Catalogue of conceptual models for groundwater–stream interaction in eastern Australia

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eWater Technical Report

Catalogue of conceptual models for groundwater–stream interaction in eastern Australia

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eWater CRC is a cooperative joint venture whose work supports the ecologically and economically sustainable use of Australia's water and river systems. eWater CRC was established in 2005 as a successor to the CRCs for Freshwater Ecology and Catchment Hydrology, under the Australian Government's Cooperative Research Centres Program.

Contents

Preface

Groundwater–surface water interaction has in recent years been acknowledged in Australia, and indeed internationally, as being a major technical area of weakness in our understanding of catchments, to the particular detriment of water resource and environmental management. Accordingly, research interest and activity in Australia is now being stepped up in this area. It is perhaps surprising, though, that it has taken so long to gain recognition of the importance of this research area in Australia, especially given the dryness of the continent, the high and increasing demand for water, and the significant dependence upon groundwater (as baseflow) of most of the streams in its intensive agricultural areas.

The dry climate pattern in the Murray–Darling Basin (MDB) and other eastern Australian areas in the 11 years since 1996 (Bureau of Meteorology 2007), coupled with increased competition for water, have certainly helped to bring due attention to the interaction of our rivers and groundwater systems.

Groundwater extraction from aquifers that are hydraulically connected to streams will reduce stream flows. Depending on the extraction volume and other factors, stream flow in a connected system could be seriously depleted in the longer term – with implications for ecosystem health, water security and water allocation, among other things. The implications will be more severe if use of groundwater resources continues to grow unchecked.

Past water management in Australia has, for the most part, not accounted for groundwater–stream interaction. Concerns have been raised in relation to the impacts of groundwater development on our major streams (and vice versa); similarly, there is concern about the inadequacy of managing groundwater and surface water resources in isolation. In terms of total water conservation and aquatic environment protection, the validity of the Murray–Darling Cap on Surface Water Diversion (capped at 1993/1994 levels; MDBC 1999) can be questioned. Groundwater stores are being depleted in the MDB and the impacts of groundwater pumping have been estimated to eventually reduce MDB surface water flows by up to 600 GL/year (MDBC 2004).

Due to the complex nature of the connection between groundwater and surface water, management measures introduced to reduce groundwater use in the MDB and other stressed catchments may take decades to have a noticeable beneficial effect on surface water systems.

The necessity to better understand and account for groundwater–surface water interaction is also evident from the following list of relevant catchment management issues, some of which are covered in more detail in this catalogue:

- Double-accounting of water resources.
- Impacts of groundwater pumping on stream flow, particularly flow depletion.
- Surface water requirements for downstream users.
- Water requirements for environmental purposes (e.g. floodplain, stream, wetland ecosystems).

- Operational issues regarding groundwater requirements, which could be in terms of the resource (quantity and quality), the health of groundwater-dependent ecosystems (GDEs), or the general health of the total groundwater–surface water system.
- Conjunctive resource management strategy development and water allocation regime.
- Salinity impacts on water quality, salt loads, and ecosystem health.
- Management for climate variation/change and its impacts on groundwater–surface water systems.
- Water management boundary delineation.
- Transboundary or interstate groundwater–surface water impacts.

Numerical models developed to date have generally not accounted very well for groundwater–surface water interaction because there has been limited attention given to accurately conceptualising and parameterising the groundwater–surface water interface. Also, consistent with trends in water management, groundwater and surface water models have tended to be developed in isolation, with the result that the total water budget is not accurately represented or calculated. One of the major projects in the 2006–08 portfolio of the eWater Cooperative Research Centre (eWater CRC) addressed the deficiency in modelling and field measurement capability in the area of groundwater–stream interaction for Australian situations. This project was called Project D3 – Groundwater.

This catalogue is one of a series of three reports that are the culmination of the first tasks of Project D3. The other two reports are by Rassam and Werner (2008) and Turner (2009). The report series is intended to improve the stakeholder awareness and understanding of the connectivity, and the physical and chemical interactions of groundwater–surface water systems. It is also intended to provide a framework to underpin development of a toolkit for describing, measuring and modelling groundwater–stream interaction in stressed or threatened Australian catchments. It has the broader goal of supporting judicious, conjunctive water management to safeguard our major connected groundwater–stream systems and their associated ecosystems.

1 Introduction

1.1 Project background

This catalogue is one of a series of three reports (the other two being Rassam and Werner (2008) and Turner (2009)) that were part of the eWater CRC Project D3 – Groundwater. This project, which ran from 2006 to 2008, aimed to estimate exchange fluxes between groundwater and surface water for rivers and predict how these may change with existing or different groundwater and surface water management. In accounting for groundwater–stream interaction in the water budget, this project addressed a major recognised deficiency in the management of stressed or threatened Australian catchments (COAG 2004; Hatton and Evans 1998; Richardson et al. 2004).

Techniques for both estimation and prediction are well-developed for small areas (<1 km stream reach), but much less developed for extrapolation beyond these scales to inform management of major streams or catchments. Accordingly, the project’s aims were to develop a toolkit for modelling groundwater–stream interaction, one that could supply fit-for-purpose modelling tools to apply at different broad scales. Selection of the model and overall approach would depend on the available information, the type and size of connected groundwater–stream system, and the nature of the management issue. As input to the toolkit, the project aimed to collate and assess field measurement techniques to quantify the exchange fluxes and trial the best of these at key sites.

1.2 Aim and scope of catalogue

The overall aim of the catalogue is to provide a useful guide for natural resource managers on the fundamentals and conceptualisation of groundwater–stream interaction, and its relevance in eastern Australian settings to stream and catchment management. A key component of this aim is to develop and apply a classification framework for groundwater–stream interaction that natural resource managers will find useful in understanding and managing connected groundwater–stream systems. This framework is described in the final chapter (Chapter 10) and applied to 10 eastern Australian case studies in an appendix.

The catalogue also provides a framework for key components of the broader D3 project, including investigation of field measurement techniques and modelling approaches, field site selection, and the development of a modelling toolkit for the estimation and prediction of groundwater–surface water interaction.

The catalogue aims to impart a solid understanding of the water balance and water movement in connected groundwater–stream systems, as well as the ways in which they can be altered by human influences.

A particular emphasis of the catalogue is on the impacts of groundwater pumping on stream flow or surface water quantity. In addition, there is significant focus on the impacts of groundwater pumping on water quality and ecosystem health.

The catalogue is comprehensive in that it covers, in a broad sense, aquifer-scale interaction within the main types of eastern Australian geological landscapes. It includes 10 case studies of connected groundwater–stream systems which provide an effective representation of the main eastern Australian hydrogeological settings and the impacts of development on them.

1.3 Summary of catalogue content

Chapters 2 to 4 concentrate on the basic principles of the hydrologic cycle, groundwater occurrence and flow, and groundwater–stream interaction. Chapters 5 to 8 focus on describing in broad terms the different types of human and environmental influences on groundwater–stream interaction and the impacts of these influences on surface water quantity and quality, and ecosystem health.

Chapter 9 discusses the principles and information requirements for developing a conceptual model of groundwater–stream interaction, an essential prerequisite for developing predictive numerical models, formulating integrated catchment management plans, and determining water allocations in connected systems with significant resource competition.

Chapter 10 outlines the content, structure and use of a proposed classification framework for groundwater–stream systems to assist natural resource managers. The framework provides a way of conveniently summarising the attributes of a groundwater–stream system against a set of 11 key types of groundwater–stream interaction characteristic. It has been applied to each of 10 case studies described in the appendix. The framework has a top tier of four broad types of aquifer system based on coarse geological/physiographic groups. These are: fractured rock systems, layered or complex systems, contained alluvial valley systems, and regional systems (large systems with deep groundwater flow). Underneath the top tier, 10 other types of characteristic are defined to help conceptualise the groundwater–stream system. A simple ‘gaining/losing stream’ philosophy has been applied to help define the stream–aquifer relationship and there is provision in the framework to broadly rate the long-term impact on stream flow of groundwater pumping.

Finally, as an appendix, there is a compilation of 10 case study descriptions of connected groundwater–stream systems in different parts of eastern Australia. Most of the case studies relate to streams that are impacted in some way by groundwater pumping, but several relate to other land management influences, including salinity impacts. There are two case studies on fractured rock systems, two case studies on layered or complex systems, three on contained alluvial valley systems, and three on regional systems. Each case study includes a description of the groundwater–stream interaction, impacts of land and water development, and current management status. Each also includes a summary of the main data sets and references used in building knowledge of the groundwater–stream system, as well as a groundwater–stream interaction classification table using the template developed in Chapter 10 (Table 10.3).

At the end of the document can be found a list of references and a glossary of technical terms.

2 Hydrologic cycle

The ‘hydrologic cycle’ is the term used to describe the movement of water between the various components of the environment. These include the atmosphere, marine and fresh surface waters, groundwater, soils (unsaturated zone) and the biosphere. The global quantity of water in each segment of the environment and the rate of movement between these segments is shown in Figure 2.1. The controls on the movement of water are varied and often operate in complex spatial and temporal scales. However, it is critical to understand these controls in order to improve management of water resources.

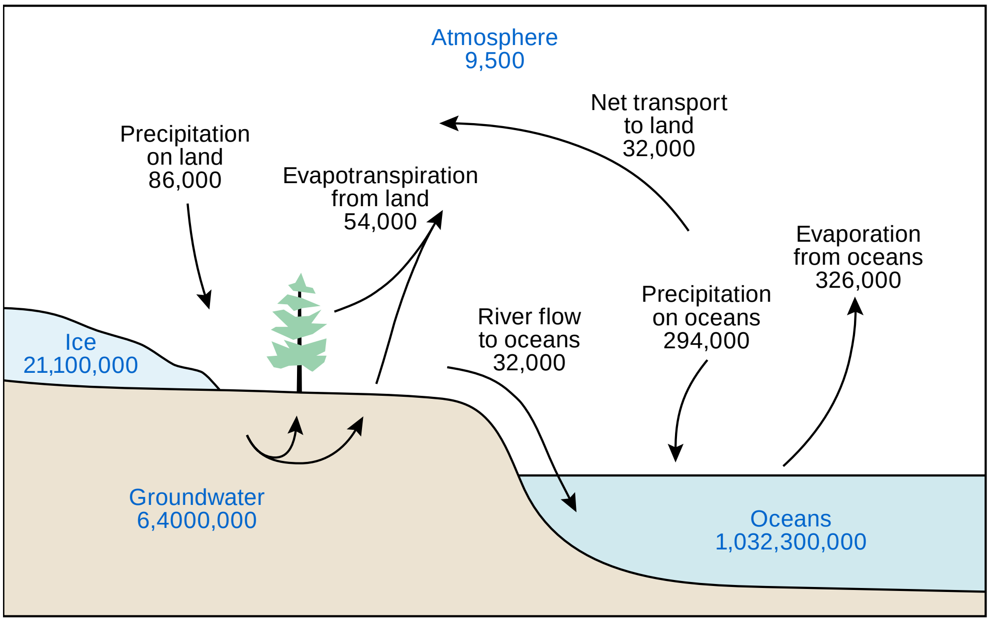


Figure 2.1. Global hydrologic cycle, adapted from Winter et al. (1998). Volumes (km^3) are in blue, fluxes (km^3/year) in black. Groundwater is the second smallest of the four main reserves of water on Earth. River flow is one of the smallest fluxes, yet groundwater and surface water are the components of the hydrologic cycle that humans use most.

The water balance is the sum of these numerous components in a given catchment or region, and will vary substantially across spatial scales as well as being subject to major temporal variability.

In addition to the total quantities and rates of water movement, the quality of the water is also of prime importance. Quality is a measure of the dissolved constituents in the water, namely inorganic and organic elements/compounds (e.g. salts, metals) and gases. Although the oceans contain the largest quantity of water, they are of high salinity. The best sources of relatively fresh water are terrestrial surface water and groundwater – both of which comprise relatively small volumes of water.

Overall it is important to understand the links between these water resource segments, the rates of movement between them and the effects on water quality due to changes in quantities and rates of exchange.

3 Principles of groundwater flow

3.1 Occurrence of groundwater

The presence of water in porous geologic media is defined as groundwater when the pore spaces are fully saturated. If the pores are not fully occupied by water, then this is known as the unsaturated or vadose zone, and is often associated with surface soils and sediments. The continuity of these water-filled pore spaces through a geologic unit represents an *aquifer* – with the contained water being the groundwater. The porosity can be either (i) between the grains of unconsolidated sediments or weathered rocks (i.e. intergranular), or (ii) in cracks or joints developed in rocks (i.e. fractured).

Where a geologic unit has water-saturated pore space but the rate of flow is very low, such as mudstone or clay, this is known as an *aquitard* and acts as an impediment to groundwater flow, thereby confining flow within the aquifer. When the water pressure (or potentiometric surface) within an aquifer is higher in elevation than the top of the aquifer due to the presence of an overlying aquitard, this aquifer is *confined* (or it may be *semi-confined* if the aquitard is significantly leaky) and flow is therefore limited to be principally through the aquifer. If there is no aquitard vertically above an aquifer, then the pressure level can rise and fall, filling or emptying available pore spaces. This is known as an *unconfined* aquifer. A typical cross-section of groundwater occurrence is shown in Figure 3.1.

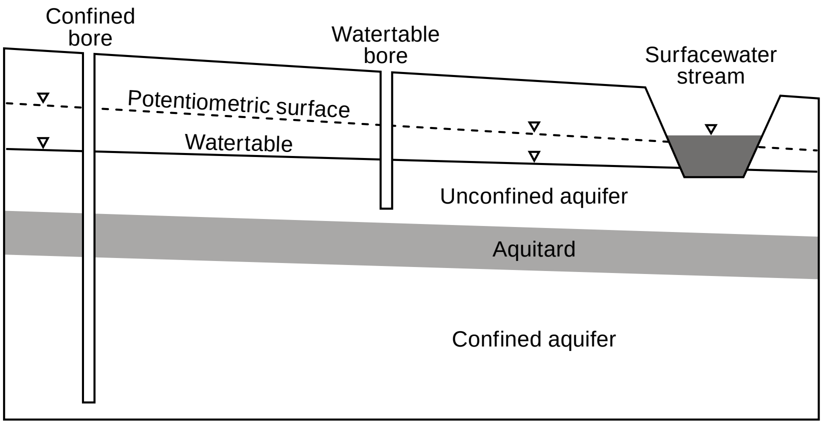


Figure 3.1. Conceptual cross-section of a two-layered aquifer system: an unconfined (watertable) aquifer and a confined aquifer. If the aquitard significantly leaks, the underlying aquifer is regarded as semi-confined. The water level in a bore developed in the confined or semi-confined aquifer will rise to the potentiometric surface.

3.2 Watertable and potentiometric surface

There are two terms, namely watertable and potentiometric surface, that are widely used to describe groundwater surfaces. The watertable is defined as the underground water surface at which the pressure is exactly equal to atmospheric (Domenico and Schwartz 1990). It is commonly interpreted as the boundary between an upper, unsaturated zone and the underlying saturated zone of an unconfined aquifer.

The potentiometric surface is an imaginary (or actual) surface that everywhere coincides with the total head of the groundwater in the aquifer (Domenico and Schwartz 1990). If the aquifer is unconfined, the potentiometric surface is the watertable surface. In a confined or semi-confined aquifer, it represents the groundwater head, or pressure level, and is an imaginary or inferred surface based upon standing water level data from bores screened in the confined aquifer. The surface in this case is commonly above the upper surface of the aquifer (e.g. Figure 3.1) due to the combined factors of (i) water intake, or recharge, to the aquifer at higher elevations, and (ii) confinement by an overlying aquitard. Groundwater is termed ‘artesian’ in areas where the potentiometric surface is above the land surface (see Figure 3.2).

3.3 Groundwater flow

The flow of groundwater through an aquifer is influenced and controlled principally by the geology and geometry (dimensions, shape, and configuration) of the aquifer, including hydraulically connected surface components (e.g. recharge areas – see Figure 3.2). Groundwater flow can be considered at different scales from micro-level or pore-scale flow processes (scales of millimetres) through to large regional flow systems (scales of hundreds of kilometres). The geology and surface topography will effectively determine the major scales for groundwater flow.

