower the water table and some of the effect of pumping will be felt in reduced ET, i.e. not a direct 1:1 impact on reduced river flow. However, the argument developed in Chapter 4 is that this may only be a temporary stage until ET is reduced or even extinguished and then the full impact of groundwater pumping will be felt in reduced stream flow. Thus, even though groundwater ET is important there may not be a major 'buffering' effect of ET on the effects of groundwater pumping. The impact on reducing ET is critically dependent on the location of the extracting bore relative to the ET and the rivers.

An example in Australia of reducing groundwater ET is documented in Groom et al. (2000) where a Banksia woodland on the Perth Coastal Plain died due to nearby groundwater pumping.

Discharge to oceans

Two scenarios can be considered: unconfined shallow aquifers with groundwater users close to the coast and deep confined systems where groundwater users can be any distance from the coast.

Groundwater users pumping from shallow unconfined aquifers located close to the coast may have no influence on reducing stream flow. In this case the groundwater captured by the bore would have otherwise discharged to the marine environment. A relatively simple analysis of the hydraulic gradient to the stream as compared with the hydraulic gradient to the coast would shed light on this question. From the author's experience this would only typically apply when bores are very close to the coast e.g. within several hundred metres, and hence is not considered a common case.

There are many deep confined regional aquifers throughout Australia which discharge offshore, often at considerable depth. Even though the aquifer recharge area may be well inland, once the aquifer becomes confined, groundwater pumping only reduces the submarine groundwater discharge (SGD) and so there is no effect on reducing the flow in overlying streams. (This of course assumes no drop in the potentiometric surface in overlying aquifers.)

This discussion only considers the effects on streams and does not consider any adverse effects of reduced SGD. An example of the effects of reduced SGD due to groundwater pumping in the Bundaberg region is shown in SKM (2005c).

Considering the major groundwater usage in Australia, there is large usage in shallow unconfined coastal aquifers, e.g. Burdekin Delta and Bundaberg, Queensland. However, most of the users are a little inland and hence the effects are mostly on reduced stream flow, rather than reduced SGD. Similarly, there are many major deep confined aquifers which discharge offshore, e.g. a small part of the Great Artesian Basin, the Otway Basin in SA and Vic. However, the usage in these aquifers is generally not great. Therefore, although locally very important, their contribution to national groundwater usage figures is substantial.

Flow to another groundwater system

A catchment scale water balance is recommended later in this report to help identify any double accounting. However, it is well recognised that frequently the surface water catchment boundary does not coincide with the groundwater boundary. Groundwater can flow across surface water catchments and often in Australia a groundwater management unit may cover several surface water catchments. Therefore, the argument that a certain amount of the recharge in a groundwater management unit will discharge to another surface water catchment, and not impact on the stream flow in the subject catchment, is true. However, it is largely a scaling issue. At the scale of multiple catchments the water balance must be met and although groundwater usage in one catchment may have no impact on reducing stream flow, it will however have a direct impact on the adjacent catchment. Thus this argument in general does not hold up.

Recharge to deeper aquifer systems

These are situations where a proportion of the recharge flows to deep aquifers and for practical planning purposes and over a sensible planning timeframe (e.g. 50 years) this recharge flows to locations which do not have streams which could be impacted upon, or

alternatively the recharge water moves so slowly that it becomes saline. An example of this case is part of the Lower Murrumbidgee aquifer in the Riverine Plains of NSW. In this case it is recognised that this proportion of the recharge does not discharge to streams and therefore its use would not reduce stream flow. It is also important however to recognise that this water does discharge somewhere and so may be an important part of the water balance elsewhere. Overall this process does reduce the impact of groundwater pumping on streams.

A separate case exists in parts of Australia where there are deep and largely isolated confined aquifers. These may be effectively fossil groundwater resources. These cases, for all practical purposes, are not connected to any surface waters, and hence use of these resources will have no practical impact on streams.

Disconnected streams

The notion of a disconnected stream applies to several different cases:

- where there is an unsaturated zone beneath the stream and further lowering of the groundwater level does not increase the seepage rate. This is discussed in Section 2.3
- where there is a clay layer on the base of the stream which significantly reduces the recharge/discharge interaction rate between groundwater and surface water
- where there is a significant aquitard between, for example, a shallow unconfined aquifer and a deeper confined or semi-confined aquifer
- where there is some other geological feature (e.g. a fault, dyke) which isolates the stream from the groundwater extraction point.

An important distinction needs to be made between naturally occurring unsaturated zones beneath streams and those newly formed disconnected streams which are a result of groundwater pumping lowering the groundwater level beneath the stream. There are many areas in Australia where the latter exists. It is believed that the former is not common.

As emphasised earlier in this report, there is no truly 'disconnected' stream; rather the seepage rate is higher than for saturated flow. The seepage rate does not decrease when a stream becomes 'disconnected'.

The broad range of hydrogeological reasons as described above possibly causing 'disconnection' usually mean that there is a constant leakage rate, not no leakage. In practice what this means, as discussed in Section 3.5, is that the time for steady state conditions is long, typically years or decades.

The presence of clay layers on the base of streams and aquitards at variable depths below the stream bed is common in Australia. These often act to reduce impacts of groundwater pumping on streams. In some cases these only act to retard the impacts so that the same impact occurs, but only over a much longer timeframe. In other cases of thick aquitards they may act as effective barriers to flow. However, it is important to realise that even though a low hydraulic conductivity clay layer may exist in the vicinity of the stream, the

effect of pumping may extend upstream and downstream many kilometres and similar hydrogeological conditions are unlikely. Thus, interference with the stream may simply be transferred elsewhere. Similarly, other geological features (e.g. dykes, faults) can occur within a catchment which, although locally may act to 'disconnect' the stream from the groundwater pumping, over a broader scale are often unlikely to act as long term barriers to groundwater pressure reduction.

It is considered that locally 'disconnected' systems do exist, but over all of Australia they are unlikely to act as effective broad scale and long term barriers to flow.

Overall impacts

As discussed in Section 4.1, any consideration of impacts must consider time lags. Groundwater pumping has been underway actively since the 1960s and across most groundwater systems in Australia the bores are frequently located close (i.e. within say 5 km) to rivers and streams. (In some catchments they are within 1 km of streams.) Consequently, in many catchments the impacts of groundwater pumping on reducing stream flows would have already been felt. Depending on the method used for the surface water resource assessment, this historical impact may have already been factored into the (reduced) surface water yield. (The drought which has existed in many parts of Australia over the last ten years has disguised this impact.) It is quite possible that the major growth in groundwater usage over the last five years, especially when the bores are not close to rivers, has not yet been felt in reduced stream flow. These impacts still await us! In those parts of Australia where groundwater development is continuing then the impacts have not usually been felt, except where the bores are very close to rivers resulting in very short term impacts, e.g. days or weeks.

Considering the above five factors which all act to reduce the impact of groundwater pumping below a 100% impact on stream flow, it is believed that reduced groundwater ET is by far the most important. Clearly, in some catchments the other factors may be dominant, especially discharge to oceans. The discussion on baseflows in Section 5.4 concluded that moving from southern Australia to northern Australia, the proportion of baseflow to total flow decreases. It is well recognised that there are more perennial streams in southern Australia and more ephemeral streams in northern Australia. This suggests different hydrologic processes in northern Australia from southern Australia, such as an increase in runoff volume in northern Australia. However, there is not sufficient technical justification to definitively explain this difference. From catchment to catchment, the range of impacts could vary from 100% to 0%. It is also emphasised that if groundwater levels fall as a result of continuing groundwater pumping, (i.e. they are not adequately recharged during the following wet season) then the importance of ET_{gw} decreases and greater impacts on streams will be felt.

7.2.3 Impacts in Surface Water Based Irrigation Areas

There are many surface water based irrigation areas in Australia where groundwater use has grown over the last 20 years. The groundwater use in these regions is often significant (e.g.

Shepparton Irrigation Region). However, it is usually relatively small in comparison with the imported surface water volumes. This makes undertaking a reasonable water balance difficult. In the Murray- Darling Basin much of this pumping is from deep aquifers. The issue has only arisen over the last 10 years in view of the dryer times, as to whether groundwater pumping actually reduces surface water availability (i.e. from channels, drains and rivers).

Numerous studies of water balances and groundwater movement in surface water dominant irrigation areas (e.g. Khan et al. 2004) have shown that vertical groundwater flow processes are dominant and horizontal flow processes are relatively minor. For example in the Murray-Darling Basin, Dudding (2004) showed that across the Victorian Riverine Plains over the last ten years there has been a steady decline in deep groundwater levels and he postulated that through vertical leakage this was also having a complementary impact in declining shallow groundwater levels. It seems quite plausible that if deep groundwater pumping is occurring then the water will often predominantly come from vertical leakage (i.e. not horizontal flow). The associated reduction in shallow groundwater levels will also likely result in decreased surface water flows. However, the greater groundwater ET in irrigation regions (often due to shallower groundwater levels) will mean that the likely impact of groundwater pumping will be less in these areas.

The likely impact of all groundwater pumping (i.e. both shallow and deep) on reducing surface water availability will usually only become important in dry times. The dynamic nature of the shallow groundwater systems, often due to the huge hydraulic loadings, will often mask the impacts on surface water availability. Nonetheless, the likely impacts discussed above will raise important issues concerning groundwater resource sharing between shallow and deep groundwater users.

7.3 Evolving Understanding of Connectivity

A concept which has gained some recognition in recent years is the concept of 'connectivity' between groundwater and surface water systems. The term 'connectivity' refers to the physical hydraulic connection between groundwater in an aquifer and surface water in a river/stream/lake, etc. The connectivity can be used to categorise systems according to the level of connection. Hence, it can be a practical mechanism for the states and territories to prioritise the allocation of limited resources to manage the issue and in turn, assign different management rules according to the connectivity category. The real challenge is assigning appropriate management rules to each category that address the issue within a relevant timeframe.

A connectivity classification can be used to categorise the connectivity on a case-by-case (or stream reach) basis according to a range of levels. This could be considered a risk based approach. For example:

- Low connectivity – in cases where groundwater abstraction impacts upon surface water resources by less than or equal to 10%, over a fifty year time period

- Moderate connectivity – in cases where groundwater abstraction impacts upon surface water resources by greater than 10% and less than or equal to 50%, over a fifty year time period
- High connectivity – in cases where groundwater abstraction impacts upon surface water resources by greater than 50%, over a fifty year time period.

A fifty year plus time period is used as it is the long term effects which the connectivity categorization is aimed at addressing and is also consistent with the notion of sustainable surface water and groundwater yields. As well, fifty years plus would seem a sensible timeframe over which water resource planning could occur. It is important to emphasize that this is a completely different notion from that discussed in Section 8.2 and in Appendix D. In Section 8.2 the focus is on stream flow management plans, while the focus of the connectivity classes described above is on basin wide water resource management.

The categories do not necessarily infer the ultimate level of impact. For instance, a low connectivity system does not imply that the impacts of groundwater pumping on surface water will be relatively small or insignificant. Rather, the impacts may simply be experienced in the longer term relative to those systems with moderate or high connectivity. Therefore, it is important to be mindful that while it may be useful to define the connectivity, steady state conditions (e.g. the long-term) might generate a volumetric impact on surface water flow approaching a 1:1 hydraulic relationship regardless of the connectivity category. Also, it should be recognized that steady state conditions may occur in a relatively short timeframe.

To overcome the potential confusion of, for example, a low connectivity system having a high amount of interaction, but a delayed connection, it is suggested that a better definition of connectivity would be a two-fold definition as follows:

		Steady State Impact			
		< 10%	10 – 50 %	> 50 - 90%	>90%
Time Delay	< 5 years	Low	Moderate, short term.	High, short term	Very high, short term
	5-50 years	Low	Moderate, medium term	High, medium term	Very high, medium term
	> 50 years	Very low	Moderate, delayed	High, delayed	Very high, delayed

This concept of connectivity is at the catchment scale, and not at the local scale of near a river.

In any consideration of the magnitude of surface water/groundwater interaction it is important to consider if anthropogenic factors have changed the amount of interaction. For example, land use change may raise or lower water tables which then alter the amount and even the direction of interaction. The clearing of native vegetation has profoundly altered erosion rates and in much of Australia the bed levels of streams have been significantly lowered. This generally (but not always) increases groundwater discharge rates as the

hydraulic gradient is increased. These processes need to be factored into any assessment of connectivity.

7.4 National Surface Water Groundwater Interaction Assessment Methodology

A possible national scale methodology for assessing the impacts of surface water/groundwater interaction is proposed below. The specific aim is total water resource sustainability. This methodology is proposed for discussion and does not replace the need for local scale investigations and assessments. At a broad level the methodology has three steps:

1. Define nature of connectivity
2. Define the impact of interaction
3. Define the surface water and groundwater yield.

The methodology below can be adapted for different spatial scales and hence accuracy.

1. Define nature of connectivity

At the broadest of levels, Australia could be considered to comprise four hydrogeological provinces: fractured rock, layered systems (e.g. basalts), alluvial valleys and large basins. There is obviously a continuum between these different types in many regions of Australia. These four broad types could be further subdivided into, for example, local (including perched) and regional groundwater flow systems. The four-fold classification is only to guide thinking, as similar processes (from a surface water/groundwater interaction perspective) occur in all provinces. It is also appreciated that this four-fold grouping has many hydrogeological exceptions.

Using the above four provinces (or an adaptation of the concept if appropriate) a somewhat qualitative approach to define the impact of groundwater pumping on stream flow can be deduced for large regions by using the depth to the water table, the stream bed and adjacent aquifer hydraulic conductivity and key geological characteristics. The spatial and temporal scales are very important and are driven by the required accuracy. The connectivity would typically be defined for a river reach. However, depending on the location of the groundwater pumping, the connectivity may be defined over a larger region. The above three broad characteristics can be integrated into a rating system using a scoring system (e.g. 1 to 5) for each variable. The rating system can then be developed which characterises the connectivity classification according to the above two-fold definition in Section 7.3.

2. Define the impact of interaction

All surface water catchment boundaries would need to be defined as would the approximate location of groundwater pumping in all catchments. The timing of the groundwater development (i.e. usage over time) would also need to be determined. Using the approach as outlined in Section 7.2.2 and considering the connectivity rating, then a 'double accounting reduction factor' (e.g. 50%) could be adopted for groundwater pumping in each catchment. The depth of the water table would be especially important in considering the possible significance of groundwater ET in the catchment and thus the mitigating influence of

groundwater ET. A 50 year timeframe is suggested in the next chapter. This time could be increased or decreased as required. Alternatively a steady state approach could be adopted.

3. Define the surface water and groundwater yield

Using the above input at the surface water catchment scale, and especially the location of the groundwater pumping in the catchment and the timing of when groundwater development occurred, the impact of interaction could then be used as one of the inputs to altering the divertible yield of a river to allow for groundwater pumping impacts. As discussed in Section 7.2.1, depending on time lags and when a surface water yield assessment was undertaken, the impacts of groundwater pumping may have already been allowed for, albeit inadvertently. Similarly, the groundwater 'sustainable yield' can be calculated allowing for an agreed amount of groundwater discharge to surface waters and to ET (e.g. for groundwater dependent ecosystem health). A total catchment water balance would ensure that double accounting does not occur. It is emphasised that this approach is applicable for large scale comparative analyses, but is obviously not an accurate means to define local impacts.

8. Possible Management Approaches

8.1 National Policy Development

A draft national policy to address the impacts of surface water/groundwater interaction in Australia (SKM, 2006) proposes ten policy principles to be adopted at the national level. Perhaps the most significant principle is that the jurisdictions need to assess the impacts of groundwater abstraction on streams, and if no assessment is undertaken then a 1:1 hydraulic relationship is to be adopted. The adoption of the 1:1 impact is based on the precautionary principle and although, as discussed earlier, this is unlikely to be the norm, there are many situations in Australia where this is the case.

These policy principles are designed to 'lift the bar' on sustainable water resource management in Australia. However, their high level nature means that the states and territories will need to develop more specific state policies. In addition the states and territories will need to develop the definitions and procedures appropriate to each state and territory. Also, the draft policies will need to be implemented through their water resource planning framework.

8.2 Comment on Existing Management Approaches

SKM (2006) presents an overview of existing ways in which the states and territories address surface water/groundwater interaction. All states are currently considering how they deal with this issue. In cases where there are short term impacts and the effects have a relatively obvious 1: 1 impact then these situations are being considered. However, long term impacts, especially when bores are located far from streams and in complicated hydrogeological environments, are a far greater challenge.

To the author's knowledge, no management models exist overseas which are applicable to Australia. For example, the case studies in Section 6.1 and many others documented in Glennon (2002) and in Blomquist et al. (2004), mostly deal with the more extreme cases where stream flow has significantly decreased and the dispute is either in front of the courts or cut backs are being negotiated as part of a water plan. Examples of proactive planning to deal with the matter at the catchment scale before it becomes an issue are unknown. However, the management of stream depletion effects resulting from groundwater pumping has received significant attention by Environment Southland (2004) in New Zealand. This methodology is described in Appendix E. Their approach is appropriate for New Zealand where commonly the hydraulic conductivities and gradients are much greater than in typical Australian conditions and so the time lags are all relatively short. This approach is focussed on short term impacts where low flows over summer might be affected. It is not focussed on long term and whole of catchment processes and therefore does not address the bigger issue of overall water allocations. Nonetheless, this approach is similar to that proposed later in this chapter for dealing with short term impacts.

8.3 Whole of Catchment Water Balances

Perhaps the best way to identify double accounting is to undertake a whole of catchment

water balance. This will also enable a realistic assessment of the volume of water resources (surface water and groundwater) available for consumptive use. It is the primary tool to permit the integrated management of the total water resource. A relatively detailed list of components of a whole of catchment water balance is in Appendix D. For typical 'dryland' catchments in Australia most of these components are irrelevant and therefore can be ignored. (The primary point of this whole report is item number 21 – 'non saline aquifers to surface water'.) For many regions in Australia, there will be multiple aquifers and thus the water balance will need to recognise these separate aquifers and the leakage between them.

One of the key issues from a groundwater perspective is the scale of the water balance. The adoption by the states of Groundwater Management Units (GMUs) unfortunately does not facilitate catchment scale water balances as GMUs frequently cross surface water catchments. Hence, to undertake a realistic catchment water balance will require a major cultural change amongst Australia's hydrogeologists such that the conversion of groundwater boundaries into surface water catchments will need to occur. It is recognised that there are many situations where significant groundwater flow occurs between surface water catchments. In these common cases the groundwater flow (and the associated double accounting) will need to be proportioned between the catchments. As groundwater boundaries may change with time this will also create a problem. However, it is considered that the errors involved in this approach are small relative to the other errors in a typical catchment water balance. Also, in many cases it will be desirable and even necessary to undertake the water balance at the sub-catchment scale and then aggregate the data up to the catchment scale. This aggregation of the water balance up to the catchment scale may act to hide important local processes. For example, the volume from a gaining river reach added to the volume from a losing river reach will, when aggregated up to the catchment scale, suggest that surface water groundwater interaction is not important, whereas in practice the opposite may be the case.

There are significant technical challenges in undertaking a catchment scale water balance with an acceptable accuracy. The key factors which act to complicate the water balance are discussed in section 7.2.2. For example, groundwater flowing beneath streams, both parallel to and across the stream, will significantly affect the local components of the water balance. If this flow were to exit in the catchment and discharge, to another catchment or to the ocean, then the water balance would need to allow for this. In this sense the water balance is not 'closed' from a surface water perspective. Thus a truly holistic view of the water balance is required – i.e. all surface water and groundwater aspects need to be included.

Another common point to consider is the time period covered by the water balance. It may be for a specific year or alternatively it may be a much longer period and then expressed as an average per year. In view of the much slower movement of groundwater, longer term water balances are favoured from a groundwater perspective.

Surface water and groundwater development in a catchment will have the effect of altering the catchment water balance. (In this context development refers to a high level of water allocation relative to the sustainable yield of the resource.) In a groundwater context the

development of the groundwater resources can profoundly alter the water balance. Therefore, it is generally recommended that a developed water balance be undertaken.

The output of the catchment water balance will be the available surface water and groundwater resources with the amount of interchange identified (i.e. that which was previously double accounted). How the 'interchange' water is licensed (i.e. to surface water users, to groundwater users or to both) then becomes a question which can be meaningfully discussed. Integral to this process is the identification of (surface water and groundwater) environmental water requirements. The catchment water balance can assist in both reviewing the sustainability of existing (i.e. past) water entitlements and in considering the impacts of granting new water entitlements.

8.4 Groundwater Sustainable Yield

The nationally agreed definition (National Groundwater Committee, 2000) of sustainable yield (SY) for groundwater systems is as follows:

The groundwater extraction regime, measured over a specified planning timeframe that allows acceptable levels of stress and protects dependent economic, social, and environmental values.

Currently, there is no agreed method for determining groundwater sustainable yields. Representative estimates of sustainable yield require a consideration of inflow (i.e. recharge, irrigation seepage, river and inter-aquifer leakage, groundwater inflow) and outflow (i.e. river discharge, groundwater ET, inter-aquifer leakage) parameters. Of importance to this project is the component of flow occurring between surface water and groundwater, that is, inflows occurring as river leakage and/or outflows occurring as river discharge (baseflow). There are some notable exceptions however, and these discharge flow components have generally not been factored into groundwater sustainable yield estimates across Australia. Consequently, in most cases in Australia, if double accounting is assessed this will result in a reduction in the sustainable yield for the GMUs.

A common and emerging approach adopted in some states to deal with overdeveloped groundwater systems is the declaration of an 'Annual Announced Allocation' (AAA). This management approach is often used where groundwater level response management is used (see Evans et al. 2004). In this case even though, for example, 10,000 ML/yr. may be licensed in a GMU, the AAA may be 50% for recurring years. What this means in practice is that only 5,000 ML can be used. Another way to consider this is to envisage the SY as being defined in a similar way as with surface water at a defined reliability of supply. The reliability of supply is controlled by the amount of the available water and by the definition of the 'trigger' for how failure is defined. A 'failure' would be defined, for example, as a particular groundwater level exceeded.

The use of the concept of reliability, of especially regulated surface water supplies, is well established in some surface water based irrigation regions in Australia. It represents an honest way of describing the effects of climatic variations. The move to use AAA in Australia is largely to avoid the politically hard decision to reduce licensed entitlements in

over developed GMUs. Nonetheless, it provides an opportunity to more honestly describe the effects of climatic variations on available groundwater resources. The assessment of the SY values for all of Australia's GMUs with an assigned reliability level would be a massive task. However, it would represent a significant advancement on the current approach where no reliability level is even considered. At the moment most groundwater users assume it to be at 100% reliability. This is clearly not the case. In the process of adjusting the SY values for Australia's groundwater resources to allow for surface water/groundwater interaction it would be desirable to consider the wisdom of assigning a level of reliability associated with the SY value.

In Section 8.6.3 the management option of surface water to groundwater trading is raised. A quite fundamental issue with this approach is 'what exactly is being traded?' Surface water rights are not directly comparable with groundwater rights, largely because of the different levels of reliability of the different water resources. The assignment of reliability levels to groundwater resources would then provide a common 'currency' which would allow for surface water to groundwater trading to occur. (It is important to note that there are many other issues with surface water to groundwater trading which are outside of the scope of this report.)

8.5 Management Approaches, Tools and Options

8.5.1 Define Objectives

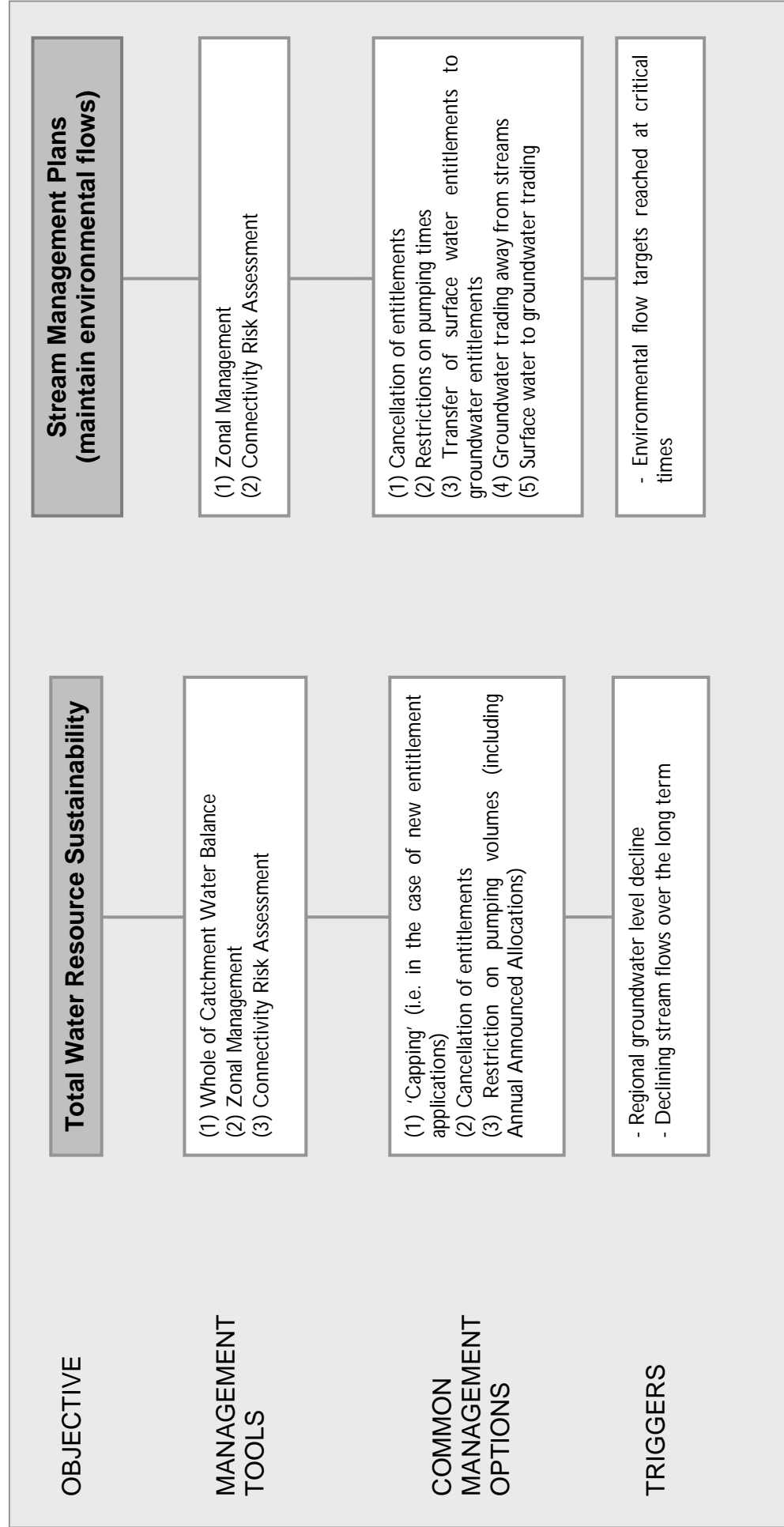
The appropriate management approach will be driven by the issue and hence the objective. In the context of this report there may be essentially two quite different objectives:

- the sustainability of the total water resource
- the need to maintain the appropriate environmental flow regime in rivers.

The first objective needs to consider long term issues (50 years plus) while the second is essentially focussed on the short term (weeks/months) requirement to ensure an appropriate environmental flow. If the first issue is not addressed then it is much harder to achieve the second objective. In this sense these different issues are clearly linked. However, in most respects they can be considered as separate. A flow chart of the process presented below is shown in Figure 8-1.

In broad terms the methodology presented below is applicable to both new and existing water licences. However, there are some significant differences. Clearly a more cautious approach can be used in the consideration of the approval of new licences. Water resource management plans are normally developed to address these issues for existing licences. Nonetheless, the same general approaches can be used. In the approval process for individual new licences not only does the impact of the new licence need to be assessed, but also the *potential cumulative* impacts of the new licence together with the existing entitlements need to be evaluated. In many catchments the decisions of the past (as a cumulative impact) may not yet be felt at the streams.

▪ Figure 8-1 Flow Chart of possible management approaches to control, mitigate or administer the impacts of surface water/groundwater interaction for new and existing water access entitlements



8.5.2 Water Resource Sustainability

The primary management tool used to ensure that no double accounting occurs is a whole of catchment water balance, as described in Section 8.3. This tool can be supplemented (note – not substituted) by the use of zonal management (see Section 8.6.3) and possibly a connectivity risk assessment. The zonal management approach may be useful, for example, in implementing a cut back policy, as is being used in the Republican River, USA (see Section 6.1.2). The connectivity assessment is essentially a risk based priority setting process to determine which regions in a catchment will have the largest impact in the shortest period of time. The different connectivity categories can also be used to apply different management rules. For example, the high connectivity river reach may have a ‘cap’ imposed in the adjacent region, while the medium and low connectivity river reaches may have varying levels of restrictions imposed.

The management options which are available to deal with double accounting and resulting double allocation include:

- ‘capping’ new licences (i.e. no new licences issued in a catchment)
- cancellation of existing licences or buy back of existing licences
- restricting pumping to particular volumes (this includes annual announced allocations).

There are many other management options but the above represent the most common ones in this case. A wide range of factors will dictate the type of management approach that will be best suited to a particular catchment system. For instance, factors that will require consideration include the hydrogeological environment, the level of surface water and groundwater use versus the volume available, the level of double accounting, the legislative and licensing framework, the environmental goals, etc. The relative cuts/restrictions that surface water and groundwater users may experience will require a technically defensible justification.

There may be no field-based triggers that define the need for this approach. A catchment may be clearly over-allocated, but because of the large time lag involved (as discussed at length earlier in this report) there may be no indicators for decades. This however, is not an argument for no monitoring. Rather the monitoring needs to recognise this time lag. Nonetheless, in many catchments regional groundwater level decline will frequently also have a significant impact on surface water resources making this the most obvious trigger for action. Declining stream flows are generally very hard to measure and interpret because of the normal large climatically driven variation. Therefore, this is usually not a good indicator. Groundwater level monitoring close to the groundwater pumping will usually, in time, identify regional trends.

8.5.3 Stream Management Plans

The maintenance of appropriate stream flows, usually for environmental purposes, represents an important reason for managing groundwater impacts. It is suggested that a useful management tool is the so called Zonal Management (Evans et al. 2005). This tool involves assessing the impacts of bores located at varying distances from the stream and

assigning the impacts into a four zone classification on the basis of time lag response so that the impacts on stream low flows can be managed.

The zonal approach is summarised below. Importantly, it is emphasised that the approach developed is representative of simplified conditions for an unconfined aquifer. The management approach with respect to surface water/groundwater interaction for semi-confined aquifers will involve greater complexity. However in general, similar principles (as presented below) will apply.

Classification of Zones

Zone 1 – Very Short Time Lag

Zone 1 will apply close to streams where there is a major interference with stream flows and the time delay between groundwater abstraction and stream flow depletion is short (e.g. within one week). With regards to an unconfined aquifer, the boundary may be in the order of 100 m from a stream.

Zone 2 – Short Time Lag

Zone 2 would apply to all groundwater users, which could *impact on stream flow over the critical low flow period of the stream during the planning timeframe*. In practice, this applies to impacts that may be typically felt within three months of the commencement of pumping. It is recognised that Zone 2 may not be necessary in some hydrogeological environments.

Zone 3 – Medium to Long Time Lag

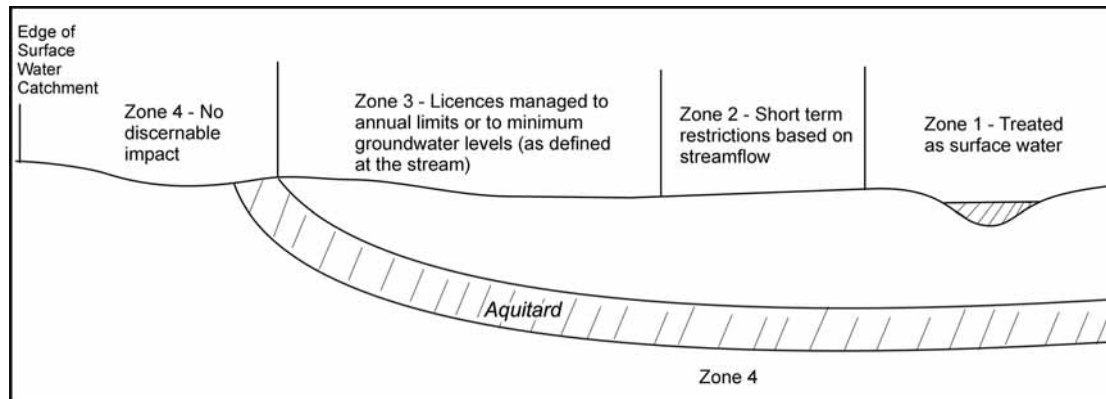
Zone 3 would apply to those groundwater users with impacts to stream flow only in the long term (in the order of 1 to up to 50 years). This would often incorporate all groundwater users in a surface water catchment, with the exception of those in Zones 1 and 2.

Zone 4 – Very Long Time Lag

Zone 4 would apply where there is no discernable impact of groundwater use on the stream. The zone would not necessarily be a certain distance from a stream, but would apply to particular hydrogeological conditions, for example, deep confined aquifers, coastal aquifers, etc.

The Zonal concept is illustrated schematically in Figure 8-2, while a geographical representation of the concept is presented in Figure 8-3.

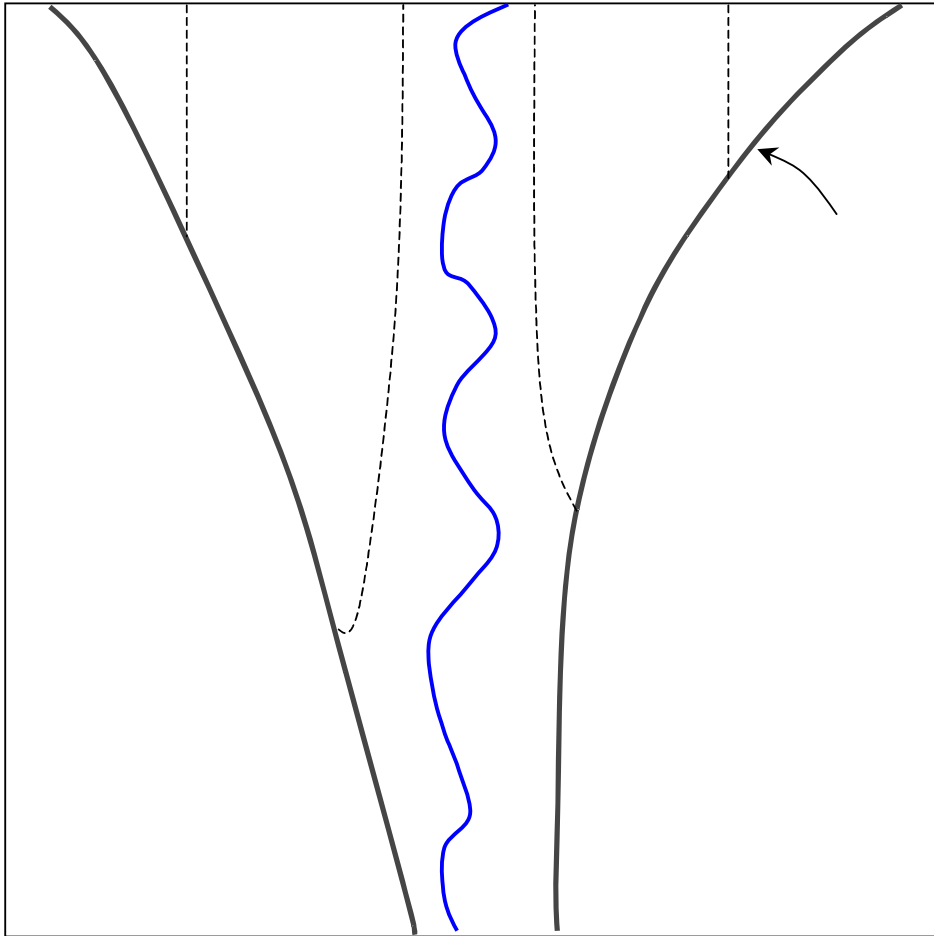
- Figure 8-2 Proposed zonal concept for managing new water access entitlements



From a technical perspective, Zone 2 is likely to exist in most hydrogeological settings particularly for alluvial sediments, as the most interactive surface water/groundwater systems are likely to be highly permeable alluvial systems. Zone 2 may also incorporate catchments where streams are incised into high yielding fractured rock aquifers.

When the width of the alluvial aquifer becomes narrow the division of the aquifer into multiple-zones may not be practicable (for instance, Zone 2 may be very narrow and impractical to administer). Zone 3 may then exist within the bedrock adjacent to the alluvial aquifer as demonstrated in the example of Figure 8-3. It is emphasised that the boundaries of the zones will be determined according to the hydrogeological characteristics of the catchment. The distances implied in the above discussion were for example purposes only and could vary greatly from catchment to catchment. Notably, although the location of the zone boundaries are dictated by hydrogeological factors, the acceptable level of interference permitted within a specified time frame, is fundamental to managing the issue.