The flow of groundwater through porous media is governed by Darcy’s Law (Freeze and Cherry 1979), which states that the flow rate is dependent on the hydraulic conductivity of the media and the hydraulic pressure gradient, shown in Equation 1. Given the low hydraulic gradients typically found in groundwater, flow is commonly controlled by the hydraulic conductivity (or permeability) of the aquifer itself.

$$v = Ki \quad (1)$$

where v is flow velocity (m/day), K is hydraulic conductivity of the porous media (m/day) and i is hydraulic pressure gradient (difference in head over difference in distance).

Based on Darcy’s Law, groundwater will flow from the point of highest hydraulic head to the lowest, and more rapidly along zones of higher conductivity. The area of highest hydraulic head often coincides with surface topography, or where aquifer sediments outcrop (or subcrop) and allow recharge to enter the aquifer. The lowest hydraulic head may coincide with a surface water feature such as a wetland, stream or lake or a marine waterbody. The extent of groundwater flow can also be influenced by other factors such as salinity and temperature differences, though this is relatively uncommon.

Figure 3.2 shows a typical cross-section of a large, regional multi-layered groundwater system. Often, based on the geology of a region, there are multiple aquifers and aquitards present. In such cases there can be multiple layers of preferred groundwater flow separated by relatively low permeability aquitards (labelled ‘impervious’ in figure). Depending on the difference in hydraulic head, there may be some vertical flow through the aquitards, although this is typically minor in comparison to lateral flow through the respective aquifers.

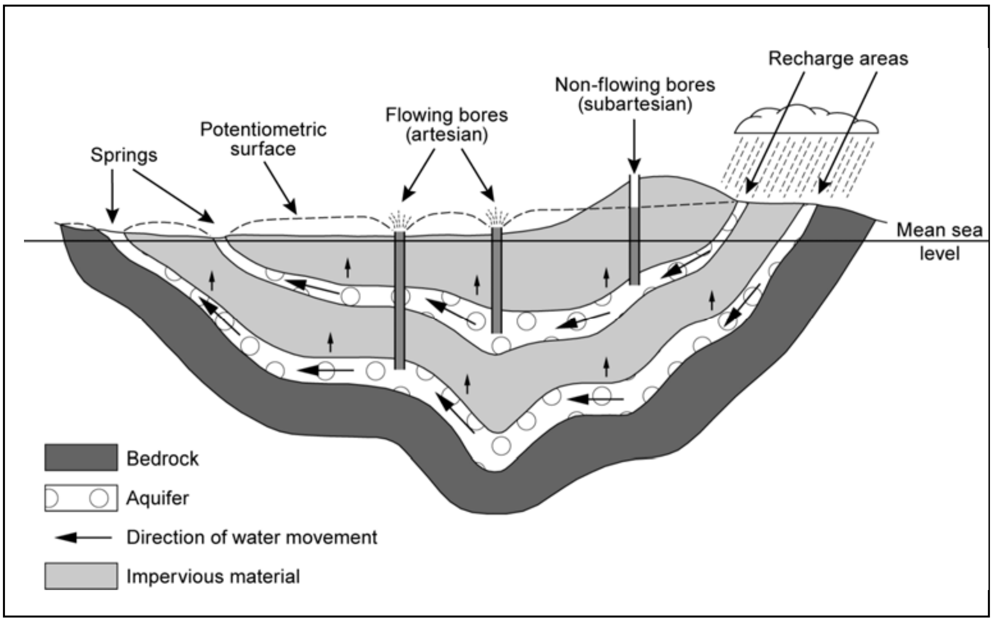


Figure 3.2. Conceptual cross-section of recharge and discharge in a large, regional two-aquifer system (modified from Cox and Barron 1998).

3.4 Recharge and discharge

Recharge is the process whereby new water infiltrates through to an aquifer, adding to its groundwater storage. This can be achieved through either point source recharge at a given area or through diffuse recharge over a large area.

Point source recharge commonly occurs where an aquifer either directly outcrops at the surface (e.g. Figure 3.2), or subcrops beneath relatively permeable soils. This allows rainfall to infiltrate through the unsaturated zone and reach the aquifer to replenish the volume of groundwater. Alternatively, point source recharge can occur through direct injection of water into the aquifer, or by leakage from surface water (e.g. rivers, wetlands).

Diffuse recharge commonly occurs in watertable or unconfined aquifers. Given that watertable aquifers outcrop at the surface by their nature, this large areal extent gives rise to small but significant recharge from rainfall or irrigation infiltrating through the unsaturated zone to the aquifer.

The exact timing and extent of recharge is one of the most difficult aspects to study and quantify in managing groundwater resources. Depending on local climatic conditions, recharge could be episodic or seasonal and typically only constitutes a very small percentage of the rainfall and water balance in a region.

The discharge from groundwater systems, based on Darcy's Law, generally occurs at the lowest point of hydraulic head in the aquifer system. This could be into a local stream, spring, lake, wetland, or a marine water body. Alternatively, discharge can occur through direct extraction via bores or via diffuse discharge from the watertable due to evaporation and transpiration. Depending on the type of discharge, it can often be measured directly or estimated indirectly.

4 Principles of groundwater–stream interaction

4.1 Groundwater–stream connectivity

Groundwater is commonly hydraulically connected to surface water (Heath 1983; Winter et al. 1998). For example, groundwater and streams often combine to form a connected water resource. Brodie et al. (2007) define a connected water resource as being the combination of surface water feature(s), such as a river, estuary or wetland, and the groundwater system(s) that can directly (or indirectly) interact in terms of the movement of water. Most groundwater systems, it could be argued, are connected to surface water when the full extent of the systems are taken into consideration.

Streams and groundwater interact in all types of landscapes and, as there are many types of landscapes and geological settings, there is much variability in the nature and degree of connectivity between surface water and groundwater systems.

Groundwater–stream connectivity exists when detectable flows occur between surface water and groundwater bodies. Winter et al. (1998) describe interaction as occurring in three basic ways:

1. streams gaining water from inflow of groundwater through the streambed (Figure 4.1);
2. streams losing water to groundwater by outflow through the streambed (Figure 4.2);
3. streams that do both, gaining in some parts and losing in others, or perhaps alternating between gaining and losing depending on periodic changes in relative stream and groundwater levels.

There are some landscapes where streams may always gain groundwater, or alternatively, always lose stream water to groundwater. However, there are other landscapes where water exchange direction varies significantly along a stream. Also, direction can alter in very short timeframes or seasonally in response to flooding or transpiration of groundwater by floodplain vegetation (Winter et al. 1998). There are also situations where the water exchange direction may be in opposite directions on opposite banks of a stream or river. That is, gaining on one side of the stream and losing on the other.

The degree of connection between a stream and a groundwater system can be determined by measuring the *seepage flux*, which is the magnitude and direction of water movement at the interface between surface water and groundwater systems (Brodie et al. 2007). It is primarily dependent upon the following:

1. the relative position and head difference of the watertable and stream surface levels;
2. the hydraulic properties of the connected aquifer system (including any geological material separating the aquifer from the stream), or its ability to transmit water to or from the stream.

A highly connected groundwater–stream system is indicated by timeframes of days to months for responses in one part of the system, say, the groundwater system, due to changes in the stream level, or *vice versa*. Brodie et al. (2007) suggest that a highly connected system may be one that experiences a significant (say, >10%) impact on catchment management targets, particularly in the medium term, say 1 to 5 years. Alternatively, Evans (2007) defines a highly connected system as one where groundwater abstraction impacts (or is predicted to impact) upon surface water resources by more than 50% over a 50-year period.

4.2 Gaining streams

The movement of water from an aquifer to a stream results in what is termed as a gaining stream (Figure 4.1). That is, the stream gains or receives at least some of its flow via seepage from a connected aquifer. For this to happen, the hydraulic head or watertable height in the adjacent aquifer must be higher than the height of the stream surface.

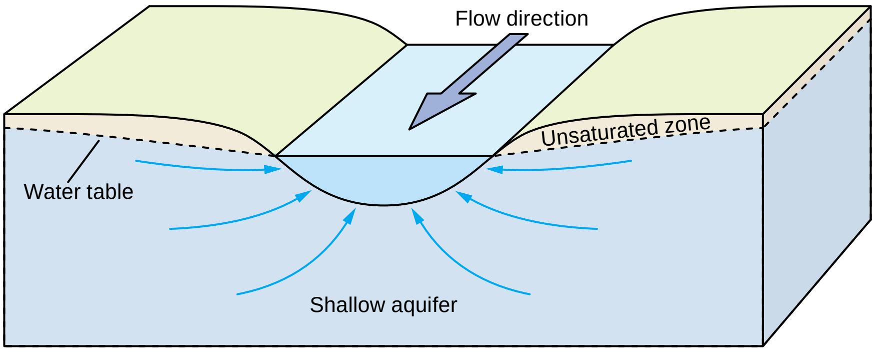


Figure 4.1. Schematic representation of stream–aquifer interaction for a gaining stream (after Winter et al. 1998).

Baseflow is a term commonly used to describe the component of groundwater discharge that contributes to flow in gaining streams. Brodie et al. (2007) define baseflow as the longer-term discharge into a stream from natural storages, notably sustaining stream flow between rainfall events. As there can be multiple natural storages in a catchment, the discharge of groundwater to a stream is termed the groundwater component of baseflow.

4.3 Losing stream with saturated connection

For a losing stream, as its name suggests, the movement of water is from the stream to an aquifer. This can occur in two basic ways. One way, as shown in Figure 4.2, is where the stream is directly connected via a saturated zone. The other, described below and shown in Figure 4.3, is via an unsaturated zone. In either case, a stream loses or contributes at least some of its flow via seepage to an aquifer. For stream loss to occur, the hydraulic head or watertable height in the adjacent aquifer must be lower than the height of the stream surface. For a losing stream with saturated connection, the adjacent watertable height will be somewhere between the stream surface and base of the streambed.

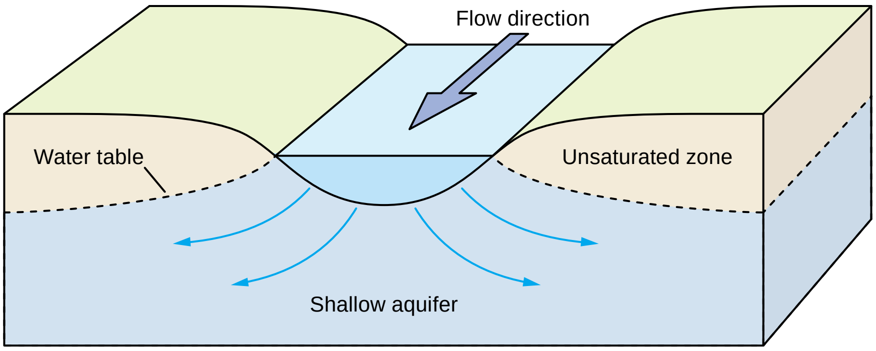


Figure 4.2. Schematic representation of stream–aquifer interaction for a losing stream with saturated connection (after Winter et al. 1998).

4.4 Losing stream with unsaturated connection

Losing streams can also be connected to the groundwater system by an unsaturated zone (Winter et al. 1998), as shown in Figure 4.3. The literature, including Winter et al. (1998), commonly refers to such streams as disconnected, or perched, streams. However, these terms can be confusing, as the groundwater system is still essentially connected to the stream via leakage from the stream through the unsaturated zone to the aquifer, and these terms do not give this indication. Therefore, it is preferred here to distinguish this type of losing stream as one with *unsaturated* connection. In this case the hydraulic head in the aquifer is below the base of the streambed.

An important feature of losing streams with unsaturated connection is that pumping of shallow groundwater near the stream does not affect the flow of the stream (Winter et al. 1998; Brodie et al. 2007), as it will not induce (further) stream leakage where unsaturated connection exists. However, the stream flow would be affected if the pumping cone of depression (see Section 5.1) was to expand upstream or downstream to reaches with saturated connection (Evans 2007).

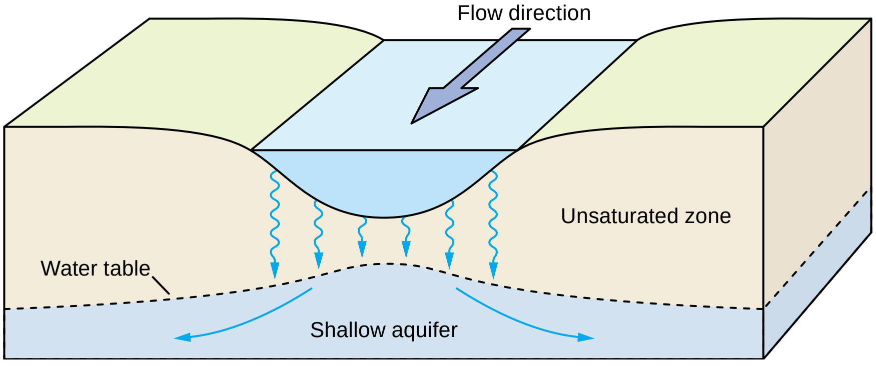


Figure 4.3. Schematic representation of stream–aquifer interaction for a losing stream with unsaturated connection (after Winter et al. 1998).

Where the stream is separated by an unsaturated zone, the watertable will have a mound below the stream (Figure 4.3). The size of this mound will depend upon the rate of stream loss through the streambed and unsaturated zone and the hydraulic properties of the aquifer. Changes in stream management such as regulation of flow from upstream storages could potentially increase or decrease the rate of recharge by the stream.

4.5 Bank storage

A common type of groundwater–stream interaction process is a rapid rise in stream level that causes water to move from the stream into the stream banks. This process is known as bank storage and is usually caused by storm precipitation, rapid snowmelt, or release of water from a reservoir (Winter et al. 1998), as shown in Figure 4.4. If the rising stream does not overtop the stream bank, most of the stream water that enters the bank will return to the stream within a few days or weeks where sediments are conductive. However, if the rising stream overtops the bank and floods large areas of the land surface, widespread recharge to the watertable can eventuate. In this case, the time taken for the recharged water store to return to the stream by groundwater flow could be weeks, months or years depending on the length of the return groundwater flow paths.

The subsurface zone where stream water flows through short segments of its adjacent bed and banks is referred to as the *hyporheic* zone. The size and geometry of hyporheic zones vary greatly in time and space. However, the scale of the zones is usually small relative to the length and volumetric transport characteristics of the stream. The chemical and biological character of hyporheic zones may differ markedly from adjacent surface water and groundwater due to mixing of groundwater and surface water within the zones (Bencala 2005; Winter et al. 1998).

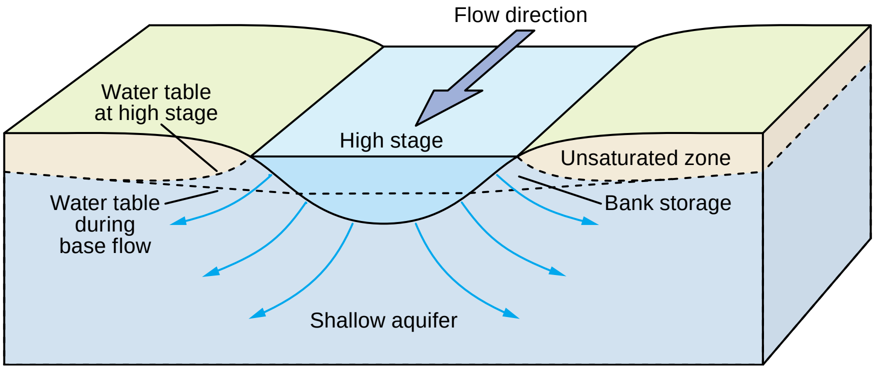


Figure 4.4. Schematic representation of bank storage (after Winter et al. 1998). When stream levels rise above adjacent watertable levels, stream water moves into the stream banks as bank storage.

5 Effects of groundwater pumping on streams

Groundwater pumping near streams is one of the most common human activities that can potentially change stream flow from gaining to losing conditions. Pumping can intercept groundwater that would otherwise have discharged to a gaining stream (*captured discharge*), or given time or a higher pumping rate, it can induce flow from the stream into the aquifer (*induced recharge*) (Winter et al. 1998).

Groundwater is a valuable resource in Australia and is used widely for agricultural, industrial and urban purposes. Groundwater extraction for agricultural purposes, in particular, has increased dramatically over the last decade and very substantially within the last five years. In some areas of Australia (e.g. parts of the Murray–Darling Basin), groundwater storage is decreasing at alarming rates that, if not arrested, may seriously harm the local community, economy and environment in the not-too-distant future.