■ Figure 8-3 Indicative location of management zones



Zone Management Arrangements

The possible management arrangements corresponding to each of the four Zones is as follows:

Zone 1 – Very Short Time Lag

All new water access entitlements in Zone 1 would be managed according to surface water extraction rules. Given the short time lag, restrictions on groundwater extraction would have an almost immediate effect on stream flow depletion.

This approach is similar to that adopted in the New Zealand Canterbury Natural Resources Regional Plan (Environment Canterbury, 2004 p. 23):

... any bore with a high hydraulic linkage, with a stream depletion effect that is greater than 90% of the average pump rate after 1 week continuous pumping, will be managed as a surface take for management purposes.

Zone 2 – Short Time Lag

As the degree of hydraulic connection between the aquifer and stream declines or the distance between the bore and stream increases, integrated management becomes more

complex. In particular, as the time lag in groundwater pumping impacting upon the stream increases, the potential for a short term reactive management response is reduced.

Management options that could be applied to water users located in Zone 2 to incorporate the complexities of time lag in order to manage stream flow impacts are:

- restricting the licensed entitlement (i.e. the volume permitted to be pumped)
- restricting pumping to particular durations or periods or according to certain triggers (e.g. minimum groundwater levels, minimum stream flow targets reached at critical times)
- implementing a pre-determined restriction for a fixed period of the year (e.g. pumping duration restricted by 75% in critical low flow months, or full dry season period)
- allowing wet season pumping only
- implementing a permanent restriction all year round.

A key technical issue is the application of the most appropriate option for identifying the timing of the restrictions. Options are:

- historical data – specifically rainfall, stream flow, groundwater levels, groundwater usage
- real time data – same data types as above, but all specifically during the irrigation season
- combination of historical and real time data.

The choice of the most appropriate data type will be based on both the available data and on the approach which has greatest community acceptance. There are significant technical, economic, environmental and social advantages and disadvantages of each different approach. The possible types of restrictions are rosters (including bans), restrictions of use to a portion of the entitlement, and wet season pumping only licences.

Most groundwater usage commonly occurs during an irrigation season. A significant cultural shift will be required by irrigators for restrictions on the duration of pumping to be understood and successfully implemented. The costs of compliance may also be significantly greater than for a volumetric restriction. For example, meter readings may only be needed three to four times a year for a volumetric restriction, but may be needed on a monthly basis for a duration or combined duration and volumetric restriction.

Zone 3 – Medium to Long Time Lag

When the time lag exceeds the length of the typical pumping season the application of temporal based restrictions as a means of contributing to stream flow targets has the potential to become extremely complex and impractical to implement. The implications of Zone 3 to water managers may therefore be in ensuring that total usage within the zone does not exceed the *sustainable yield* (as determined by way of a catchment-wide water

balance), where a key element in the sustainable yield determination may be in maintaining or delivering throughflow contributions to surface water systems or achieving minimum groundwater levels.

Zone 4 – Very Long Time Lag

As the impacts associated with groundwater abstraction and stream flow depletion will not be apparent for the very long term (i.e. over 50 years) in Zone 4, no active management in relation to surface water/groundwater interaction impacts is considered necessary.

8.5.4 Transfers and Trading

The transfer of surface water entitlements to groundwater entitlements will have the benefit of 'smoothing' the impacts of water usage over a full 12 months rather than the impacts being felt during the few months of the irrigation season if direct surface water extraction were to occur. In general no money 'changes hands' when transfers occur.

Trading refers to two cases: groundwater trading away from a stream, and surface water to groundwater trading. The zonal method can assist with both cases. With respect to surface water to groundwater trading, this approach may result in trading only being permitted between surface water and groundwater in Zone 1. The trading regime and its associated rules would ultimately be subject to the conditions defined in a Water Management Plan. As raised in Section 8.4, surface water to groundwater trading is currently difficult because of the different reliabilities of surface water and groundwater. The assignment of a reliability to groundwater will overcome one of the major hurdles.

A similar approvals process would also be necessary for the trading of groundwater to occur in a capped groundwater system. Importantly, the potential for groundwater trading to impact on surface water resources should be recognised in the approvals process. One mechanism to minimise the impact on surface water resources may be to only permit groundwater trading (i) within the same zones and/or (ii) away from the river, from inner to outer zones (i.e. from Zone 1 to Zone 2, 3 and 4 or Zone 2 to Zone 3 and 4, etc). Any rules governing groundwater trading would need to be developed on a case-by-case basis according to a sound hydrogeological knowledge of the catchment and a consideration of how any trading may affect the interaction between groundwater and surface water.

Even though the above focus is on water quantity considerations, there are cases where trading from surface water to groundwater may not be desirable from a water quality perspective. For example, it is well known that in the Daly River in the Northern Territory groundwater inflows provide a thermal refuge for nesting of turtles. Groundwater provides a relatively constant temperature inflow, whereas surface water flows fluctuate widely in temperature. Groundwater pumping can reduce these inflows and so surface water to groundwater trading can adversely impact on this groundwater dependent ecosystem.

9. Conclusions and Overall Strategy for Australia

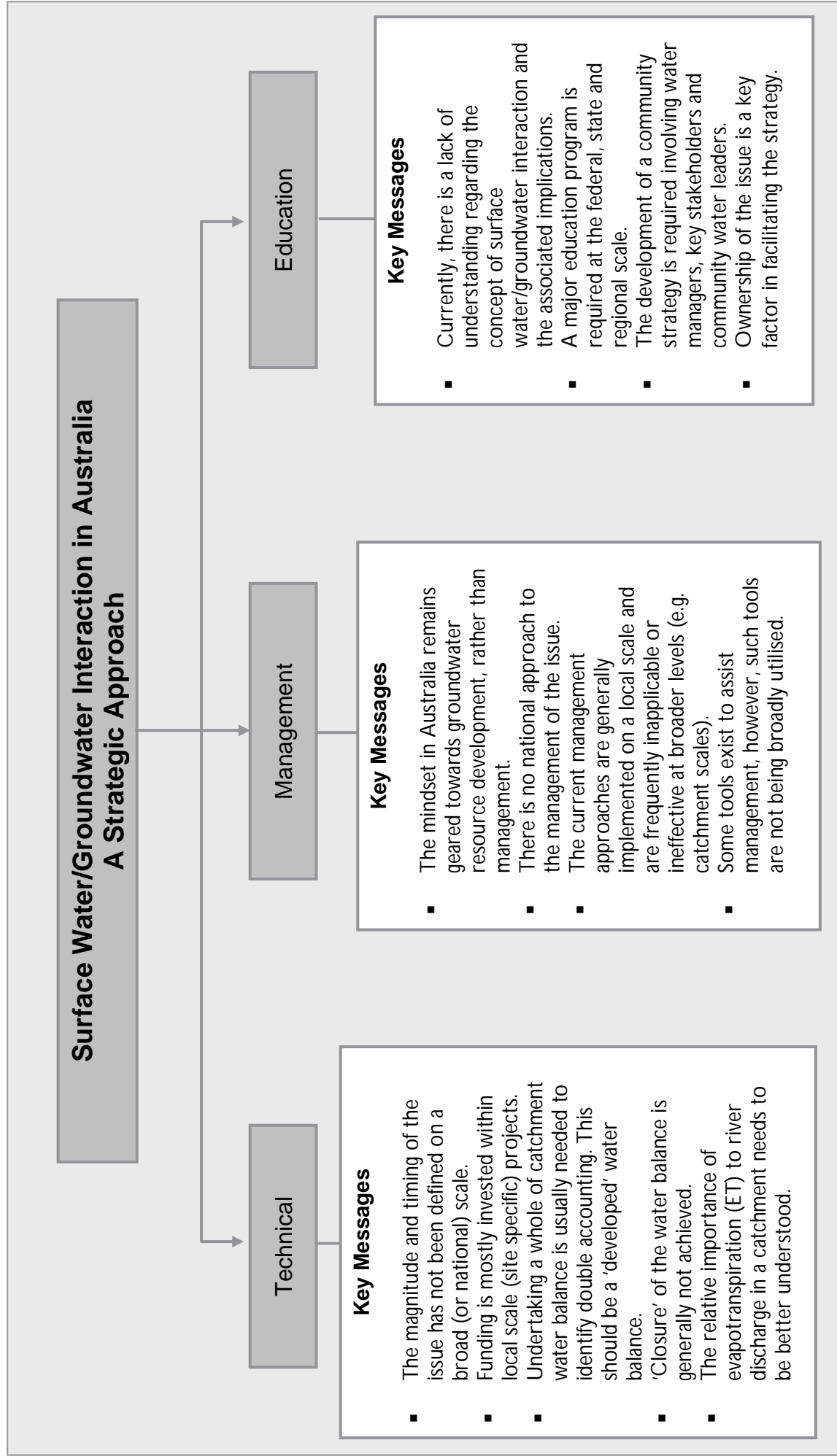
9.1 Overview

The lack of technical understanding of surface water/groundwater interaction in both technical and general community circles has substantially led to our current situation. This has however been brought to our attention by the dryer conditions over the last decade, the rapidly increasing demand for water and the general community desire for greater environmental flows in our rivers.

Addressing the impacts of surface water/groundwater interaction in Australia requires a cultural change in the way we manage water. The historical separate management of surface water from groundwater is the primary cause of the issue. This institutional barrier has been maintained by a lack of technical understanding. Thus it is proposed that an overall strategy for Australia would comprise three key elements: technical, management and education. **Figure 9-1** presents an overview of key messages which summarises the challenges that we face in these three broad areas.

It is tempting to conclude that the changes and the impacts alluded to in this report will fall almost totally on groundwater users. This should not be the case. A fundamental policy principle should be that all water users be treated equally. Even though much of this report is focussed on the impacts of groundwater pumping on reducing stream flow, it is clear that direct surface water extraction from rivers and the impacts of dams have a much greater impact on river flows. Our water licensing systems have been almost completely separate and therefore it is not legally, socially or economically appropriate to imagine that groundwater users should bear the burden of correcting the poor water licensing decisions of the past. The over allocation of both our surface water and groundwater resources should be addressed equally by all water users and the possible cuts and restrictions should not only apply to groundwater users.

Figure 9-1 Surface water/groundwater interaction in Australia – a strategic approach



9.2 Technical

The key technical conclusions from this report are:

- The magnitude and timing of double accounting of our surface water and groundwater resources has not been defined at the national scale. Even though there are many local studies which commonly demonstrate a significant level of interaction, a broad scale understanding does not exist.
- A significant time lag may exist between when groundwater pumping commences and effects are felt at rivers. The processes affecting this time lag are relatively well understood.
- Baseflow analysis usually overestimates groundwater discharge, although not always. Hence, caution is needed in its application. The conceptual hydrogeological model should dictate the amount by which the baseflow analysis should be altered to provide a meaningful estimate of groundwater discharge. There is a need to undertake more detailed case examples linked to detailed field measurement where the different components of baseflow are assessed and greater confidence in understanding the groundwater component is obtained. The role of climate in influencing baseflow needs further assessment.
- Greater confidence in defining the impacts of groundwater pumping on streams will be achieved by better quality total catchment water balances. The lack of detailed field studies where the full water balance is 'closed' is a concern.
- An important distinction needs to be drawn between the natural catchment water balance, (albeit often with cleared native vegetation) and the developed catchment water balance with significant groundwater pumping underway. The development of the groundwater resources can profoundly alter the water balance.
- Groundwater pumping has been underway actively since the 1960s and across most groundwater systems in Australia the bores are frequently located close to rivers and streams. Consequently, in many catchments the impacts of groundwater pumping on reducing stream flows would have already been felt. Depending on the method used for the surface water resource assessment, this historical impact may have already been factored into the (reduced) surface water yield.
- In many catchments in Australia ET from groundwater is an important factor acting to reduce the impact of groundwater pumping on stream flow. Groundwater ET is often vital to maintain the health of groundwater dependent ecosystems (e.g. vegetation).
- It is considered that the impacts of groundwater pumping on reducing stream flow can vary from 100% to 0%, depending on various hydrogeological characteristics. Nonetheless, for many situations, especially where the bore is close to a stream and unconfined aquifers exist, the impact will be 100% in steady state. At the catchment scale, as groundwater levels fall as a result of continuing groundwater pumping, then the importance of ET_{gw} decreases and greater impacts on streams will be felt.

These technical conclusions are believed to provide a sufficient foundation to proceed with addressing surface water/groundwater interaction issues in Australia. Even though significant technical work is required, the fundamental processes are clear.

9.3 Management

- There is no common or agreed national approach on how to manage surface water/groundwater interaction.
- The amount of double allocation of groundwater and surface water resources in Australia is unknown.
- Current management, where it exists, is geared towards local scale short term impacts while catchment scale medium to long term impacts are generally not addressed.
- Different management approaches are required depending on whether total water resource sustainability or management of environmental flows in streams are being addressed. Both issues are best addressed in the context of a total catchment water balance.
- Zonal management offers a tool to assist in the management of minimum stream flows.

The above management conclusions call for the development of integrated surface water and groundwater management plans in many catchments in Australia. There are some situations where this would not be sensible or necessary. Nonetheless, not until the jurisdictions begin to develop confidence in integrated planning will this issue be adequately addressed.

9.4 Education

How to gain community ownership of the implications of surface water/groundwater interaction represents a major challenge. Effective groundwater management relies more on community goodwill than surface water management. This is because of the common scattered nature of bore locations and the resulting difficulty in ensuring compliance. Hence, good groundwater management is dependent on community understanding. In an issue such as this, the potential for one interest group (e.g. surface water users) to campaign against another interest group (e.g. groundwater users) is high. The resulting community disharmony would not be conducive to integrated water management. It also makes reaching consensus very challenging, where difficult decisions on cuts to water allocations are required. The lessons from the USA case studies in Section 6.1 all show that the legal system is unable to effectively address this issue. Therefore, a comprehensive education program is required to explain both the technical and management aspects of surface water/groundwater interaction. This education program should initially focus on water managers and key community water leaders.

10. Recommendations

The recommendations from this study have been divided into three groupings: technical, management and education. All of these recommendations need to be adopted if the issue of surface water/groundwater interaction is to be addressed in a systematic and consistent manner in each jurisdiction.

10.1 Technical

- 1) Undertake whole of catchment water balances to identify possible double accounting. A developed water balance should be undertaken if possible.
- 2) More studies to 'close' the water balance are required to gain confidence in the water balance components.
- 3) Undertake field and modelling studies to better understand the proportion of pumped water that is likely to be derived from intercepted stream discharge as opposed to other sources (including groundwater ET).
- 4) Undertake a national assessment of the extent of double accounting of Australia's water resources. To explicitly identify double accounting it is suggested that the aquifer classification approach described in Section 7.2 could be used to classify all aquifers in Australia. Initially an agreed methodology should be developed. This methodology would inevitably be semi-quantitative at best, as the required detailed data is not available over most of Australia.
- 5) Develop a toolbox of assessment methods and approaches to define the process of surface water/groundwater interaction, the level of connectivity and double accounting of water resources. Different levels of desk-top (i.e. not field-based) approaches should be presented in the toolbox from 'back-of-the-envelope' calculations to sophisticated numerical modelling. An important component of the toolbox will be to develop approaches to conducting a catchment-wide water balance to proportion the representative volume of surface water and groundwater available per time period according to the degree of interaction. Importantly, the toolbox should be developed with consistent definitions and terminologies agreed to by the states and territories.
- 6) Identify those Groundwater Management Units in Australia which should have their boundaries modified to better allow for surface water/groundwater interaction. This may mean adopting surface water catchments in some cases. (This especially applies to those Groundwater Management Units which cross state/territory borders.)
- 7) Undertake further research and application (i.e. case studies) on interpreting river baseflow analyses from a groundwater discharge perspective. This also applies to understanding the influence of climate on baseflow.

10.2 Management

- 8) Develop a toolbox to present a range of practical management options and procedures concerning both existing and new water licences aimed at managing the impacts associated with surface water/groundwater interaction. This management focussed toolbox would need to have active input from the states and territories.

- 9) Identify the level of double allocation of groundwater and surface water resources in Australia. This needs to actively involve the states and territories. A methodology needs to be developed and agreed at the start of the task.
- 10) Start the development of Integrated Surface Water and Groundwater Management Plans. (Note – there will be some regions where this will not be appropriate.)

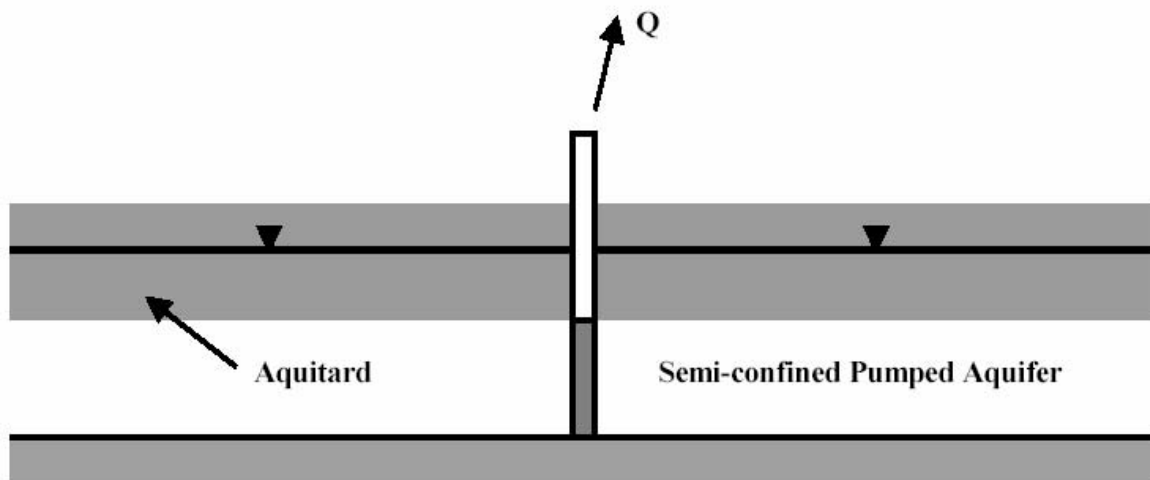
10.3 Education

- 11) Design a comprehensive education program focussed on water managers and key community water leaders.
- 12) Negotiate with the states and territories on where/how/who/what should be the focus of the education program.

Appendix A Hunt (2003a) Analytical Solution for Semi-confined Aquifers

Boulton (1963) obtained a solution for delayed drainage or delayed yield that occurs when an unconfined aquifer is pumped. In a later publication, Boulton (1973) showed that this type of aquifer response (i.e. delayed drainage) can also occur when a semi-confined aquifer, bounded on top with an aquitard containing a shallow water table, is pumped. This conceptual model is shown in Figure A-1 (the water surface shown in this figure is the water table in the aquitard). Immediately after well abstraction begins the pumped aquifer behaves as a confined aquifer. After the initial period of pumping, water starts to move downward through the aquitard to recharge the pumped aquifer, and during this period the aquifer response is described closely with the Hantush solution for flow to a well in a leaky aquifer. Unlike the Hantush solution, though, the Boulton solution allows the free surface (i.e. the water table) in the aquitard to move downward as water is drained from the aquitard into the pumped aquifer. Thus, at larger times piezometric levels in the aquitard and in the pumped aquifer approach each other, and the aquifer response becomes similar to the response predicted with the Theis solution for an unconfined aquifer with a storage coefficient equal to the effective porosity of the aquitard.

- **Figure A-1:** Conceptual model for delayed yield solution developed by Boulton (1973) for a pumped aquifer bounded with an aquitard containing a shallow water table



Hunt (2003a) describes the principles of analysing pumping tests using the Boulton solution for semi-confined aquifers. This is then developed into an extension of the Hantush-Jacob semi-confined aquifer model in which the Boulton delayed-yield solution is used to predict the long-term behaviour of a semi-confined aquifer with finite storage. From this background Hunt (2003a) develops a solution for stream-depletion in which pumping from a well depletes flow from a nearby stream. Hunt (2003a) notes:

Abstracting water from a well beside a stream also depletes water from the stream. In fact, if pumping continues for a long enough time, and if the stream continues to flow, then flow depleted from the stream ultimately equals flow abstracted by the well. However, at smaller values of time well abstraction exceeds stream depletion. (Hunt, 2003a p.14).

Hunt (2003b) obtained a mathematical solution for the conceptual model for stream flow depletion, due to pumping from a semi-confined aquifer, as shown below. The aquifer is semi-confined in which the stream partially penetrates the top aquitard. The solution to the problem shown is presented below. The pumped well is located at distance L from a long straight stream that extends to plus and minus infinity. The parameters shown below are:

L = distance of the bore from the stream (m)
 Q = pumping rate from the bore (m^3/day)
 b = stream width (m)
 B' = aquitard saturated thickness (m)
 B'' = aquitard thickness beneath the streambed (m)

Parameters not shown in the figure but part of the model and required in the solution include:

T = Transmissivity of the pumped aquifer (m^2/day)
 K' = Vertical hydraulic conductivity of the aquitard (m/day)
 S = Storage co-efficient of the aquifer (-)
 S' = Specific yield of the aquitard (-)

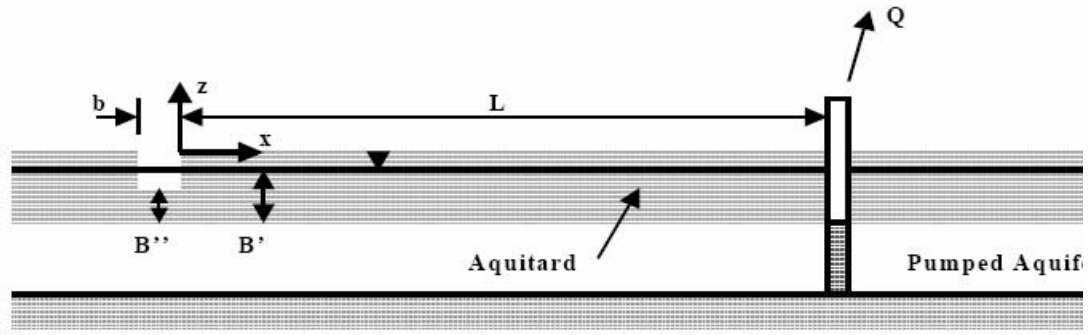


Fig. 6 Geology for the stream depletion problem.

The problem shown in Fig. 6 is described by the solution of the following problem:

$$T \left(\frac{\partial^2 s}{\partial x^2} + \frac{\partial^2 s}{\partial y^2} \right) = S \frac{\partial s}{\partial t} + \left(\frac{K'}{B'} \right) (s - \eta) \quad (-\infty < x < \infty, -\infty < y < \infty, 0 < t < \infty) \quad (33)$$

$$\sigma \frac{\partial \eta}{\partial t} + \left(\frac{K'}{B'} \right) (\eta - s) = 0 \quad (-\infty < x < \infty, -\infty < y < \infty, 0 < t < \infty) \quad (34)$$

$$\text{Limit} \left(R \frac{\partial s}{\partial R} \right)_{R \rightarrow 0} = -\frac{Q}{2\pi T} \quad \left(R = \sqrt{(x-L)^2 + y^2}, 0 < t < \infty \right) \quad (35)$$

$$\left(T \frac{\partial s}{\partial x} \right)_{x=0+} - \left(T \frac{\partial s}{\partial x} \right)_{x=0-} = \lambda s(0, y, t) \quad (-\infty < y < \infty, 0 < t < \infty) \quad (36)$$

$$(s)_{x=0+} - (s)_{x=0-} = 0 \quad (37)$$

$$s(x, y, 0) = \eta(x, y, 0) = 0 \quad (-\infty < x < \infty, -\infty < y < \infty) \quad (38)$$

$$\text{Limit}(s)_{R \rightarrow \infty} = 0 \quad (0 < t < \infty) \quad (39)$$

where s = drawdown in the pumped aquifer, η = drawdown of the free surface in the aquitard and λ is a streambed leakage parameter defined by

$$\lambda = K'' \frac{b}{B''} \quad (40)$$

where B'' denotes the aquitard thickness beneath the streambed, which may differ from the aquitard saturated thickness, B' , at points away from the stream. Eqs. (33) - (34) are the partial differential equations that describe flow in a delayed-yield aquifer, where K'/B' is replaced with an equivalent value given by Eq. (31) if more than one layer exists above the pumped aquifer. Eq. (35) requires that flow seeping into the well equal the well abstraction, and Eqs. (36) and (40) require that the difference in aquifer flow (per unit stream length) along the two stream sides equal the flow (per unit stream length) that

has seeped vertically downward through the aquitard from the stream. Eq. (37) requires that drawdowns in the pumped aquifer be continuous under the stream, Eq. (38) requires that drawdowns vanish at $t = 0$ in both the aquitard and pumped aquifer and Eq. (39) requires that drawdowns in the pumped aquifer vanish at infinity.

If Eqs. (33) - (39) are applied to the more general layered aquifer discussed in the previous section, then it is important to note that not only must K'/B' be replaced with the equivalent value given by Eq. (31) but λ must also be replaced with an effective value given by

$$\lambda_{\text{effective}} = \frac{b}{\sum_{i=1}^{n-1} (B'/K') + B''/K'} \quad (41)$$

Thus, increasing the number of layers above the pumped aquifer reduces the values of both K'/B' and λ . In this case, the top layer **must** be an aquitard that contains both the free surface and the partially penetrating stream. If this is not the case, then lateral piezometric gradients in the top layer may cause significant horizontal outflow from the stream, and Eq.(36) neglects this horizontal outflow.

A user-defined function in Function.xls computes aquifer drawdowns in the aquifer with

$$\frac{sT}{Q} = W_{-4} \left(\frac{x}{L}, \frac{y}{L}, \frac{tT}{SL^2}, \frac{\lambda L}{T}, \frac{(K'/B')L^2}{T}, \frac{S}{\sigma} \right) \quad (42)$$

Flow depleted from the stream, ΔQ , can also be computed by using

$$\frac{\Delta Q}{Q} = Q_{-4} \left(\frac{tT}{SL^2}, \frac{(K'/B')L^2}{T}, \frac{S}{\sigma}, \frac{\lambda L}{T} \right) \quad (43)$$

Typical dimensionless plots computed from Eqs. (42) and (43) are shown in Figs. 7 and 8. Points to note include the reverse in curvature that occurs for all curves that describe a delayed-yield aquifer response and the horizontal asymptote, indicating steady flow, that occurs for both drawdown and stream depletion. The asymptotic value of one for stream depletion indicates that any well pumped for a sufficiently long period of time eventually obtains all of its flow from the adjacent stream, and a horizontal asymptote for the drawdown curves occurs because the stream is assumed in the mathematical solution to contain an infinite amount of water that can be recharged to the aquifer. A horizontal asymptote in the drawdown solution distinguishes the stream-depletion solution from the Boulton solution for flow to a well in an aquifer of infinite horizontal extent, which does not have a similar steady-flow asymptote. Fig. 9 shows the result of fitting these mathematical solutions to some field data obtained by Weir (1999).

Strangely enough, this solution for a stream of zero width can also be used to model flow to a well beside a stream whose width extends from $x=0$ to $x=-\infty$ simply by increasing $\lambda L/T$ until the solution stops changing. This can be thought of as the result of letting $b \rightarrow \infty$ in Eq.(40), and it may require setting $\lambda L/T = 10,000$ or more. This follows from the fact that all of the equations that describe flow for negative values of x

become homogeneous in the limit as $\lambda \rightarrow \infty$. Thus, taking this limit gives the solution $s = \eta = 0$ when $-\infty < x < 0$ and $-\infty < y < \infty$.

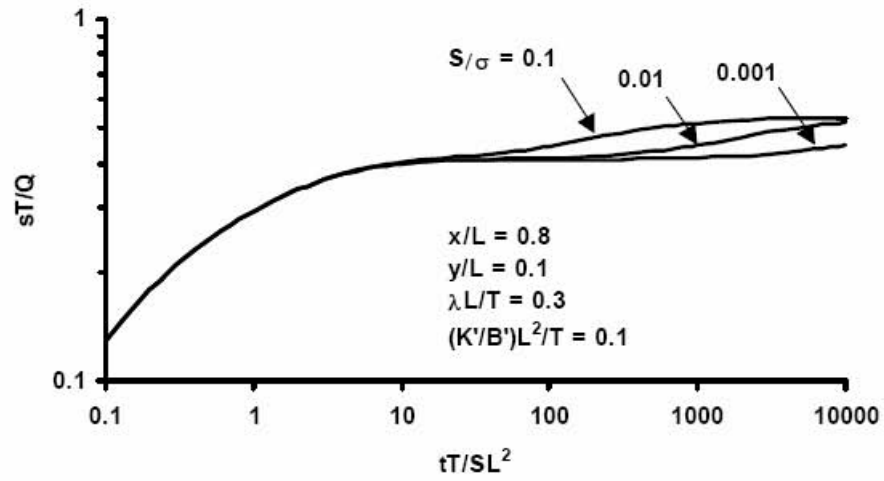


Fig. 7 Typical drawdowns calculated from Eq. (40).

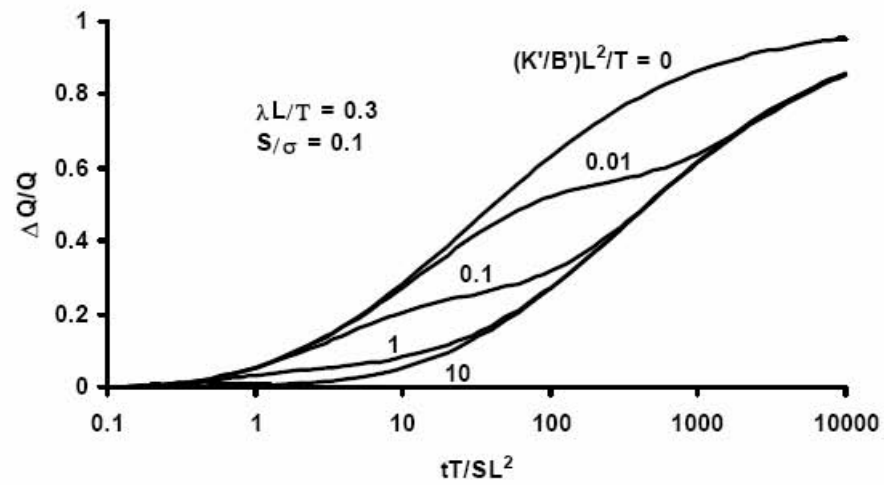


Fig. 8 Typical stream-depletions calculated from Eq. (41).

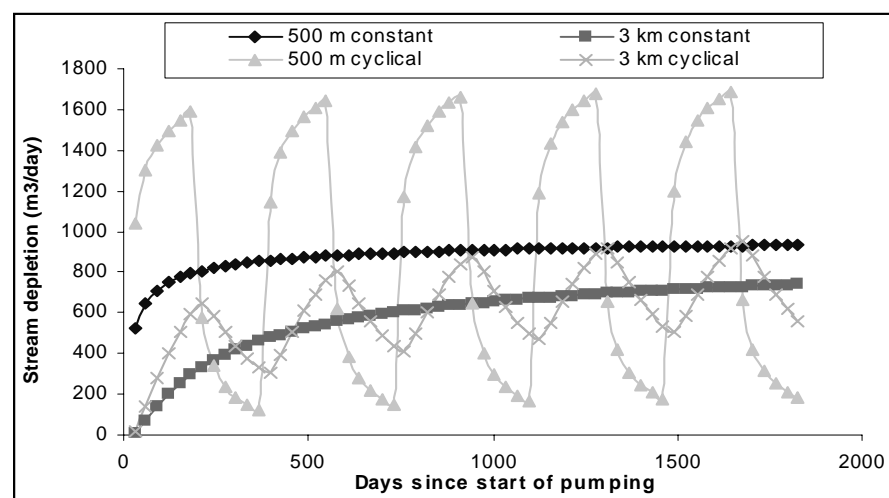
Discussion of Model Assumptions

- The model is based on the Theis equation, which assumes the aquifer is of infinite areal extent. If the model is applied in a relatively narrow valley, the model will underpredict the magnitude of the drawdown, which in turn will mean vertical seepage and river losses will be underestimated by the model.
- Regarding the conceptual model of the site, Hunt (2003a p. 16) states:

... the top layer must be an aquitard that contains both the free surface and the partially penetrating stream. If this is not the case, then lateral piezometric gradients in the top layer may cause significant horizontal outflow from the stream, and Eq.(36) neglects this horizontal outflow.

If the upper layer in the model is partly an aquifer rather than an aquitard, the Hunt model will underestimate the rate of stream flow loss because it neglects horizontal flow. This does not mean that the model results are invalid, but simply that the results will be an underestimate of actual losses from the river, because the impact of lateral flow in the aquifer is not included in the model.

- The model does not allow for intermittent pumping. A constant pumping rate over time is required. Numerical modelling conducted by Braaten and Gates (2004) demonstrated that the total long term impact on stream flow by cyclical pumping from a semi-confined aquifer can be adequately modelled by continuous pumping, as shown in Figure A-2. This figure demonstrates that while there is seasonal variation evident in the intermittent pumping, the total cumulative reduction in stream flow is the same as under continuous pumping.
- **Figure A-2: Impact of cyclical versus continual pumping on stream depletion. Example from Braaten and Gates (2004), Figure 1: a bore pumping at a constant rate of 1,000 m³/day; and a bore pumping in a cyclical pattern of six months on at 2,000 m³/day and six months off**



- The Hunt (2003b) model assumes that the water balance (recharge and discharge) are in equilibrium prior to pumping. Pumping increases the rate of discharge which requires the rate of recharge to increase or the rate of discharge at other sites to decrease.

Appendix B Hypothetical Catchment Modelling

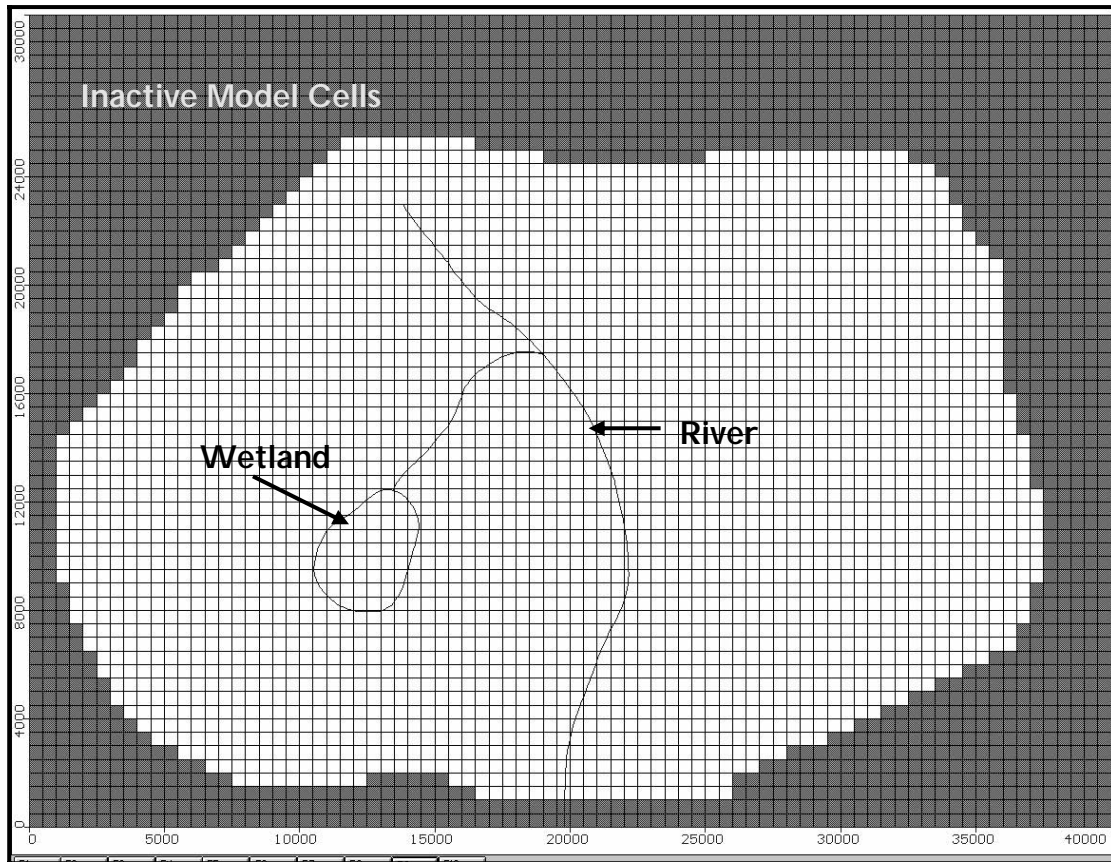
A simple finite difference numerical groundwater model was developed to assist with understanding and illustrating the mass balance changes that occur when groundwater pumping is introduced to a catchment.

The model has been developed in the Visual Modflow package and utilises the MODFLOW 2000 numerical simulation code. The model represents a hypothetical catchment considered to be typical of semi-arid areas of Australia. It includes a relatively flat terrain and large areas of shallow water table resulting in evapotranspiration (ET) from the water table being an important feature of the mass balance. The hypothetical catchment is drained by a centrally located river running north to south and includes a large wetland that is sustained by shallow groundwater fluxes. The model was constructed as a single layer and the aquifer is assumed to be unconfined.