Groundwater pumping can also reduce downstream water security. A number of studies (e.g. SKM 2003) highlight the potential impact of increasing groundwater use on stream flow and initiatives such as the limit, or 'Cap', on surface water diversions from the Murray River system (capped at 1993/1994 levels; MDBC 1999) and, indirectly, on The Living Murray (MDBC 2005).

In connected groundwater–surface water systems, there are variable time lags of days to years, or even decades, between the start of groundwater extraction and the time at which the full impact of that pumping is realised in the streams (Braaten and Gates 2004; Glover and Balmer 1954; Hunt 1999; Jenkins 1968; Sophocleous et al. 1995; Theis 1941). In the cases where response lag times are long, this means that there will be an ongoing impact in the streams due to historical pumping regimes, even if all groundwater pumping were to cease at once. Management of this legacy of pumping will be complex.

Several studies have attempted to predict future groundwater extraction in regional aquifer systems in Australia (e.g. SKM 2003). All studies assume that the sustainable or permissible yield will ultimately be the effective upper annual limit to extraction from a managed aquifer system. The major difference between regions is in how fast this limit will be achieved. Some studies use simple linear models based on long-term average rates of increase, while others highlight the recent increased rates of extraction and assume a non-linear increase. In the case of the Murray–Darling Basin, all studies agree that more groundwater will be extracted from the Basin's groundwater systems, and that this extraction will continue to erode surface water flows (e.g. REM 2005; SKM 2003).

5.1 How is stream flow reduced by groundwater pumping?

As a groundwater body is pumped, the water level around the pumping bore will be drawn down in the shape of a so-called pumping *cone of depression*. Over time, this cone of depression will expand and deepen at a rate that depends on the hydraulic characteristics of the aquifer and the pumping rate (Domenico and Schwartz 1990; Freeze and Cherry 1979; Heath 1983). After an extended period of pumping, expansion of the cone may slow considerably due to increased inflows of groundwater further away, or outside the aquifer altogether. The sources of this water can be surface water bodies such as rivers, groundwater that would otherwise discharge to the stream, or other overlying saturated formations. There are several ways in which groundwater extraction can lead to reduced stream flows. Three common processes are described below.

Induced recharge

When sufficiently close to a river or stream, a pumping bore, or bore field, can influence the hydraulic gradient between the area of pumping and the stream in two basic ways. Firstly, in the case of an already losing stream, it can increase the hydraulic gradient, thus increasing flow from the stream to the aquifer. Secondly, in the case of a gaining stream, it can reverse the gradient, such that water stops flowing from the aquifer to the stream and is instead induced to flow from the stream to the aquifer (Brodie et al. 2007; REM 2006; Winter et al. 1998; Figure 5.1, Example C). In both cases, the volume of water moving to the aquifer from surface water is greater than when there is no pumping. This increase in the seepage flux is called induced recharge. This type of leakage from streams is effectively a form of groundwater recharge. Sometimes this effect becomes apparent as reductions in stream flow; that is, a volume of stream water that is lost between two stream gauging stations. In other cases it is not identified at all. It can occur under natural conditions, but groundwater extraction can exacerbate it by increasing the difference in hydraulic head, or water pressure, between the stream and the groundwater system. In some circumstances, induced recharge can be used as a mechanism to 'filter' contaminated stream water by pumping groundwater and inducing flow through an aquifer matrix.

In general, the timeframe for the onset of the impacts of induced recharge will be short, but the time to full impact depends on a range of factors including the volumes of stream flow and pumped groundwater, how much the hydraulic gradient has changed, and the properties and connectivity of the aquifer. In some circumstances where the aquifer is pumped at high rates, the water level can be drawn below the streambed causing the stream–aquifer relationship to change to one of connection via an unsaturated zone, alternatively called disconnection (see previous chapter). However, induced recharge will not occur in a stream–aquifer system that is already connected in this way under natural conditions, as in such a case leakage to the aquifer will already be at a maximum.

Captured discharge

When groundwater pumping occurs further from the stream and/or not in sufficient amount to reverse the near-stream hydraulic gradients, the major impact could be that groundwater will be extracted that would otherwise have flowed into the stream. Captured discharge can affect the stream itself by diminishing stream flow (Figure 5.1, Example B). It can also manifest away from the stream, for example, as reduced water supply to groundwater-dependent ecosystems in lakes, wetlands or billabongs.

The time scales of captured discharge depend on the distance of the pumping from the stream, the pumped groundwater and stream flow volumes, the change in hydraulic gradient, aquifer properties, and degree of aquifer confinement. In some cases where pumping is close to the stream and there is a large change in the hydraulic gradient, the impacts may be felt almost immediately.

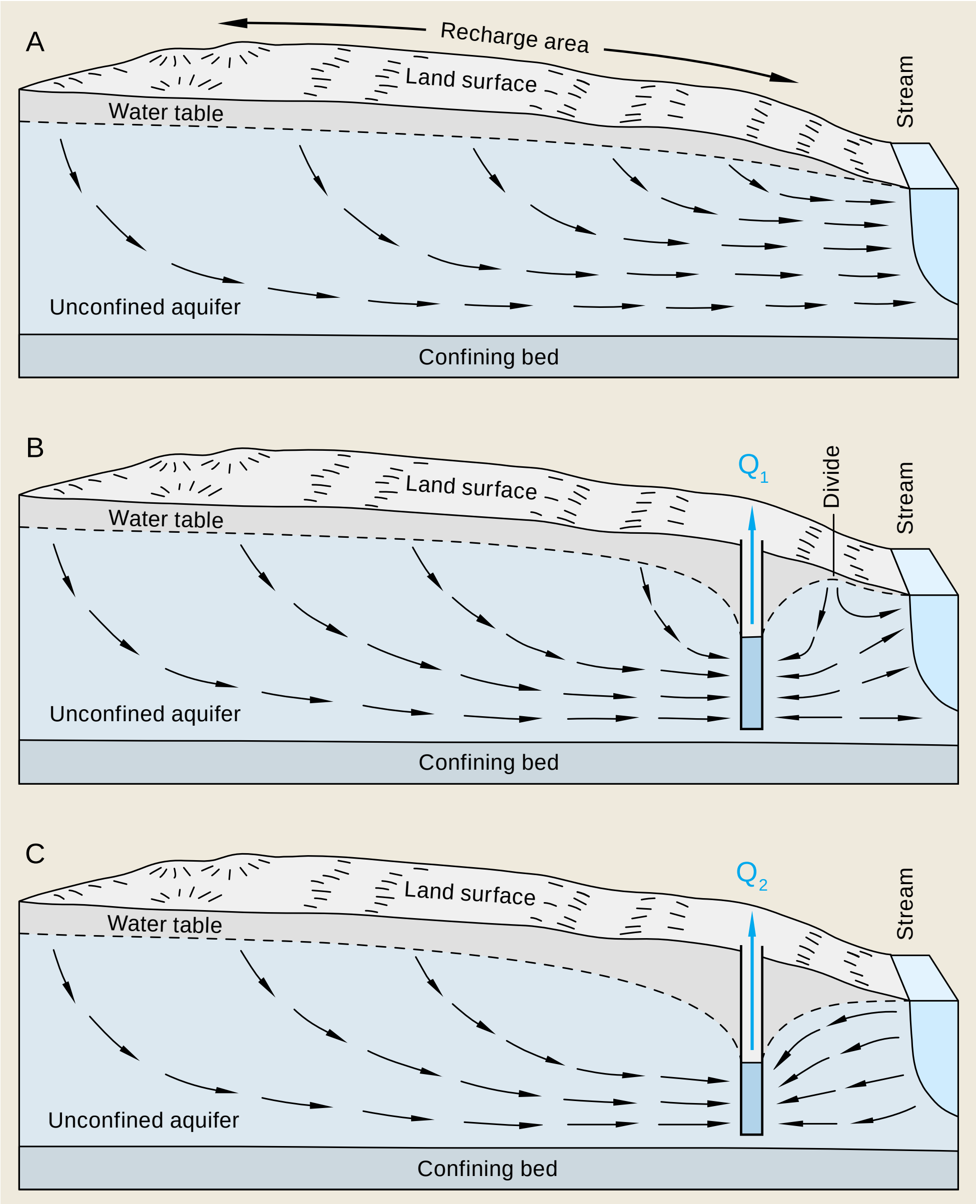


Figure 5.1. Schematic examples of groundwater–stream interaction. (A) natural groundwater discharge to a stream, (B) reduced discharge to the stream due to groundwater pumping, and (C) induced recharge from the stream due to groundwater pumping (after Winter et al. 1998).

Induced leakage

A more complex form of water losses can occur in semi-confined aquifers. Pumping from such aquifers can cause water to leak out of the semi-confining layer above. This induced leakage will be a one-off component of the water budget, unless the leakage is matched by water being added at the top of the semi-confining layer, which could be from irrigation or from a stream. If there is no addition of water to the semi-confining layer to compensate for the induced leakage, then the semi-confining layer will dewater, potentially causing contraction of that layer and land subsidence (REM 2006). The response of the aquifer to induced leakage from the semi-confining layer is usually indistinguishable from that of induced recharge. This can be a problem when trying to establish the sustainability of a developed water budget.

5.2 Double accounting

Double accounting of water resources occurs when water is accounted for twice in connected surface and groundwater systems; once when it is accounted for in a surface water budget and again when it is accounted in a groundwater budget (SKM 2003, 2006). When, for example, groundwater is pumped, and a proportion of the water recovered is actually derived from the surface water account, the surface water account is less than it would have been in the absence of pumping, thus the available initial surface water account is overstated. The converse is also true: if surface water is removed and induces groundwater inflow to the stream, then the groundwater account is less than it would have been in the absence of removal, and the initial groundwater account is overstated. Double accounting is an avoidable accounting artefact caused by an incomplete understanding of the water system and, where applied, may lead to unsustainable use of overall water resources.

5.3 Impacts differ between regions

Major groundwater systems with linkages to the surface water differ in the way they behave, and in the processes by which they are recharged and discharge. This has important consequences for the impact of groundwater extraction on surface water resources.

Using the Murray–Darling Basin as an example, connected groundwater–stream systems with saturated connection generally occur in the south-eastern parts of the Basin, while systems with unsaturated connection (or disconnected systems) mostly occur in the north (REM 2006). Aquifers in the South Australian part of the Basin are connected at the discharge end with the Murray River, but the timing of the onset of impacts is extremely long, and the salinity of the Mallee Limestone (or Murray Group) system means that a reduction in discharge will (or could) provide a salinity benefit (REM 2005).

The regions at highest risk will be those where the current and potential future extraction of groundwater is high and where the aquifer and stream are strongly connected. This situation occurs in the alluvial valleys of New South Wales. A good example is the Mid-Murrumbidgee River valley (see Case Study 6).

Other areas where extraction rates are high at present, such as the Shepparton–Katunga (Victoria) and Lower Murrumbidgee (NSW) regions, have a similarly high level of risk. However, the situation in these areas is complicated by the presence of a semi-confining layer. In the Shepparton–

Katunga region, high levels of groundwater extraction contribute to salinity mitigation (REM 2005).

Areas such as the Lower Namoi in the northern part of the Murray–Darling Basin are at lower risk, even though historical pumping levels are high. This is because the stream and aquifer are mostly connected via an unsaturated zone (Ivkovic 2006; REM 2005; see Section 4.4).

5.4 What will happen to our water resources?

Using the Murray–Darling Basin as an example, three studies, SKM (2003), MDBC (2004) and REM (2005), have estimated the impact of groundwater pumping on total surface water resources of the Basin. Direct comparison of the studies is not valid due to the use of different assumptions, time periods and starting and ending points. However, their results are similar and indicate significant impacts now and into the future.

SKM (2003) estimated future rates of groundwater extraction and reviewed the implications of future use on the integrity of the Cap (on diversions from the Murray River system). It concluded that the Cap could be undermined by around 186 GL per year (or 2%). Another study by MDBC (2004) undertook further analysis of groundwater data and found that, at 2002/2003 extraction rates, 327 GL/year of annual stream flow is diverted because of groundwater pumping. It also predicted a further reduction of 274 GL/year, making a total predicted reduction of about 600 GL/year in the future. The third study by REM (2005) estimated that increased groundwater extraction from aquifers that are connected to streams could reduce annual stream flow by up to 550 GL/year.

5.5 Time lag between pumping and changes in stream flow

The timing of the impact of groundwater pumping on surface water in connected systems is difficult to predict. Braaten and Gates (2004) used a modelling approach to explore the time lags associated with pumping-induced stream depletion at various distances from a stream in four different alluvial stream–aquifer systems (narrow and wide valley unconfined aquifers, and narrow and wide valley semi-confined aquifers). They found that in unconfined systems, time lags for stream flow depletion became longer with increasing distance from the stream but were significantly shorter in narrow valleys (5 km) compared to wide valleys (40 km). The most sensitive parameters for unconfined conditions were the distance of pumping from a stream, and aquifer properties. For semi-confined systems, time lags were found to be significantly longer due to the overlying aquitard. While distance from the stream had a large effect on time lag in wide valleys, it had little effect in narrow valleys due to rapid lateral transmission of drawdown. The most sensitive parameters for semi-confined systems were the aquitard leakage rate and properties of the aquitard layer (Braaten and Gates 2004).

Another recent modelling study by REM (2005) estimated the timing of the response of surface water systems to groundwater extraction. The results suggest that the onset of the initial impact on stream flow from groundwater extraction is rapid, but it takes several decades for the full impact to be

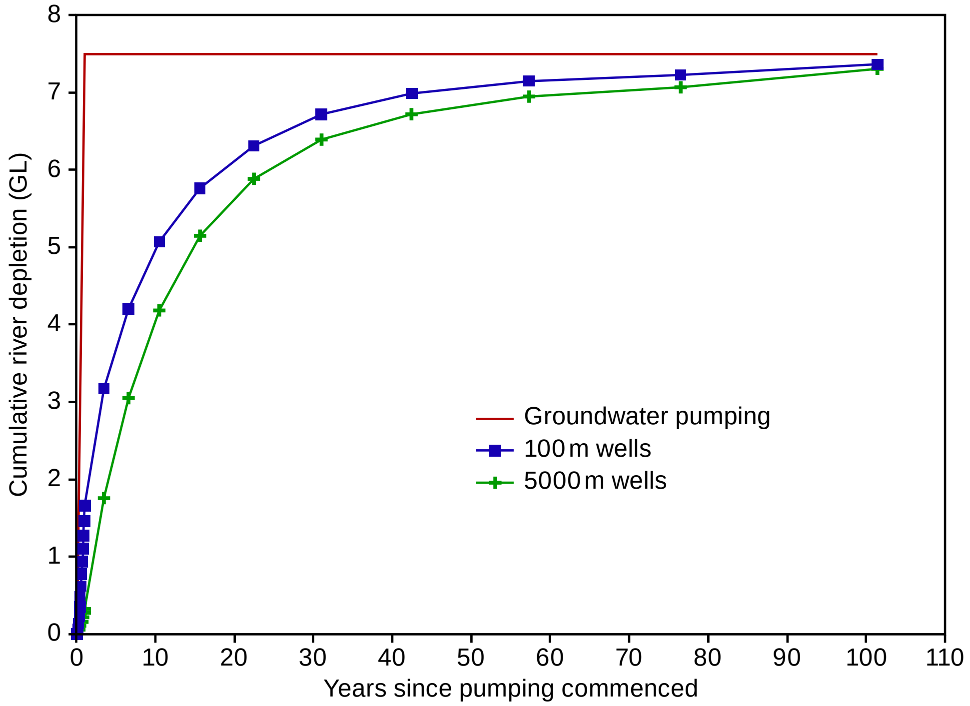


Figure 5.2. Examples of time taken for the realisation of full pumping impact on a river or stream. Groundwater pumping changes the balance of water exchange between the stream and the groundwater system, and can also affect groundwater-dependent ecosystems (after REM 2005).

realised. Examples of the time taken to reach the full impact are provided in Figure 5.2.

The lag between the onset and the full realisation of pumping impacts means that at any one time there is a legacy of impacts due to past development. This legacy of previous pumping slows the rate of stream flow change: large changes in short-term pumping do not have a correspondingly large change on stream impacts. Aquifer management plans need to take this slow or delayed response into account.

6 Effects of other human activity on groundwater–stream interaction

As discussed in the previous chapter, groundwater pumping can have a significant impact on groundwater–stream interaction and stream flow. This section will discuss a range of other human activities that affect the interaction of groundwater and surface water.

6.1 Land use change

One of the most significant landscape changes in Australia is the clearance of native vegetation for agriculture or mining. The modification of landscape cover changes the infiltration, evapotranspiration and runoff characteristics of the land surface. This affects surface water and groundwater flows and the hydrologic balance, as well as the interaction of groundwater and surface water. The hydrologic or water balance responses following landscape change to non-indigenous or lower water-using vegetation cover can result in rising watertables and increased land and river salinisation, changed flood frequency and flow regime, and increased surface waterlogging. This affects the supply of drinking and irrigation water, with serious economic, social and environmental consequences for rural and urban communities. Increased salinity can also change the habitats of aquatic fauna in stream and riparian zone systems (NLWRA 2001a).

Agricultural activities (e.g. application of pesticides and fertilizers) also provide sources of contaminants that could discharge either into groundwater or surface water. This contamination process could be accelerated by the change in interaction of groundwater and surface water. A study carried out by Baskaran et al. (2002) found that the impact of sugarcane cropping on groundwater quality was substantial in the Lower Pioneer catchment in Queensland.

For some years, planting of trees has been promoted intensively as a solution in the control of dryland salinity, as well as improving farm productivity and profitability. However, trees act like pumps, drawing water from the subsoil and watertables by virtue of their deep rooting capability. Dense stands of trees can create local groundwater depressions that allow groundwater from surrounding areas to flow toward the groundwater depression. Large-scale reafforestation has been shown to significantly affect the interaction of groundwater and surface water. For example, a 320 hectare pine (*pinus radiata*) plantation has significantly reduced recharge and lowered the groundwater level in the Pine Creek area of the Goulburn catchment in Victoria (Cheng et al. 2006; Zhang et al. 2003). The whole of the Pine Creek subcatchment was converted from open grassland to pine plantation in 1986 and 1987. The subsequent reduction in recharge and watertable has altered the relationship between the stream and aquifer from dominantly gaining to dominantly losing. Consequently, both the flow and salt load from the Pine Creek subcatchment have significantly diminished (Dawes et al. 2004; Zhang et al. 2003).

Mining has played a vital part in the Australian economy. Activities associated with mining commonly require the manipulation of large quantities of water and can have significant impacts on the interaction of groundwater and surface water. For example, the Great Artesian Basin (GAB) has natural outflows, or groundwater discharges, which emerge as springs, over many millennia. Mining (and farming) activities since European settlement have resulted in a substantial decline in GAB groundwater levels and consequent drying of the mound springs in many places (Mudd 2000). Also, alluvial mining and dredging activities can alter stream geomorphology by deepening channel incision or removing or mixing streambed deposits. If channel incisions intersect groundwater and there are sufficient hydraulic gradients toward the incision then increased groundwater discharge may occur.

6.2 Irrigation development

During the second half of the 19th century, a number of factors including an expanding population, closer settlement, and severe droughts, led to a heightened interest in the potential of irrigation and in spectacular projects involving large reservoirs and extensive water distribution systems in Australia. In the first half of the 20th century, irrigation was also seen as an effective means of increasing agricultural production, resulting in Commonwealth and State Government schemes for the settlement of returned soldiers from the First and Second World Wars (Hallows and Thompson 1995). The development of irrigated agriculture in Australia has coincided with the development of regional Australia, particularly in the Murray–Darling Basin.

While irrigation has delivered substantial benefits to regional communities and the nation, some drawbacks associated with inefficient or excessive use of irrigation water have been identified. Major issues include irrigation-induced salinity, water over-allocation, altered stream flow due to regulation, surface water quality decline, excessive groundwater drawdown, pumping bore interference, groundwater quality decline, groundwater pumping-induced stream flow depletion, and pumping-induced land subsidence.

The amount of applied irrigation water generally depends on climate, soil characteristics and type of crop. The majority of the applied water is lost through evapotranspiration and the remainder is retained in the soil. However, some of the water either infiltrates through the soil zone to recharge the groundwater system, or it returns to a local surface water body through the drainage system or as baseflow discharge. This excess water can cause the watertable to rise, bringing groundwater and salt into the root zone or even to the land surface. Irrigation-induced rising watertables have commonly resulted in land salinisation, as well as increased outflows of shallow, saline groundwater to surface water bodies downgradient of the irrigation area. This problem is very widespread in Australia, particularly in the Murray–Darling Basin (Jolly et al. 2004). Research in the Lower Murrumbidgee region has concluded that irrigation without sufficient drainage has caused watertables to rise in many areas from at least 20 m below the ground surface to very near the ground surface. It has further concluded that the rising watertables resulted in increasing salt discharge to streams, land salinisation and waterlogging (Lawson and Webb 1998).

Although many irrigation systems initially used surface water only, the use of groundwater for irrigation has increased significantly in some areas for a number of reasons:

1. dry climatic conditions, particularly since 1996 in south-eastern Australia,
2. groundwater resources offer a viable irrigation alternative in many areas,
3. groundwater may be more readily available than surface water,
4. a system of supply canals is not needed, and
5. many types of sprinkler systems can be used on irregular land surfaces.

Intensive groundwater extraction for irrigation can cause declines in groundwater levels, consequently reducing groundwater discharge to the streams and/or inducing flow from the streams to groundwater systems (see previous section). Also, the use of poorer quality groundwater (i.e. moderately saline) could exacerbate salt build-up in the soil.

6.3 Modifications to river valleys

Engineering works along river valleys, such as construction of levees, reservoirs and drainage systems can alter the interaction of groundwater and surface water.

Levees for containing or diverting floodwaters can alter how and where recharge to the aquifer occurs during high flow events. They can therefore lead to undesirable excessive recharge in specific areas where floodwaters have been retained or diverted, causing watertable rises and altered groundwater–stream relationships. Also, large floods can overtop or breach the levees, resulting in widespread flooding.

The effects of reservoirs on the interaction of groundwater and surface water are greatest near the reservoir and directly downstream from it. Reservoirs can cause a permanent rise in the watertable that can sometimes extend a considerable distance from the reservoir, because the base level of the stream, to which groundwater gradients had adjusted, is raised to the higher reservoir levels. Near the dam, reservoirs commonly lose water to shallow ground water, but this water usually returns to the river as base flow directly downstream from the dam. In addition, reservoirs can cause temporary bank storage at times when reservoir levels are high. In some cases, this temporary storage of surface water in the groundwater system has been found to be a significant factor in reservoir management (Winter et al. 1998).

Drainage of land is a common practice preceding agricultural and urban development in coastal and riverine landscapes in Australia (e.g. Westernport Basin, Victoria). Artificial drainage systems can change the areal distribution of groundwater recharge and discharge. These changes can ultimately affect the base flow to streams, which in turn affects riverine ecosystems. Drainage also alters the water-holding capacity of topographic depressions as well as the surface runoff rates from land with very low slopes. More efficient runoff caused by drainage systems results in decreased recharge to groundwater and greater contribution to flooding (Winter et al. 1998).

6.4 Stream regulation

Many rivers are regulated for the purposes of water supply and flood control in Australia. River regulation may cause high flows and low flows to differ considerably in magnitude and timing compared to natural flows. Significant changes to flows could result in alterations to the groundwater–stream relationships, both seasonally and in the longer term. Consequently, recharge to, or discharge from, the connected groundwater system may alter in time and space. As a further consequence, the environmental conditions in river valleys downstream of reservoirs may alter as organisms try to adjust to the modified flow conditions. For example, the movement of water to and from bank storage under controlled conditions would probably be much more regular in timing and magnitude compared to the highly variable natural flow conditions, which probably would lead to less biodiversity in river systems downstream of reservoirs. A study carried out by Jolly et al. (2004) found that river regulation led to a reduction in frequency and duration of floods and resulted in severe health decline of the native riparian vegetation communities on the Chowilla Floodplain of the lower River Murray in South Australia.

6.5 Stream diversions

Artificial diversion of water from streams for consumptive uses such as irrigation, urban supply or industry is a common practice in urban and intensive agricultural areas in Australia. This practice can significantly alter, and sometimes (e.g. mid–lower Murray–Darling Basin) lead to the reversal of the annual river flow patterns (Figure 6.1). Such changes in the stream stage relative to surrounding groundwater levels can affect the interaction of groundwater and surface water, impacting the health of streams and other aquatic ecosystems.

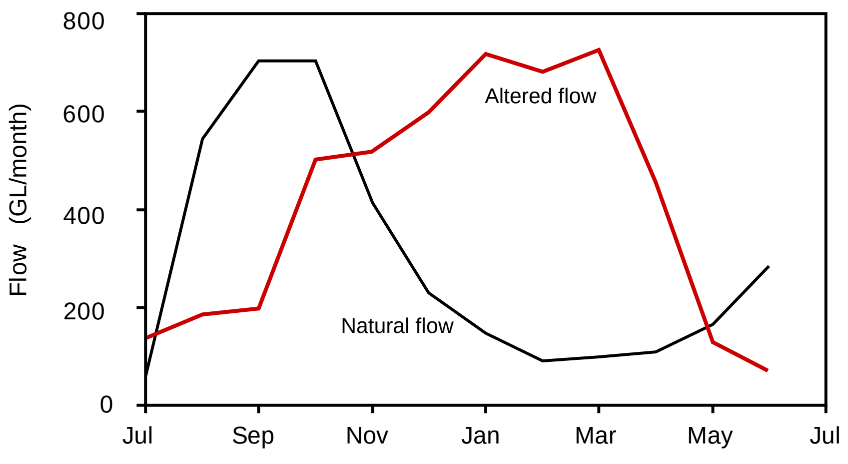


Figure 6.1. Mean monthly river flow in the River Murray at Albury (after NLWRA 2001b).

6.6 Urban development

Urbanisation not only provides sources of contamination to surface water and groundwater, but can also significantly alter the water budget. Urban development can cause changes in the fluxes and spatial distribution of evapotranspiration, groundwater recharge and surface runoff. A study undertaken by Cook et al. (2001) found that the average groundwater recharge rate increased from approximately 1.3 mm/yr under remnant native vegetation to 55 mm/yr under urban areas in Wagga Wagga, New South Wales. The increase in recharge has brought watertables close to land surface and altered the hydraulic gradient to the surrounding streams. Evapotranspiration from the shallow watertables has also concentrated the naturally occurring salts in the groundwater and soils, leading to salinisation. This salinisation process has not only damaged infrastructure and land in places such as Wagga Wagga, but has also resulted in water quality and stream degradation in areas where the shallow aquifer is closely connected to streams.

In addition, urban development is often accompanied by artificial drainage and groundwater extraction for water supply. As discussed previously, these activities can affect the interaction of groundwater and surface water.

7 Effects on water quality and groundwater-dependent ecosystems

7.1 Effects of groundwater–surface water interaction on water quality

As discussed previously, almost all surface water bodies (streams, lakes, reservoirs, wetlands, and estuaries) interact with groundwater. These interactions take many forms. Development of either of these resources affects the quantity and quality of the other. In many situations, surface water bodies gain water and solutes from groundwater systems and in others the surface water body is a source of groundwater recharge and causes changes in groundwater quality, including temperature. As a result, withdrawal of water from streams can deplete groundwater or conversely, pumpage of groundwater can deplete water in streams, lakes, or wetlands. Pollution of surface water can cause degradation of groundwater quality and conversely pollution of groundwater can degrade surface water.

In Australia, salinity (both dryland and irrigation) is one of the biggest contributors to water quality and stream degradation in many river systems. In the past century, groundwater has risen towards the ground surface in many parts of Australia due to either the removal of deep-rooted native vegetation or application of irrigation water. As the watertable has moved upwards, salt has been mobilised and brought towards the soil surface leading to increased shallow groundwater and stream salinity across much of temperate Australia (McFarlane and Williamson 2002). This affects the supply of drinking and irrigation water, with serious economic, social and environmental consequences for rural and urban communities. Increased salt concentrations also change the habitats of aquatic fauna in wetland, stream and riparian zone systems (NLWRA 2001). To tackle these water quality problems, Federal, State and Territory Governments have worked with people in communities via a number of programs such as the National Action Plan for Salinity and Water Quality and the Natural Heritage Trust.

Irrigated agriculture uses 72% of total water diversions in Australia and its potential to generate return flows to river systems in terms of both quantity and quality is significant (Hornbuckle et al. 2005). The return flows generally have poorer quality largely due to evapotranspiration, the use of poorer quality groundwater, and application of fertilizers and pesticides to crops. Therefore, the water quality of the water bodies that receive the return flow is affected. If irrigation return flow is drawn back into an aquifer due to groundwater withdrawals, the groundwater system also will be affected by the quality of that surface water.

Intensive groundwater extraction for irrigation and town supply can cause significant declines in groundwater levels, consequently reducing groundwater discharge to surface water bodies and/or inducing flow from the water bodies to groundwater systems. This not only can threaten water supply security, but also could degrade groundwater quality (e.g. seawater intrusion).

Traditionally, management of water resources in Australia has focused on surface water or groundwater as if they were separate entities. However, there is now an increasing emphasis on integrated water resource management that recognises the importance of the role that groundwater and surface water interactions play in affecting water quality throughout the hydrologic system. Thus, a clear understanding of the linkages between groundwater and surface water is central to the effective management of land and water resources.

7.2 What are groundwater-dependent ecosystems?

Groundwater-dependent ecosystems (GDEs) are defined as the ecosystems that are dependent on groundwater for their existence and health (NWC 2005). Their dependence on groundwater is highly variable, ranging from partially to wholly dependent. These ecosystems represent a diverse and important component of biological diversity, which include wetlands, vegetation, mound springs, river base flows, cave ecosystems, playa lakes and saline discharges, springs, mangroves, river pools, billabongs and hanging swamps. There is a number of different GDE classifications proposed in Australia (e.g. Hatton and Evans 1998; SKM 2001; Eamus et al. 2006). Hatton and Evans (1998) identified four types of GDEs primarily based on their locations:

1. Terrestrial vegetation – vegetation communities and dependent fauna that have seasonal or episodic dependence on groundwater.
2. River base flow systems – aquatic and riparian ecosystems that exist in or adjacent to streams that are fed by groundwater base flow.
3. Aquifer and cave ecosystems – aquatic ecosystems that occupy caves or aquifers.
4. Wetlands – aquatic communities and fringing vegetation dependent on groundwater fed lakes and wetlands.

Based on the same approach, SKM (2001) identified two additional types of GDEs:

1. Terrestrial fauna – native animals that directly use groundwater rather than rely on it for habitat.
2. Estuarine and near-shore marine ecosystems – coastal, estuarine and near-shore marine plant and animal communities whose ecological function has some dependence on discharge of groundwater.

Eamus et al. (2006) used a markedly different approach for their GDE classification scheme. Considering a common type of groundwater resource that ecosystems rely on, Eamus et al. (2006) proposed three simple primary classes:

1. Aquifer and cave ecosystems, where stygofauna (groundwater-inhabiting organisms) reside within the groundwater resource.
2. All ecosystems dependent on the surface expression of groundwater.
3. All ecosystems dependent on the subsurface presence of groundwater, often accessed via the capillary fringe (non-saturated zone above the water table) when roots penetrate this zone.

7.3 Effects of groundwater–surface water interaction on GDEs

The dependence of ecosystems on groundwater ranges from complete to partial. The degree and nature of dependency influences the extent to which ecosystems are affected by changes to the groundwater system.

According to SKM (2001), the dependency of ecosystems on groundwater is influenced by one or more of four basic groundwater attributes, as follows:

- Groundwater flow or flux – the rate and volume of supply of groundwater.
- Groundwater level – for unconfined aquifers, the depth to the watertable.
- Groundwater pressure – for confined aquifers, the potentiometric head of the aquifer and its expression in groundwater discharge areas.
- Groundwater quality – the chemical quality of groundwater expressed in terms of pH, salinity and/or other potential constituents, including nutrients and contaminants.

The response of ecosystems to change in these attributes is variable. There may be a threshold response in some cases, whereby an ecosystem collapses completely if a certain attribute value is exceeded. Examples might be individual mound spring communities supported by groundwater discharge from the Great Artesian Basin (GAB). These would cease to exist if pressures in the GAB fell to the point where there was no further surface discharge. In other cases a more gradual change in the health, composition and/or ecological function of communities is expected as, for example, may occur with increasing groundwater salinity or contaminant concentration. The water regime for some dependent ecosystems may also be characterised by variability in time (SKM 2001).