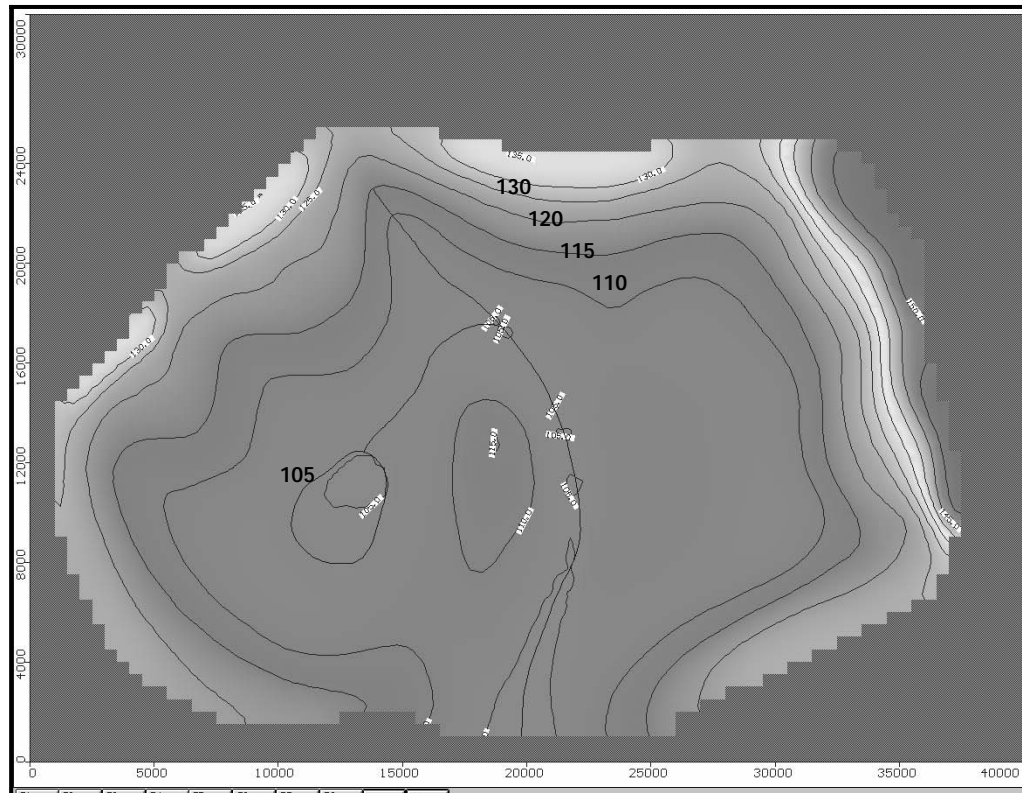
The model covers an area of approximately 700 km² and has been discretised into uniform square grid cells of 500 m sides. The model grid structure and layout is presented in Figure B-1. The single model layer incorporates a hypothetical topographic surface ranging from 160 to 100 m Australian Height Datum (AHD) as its upper surface and its bottom is set at a constant elevation of 0 m AHD. The topographic surface that forms the top of the model is shown in Figure B-2.

The model includes hydraulic conductivity value of 2 m/d and a specific yield of 0.1. These parameters are typical of a fine sand. The aquifer is recharged by rainfall that has been set at an average rate of about 7 mm/year. If it is assumed that recharge is 2% of rainfall then the recharge rate represents an annual rainfall of about 350 mm. ET has been defined as a linear function with depth to water table. The maximum ET rate has been defined as 50 mm/year and the extinction depth is set at 1 m.

■ Figure B-1 Model grid layout and features



■ Figure B-2 Topographic contours of model top (values are in mAHD)



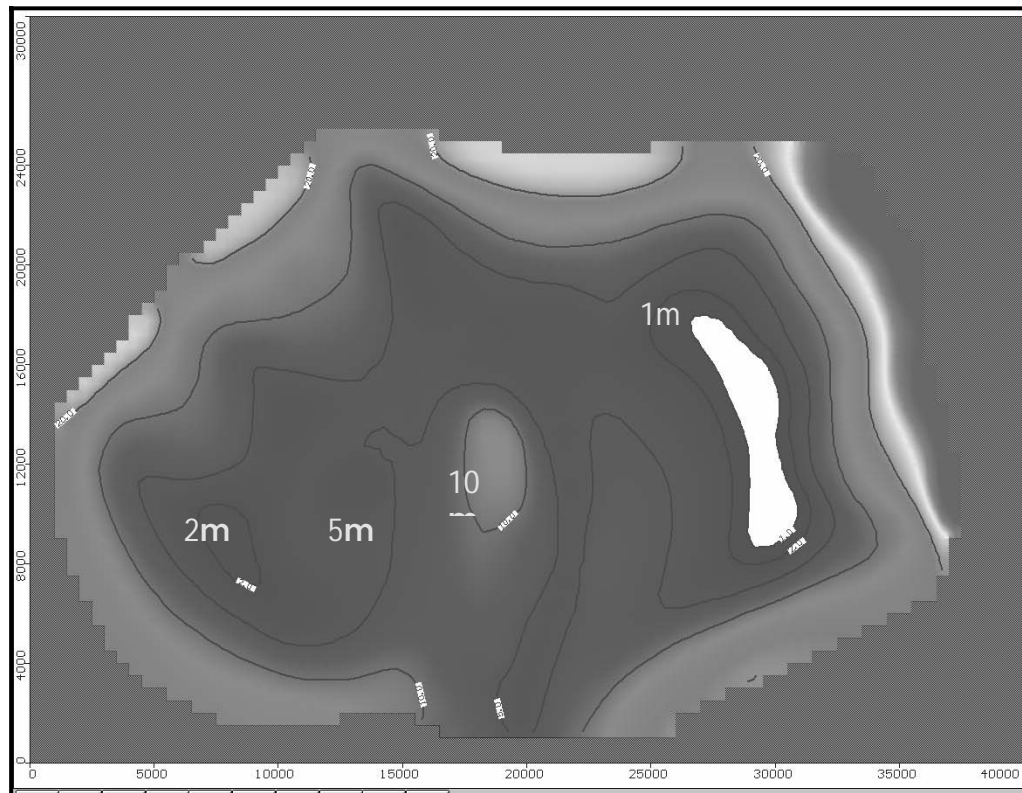
The model was run in steady state with no groundwater extraction. The model mass balance is shown in Table B-1. It can be seen that rainfall recharge (Recharge in Table B-1) is the principal means of aquifer replenishment. Recharge from river leakage is relatively small. Groundwater outflows include discharge to rivers and wetlands, ET and groundwater flowing out of the model domain. River leakage IN indicates a losing stream, while river leakage OUT represents a gaining river. ET represents approximately 5% of the water balance.

Figure B-3 shows the model predicted depth to water table showing the region in which ET is active highlighted.

■ Table B-1 Model mass balance [ML/day]

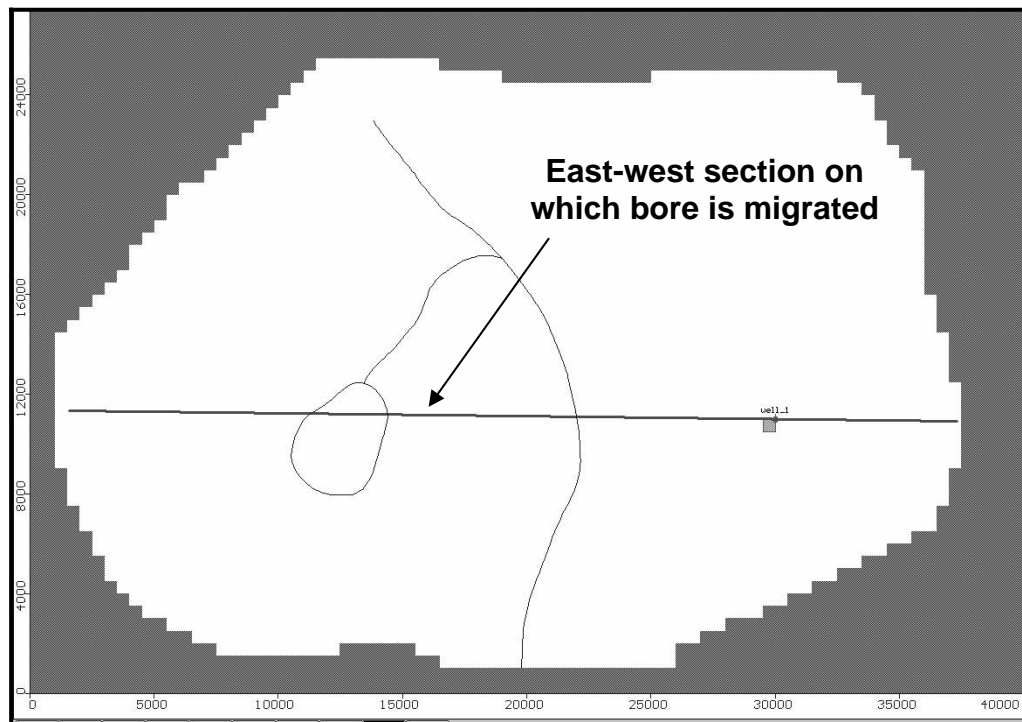
	IN	OUT
River Leakage	0.93	6.19
Recharge	12.88	
Evapotranspiration		0.69
Groundwater Outflow		2.88
Groundwater Discharge to the Wetlands		3.95
Totals	13.81	13.71

■ Figure B-3 Water table depth



The mass balance includes a 0.8% discrepancy associated with mathematical inaccuracy. A pumping bore was added to the model to investigate changes in mass balance caused by groundwater extraction. It was found that as groundwater extraction is added to the model the rates of groundwater discharge to the rivers and wetlands and to ET reduce to accommodate the increased groundwater outflows. The location of the bore was varied to investigate how the mass balance changes with extraction location. The bore was progressively migrated in 2,500 m steps along an east west section (Refer to Figure B-4) through the aquifer. In each case the bore pumping rate is assumed to be 1 ML/day.

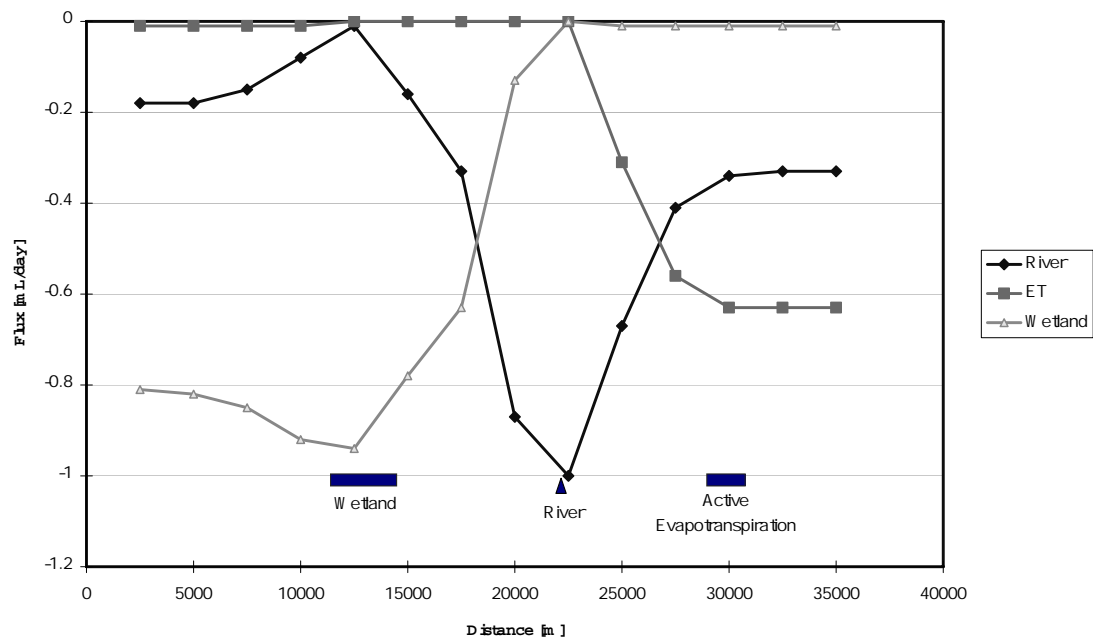
- **Figure B-4 Locations of pumping bore**



Results are presented in the form of the changes in the mass balance fluxes caused by the additional outflow associated with the groundwater pumping. It was found that in all cases the changes in mass balance were limited to the following terms: groundwater discharge to the wetland, groundwater discharge to the river (baseflow) and ET. Results are shown graphically in Figure B-5 as a plot of change in the three mass balance flux components against the position of the bore along the section.

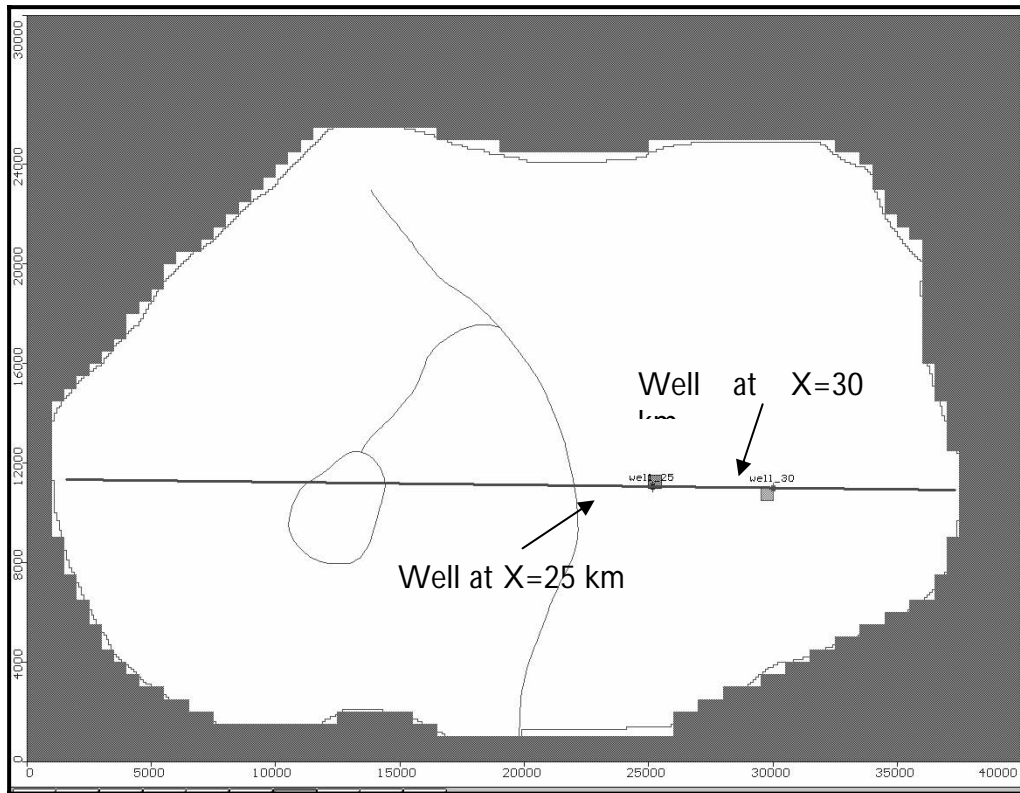
It can be seen that the changes in mass balance component vary as the bore moves from west to east across the aquifer. It is of interest to note that impacts on surface waters (i.e. wetlands and river flows) is found wherever the bore is located.

■ Figure B-5 Changes in mass balance caused by groundwater extraction – change in flux vs position of pumping bore

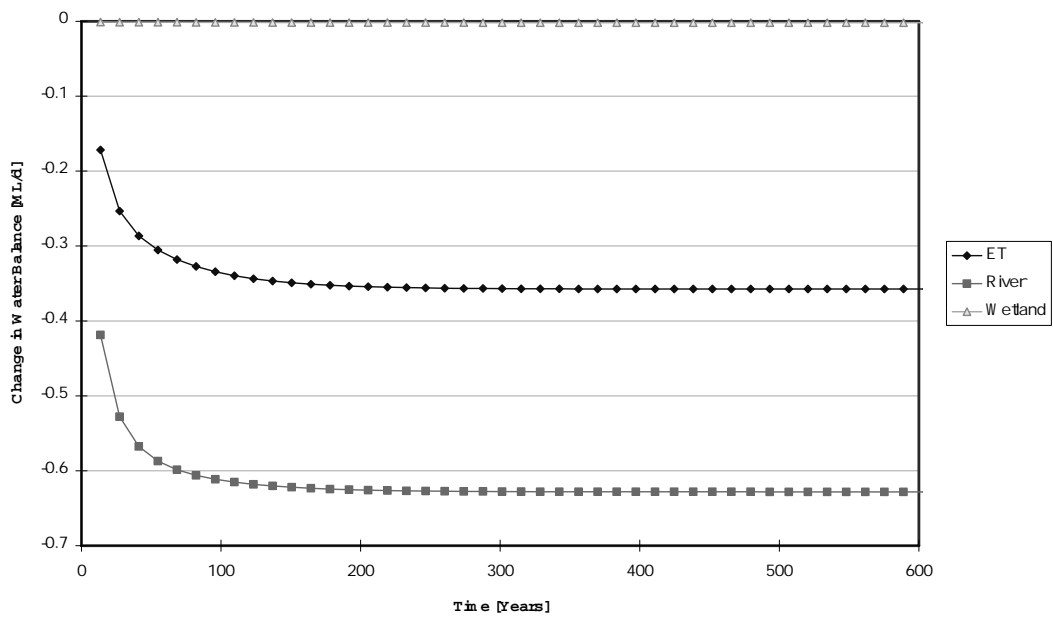


The model was run in transient mode to determine the time taken for the water balance adjustments to take effect following the introduction of pumping. Two transient models were run with the bore located at a distance of 25 km and 30 km respectively (refer to Figure B-6 for locations of the pumping bores). These distances represent pumping 3 km and 8 km from the river. Results of the two model runs are presented in Figure B-7 and Figure B-8 as plots of the changes in river, ET and wetland fluxes with time. It can be seen that steady state conditions are attained after 200 or 300 years depending on location of the bore. Water balance stabilisation is reached earlier when the bore is located closer to the river.