There are a number of human activities which have potential to alter the water regime experienced by groundwater-dependent ecosystems. SKM (2001) identified the following activities:

- Water resource development.
- Changes in land use – particularly from native vegetation to agriculture, or agriculture or native vegetation to plantation forestry.
- Activation of acid sulphate soils in coastal areas by drainage, dredging or groundwater extraction.
- Dewatering or water resource development associated with mining.
- Commercial, urban or recreational developments.

Consumptive use of water resources poses a major threat to groundwater-dependent ecosystems in many landscapes across Australia. This is particularly true in the more intensively developed landscapes of eastern and south-western Australia. Consumptive use can impact on any of the four main groundwater attributes listed above. For example, consumptive use of groundwater can significantly lower the watertable in an unconfined aquifer and reduce base flow in streams. This potentially threatens terrestrial fauna, in-stream aquatic communities, and cave and aquifer ecosystems.

Intensive agricultural land use is invariably associated with changes in vegetation cover and recharge–discharge relationships across catchments and groundwater basins. As mentioned previously, the introduction of dryland agriculture has resulted in an increase in shallow water tables and dryland salinity across much of southern Australia. Fragmented remnant native vegetation in lower parts of landscapes is particularly vulnerable to the effects of shallow water tables and salinity. Dieback of vegetation is common and it is reported that several hundred indigenous plant species are at direct risk of extinction due to dryland salinity (Hatton and Salama 1999). Irrigation development has similar impacts on GDEs, but to a lesser extent.

Application of agricultural chemicals (fertilisers, herbicides, insecticides) may result in contamination of groundwaters and affect groundwater-dependent ecosystems in various ways.

Activation of acid sulphate soils by drainage, dredging or groundwater extraction may affect GDEs in coastal areas, as it may release toxic concentrations of aluminium, iron and other metals (NSW EPA 1998). The most common GDEs threatened by this process include those in estuarine or coastal environments, together with associated vertebrate and invertebrate communities, aquatic ecosystems in estuaries of base flow dependent streams and coastal wetlands supplied by groundwater.

Urban and commercial development in Australia threatens GDEs in several ways. These developments are often associated with an intensification of groundwater resource development and construction of drainage systems, resulting in declining groundwater levels and reducing discharge fluxes in aquifers. Groundwater quality can be degraded by discharge of effluent from septic tanks, leakage from contaminated sites (landfills) and underground fuel tanks, application of fertilisers and pesticides to parks, gardens and recreation areas, and spills of industrial chemicals. Impacts on the quantity and quality of groundwater may affect groundwater-fed wetlands, riparian vegetation and dependent terrestrial ecosystems in the surrounding areas of the developments.

Many mine-related activities have impacts on GDEs, although their impacts vary with the type and scale of mining, intensity of groundwater pumping and the proximity to GDEs. Mine dewatering has the intended result of removing groundwater from the proximity of mine workings, but can have unintended effects that can significantly lower the watertable or aquifer pressure at distance, particularly in large open cut mines and/or where mines intersect highly transmissive aquifers (e.g. deep leads). Lowering of water table levels could reduce or even eliminate cave or aquifer ecosystems that use the groundwater as habitat and are situated in close proximity to the mine. Baseflow dependent ecosystems, wetlands and groundwater-dependent terrestrial or riparian ecosystems may be threatened by large changes in groundwater level or pressure.

Subsidence caused by longwall mining can affect surface water flow, lower groundwater levels, decrease groundwater–surface water interactions and degrade water quality.

Tailings dams associated with mining operations may result in a local elevation, or mounding, in groundwater levels. The impacts on nearby GDEs are similar to those of dryland salinity.

Mining also poses several hazards to groundwater quality. Solution mining (e.g. for gold or uranium) using toxic chemicals like cyanide may completely destroy any aquifer ecosystem present. Accidental spillage from tailings dams may contaminate surface water and groundwater systems and damage the ecosystems they support.

Mining-related industrial activities (e.g. on-site processing) and residential development may also affect GDEs. Mine-related construction activities, such as diversion and/or canalisation of streams, may threaten GDEs close by.

7.4 The key challenges

The management of water resources in Australia has been predominantly concerned with assessment and development of water resources for water supply, and environmental flows in surface water. Until recent times, GDEs received relatively little attention from either government or researchers. Whereas significant activity has occurred in this area recently (e.g. Eamus et al. 2006; Eamus and Froend 2006; Hatton and Evans 1998; SKM 2001), many policy and technical issues still remain in improving awareness and knowledge of GDEs. One of the major challenges is to provide quantitative criteria on which to base protection of ecosystems. There is currently little knowledge of indicators of ecosystem stress that would allow adaptive management. There is also no guidance on what impacts are acceptable. Indeed, there are no universally accepted ways of valuing ecosystems, and no objective way of determining the costs of loss of ecosystem function (NGC 2004). To address current policy and technical issues, NGC (2004) identified several policy research areas and technical research areas.

SKM (2001) and Eamus and Froend (2006) also identified many current issues and made several recommendations for future research and management frameworks. The key research areas identified by SKM (2001) and Eamus and Froend (2006) include:

- Identification and mapping of GDEs.
- Determination of the conservation status of GDEs, particularly those ecosystems most threatened by groundwater resource development and land use factors.
- Development of a priority ranking of GDEs, based on conservation status and vulnerability to, and risk of, changed water regime.
- Understanding the response of key GDEs to changes in their water regime (including timing and rate of changes).
- Development of effective monitoring and data collection programs.
- Uncertainty analysis associated with modelling of GDEs and groundwater.

8 Effects of climate change

The concentration of greenhouse gases such as carbon dioxide and methane in the atmosphere has a significant effect on the heat budget of the earth's surface and the lower atmosphere. There is now new and stronger evidence that rising levels of greenhouse gases have raised the global average surface temperature over the past century. In this time, Australian average temperatures have risen by 0.7ºC, and the warming trend appears to have emerged from the background of natural climate variability in the second half of the 20th century. This rising trend is even more significant over the Murray–Darling Basin (Figure 8.1). The warming trend may be altering regional precipitation and evaporation patterns in Australia. Rainfall has increased in north-western Australia over the last 50 years, but decreased in the south-west of Western Australia, and in much of south-eastern Australia, especially in winter (Figure 8.2) (Pittock 2003).

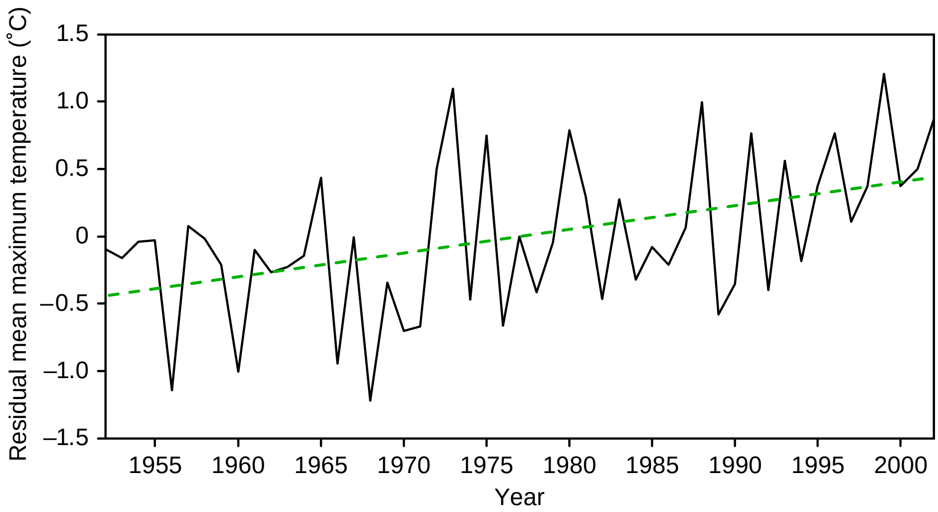


Figure 8.1. Residual mean maximum temperature for the Murray–Darling Basin between 1952 and 2002. The values are plotted after using a linear regression relationship to remove the variability of temperature associated with variations in rainfall. The dotted line is the linear regression with time, which shows a rising trend for this period of 1.75°C per century (after Nicholls 2004).

Climate change would clearly have profound effects on the hydrologic cycle. As an important component of the hydrologic cycle, groundwater–stream interaction could be significantly affected by climate change in relation to groundwater recharge, floodplain evapotranspiration, streamflow and water use.

8.1 Recharge and evapotranspiration

Spatial and temporal changes in temperature and precipitation will ultimately cause a shift in the water balance that will be evident in changes to stream flow, aquifer recharge and, hence, groundwater–stream interaction relationships. For example, variations in the amount of precipitation, the timing and distribution of precipitation events, and the form of precipitation are all key factors in determining the amount and timing of recharge to aquifers and flow in

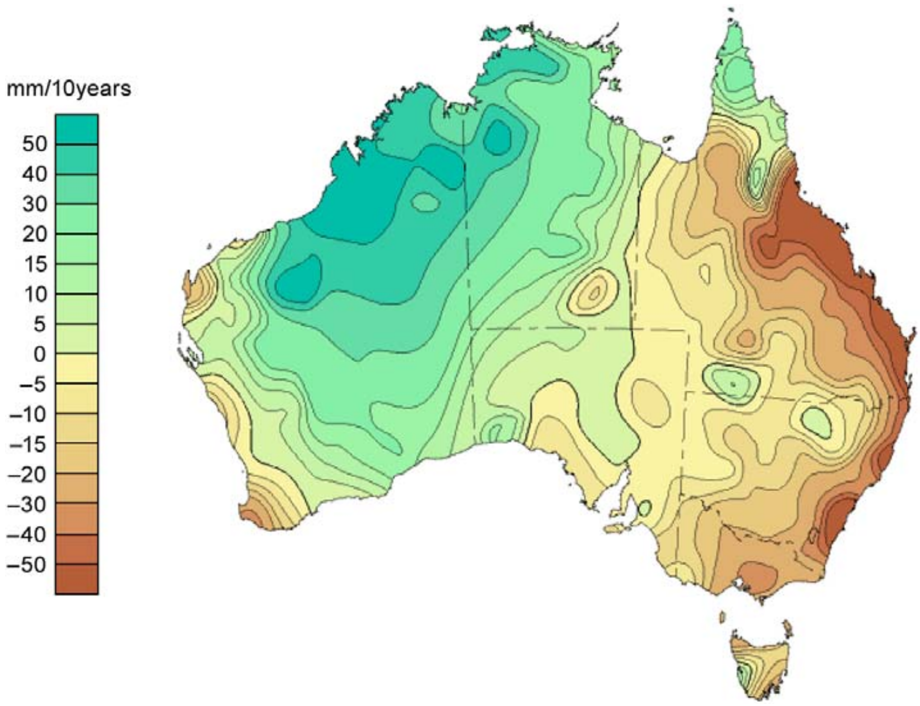


Figure 8.2. Trends in annual total rainfall 1950–2007 (Bureau of Meteorology 2007). See also Pittock (2003, Figure 2.9).

streams. Climate induced alterations to aquifer recharge or stream flow could radically alter the direction and quantity of seepage flux between a stream and connected aquifer, affecting the behaviour, health and use of either resource.

Water levels in an aquifer are often observed to respond consistently to precipitation (e.g. Figure 8.3), although the nature of the response can be complex and depends on aquifer geometry and properties, time of year, prior conditions, and so on. In most instances, the water level response to precipitation is positive, but slightly delayed in an aquifer, attenuating with depth or distance from the recharge source. It is usually more pronounced in unconfined than in semi-confined aquifers. However, recent studies have shown that increased annual precipitation does not necessarily correspond to an increase in recharge, as would be normally anticipated (e.g. Nastev et al. 2005).

An increase in extreme events, such as droughts and heavy precipitation, can also be expected to impact on water levels in aquifers. Droughts result in extensive declining water levels, not only because of reduction in rainfall, but also due to increased evaporation and a reduction in effective infiltration that may accompany drying soils. Extreme precipitation events (e.g. heavy rainfall and storms) may lead to less groundwater recharge because much of the precipitation is lost as runoff and evaporation. So, although the cumulative precipitation over the course of a year may be more than average, it is possible that the total amount of recharge to aquifers may be less than average due to the nature and timing of the rainfall being less conducive overall to recharge.

Evapotranspiration is not only affected by variations in temperature and precipitation, but also influenced by other factors such as the concentration of carbon dioxide. Higher levels of carbon dioxide in the atmosphere are expected

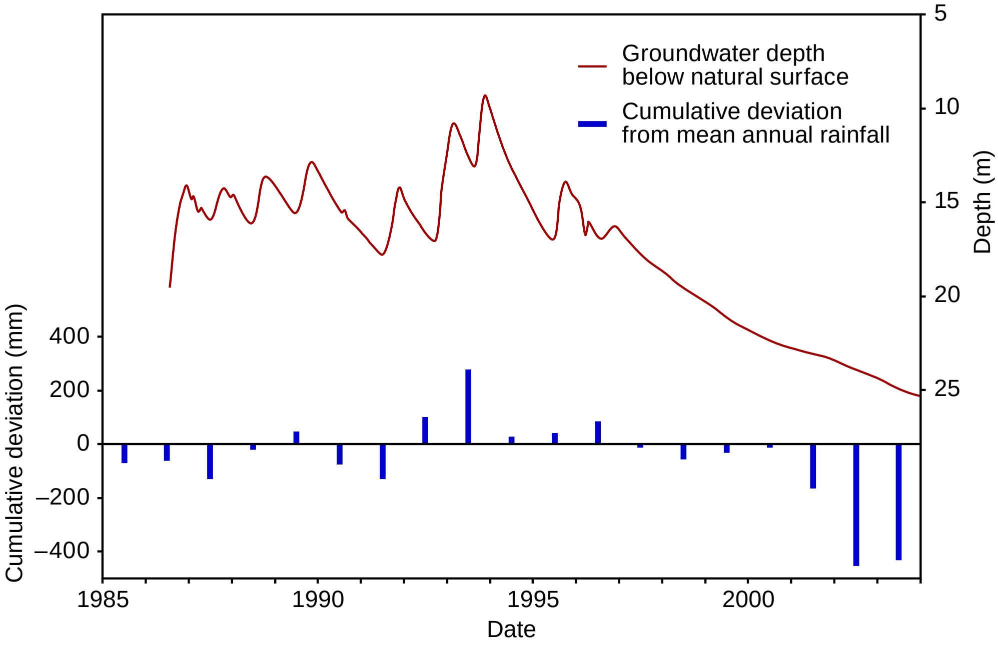


Figure 8.3. Hydrograph of groundwater levels in Bore 48 (Mt Camel Range, Victoria). Also shown is the cumulative deviation from mean annual rainfall 1950–2003 at Colbinabbin, northern Victoria (after Reid et al. 2006).

to improve the efficiency of photosynthesis in plants, which could in turn cause more rapid evapotranspiration.

8.2 Stream flow and water supply

Climate change also has a significant effect on stream flow and water supply in catchments. In areas where climate change causes reduced precipitation, stream flow and surface water storage will usually decrease in greater proportion than precipitation. In areas where greater precipitation is not matched by increased evaporation, more floods and higher lake and river levels will be experienced. Diminished snow accumulation in winter would reduce the spring runoff that can be vital to replenishing lakes and rivers; a 10% decline in precipitation coupled with a 1–2ºC rise in temperature could reduce runoff by 40–70% in drier basins (IUCC 1993).

Declines in stream flow and water storage have been observed in many parts of Australia over the last 50 years, particularly in recent years (Figure 8.4). This declining trend not only leads to water shortages in many catchments, but also results in increased utilisation of groundwater and falling water levels in aquifers. The implications of this are potentially very serious, particularly for highly connected groundwater–stream systems.

Assuming no significant increase in rainfall, rising air temperatures could lead to generally shallower surface water levels due to higher surface water temperatures and enhanced evaporation. They could also lead to lower groundwater levels near streams due to enhanced evapotranspiration.

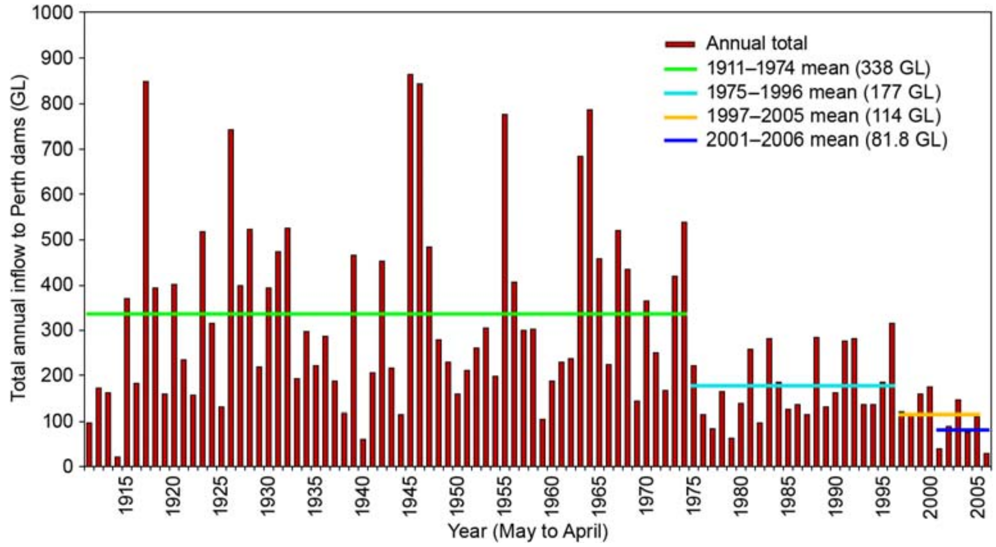


Figure 8.4. Annual streamflow into Perth's water supply dams. Note that the decrease in average inflow after 1974–75 is about 50% in response to a rainfall decrease of about 10–20% (depending on location). This has had to be compensated by increased withdrawal of groundwater (Water Corporation 2007). See also Pittock (2003).

8.3 Current research

In Australia, most research on the potential impacts of climate change to the hydrologic cycle has focused on forecasting the potential impacts to surface water (e.g. Chiew et al. 1998; Chiew and McMahon 2002; Power et al. 1998). Relatively little research has been undertaken to determine the sensitivity of aquifers to changes in the key climate change variables, namely, precipitation and temperature. Our understanding of climate change impacts on groundwater–stream interaction remains limited. Internationally, only a few studies have been reported in the literature on the impacts of climate change to groundwater (e.g. McLaren and Sudicky 1993; Rosenberg et al. 1999). There are two important factors that complicate and limit our understanding and ability to assess the impacts of climate change on groundwater:

- Timing of recharge. While surface water typically has a rapid response to climate variability, the response of groundwater systems is often difficult to detect or assess because the magnitude of the response is usually smaller and delayed. Evidence of longer-term variations in climate is often not well preserved in aquifers. Thus, the magnitude and timing of the impact of climate change on aquifers is generally difficult to recognize and quantify.
- Aquifer characteristics. Different types of aquifer respond differently to surface stresses. For example, shallow aquifers consisting of weathered, fractured bedrock or unconsolidated sediments are more responsive to stresses imposed at the ground surface compared to deeper aquifers. Consequently, shallow aquifers are quite sensitive to local climate variability (seasonal variation), whereas water levels in deeper aquifers are affected more by longer-term, regional scale variations or changes (decadal or greater).

9 Conceptual models

A *conceptual model* of a biophysical system is developed from the collation, synthesis and interpretation of available biophysical and resource management datasets. It summarises or encapsulates the current understanding of the key governing processes, factors and dependencies of the system, and how the system responds to variations in these.

Conceptual models are important as a first stage of predictive modelling in defining the dynamic framework, the boundary conditions, key parameters, assumptions, and predictive modelling approach. They can also form the foundation for further field studies. With supporting descriptions, they can be presented in a number of ways, including cross-sectional, block diagram or graphical form (e.g. Figure 9.1).

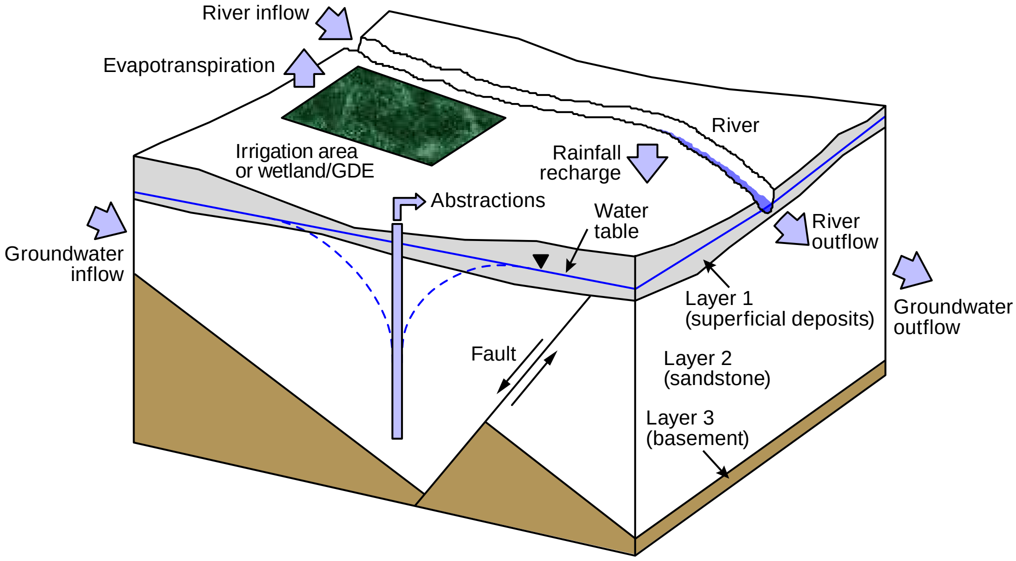


Figure 9.1. Example of a block diagram presentation of a conceptual model for a groundwater system that has hydraulic connection to a river (after Middlemis et al. 2001).

Given sufficient supporting data, conceptual models can be readily developed for groundwater–stream interaction and are an effective means of conveying the scale, function, interaction and behaviour of connected groundwater–stream systems.

Based on Brodie et al. (2007), the key elements of a groundwater–stream interaction conceptual model are:

1. Catchment framework: defining the study area boundaries in terms of groundwater and/or surface water divides.
2. Geological framework; the geological structure and composition of the area, as well as the geomorphology.
3. Hydrogeological framework: the distribution, configuration and properties of the aquifers and aquitards making up the catchment study area.

4. Surface water framework: the type and configuration of streams, together with associated floodplains and/or wetlands.

5. Hydrological framework: the key factors and processes defining the movement of water throughout the landscape, including rainfall, evapotranspiration, climate pattern, runoff, stream flow and groundwater flow.

6. Ecosystem framework: the key environmental assets that have a dependency on the study area's surface water and groundwater features, such as wetland ecosystems, endangered aquatic species or important vegetation communities.

7. Anthropogenic framework: the human-induced factors that can influence groundwater–stream interaction in terms of water quantity and quality, such as groundwater pumping, land clearing, intensive agriculture, drainage, flood mitigation works, stream diversion, mining, and so forth. Also includes the social dependencies of the connected water resource such as heritage and cultural values.

Conceptual models of groundwater–stream interaction need to describe the characteristics of the surface water and groundwater systems of an area or catchment, as well as their interactions or exchanges of water, both in time and space. Considerable complexity and variability are common in groundwater–stream systems. Therefore, in order to understand the relationships and processes with some confidence, the models are reliant upon a substantial amount of baseline information. Based on Brodie et al. (2007), this essentially includes:

1. Collation and interpretation of existing regional datasets that can be used to describe the physical attributes related to all the above seven framework elements of the conceptual model. As a first stage, catchment-wide datasets such as climate, topography, surface drainage, geology, geomorphology, geophysics, and land use need to be gathered and processed.

2. Collation and interpretation of existing monitoring data that can describe the variation in time and space of groundwater–stream systems. Key datasets are the available time series records of groundwater and stream levels, flow, quality parameters and groundwater extraction.

3. Identification of key information gaps and the initiation of specific studies to clarify key processes. A preliminary conceptual model based on the above two steps can be developed to assist this process.

A broad array of methods now exists to assess the connectivity and degree of interaction between streams and groundwater. Based partly on Brodie et al. (2007) and Turner (2006), the main types of assessment methods or tools are summarised below:

Field observations – field reconnaissance with the possible aid of aerial photography.

Seepage measurement – direct measurement at the interface using seepage meters and similar devices.

Ecological indicators – identifying or mapping specific vegetation or biota indicating groundwater discharge.

Geological mapping – defining the geological and geomorphological features and boundaries that control or influence groundwater flow.

Hydrogeological mapping – determining hydrogeological setting by overlaying information on groundwater conditions or parameters.

Geophysical or remote sensing survey – using geophysical or remote sensing technologies to map geological properties; these can be subdivided into ground, airborne, satellite and in-stream.

Hydrographic analysis – using various techniques to analyse the time series records of groundwater levels and stream flows (e.g. baseflow recession) to assess or measure connectivity and groundwater discharge to streams.

Hydrometric or flownet analysis – calculating seepage flows based on Darcy's Law (see chapter on 'Principles of Groundwater Flow') using estimations of hydraulic gradient from groundwater level and stream stage data, and estimations of hydraulic conductivity based on pumping tests or slug tests.

Hydrochemical studies – involves various techniques and a wide range of possible dissolved chemical constituents, such as isotopes and major ions, and using these as environmental tracers to determine the origin and movement of water.

Temperature studies – using time series temperature monitoring of both streams and groundwater to characterise seepage flux and the relative influence of groundwater and stream processes.

Artificial tracers – monitoring the movement in streams and bores of an introduced tracer such as fluorescent dye or an organic compound (e.g. ethanol).

Water budgets – estimating inputs and outputs of water (e.g. river reach water balance).

Geographic Information System (GIS) analysis – automated overlaying or mapping of spatial data sets from two or more of the above methods, sometimes incorporating a digital elevation model (DEM), to enhance interpretation of groundwater–stream interaction, especially over larger areas.

A baseline assessment using at least some of the above-listed methods or tools enables a conceptual model of groundwater–stream interaction to be developed. This model can be used to describe the function and behaviour of the connected groundwater–stream system, as well as the impact of existing developments on the stream (Brodie et al. 2007). Desired outcomes of the conceptualisation include:

- Portrayal of the nature, geometry and boundaries of the groundwater–stream system and the groundwater–stream interaction;
- Classification of stream–aquifer relationships and connectivity, and an indication of the actual or potential impacts of development on water quantity and quality (see next chapter).

Default data sets are another important basic requirement for modelling of groundwater–stream interaction. Such data sets are needed to check numerical model performance and validate against another model's performance. They typically comprise parameter values for land uses, stream reach characteristics, permeabilities, DEMs, groundwater flow systems, soils, climate, and so on. One of the other two reports in this current Project D3 series, Turner (2008), presents new approaches for generating default data sets, as well as techniques to up-scale and map them objectively over large regions at scales of relevance to water resources management. The new approaches described by Turner (2008) are spectral analysis, typology, and terrain analysis using high resolution GIS/DEM and frequency analysis.

Numerical modelling that is informed by the default data sets and conceptual model outcomes can then be applied to test the hydrogeological understanding and ultimately enhance this by identifying weaknesses, strengths and critical factors in the model (Rassam and Werner 2008). Further field assessment methods may be required in order to revise the conceptual model. Once the conceptual model is sufficiently improved and the numerical model is validated against this, the numerical model can then be used to quantify the seepage fluxes and water balance, and predict their change with time using different resource management, climate or catchment condition scenarios.

10 Groundwater–stream interaction classification

The main focus of this catalogue is on aquifer-scale stream interaction processes, particularly in the context of the impacts of groundwater pumping on water quantity. Therefore, an aquifer system approach incorporating clear groundwater–stream connectivity attributes is outlined here as the basis for a proposed classification framework for groundwater–stream interaction to assist water resource managers (see also Chapter 1). The proposed framework is primarily derived from the outcomes of two Project D3 workshops conducted during 2006.

10.1 Types of aquifer system

The starting point of the proposed classification framework is a broad aquifer system classification based on coarse geological/physiographic groups. The types of aquifer system are defined in Table 10.1.

Table 10.1. Broad types of aquifer system to assist classification and conceptualisation of groundwater–stream systems. This could be further sub-divided if required based on specific geology.

Aquifer system	Explanation
1. Fractured rock systems	Consolidated, fractured bedrock systems, including karst systems (e.g. limestone) and deeply weathered bedrock
2. Layered or complex systems	Layered, multiple or geologically complex systems, including volcanic systems
3. Contained alluvial valley systems	Relatively narrow, bounded alluvial valley systems, including palaeochannels
4. Regional systems	Large scale systems with deep flow

10.2 Stream–aquifer relationship and connectivity

A simple ‘gaining/losing stream’ philosophy has been used as the basis to develop a framework for the stream–aquifer relationship, hydraulic conductance and pumping impact (Table 10.2). The framework divides stream–aquifer relationships into several categories that can be applied to small and large scales and different timeframes.

The hydraulic conductance between the stream and the aquifer is directly proportional to the hydraulic transmitting potential (or transmissivity) of the connected aquifer and also, in the case of a semi-confined aquifer (i.e. leaky aquifer; see Glossary), any geologic materials separating the stream from the aquifer. Both the degree and timeframes of pumping impact on streams are primarily dependent on the hydraulic conductance, size (and complexity) of the aquifer system, volume of pumping and distance of pumping from the stream (Braaten and Gates 2004; Brodie et al. 2007). Other factors influencing pumping impacts include floodplain evapotranspiration, stream disconnection (i.e. where the stream is separated from the watertable by an unsaturated zone; Section 4.4), and flow to other groundwater systems or aquifers that are not hydraulically connected to streams (Evans 2007). However, the major long-term determinant on the degree of pumping impact on stream flow is the total volume of groundwater abstracted (Jenkins 1968; REM 2006; Winter et al. 1998).

Braaten and Gates (2004) concluded that classification of stream–aquifer systems for management must (also) take into account whether the connected aquifer is unconfined or semi-confined, wide or narrow, whether the stream is regulated or not, and whether it flows reliably or intermittently.

Table 10.2. Framework for defining the stream–aquifer relationship, connectivity and pumping impact. This is partially based on Brodie et al. (2007), REM (2005, 2006) and Winter et al. (1998). In all cases below, the aquifer is unconfined or semi-confined.

Relationship of stream to aquifer or groundwater system	Hydraulic conductance between stream and aquifer (directly proportional to transmissivity of aquifer and any materials separating stream and aquifer)	Long-term impact of pumping on stream flow (dependent mainly on hydraulic conductance, size of aquifer, volume of pumping and distance of pumping from stream)
Gaining (stream receives water from aquifer system)	High, medium and low. Simple relationship for unconfined but, for semi-confined, is also dependent on transmissivity of materials between stream and aquifer	High (> 15%), medium (5–15%), low (< 5%), very low (< 1%)
Losing: saturated connection (stream contributes water directly to aquifer system via saturated connection)	High, medium and low. Relationships as above	High (> 15%), medium (5–15%), low (< 5%), very low (< 1%)
Losing: unsaturated connection (stream contributes water to aquifer system but is separated from aquifer by unsaturated zone)	Not strictly applicable, although infiltration capacity of unsaturated zone (high, medium or low) will govern recharge from stream	No direct impact on stream but may impact degree of hydraulic separation and, possibly, the recharge from stream to aquifer
Variably gaining and losing a. spatially b. temporally	High, medium and low. Relationships as above	High (> 15%), medium (5–15%), low (< 5%), very low (< 1%). No direct impact where stream is losing via unsaturated connection

10.3 Classification framework and its use

Based mainly upon the outcomes of two workshops held during 2006, the following list gives the types of characteristics, or defining features, that have been selected to help classify and distinguish stream–aquifer systems for the conceptualisation of groundwater–stream interaction (see Table 10.3).