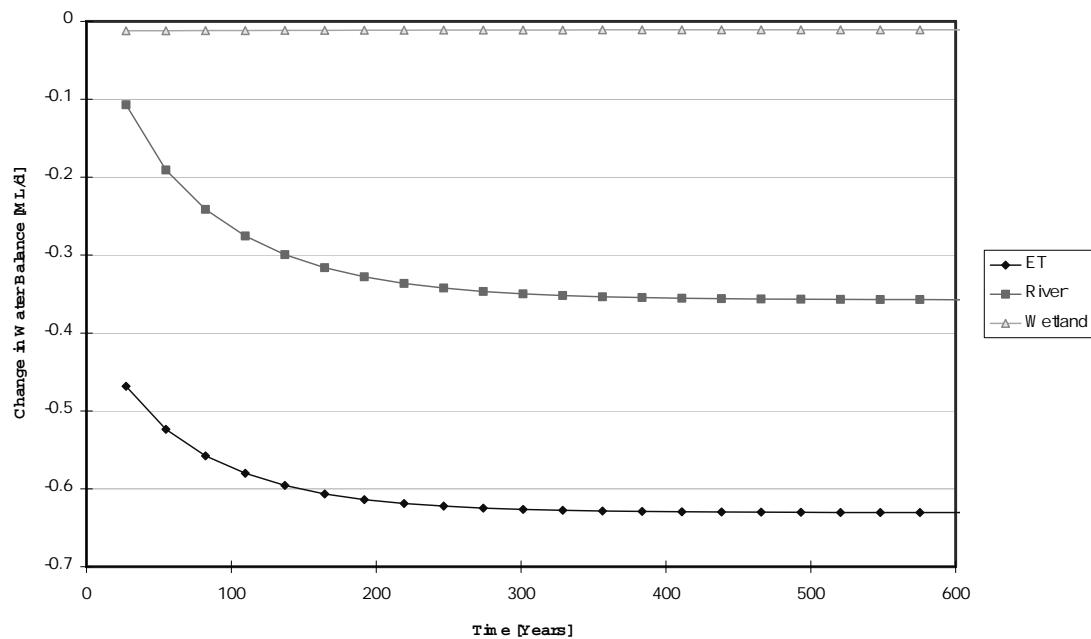
■ Figure B-6 Bore locations in transient models



■ Figure B-7 Changes in water balance components – bore located at X = 25,000 m



- Figure B-8 Changes in water balance components – bore located at X = 30,000 m



The key conclusions from this hypothetical modelling are:

- The recharge rate over the model does not stabilise the cone of depression and therefore the impact is not prevented from reaching the river
- The location of the pumping bore has a major influence on the relative impact on ET and discharge to the river
- When the bore is introduced, the water comes from the river and ET. Depending on location of the bore, the impact on reducing river flows will be greater over time than the impact on reducing ET
- Even when the bore is located directly in the middle of the active ET_{gw} zone (i.e. at 8 km from the river), there is still significant impact of groundwater pumping on the river. Obviously when the bore is close to the river the impact on reduced stream flow is approaching 100%.
- The long time to reach steady state is because of the very flat hydraulic gradient (0.0005) and the low hydraulic conductivity (2 m/d)
- It is considered that any *increase* in rainfall recharge to the water table aquifer or *decrease* in ET rates from the water table aquifer will be negligible within the area as a result of pumping, as the water table is generally too deep for either of these processes to occur to any significant extent. Consequently, the only major water source that can return the water balance to equilibrium is the river. As a result, ***exclusion of recharge or discharge from other sites does not significantly impact on this assessment.***

Appendix C Baseflow Separation Analysis Methods

This appendix presents a summary of the techniques available to undertake a baseflow analysis and the methods used to prepare stream flow data for the analysis.

Stream flow Data Accuracy

The accuracy of an estimate of baseflow in a stream is firstly dependent on the accuracy of the stream flow gauge recording stream flow data. The measurement error associated with stream flow gauges is typically in the order of 5 – 10%, depending on the stability of the channel cross section. For concrete V-notch weirs during low flow conditions, errors in stream flow could be as low as 1%, whilst errors will increase at high flows. These relatively low errors at low flows indicate that stream flow data accuracy does not inhibit the accurate estimation of baseflow, other than at stream flow gauging stations with highly variable geomorphic conditions.

This illustrates the principal advantage of using baseflow separation in surface water/groundwater interaction studies. There is a high degree of confidence in the upper bound of baseflow, because it is limited by the value of observed stream flow, which can be determined reasonably accurately.

Influences on Low River Flows

There are various activities that can affect stream flows and mimic or interfere with the signal usually associated with baseflow. These include:

- Flow regulation from upstream reservoirs – reservoirs that release outflows that are different from inflows will produce a low flow signal that can be misinterpreted as baseflow at downstream flow gauges. Neal et al. (2004) adopted a criterion that not more than 10% of the catchment should be upstream of flow regulating structures when selecting stream flow gauges for regional baseflow assessment, which should be regarded as an upper limit for local investigations.
- Major diversions – diversions for consumptive use such as irrigation channels, urban diversions, etc. These diversions can decrease low flows and appear to reduce estimates of baseflow.
- Urbanisation – in urban areas, activities such as excess garden or sports field watering can increase low flows during summer that appear similar to baseflow in stream flow data.
- Return flows – water can be returned to rivers from sewage treatment plants or from industry. Power stations in particular often discharge cooling tower water to streams. This will increase low flows and appear similar to baseflow.
- River evaporation and evapotranspiration – evaporation from the river surface and plant water uptake will generally be a negligible influence on stream flows for catchments less than 1,000 km². For larger catchments, baseflow expressed at an upstream location may

be reduced at the stream flow gauging station because of these reach losses, particularly during summer low flow conditions when baseflow is most evident.

In catchments where in-stream flows are affected by some of the above influences, baseflow separation should not be attempted without treatment of the data and even then with caution. This can be achieved by either accounting for those upstream influences in the stream flow data at the gauging station location, or by undertaking baseflow separation on inflows between stream flow gauging stations. In both cases, flow monitoring errors are likely to compound resulting in much scope for variability and uncertainty in baseflow estimates. Baseflow should be relatively stable (or follow an exponential decay function in the absence of catchment rainfall) on successive days, so comparison of baseflow estimates on successive days will give an indication of the uncertainty in those estimates.

Stream flow Data Preparation

Stream flow data often contains missing data due to hydrographic equipment failures or events occurring outside of the range for which the stream flow recording equipment has been rated. Equipment failures are unavoidable to a large extent and some missing data is likely to occur in most stream flow records. Events below the instrument threshold typically occur when a region enters an unprecedented drought and stream flows drop below previously rated stream flows. It is therefore important to re-rate stream flow gauges during drought, because the opportunity to re-rate stream flows will be lost once the drought has passed.

Stream flow data infilling should be minimised, because any baseflow signal identified in the infilled data will generally reflect the infilling technique and not the actual baseflow processes. An example of this is the use of regressions to infill stream flow data. If stream flow data is infilled from an adjacent stream flow gauge, then the baseflow properties of the infilled data will reflect those of the stream flow data used to infill the missing data, and may or may not reflect the behaviour in the catchment itself. Similarly, the use of a rainfall-runoff model will have a pre-defined baseflow recession constant, which may or may not reflect actual baseflow behaviour, depending on the suitability of the model calibration and the range of flows over which it is calibrated. If any infilling of data is undertaken, consideration should be given to the likely compatibility of baseflow properties between the raw data at the site of interest and the infilled data.

There can be advantages in infilling stream flow data in baseflow studies if only short periods of data are missing. Having a complete record allows baseflow statistics to be prepared for different seasons using a comparable length of record. Neal et al. (2004) adopted a maximum extent of infilled data of 5% of the record for use in regional baseflow assessment, which is a reasonable guide for local investigations as well. For some local investigations, no infilled data may be preferred, particularly for those looking at the influence of groundwater pumping on baseflow, which will only be observed in the gauged stream flow data and not in the infilled data.

Baseflow Separation Techniques

Various techniques are available to separate baseflow from recorded stream flow data. These include traditional graphical procedures and more recent automated procedures. Documented hydrologic techniques are generally targeted towards removing baseflow from flood hydrographs for flood analysis, rather than seeking to retain baseflow for studies in surface water/groundwater interaction.

It is important to note that all baseflow separation techniques, either graphical or automated, are ideally suitable for comparative analysis to ascertain relative baseflow contributions between sites or at the same site over time. Accurate quantitative determination of the absolute magnitude of baseflow is not readily achievable through baseflow separation alone. Baseflow hydrographs for detailed at-site investigation should be conditioned by local knowledge of both aquifer and stream flow characteristics, regardless of the baseflow separation technique applied. Nonetheless, considering the relatively low accuracy of many hydrogeological assessments, the errors involved in quantitative baseflow analysis are comparable with or less than the often significant errors in many groundwater assessments.

General Characteristics of Baseflow

The shape of a baseflow hydrograph is partly subjective, but there are some common features to the curve, as presented by Nathan and McMahon (1990):

- a) Baseflow recession continues after the rise of the total hydrograph due to the initial outflow from the stream into the adjacent stream banks
- b) Baseflow will peak after the total hydrograph due to the storage-routing effect of the sub-surface stores
- c) The baseflow recession will most likely follow an exponential decay function (a master recession curve)
- d) The baseflow hydrograph will rejoin the total hydrograph as direct runoff ceases.

Techniques for developing a master recession curve are documented in Nathan and McMahon (1990). Of these techniques, the matching strip method is reasonably robust and in wide application. The matching strip method involves lining up the tails of different hydrograph events on a logged vertical axis until they match to reveal a single slope, which defines the master recession curve. The master recession curve can have more than one equation over different flow ranges, corresponding to different discharge rates from different aquifers connected to the stream.

The following techniques attempt to interpret the above criteria for defining the baseflow hydrograph. Even the most sophisticated baseflow separation techniques are constrained by the need to identify the point at which surface runoff is assumed to cease, the location of which is largely a matter of conjecture. Regardless of the technique applied, baseflow estimates can often include some interflow during receding flood events and will generally represent an upper bound on actual baseflow contribution to streams.

Graphical Procedures

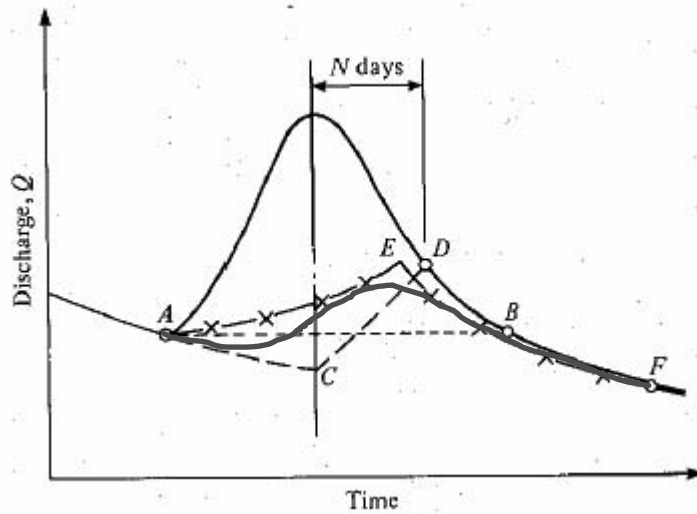
Graphical procedures for separating baseflow use a variety of techniques, outlined in Viessman et al. (1977). With reference to Figure C-1, techniques for baseflow separation include:

- Drawing a horizontal line from the point at which surface runoff begins (point A) to an intersection with the hydrograph recession as indicated by point B. This assumes no change in baseflow over the course of the runoff event, which is unlikely to be the case in practice.
- Projecting the initial recession curve downward from A to C, which lies directly below the hydrograph peak. The baseflow hydrograph reconnects to the total hydrograph at point D, which occurs N days after the hydrograph peak. N is based on the formula $N = (A/2.589988)^{0.2}$ where A is the catchment area in square kilometres. This approach has the advantage of allowing some lag of baseflow response to rainfall relative to quickflow response.
- Fitting a baseflow master recession curve and then projecting that backwards until the recorded hydrograph deviates from the master recession curve (point F). This is the point at which surface runoff ceases. The curve is projected backwards arbitrarily to some point E and its shape from A to E is arbitrarily assigned. This approach again allows for some lag in baseflow relative to quickflow.
- Drawing a straight line from A to F. This suffers from a similar issue to drawing a horizontal line from A to B, in that it does not allow baseflow to rise during a quickflow event.

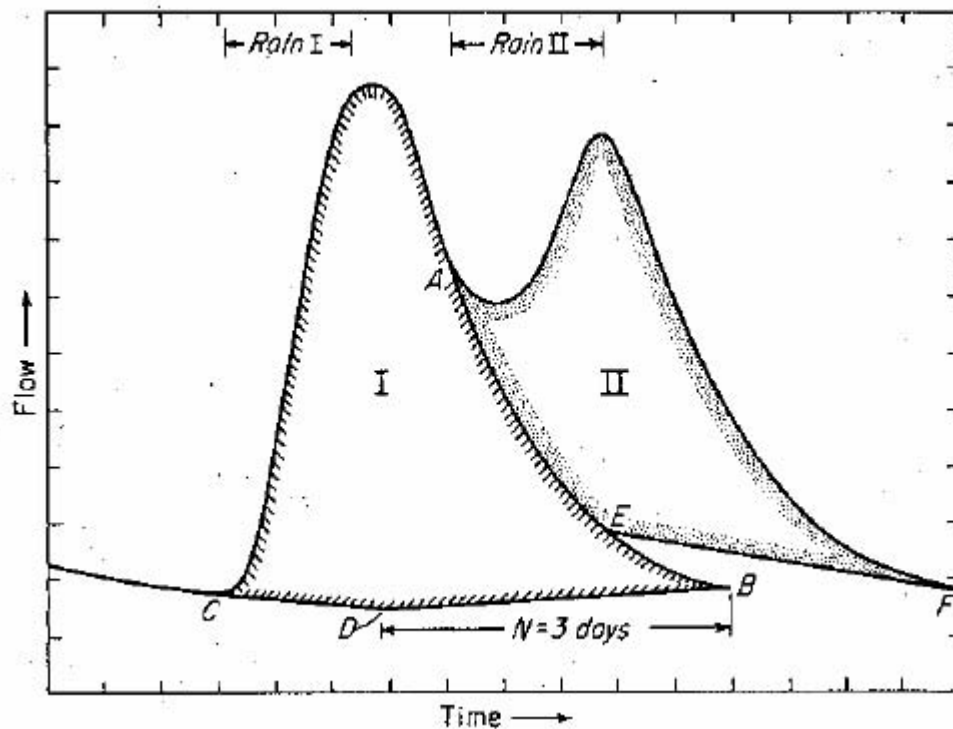
From the above graphical procedures, the approach most grounded in observed baseflow properties utilises the master recession curve at the start and end of the surface water event to define the rate of departure of the baseflow from the total flow hydrograph. Thereafter, the most realistic approach is similar to lines ACDB and AEF, but acknowledges that baseflow response is likely to be non-linear because it is heavily damped and that baseflow peaks and troughs will lag behind surface water peaks and troughs. This most likely baseflow hydrograph is depicted by the red line in Figure C-1, the curvature of which relies on subjective judgement.

The graphical analysis becomes more complicated when continuous time series data is analysed for baseflow. This is because a peak flow can occur that is rapidly followed by a second peak flow before surface runoff has ceased from the first event. This problem is not relevant to most event-based hydrologic flood studies, and has therefore been given less attention than the separation techniques discussed for a single peak hydrograph presented above. Linsley et al. (1982) projects the small segment of recession between peaks, using the master recession curve. A similar analysis to the above is then undertaken on the first hydrograph, with the line EF in Figure C-2 projected backwards using the master recession curve. It can be seen from this example that as hydrographs become more complicated, the more difficult and time consuming it is to separate out baseflow using graphical techniques.

- Figure C-1: Baseflow separation hydrographs (Viessman et al. 1977)



- Figure C-2: Baseflow separation hydrographs (Linsley et al. 1982)



Automated Procedures

Automated procedures predominantly involve the use of digital filters, commonly used in signal analysis and processing, that apply mathematical rules to separate baseflow. Automated baseflow separation techniques are documented in Grayson et al. (1996) and Nathan and McMahon (1990) as follows:

Method 1 – Institute of Hydrology (1980) Smoothed Minima Technique – The basis of this technique is summarised in Nathan and McMahon (1990). First, the minima of 5-day non-overlapping periods are found for the entire period of record. Next, this minima series is searched for values that are less than 1.11 times the two outer values; such central values are defined as turning points. The baseflow hydrograph is then constructed by simply connecting all of the turning points. The outcomes from this process for two examples are shown in Figure C-3.

Method 2 - Chapman and Maxwell (1996) – This method is suited to baseflow separation for long periods of flow record. It requires an estimate of the constant 'k' which can be considered as the recession constant of the hydrograph. Standard hydrology texts provide a number of ways to calculate recession constants, such as the matching strip method of developing a master recession curve, outlined in Nathan and McMahon (1990).

$$q_b(i) = [k/(2-k)]*q_b(i-1) + [(1-k)/(2-k)]*q(i)$$

$$\text{Subject to } q_b(i) \leq q(i)$$

where: $q_b(i)$ is the filtered baseflow response for the i th sampling instant

$q(i)$ is the original stream flow for the i th sampling instant

k is the filter parameter given by the recession constant

This filter is run as a single pass through the data.

Method 3 – Boughton (1993); Chapman and Maxwell (1996) – This is a more flexible digital filter that has been used to match flow path separation data for storm events from tracer studies. The equation is:

$$q_b(i) = [k/(1+C)]*q_b(i-1) + [(C)/(1+C)]*q(i)$$

$$\text{Subject to } q_b(i) \leq q(i)$$

where: $q_b(i)$ is the filtered baseflow response for the i th sampling instant

$q(i)$ is the original stream flow for the i th sampling instant

C is the parameter that enables the shape of the separation to be altered

This filter is run as a single pass through the data.