A. Aquifer system (refer to Table 10.1).
B. Aquifer scale (local, intermediate or regional scale based on maximum flow path length – Walker et al. (2003)).
C. Aquifer width (narrow (<5 km), broad or variable)
D. Recharge (process/location).
E. Discharge (process/destination).
F. Floodplain (narrow/incised, broad, terraced, variable).
G. Stream flow (regulated, unregulated, mostly reliable, variable, intermittent – based on Braaten and Gates (2004)).
H. Stream–aquifer relationship (refer to Table 10.2).
I. Aquifer connectivity or confinement status (refer to Table 10.2).
J. Hydraulic conductance (refer to Table 10.2).
K. Long-term pumping impact on stream flow (refer to Table 10.2).

In the above list, items A to E relate to the aquifer system, F and G relate to the floodplain and stream, and H to K cover the interaction of the stream and aquifer system. Using this list and Tables 10.1 and 10.2, Table 10.3 sets out a proposed classification framework for describing the main attributes to help conceptualise stream–aquifer systems. The template is not a relational table but simply reads from left to right with a choice of attributes to select against the eleven types of characteristic (A to K) in the left hand column.

When using Table 10.3 to classify or characterise a study area, boxes can be highlighted to identify applicable attributes based upon expert interpretation of the available information. There are some rows where only one attribute will be applicable but other rows where more than one attribute could be applicable. Examples of the latter case are: D (Recharge), E (Discharge), G (Stream flow), and I (Aquifer connectivity or confinement status).

In some large stream–aquifer systems with complex or deep groundwater flow, all three listed attributes for I (Aquifer connectivity or confinement status) – unconfined, semi-confined and confined – could be applicable, as the hydraulic connectivity status of different aquifers, particularly deeper ones, can vary. The hydraulic conductance will also vary, becoming lower with increasing degree of confinement (i.e. increasing thickness and/or decreasing permeability of material separating the aquifer from the stream).

Stream–aquifer relationships will vary to some degree in most systems, so classification of the relationship for a study area should consider the dominant relationship over time and space. The variably gaining and losing option should only be chosen when it is clear that there is significant variation in the flux direction over time and/or space.

When interpreting whether or not the throughflow/interflow attribute applies to D (Recharge) or E (Discharge), it is important to consider the whole study area or main aquifer system as it relates to the areas outside it or other aquifers. The attribute will apply if (i) the area comprises an open system whereby significant groundwater flow enters it from outside (recharge), or significant groundwater flow exits the area (discharge), and (ii) an adjacent aquifer within

Table 10.3. Proposed classification framework template to aid characterisation and conceptualisation of stream–aquifer systems and groundwater–stream interaction at aquifer or catchment scale. This template has been used to classify groundwater–stream interaction in each case study area in the catalogue.

Type of characteristic	**Attribute**				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping/ subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

the study area supplies (recharge) or receives (discharge) significant groundwater flow to/from the main stream–aquifer system.

As explained in Table 10.2, the hydraulic conductance (J in Table 10.3) is not strictly applicable in the case of a losing stream with unsaturated connection. Therefore, in such a case, ‘high’, ‘medium’ or ‘low’ can be highlighted in the classification table together with the ‘unsaturated connection’ attribute. This will then instead indicate that the unsaturated zone has a high, medium or low infiltration capacity.

Although Table 10.3 is essentially a qualitative information table, the ability to fill it out completely and confidently may still be hampered by insufficient available knowledge. Inevitably, some selected attributes will have a degree of professional judgement or subjectivity attached to them in the absence of adequate data. Where this applies, it is recommended to indicate it, with qualifications supplied where appropriate. In addition, it is recommended one gives an overall confidence rating to any completed classification, as well as highlighting key knowledge deficiencies.

The classification table is intended as a simple tool to assist conceptualisation of groundwater–stream interaction at aquifer or catchment scales and aid development of conjunctive water resource management strategies. It is not a tool to be used on its own to inform management decisions and is not designed to be used at stream reach, or smaller, scales. The table can be used initially to gauge the extent of conceptual knowledge of a stream–aquifer system (and identify knowledge gaps), and provide a sense of the groundwater–stream interaction issues and management implications. It could also be used in combination with other information to periodically provide updated overviews of the stream–aquifer system knowledge.

Descriptions of 10 case studies of connected groundwater–stream systems in eastern Australia follow this chapter. Included are two case studies on fractured rock systems, two case studies on layered or complex systems, three on contained alluvial valley systems, and three on regional systems. Most of the case studies relate to streams that are impacted in some way by groundwater pumping. Several relate to other land management influences, including salinity impacts. Each case study includes a description of some of the physical characteristics of the area, the groundwater–stream interaction, impacts of groundwater pumping or other development, and management status.

The Table 10.3 classification template has been used to conveniently summarise the interpreted groundwater–stream interaction characteristics of each case study area (Tables CS1.2, CS2.3, CS3.2, CS4.2, CS5.2, CS6.2, CS7.2, CS8.2, CS9.4 and CS10.2). Highlighted boxes identify the applicable attributes against each type of characteristic in the case study area based on expert interpretation of the available knowledge. The derived classification tables are included at the end of each case study description together with a classification confidence rating of high, medium or low.

Table 10.4 provides an idea of the wide variation in groundwater–stream interaction characteristics across eastern Australian landscapes by using the collective classification results of all 10 case studies. All 10 case study attributes have been mapped into the Table 10.3 template using the relevant case study number in the appendix.

Table 10.4 shows that the case studies presented in the catalogue cover the defined broad aquifer types and most attributes quite well. However, the case studies only make up a small proportion of the full range of possible combinations of characteristics. Contained alluvial valley and regional alluvial systems probably have the best groundwater–stream interaction knowledge bases, as they are the most common sources of high yielding, good quality groundwater.

Table 10.4. Proposed groundwater–stream interaction classification framework into which all 10 case study classifications have been mapped. 1 = Case study 1 (Scott Creek); 2 = Case study 2 (Yass Valley), etc.. For individual classifications, refer to the table at the end of each case study in the appendix (Tables CS1.2, CS2.3, CS3.2, CS4.2, CS5.2, CS6.2, CS7.2, CS8.2, CS9.4 and CS10.2).

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
	1,2	3,4	5,6,7	8,9,10	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
	1	2,4,5	3,6,7,8,9,10		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
	1,7	2,3,4,8,9,10	5,6		
D. Recharge	Rainfall	Stream	Riverine/flood	Throughflow/ interflow	Artificial (including irrigation returns)
	1,2,3,4,5,6,7,9, 10	1,5,6,8,9,10	5,6,8,9,10	2,3,4,6,7,8, 10	5,6,7,8,9,10
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
	1,2,3,4,5,6,7,8	1,2,3,5,6,8	5	1,2,3,4,6,7, 8,9,10	1,2,3,4,5,6,7,9
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
	1,2,3,4,7	8,9,10	7,8	5,6	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
	6,8,9	1,2,3,4,5,6,7,10	3,6,7,8,9	1,2,5,10	4
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
	3,4,7	9	10	1,2,5,6,8	
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
	1,2,3,4,5,6,7,8, 9,10	2,3,4,6,8,9,10	6,9,10		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
	3,5,6,7	1,4,6,7,8,9	2,9,10	10	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact
	1,3,4,5,6,7	2	8,9		10

Case study 1: Scott Creek, SA (fractured rock system)

CS1 Location

The Scott Creek Catchment (SCC) is a relatively small (27 km^2) sub-catchment of the Onkaparinga River Catchment in the Mount Lofty Ranges, South Australia and is located approximately 30 km south-east of Adelaide (Figure CS1.1). Scott Creek is a perennial stream and a tributary of the Onkaparinga River in the Mount Lofty Ranges (MLR). Approximately 60–70% of metropolitan Adelaide's water supply is sourced from the MLR. The groundwater and surface water resources in the MLR are now prescribed and are under a moratorium of further development until the water allocation plan (WAP) has been completed.

CS1 Climate, physiography and hydrology

The SCC is characterised by a temperate climate, experiencing warm dry summers and wet cool winters. Average daily temperatures range from 8–14°C in winter to 14–27°C in summer. Mean annual evaporation is 1555 mm/year and mean annual rainfall ranges from 804 mm/year at the bottom of the catchment to 1009 mm/year in the upper reaches of the catchment (Bureau of Meteorology 2006). Most of the rainfall occurs in winter and spring (May to October).

The topography of SCC varies from steep slopes to gently undulating land. The main channel of Scott Creek runs in a north–south direction and the steeply sloped valleys are dissected by minor tributaries of Scott Creek. Land use is dominated by native vegetation (~50%) and pasture for grazing stock (~45%).

There are two gauging stations in the SCC; one at Scott Bottom and one at Mackreath Creek, a minor tributary to the main watercourse (Figure CS1.1). The mean annual streamflow of Scott Creek measured at Scott Bottom is approximately 3,710 ML/year (James-Smith and Harrington 2002). Low flows occur during November through to May. Due to increased rainfall from May to October, high flows usually occur during this period with maximum flow usually observed around August. Baseflow is dominant during the summer months with very few recorded occasions when flow has ceased during the last 36 years. This suggests that groundwater discharge to the creek is extremely important for maintaining flows and supporting the groundwater-dependent ecosystems, particularly during drier months of the year.

CS1 Geological setting

The Mount Lofty Ranges form the central portion of the Adelaide Geosyncline and encompass a suite of meta-sedimentary and igneous rocks that range in age from Palaeoproterozoic (>1600 Ma) through to Permian (250-300 Ma) (Drexel and Preiss 1993; 1995). The SCC is characterised by steep relief with a thin regolith zone underlain by fractured bedrock, which is exposed at the surface in some areas. The geology is structurally complex, with a diverse range of metamorphosed sedimentary formations including siltstone, sandstone and dolomite (Figure CS1.2). A schematic east–west geological cross section at the bottom end of the SCC is shown in Figure CS1.3. The quartzite and sandstone are relatively resistant to weathering compared with dolomite and siltstone, and thus form the elevated ridge tops of the catchment. The valleys and depressions in the landscape are made up of regolith material (James-Smith and Harrington 2002).

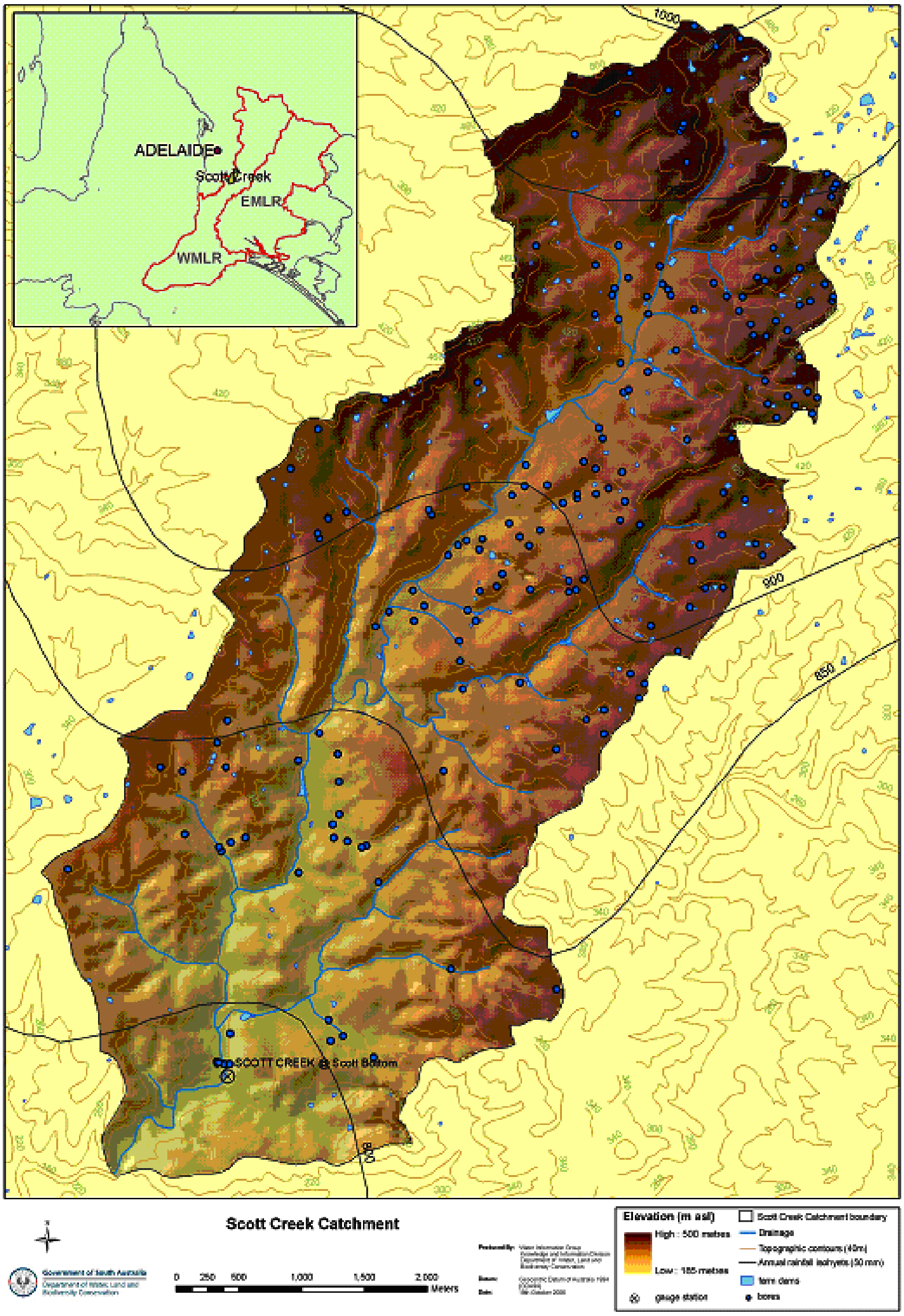


Figure CS1.1. Plan of Scott Creek Catchment showing location, physiography, drainage and rainfall.

The regolith on the hill slopes and in the valley bottom of SCC are considered to be highly spatially variable, both in depth and degree of weathering, as observed at nearby outcrops. The thickness of this regolith ranges from tens of centimetres to greater than 20 metres. Preferential weathering processes are thought to occur in highly fractured zones or in areas exposed to increased chemical or physical weathering. Chittleborough (1992) discusses the potential origin and processes controlling the generation of these soils. Detailed soil studies by Smettem et al. (1991) and Leaney et al. (1993) describe the runoff processes and conclude that horizontal flows are initiated above the B–C horizon boundary rather than the A–B horizon boundary once infiltration of the macropore system has occurred.

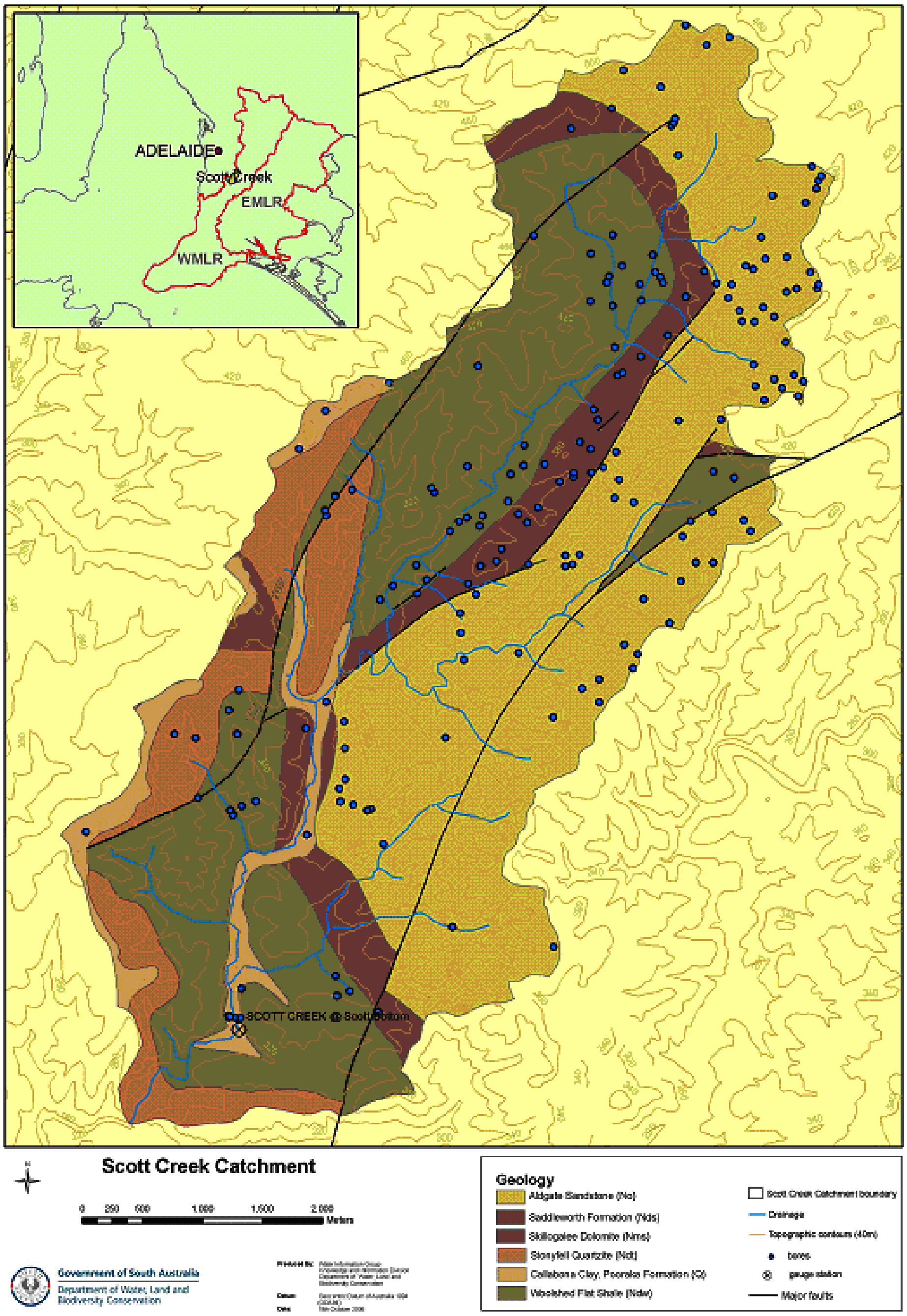


Figure CS1.2. Geology and distribution of wells in Scott Creek Catchment.