Method 4 – Lyne and Hollick Filter from Nathan and McMahon (1990) – The methods above have a better theoretical basis than the Lyne and Hollick filter, but the latter has been widely applied to daily data and there is a body of statistical information on baseflows across much of Australia in Nathan and Weinmann (1993) and Neal et al. (2004). The advantage of the Lyne and Hollick filter is also that it is not dependent on the local estimation of a baseflow recession or other baseflow separation constant for an individual site.

$$q_f(i) = q_f(i-1) + [q(i) - q_f(i-1)] * (1 + \alpha) / 2$$

For $q_f(i) \geq 0$

where: $q_f(i)$ is the filtered quickflow response for the i th sampling instant

$q(i)$ is the original stream flow for the i th sampling instant

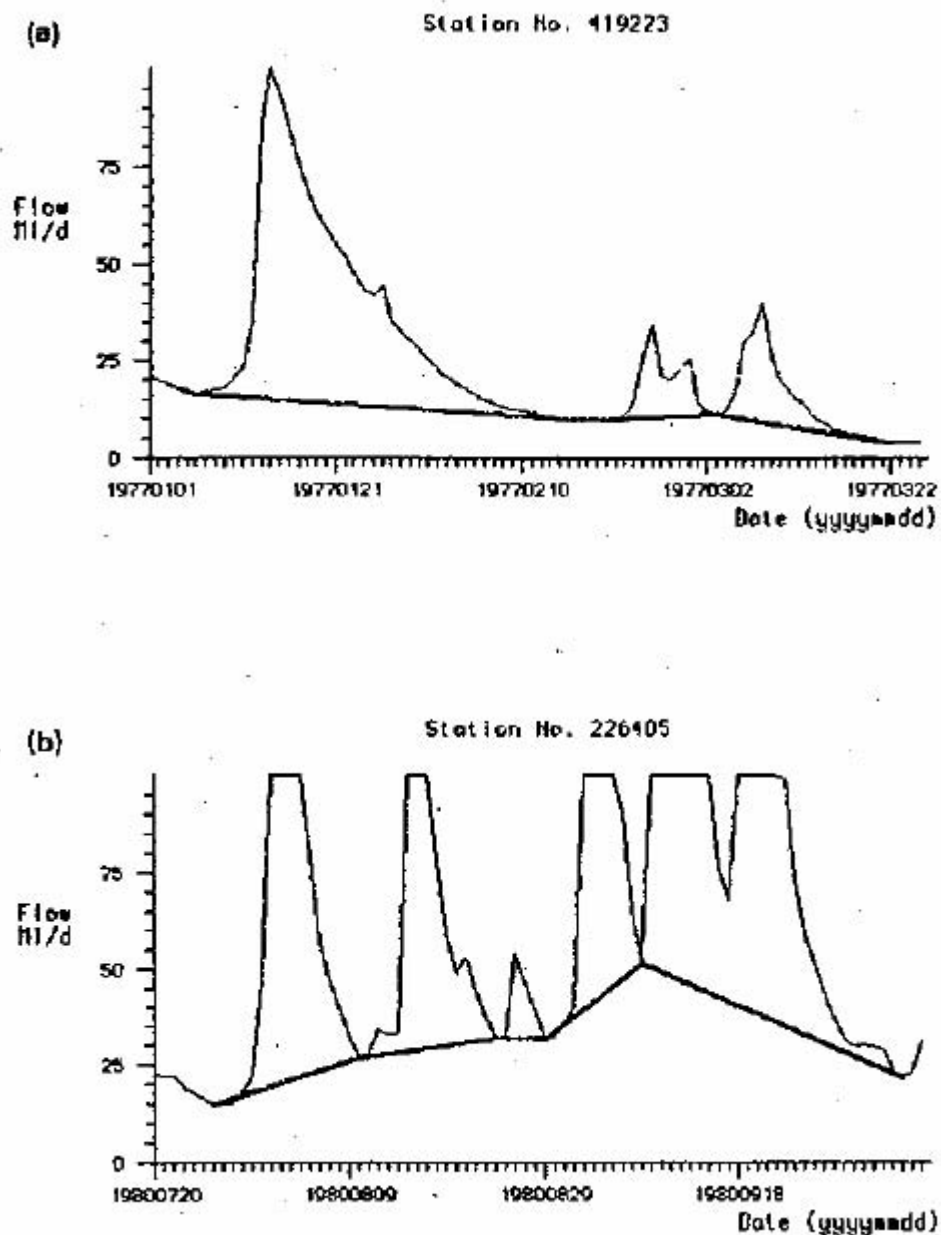
α is the filter parameter that enables the shape of the separation to be altered

After applying this equation, the baseflow q_b is equal to $q - q_f$. If q_f is less than zero, then q_b is set equal to q .

This filter is run in three passes. The first and third passes are 'forward' passes using the equation above directly, whereas the second pass is a backwards pass using $i+1$ instead of $i-1$ in the equation. In the first pass, q_i is the measured stream flow, in the second pass it is the computed baseflow from the first pass, and in the third pass it is the computed baseflow from the second pass. These passes act to smooth the data. Using more passes would further smooth the data. An example of the use of the Lyne and Hollock filter is in Figure C-4.

A filter parameter value (α) of 0.925 was found to provide the best match to graphical baseflow hydrograph estimates across a number of catchments in Victoria in Nathan and McMahon (1990). Changing this parameter affects the degree of attenuation. The estimated baseflow is fairly sensitive to the value of the filter parameter. Changing the filter parameter by ± 0.025 ($\pm 3\%$) has been shown to change the baseflow index by up to +14% and -26% in five example catchments (Nathan and McMahon, 1990). Increasing the filter parameter (e.g. from 0.925 to 0.95) acts to reduce the baseflow component. It is suggested that in tropical climates during the wet season where the baseflow may be overestimated, the use of a higher value for α might be considered. This needs to be further evaluated. It is noted that during the dry season where the baseflow component may be approaching 100%, a higher α will not affect the result.

Figure C-3: Examples of continuous baseflow separation using the smoothed minima technique (Nathan and McMahon, 1990)



Suggested Approach

The principal advantage of using baseflow separation in surface water/groundwater interaction studies is that there is a high degree of confidence in the upper bound of baseflow, which is limited by the value of observed stream flow.

The suggested approach for baseflow separation depends on the nature of the study that is being undertaken. All baseflow separation techniques, either graphical or automated, are suitable for comparative analysis to ascertain relative baseflow contributions between sites or at the same site over time. Accurate quantitative determination of the absolute magnitude of baseflow is not achievable through baseflow separation alone. Baseflow hydrographs for detailed at-site investigation should be conditioned by local knowledge of

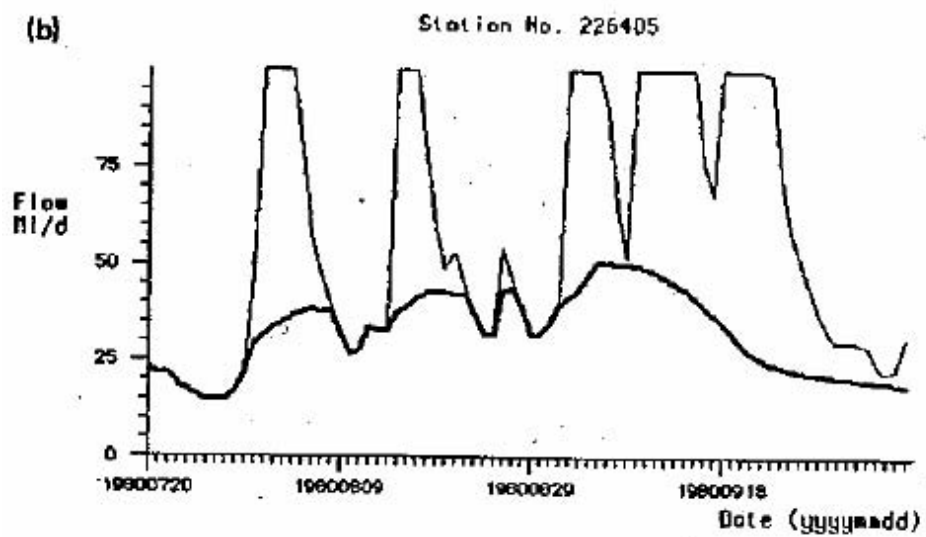
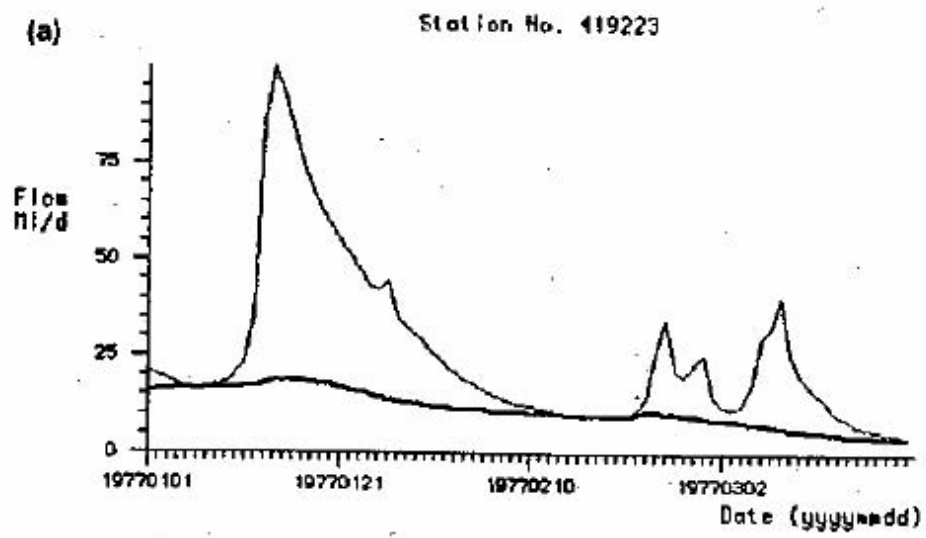
both aquifer and stream flow characteristics, regardless of the baseflow separation technique applied.

For regional studies, it is suggested that the Lyne and Hollick filter used in Nathan and McMahon (1990) is adopted. This method is quick, robust and allows objective comparison of results across catchments. This digital filter used in Nathan and McMahon does not have any inherent advantages over alternative filters, however there is a large body of statistical information on baseflows estimated using the Nathan and McMahon technique in Nathan and Weinmann (1993) and Neal et al. (2004) for much of Australia, and some attempt has been made in Nathan and McMahon (1990) to standardise digital filter parameters to be consistent with manual baseflow separation techniques.

For local investigations, it is suggested that the Lyne and Hollick filter used in Nathan and McMahon (1990) is adopted and then adjusted manually based on knowledge of the master recession curve behaviour, plus any relevant hydrogeological information and knowledge of catchment and stream flow characteristics. The digital filter will form the default baseflow time series from which to work, but this can be manually adjusted for individual events as required. Comparison with manual methods is also helpful. The general characteristics of baseflow should be preserved at all times and any changes made to one part of the baseflow hydrograph should equally apply to similar events elsewhere in the baseflow hydrograph.

Given the subjective nature of fitting a baseflow hydrograph for local investigations, it is of paramount importance to document the principles and/or method applied to derive the baseflow hydrograph, including any manual adjustments made.

- Figure C-4: Examples of continuous baseflow separation using the Lyne and Hollick Filter (Nathan and McMahon, 1990)



Appendix D Whole of Catchment Water Balance

A whole of catchment water balance would comprise:

Scope:

- Period start and end (i.e. time period of water balance)
- Physical reporting entity, usually a surface water catchment

Opening balance, volume of water stored in

- 1) Major on-river reservoirs
- 2) Farm (catchment) dams (on-stream, off-stream)
- 3) Off river storages
- 4) Aquifers – renewable storage 1– non-saline
- 5) Aquifers – renewable storage – saline
- 6) Aquifers – non-renewable 2 – non-saline
- 7) Aquifers – non-renewable – saline
- 8) Soil (unsaturated zone)
- 9) Snow cover
- 10) River channels

Inflow

- 11) Rainfall
- 12) Surface inflow from adjoining catchments
- 13) Returns from consumptive users
- 14) Inflow from aquifers outside of the catchment

Internal Interchange

- 15) Rainfall to surface water
- 16) Surface water to soil (unsaturated zone)
- 17) Rainfall to soil (unsaturated zone)
- 18) Soil (unsaturated zone) to saline aquifers
- 19) Soil (unsaturated zone) to non-saline aquifers
- 20) Saline aquifers to surface water
- 21) Non-saline aquifers to surface water
- 22) Extraction for consumptive use inside the physical entity
- 23) Returns from consumptive use inside the physical entity

Outflow

- 24) Evapotranspiration from soils and aquifers
- 25) Evaporation from surface water and interception
- 26) Consumptive use (urban water use)
- 27) Surface flow out of the physical entity
- 28) Aquifer flow out of the physical entity
- 29) Extraction for consumptive use outside the physical entity

Closing balance, being the water in storage

- (items as per opening balance)
- 1) *Renewable* storage is the volume of aquifer storage available for extraction in the short term, which fully recovers during the planned timeframe.
 - 2) *Non-renewable* storage is the volume of aquifer storage which is not replaced within the planned timeframe.

Appendix E Management of Stream Depletion Effects from Environment Southland (2004)

Due to the buffer provided by aquifer storage, groundwater abstraction generally does not have an immediate or direct effect on stream flows. Rather, effects tend to be diffuse, occur some time after abstraction commences and at a rate lower than the overall rate of groundwater abstraction. Because of the nature of surface water/groundwater interaction there are no clear thresholds between insignificant and significant effects and it is necessary to define arbitrary categories in order to establish an effects-based management regime. It is considered appropriate to recognise four categories of groundwater abstractions in terms of their hydraulic connection to surface water:

1. Takes which are equivalent to direct surface water abstractions
2. Takes which are amenable to regulation/mitigation by pumping controls
3. Takes for which pumping controls are not an effective means of regulation/mitigation but which still have a potentially significant effect on surface water
4. Takes for which pumping controls are not an effective means of regulation/mitigation and have an overall minor effect on surface water.

Rationale for Definition of Hydraulic Connection Categories Direct Hydraulic Connection

The direct hydraulic connection category represents the situation where groundwater abstraction has an immediate effect on an adjacent surface waterway. In this situation stream depletion effects develop rapidly to a level close to the maximum instantaneous pumping rate once abstraction commences and dissipate rapidly when abstraction is ceased. The overall proportion of the water abstracted derived from aquifer storage is low and the groundwater take can be reasonably managed as though it were a direct surface water take.

The criteria proposed for determining a direct hydraulic connection to a surface waterway is where the stream depletion effect occurring after seven days continuous abstraction at the maximum instantaneous rate is greater than 80% of the pumping rate.

Figure E-1 illustrates the characteristic development of stream depletion effects resulting from a groundwater take classified as having a direct hydraulic connection to an adjacent surface waterway. The dotted line shows a rapid reduction in stream depletion if pumping is stopped after 75 days.

- Figure E-1 Typical stream depletion response for a bore having a direct hydraulic connection to a surface waterway (the dotted line represents the effect of stopping pumping after 75 days)

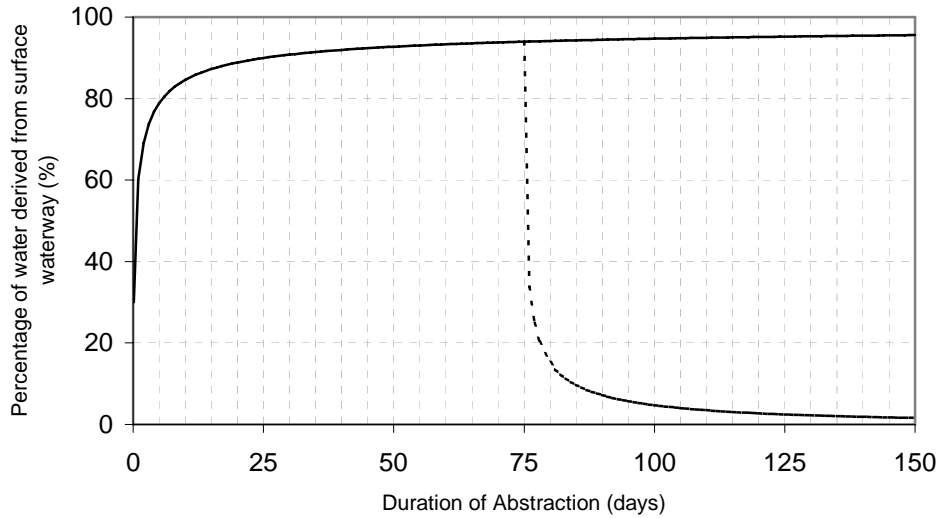
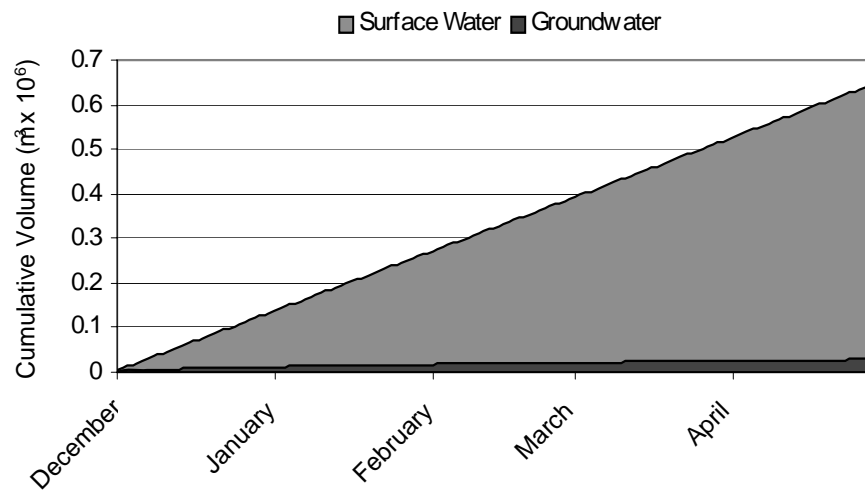


Figure E-2 illustrates the relative volume of water derived from groundwater storage for a take of 50 litres per second over a nominal irrigation season of 150 days. The figure shows that for a groundwater take in direct hydraulic connection with a nearby surface waterway, by far the majority of water is derived from the stream with limited contribution from aquifer storage.

- Figure E-2 The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a direct hydraulic connection



Due to the immediacy of stream depletion effects resulting from a groundwater take assessed as having a direct hydraulic connection to a surface waterway, it is appropriate to consider the actual stream depletion effect in terms of the maximum instantaneous pumping rate. Groundwater takes assessed as having a direct hydraulic connection will be subject to the flow regime established for the relevant surface waterway.

High Hydraulic Connection

This category of hydraulic connection covers the situation where although stream depletion effects develop reasonably slowly following commencement of pumping, after an extended period of abstraction stream depletion may comprise a relatively high proportion of the overall pumping rate.

The criteria proposed for determining groundwater takes with a high degree of hydraulic connection to a nearby surface waterway is where the stream depletion effect resulting from seven days continuous abstraction at the maximum rate is less than 80% of the pumping rate but the effect of 150 days pumping at the continuous rate required to supply the seasonal volume is greater than or equal to 60% of the pump rate.

Figure E-3 illustrates the characteristic stream depletion behaviour for this category of groundwater take. The relatively rapid reduction in stream depletion effects following the cessation of abstraction means that pumping controls can provide a timely mitigating effect on stream depletion during periods of low flow.

- **Figure E-3** Typical stream depletion response for a bore having a high degree of hydraulic connection to a surface waterway (the dotted line represents the effect of stopping pumping after 75 days)

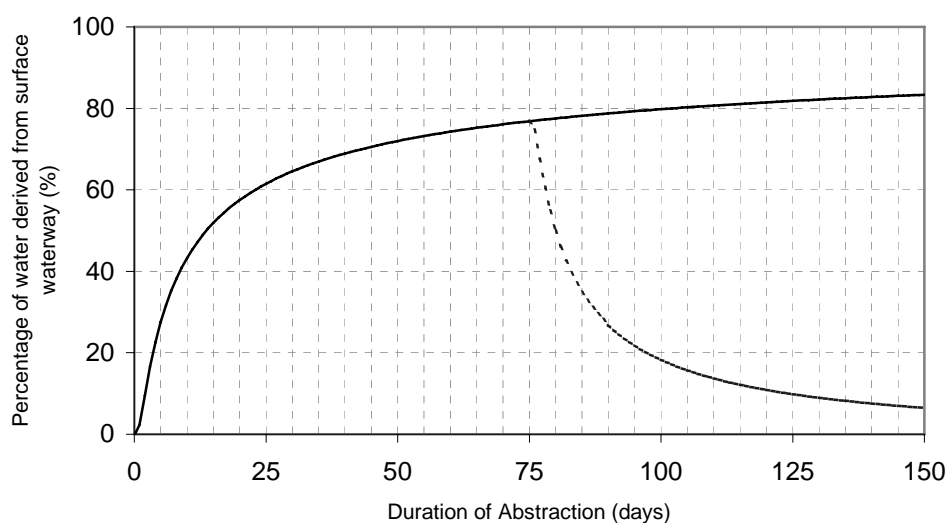
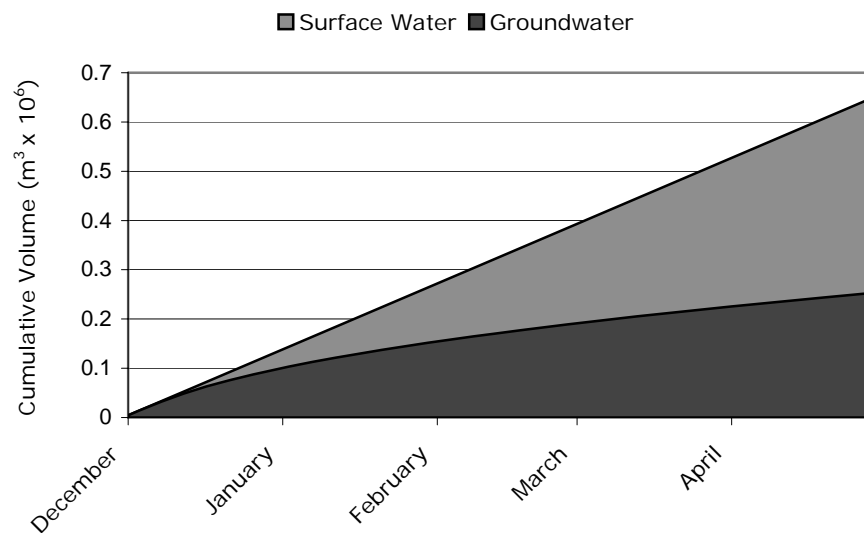


Figure E-4 shows the relative contributions of groundwater storage and flow loss from adjacent surface waterways to the total volume of groundwater abstraction for a nominal groundwater take at an average rate of 50 litres per second over a period of 150 days. The figure shows that while a majority of water abstracted immediately following commencement of pumping is derived from groundwater storage the relative contribution of flow loss from nearby surface waterways increases with the duration of pumping.

■ Figure E-4 The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a high degree of hydraulic connection



The rate at which stream depletion effects develop is a function of the distance of the abstraction point from the stream as well as the hydraulic properties of the aquifer and stream bed. In situations where stream depletion effects develop rapidly and persist for the remainder of the pumping period it is appropriate to consider the potential stream depletion effect in terms of the instantaneous rate of take. However, in situations where stream depletion effects develop more slowly it is more appropriate to consider resulting effects in terms of the average seasonal abstraction rate. It is therefore proposed that the stream depletion effects resulting from a groundwater take classified as having a high degree of hydraulic connection to a surface waterway will be calculated as the maximum of either:

- the effect of continuous pumping at the maximum permitted rate of take for the period taken to supply the seasonal allocation
- the effect of 150 days pumping at the continuous rate required to deliver the seasonal volume.

This method of calculation makes allowance for situations where Resource Consent

Applications may be granted with a seasonal volume that allows abstraction at the maximum rate for a period of less than 150 days.

The calculated rate of stream depletion will be counted as part of the allocation for the relevant surface water body with the remaining portion of the abstraction included in the allocation volume for the relevant groundwater zone. Where the calculated rate of stream depletion exceeds 2 litres per second a groundwater take assessed as having a high degree of hydraulic connection will be subject to the minimum flow regime for the relevant surface waterway.

Moderate Hydraulic Connection

This category of groundwater take is intended to cover situations where, although a relatively significant proportion of the groundwater water abstracted from a bore may be derived from nearby surface waterways after extended pumping, stream depletion effects dissipate so slowly that pumping controls do not provide an effective means of mitigating the effects of groundwater abstraction during periods of low flow.

The criteria proposed for determining a groundwater take with a moderate degree of hydraulic connection is where the stream depletion effect resulting from seven days continuous abstraction at the maximum rate is less than 80% of the pumping rate and the effect of 150 days pumping at the continuous rate required to supply the seasonal volume is between 30% to 60% of the pump rate.

Figure E-5 illustrates the characteristic stream depletion behaviour for this category of groundwater take. The illustration shows stream depletion effects take some time to develop following commencement of pumping, but after extended pumping water derived from adjacent surface waterways may comprise a significant proportion of the overall volume of water being abstracted.

Figure E-5 also shows the limited effectiveness of pumping controls to mitigate stream depletion effects resulting from a groundwater take with a moderate degree of hydraulic connection during periods of low flow. The dotted line represents the calculated stream depletion effect if pumping is stopped after 75 days. In the situation illustrated the rate of stream depletion continues to increase for approximately ten days after abstraction has , and it is not until approximately 20 days after abstraction has ceased that the rate of stream depletion falls below the rate occurring at the time when abstraction stopped.

- Figure E-5 Typical stream depletion response for a bore having a moderate degree of hydraulic connection to a surface waterway (the dotted line represents the effect of stopping pumping after 75 days)

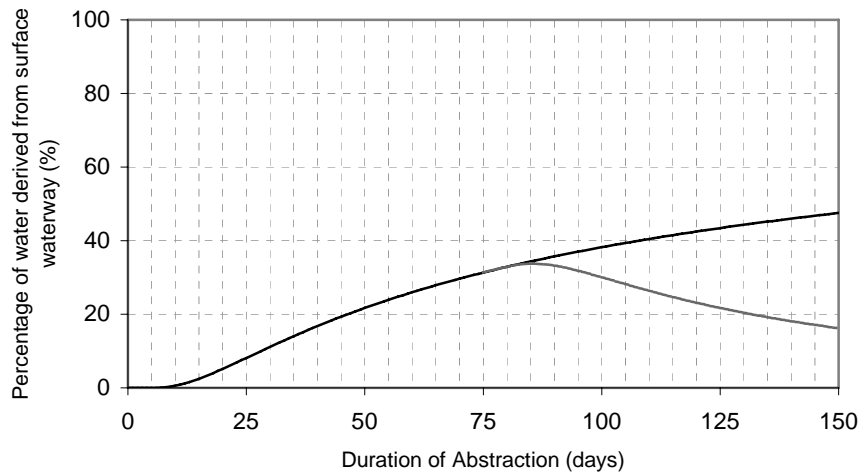
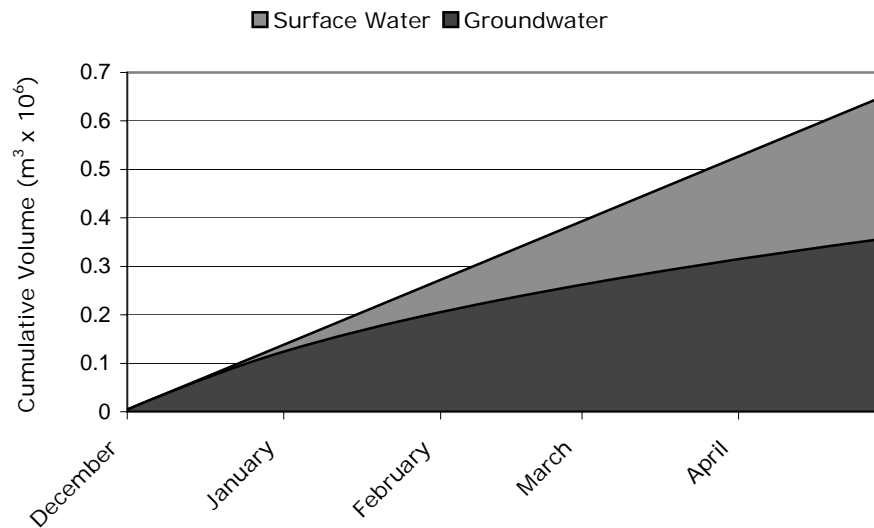


Figure E-6 shows the relative contributions of groundwater storage and flow loss from adjacent surface waterways to the total volume of groundwater abstraction for a nominal groundwater take at an average rate of 50 litres per second over a period of 150 days.

- Figure E-6 The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a moderate degree of hydraulic connection.



Low Hydraulic Connection

In the case of a groundwater take assessed as having a low degree of hydraulic connection to an adjacent surface waterway, stream depletion effects develop very slowly and represent a relatively small proportion of the water being abstracted.

The criteria proposed for determining groundwater takes with a high degree of hydraulic connection to a nearby surface waterway, is where the stream depletion effect resulting from seven days continuous abstraction at the maximum rate is less than 80% of the pumping rate, and the effect of 150 days pumping at the continuous rate required to supply the seasonal volume is less than 30% of the pump rate.

Figure E-7 shows the characteristic stream depletion response for this category of groundwater take. In this case stream depletion effects take considerable time to develop and there is little or any mitigating effect gained by imposition of pumping controls.

Figure E-7 Typical stream depletion response for a bore having a low degree of hydraulic connection to a surface waterway (the dotted line represents the effect of stopping pumping after 75 days)

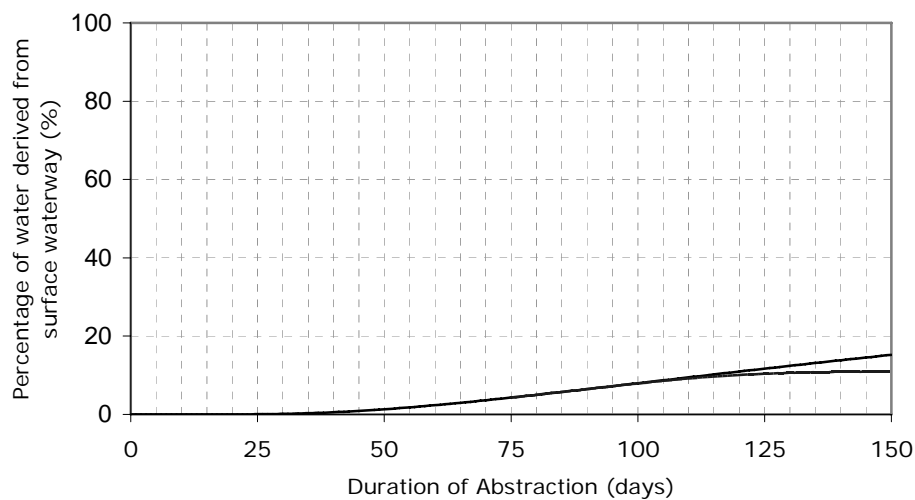


Figure E-8 shows that a majority of the water abstracted is derived from groundwater storage with limited contribution from nearby surface waterways.

- **Figure E-8** The relative contribution of groundwater storage and induced flow loss from adjacent surface waterways for a groundwater take assessed as having a low degree of hydraulic connection

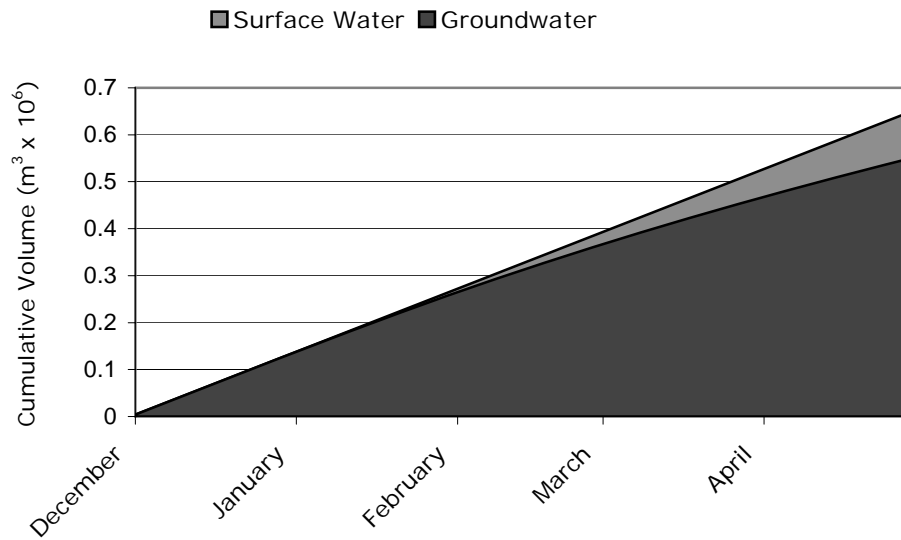
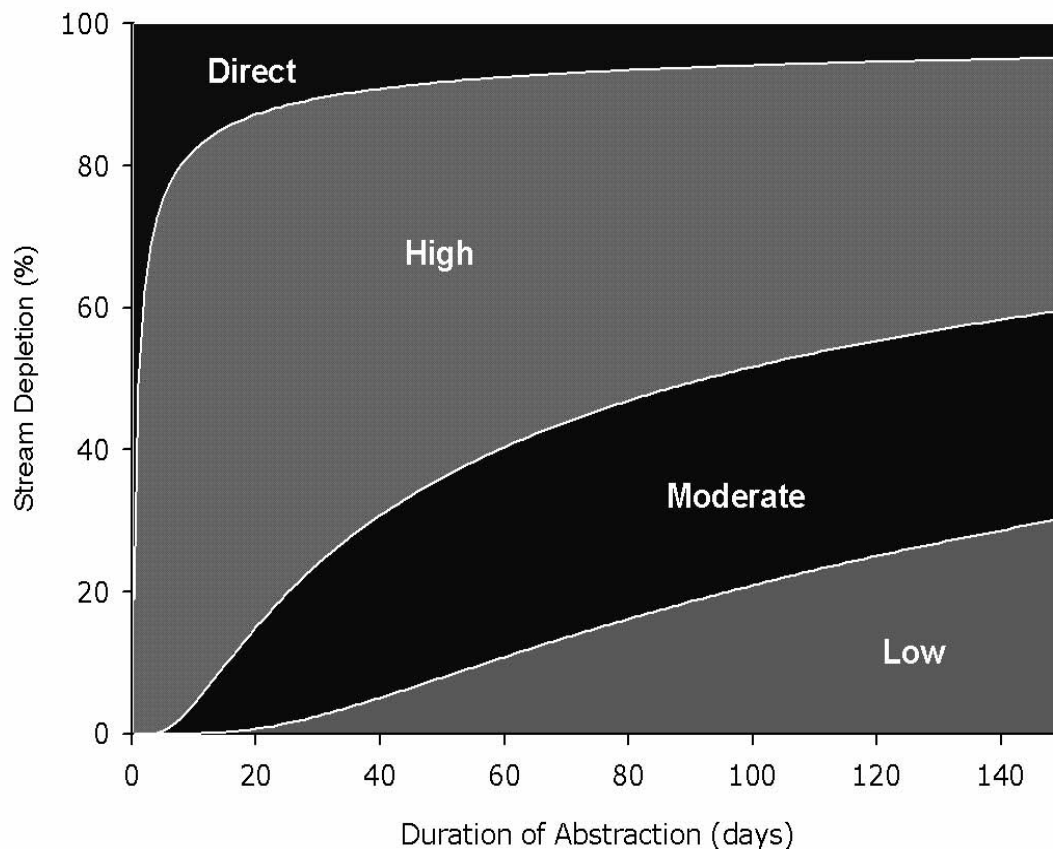


Figure E-9 illustrates the categories of hydraulic connection proposed for the management of stream depletion. The hydraulic connection categories are shown in terms of the stream depletion effect as a percentage of the overall pumping rate. Table E-1 summarises the definition and management approach for each of the hydraulic connection categories proposed.

- **Figure E-9** Hydraulic connection categories proposed for the management of stream depletion effects



■ Table E-1 Definition and management of proposed categories of hydraulic connection

Hydraulic Connection Category	Definition	Amenable to pumping control	Proposed Management
Direct	Stream depletion rate >80% of pumping rate after seven days continuous abstraction	Yes	Allocation managed as a direct surface water take and subject to relevant flow regime
High	Stream depletion rate >60% of pumping rate after 150 days continuous abstraction	Yes	<ul style="list-style-type: none"> ➤ Subject to minimum flow cut-off based on flow regime of relevant surface water body ➤ Stream depletion effect counted as part of allocation of surface water body ➤ Remaining allocation counted against relevant groundwater management zone
Moderate	Stream depletion rate 30–60% of pumping rate after 150 days continuous abstraction	No	<ul style="list-style-type: none"> ➤ Stream depletion effect counted as part of allocation of surface water body ➤ Remaining allocation counted against relevant groundwater management zone
Low	Stream depletion rate <30% of pumping rate after 150 days continuous abstraction	No	Allocation managed as a groundwater take only

Management of Cumulative Stream Depletion Effects

While the stream depletion effect resulting from an individual groundwater take may be relatively minor, the potential exists for multiple groundwater takes within a surface water catchment to have a significant cumulative impact on stream flow. This cumulative stream depletion effect will add to any flow reductions resulting from surface water takes within the catchment. Analytical and numerical modelling techniques enable a quantitative estimation of stream depletion effects resulting from groundwater abstraction based on the hydraulic connection categories outlined in Policy x.

The cumulative stream depletion effects policies are intended to enable the integrated management of surface and groundwater resources. This will ensure flow regimes established for surface waterways are not compromised by stream depletion effects resulting from groundwater abstraction.

Policy x: *The total stream depletion effect resulting from groundwater and surface water abstractions subject to minimum flow cut-offs is managed in accordance with any relevant surface water allocation regime.*

This policy seeks to control the overall magnitude of flow reductions occurring in surface waterways as a result of the cumulative effects of ground and surface water abstractions assessed as having a direct or high degree of hydraulic connection by the application of relevant minimum flow cut-offs.

In the case of groundwater takes assessed as having a moderate or low degree of hydraulic connection, the resulting stream depletion effects dissipate so slowly that pumping controls do not provide an effective means of mitigating the effects of groundwater abstraction during periods of low flow. To address this issue Policy y proposes that the calculated stream depletion effect resulting from takes assessed as having a moderate or low degree of hydraulic connection are managed in accordance with flow allocation limits established for the relevant surface waterway.

Policy y: The total stream depletion effect resulting from groundwater and surface water abstractions not subject to minimum flow cut-offs is managed in accordance with flow allocation limits established by any relevant surface water flow regime.

Policies x and y recognize the trade-off between minimum flow and flow allocation inherent in the establishment of surface water allocation regimes.

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