CS1 Hydrogeology

The dominant aquifer systems in the MLR are fractured rock aquifers. In the SCC there are approximately 150 bores. While some of these are completed in the shallow alluvial aquifers, the majority are located in the fractured metasediments due to higher yields and quality. These include the Aldgate Sandstone, Skillogalee Dolomite, Woolshed Flat Shale and Stonyfell Quartzite (Figure CS1.2). The Woolshed Flat Shale dominates the area around Scott Bottom. The eastern side of the catchment is predominantly Aldgate Sandstone and, to a lesser degree, Skillogalee Dolomite. The higher topography on the western side is Stonyfell Quartzite (James-Smith and Harrington 2002). Both regional and local groundwater flows are believed to follow a subdued form of the topography discharging along stream reaches. Actual hydraulic conductivity values of the fractured rock vary by many orders of magnitude depending on the aperture, spacing and connectivity of dominant fractures and the geology type.

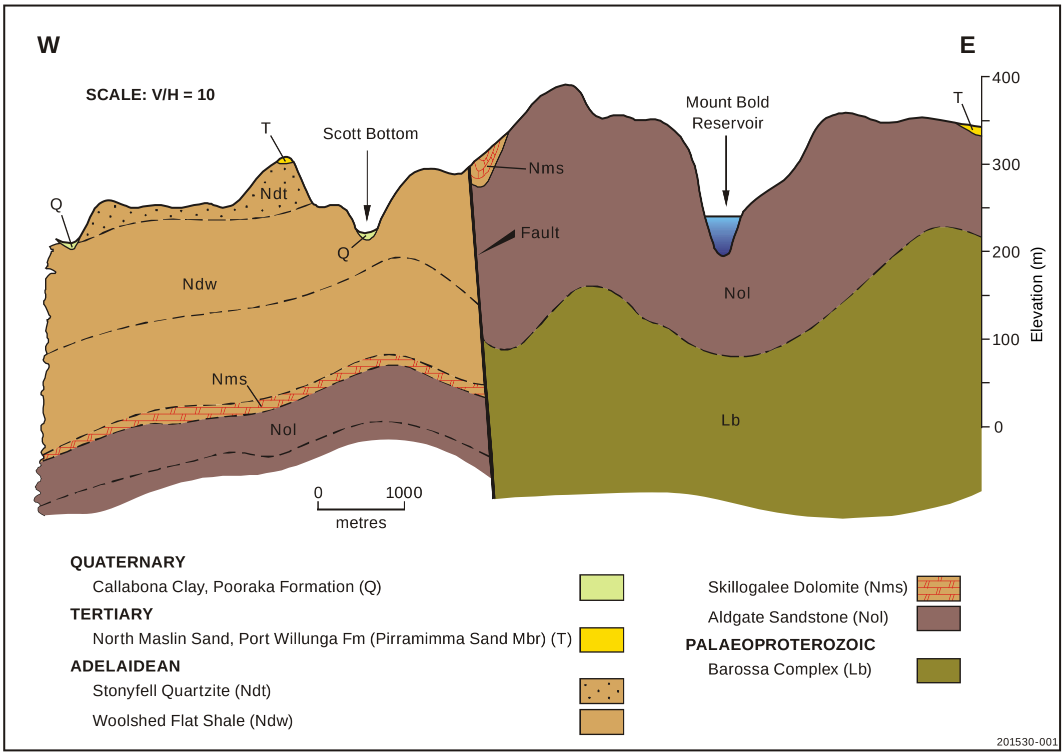


Figure CS1.3. Schematic geological east–west cross section at Scott Bottom, Scott Creek Catchment (after James-Smith and Harrington 2002).

CS1 Groundwater–stream interaction

Groundwater–surface water interactions in SCC and the greater MLR play an important role in catchment-scale water and/or salt balances. Studies by Harrington and Love (2000) and Love et al. (2002) in the Clare Valley have shown that groundwater discharge to streams is an important mechanism for removing salt from the catchments. It is also a significant component of the water balance, particularly during the summer months when rainfall is low. Conversely, many of the ephemeral creeks throughout the MLR may be a source of groundwater recharge during times of high flow. A reduction in surface runoff to streams and hence, a potential reduction in groundwater recharge, has been attributed to the construction of farm dams. McMurray (2001) determined that approximately 5% of modelled surface runoff is being captured by farm dams in the SCC. In other regions of the MLR, farm dam development has exceeded the capacity of the catchment and significantly reduced surface runoff to streams.

Groundwater flow in fractured rock aquifers is potentially rapid. However, the degree of connection between the aquifers and the stream, and the contribution of groundwater to streamflow generation is poorly understood. Figure CS1.4 shows a conceptual model of groundwater–surface water interactions in a fractured rock environment typical of the MLR. Recent studies at the Scott Creek site at Scott Bottom (Harrington 2004b; Cranswick 2005) have suggested that the source of groundwater discharging to the stream is derived from the shallow, rapid interflow as opposed to deeper groundwater from the fractured rock aquifer. According to Harrington (2004b), two thirds of the potential recharge flux is lost to the stream via interflow. Cranswick (2005) reported that active recharge is occurring at the site and the vertical extent of the young groundwater (<50 years) is approximately 20 metres in depth. Lateral groundwater flow is extremely variable and controlled by the hydraulic properties of the regolith zone material. Hydraulic and hydrochemical data indicate that both recharge and discharge are occurring near the stream and that there is significant vertical circulation of young water, which decreases upslope corresponding to the regolith zone thickness. Figure CS1.5 shows an integrated conceptual model of the Scott Creek field site at Scott Bottom.

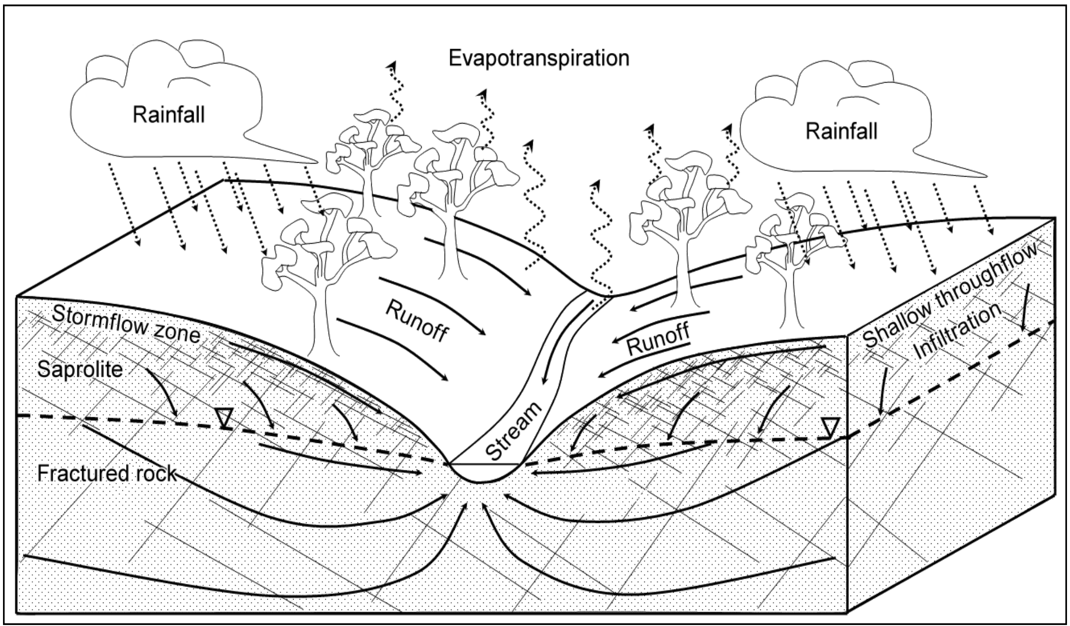


Figure CS1.4. Conceptual model of a fractured rock system. Interactions occur via soil stormflow, saprolite and fractured rock zones, common flow paths, runoff, shallow throughflow, infiltration and baseflow.

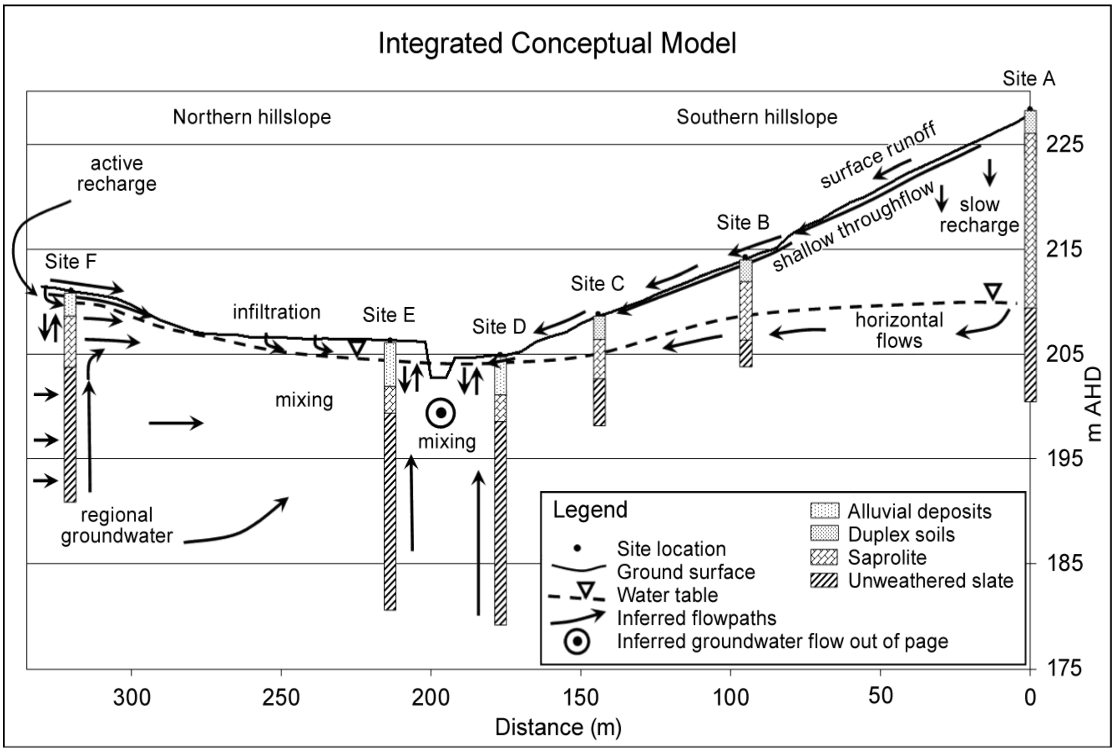


Figure CS1.5. Integrated conceptual model of the Scott Creek field site (Cranswick 2005). Inferred flowpaths are shown, with surface runoff and shallow throughflow occurring above and in the soil horizons; horizontal and vertical flows occur within the saprolite and fractured rock.

CS1 Groundwater development and impact on streams

At present there is a poor understanding of the amounts and distribution of water usage throughout the SCC, as the water resources in the MLR have only recently been prescribed. The most common use of groundwater and surface water in the SCC is for stock and domestic purposes, and to some extent for irrigated horticulture, although irrigation volumes are more significant than those for stock and domestic uses. Scott Creek, like many of the other watercourses in the MLR, also contributes to the major water supplies for metropolitan Adelaide and regional towns, and supports groundwater-dependent ecosystems (GDEs).

The impacts of pumping on groundwater and surface water resources are relatively unknown in the MLR fractured rock environment. However, an investigation by Harrington (2004b) concluded that the most suitable groundwater resource in the SCC appears to be that which is stored in the deeper soils and weathered bedrock. Whilst this resource is usually replenished on an annual basis, more than two thirds of the total recharge flux is lost to the streams via interflow. Accordingly, future groundwater development in the catchment should be managed in such a way that it does not reduce groundwater contributions to the stream, particularly in those areas identified as having significant groundwater inputs.

CS1 Management intervention and status

Prescription of the water resources in the MLR under the *Natural Resources Management Act 2004* has been issued to mitigate increasing development of the resources and ensure secure access for all water users including primary producers, industries, rural townships and the environment (GDEs). Under prescription, all users of the prescribed water resource will be required to have a licence, which specifies a water allocation. The only exemption from the licensing requirements is stock and domestic use.

Department of Water, Land and Biodiversity Conservation (DWLBC) is currently undertaking technical investigations to determine the capacity of the groundwater and surface water resources, estimates of groundwater recharge, zones of influence in fractured rock aquifers and groundwater–surface water interactions. The technical investigations will contribute to the development of the WAP for both the eastern and western Mount Lofty Ranges. The WAP for the western MLR, which includes SCC, is being developed by the Adelaide and Mount Lofty Ranges Natural Resource Management Board (AMLRNRM Board) and DWLBC in consultation with the community and is due for completion by 2008. The WAP for the eastern MLR has a similar deadline.

As part of ongoing research on groundwater–surface water interactions in fractured rock aquifers, DWLBC has installed a detailed investigation site at Scott Bottom to further advance the hydrogeological investigations by James-Smith and Harrington (2002) and Harrington (2004a; 2004b). The site includes the existing stream gauging station, pluviometer, 4 nested tensiometers, 8 deep observation bores into the fractured rock up to 96 metres deep, and a perpendicular stream transect of six sets of multi-depth piezometers on two opposing hillslopes. Piezometer depths range from 1.5 to 28.5 m with a number of screened intervals in the unweathered bedrock, saprolite, and soil horizons at each site (Figure CS1.5). This research together with a research program by Flinders University will provide a better understanding of the role of groundwater in streamflow generation, potential pathways, processes and residence times of subsurface flow during different hydrological events. Table CS1.1 summarises the data sets obtained to date.

CS1 Data

Table CS1.1 summarises the accumulated data sets and data collection methods for conceptualisation of groundwater–stream interaction in the case study area.

Table CS1.1. Accumulated data sets and applied field and data collection methods in the Scott Creek Catchment.

Data sets	Period of data record	Field or data collection methods
Stream flow at Scott Bottom	1969–present	Instantaneous
Rainfall at Scott Bottom	1991–present	Daily total
EC at Scott Bottom	1972–present	Instantaneous
Stream flow at Mackreath Creek	2001–present	Instantaneous
Rainfall and pan evaporation at Mt Bold Reservoir	1938–present	Daily total
Drillhole database for bores in SCC		SAGeodata
Hydrochemistry of stream, shallow piezometers and regional bores	2004–present	Field sampling
DEM 25 m grid		Desktop

CS1 Groundwater–stream interaction classification

Table CS1.2. Classification of Scott Creek using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to Scott Creek for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as medium.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow /interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow /interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Case study 2: Yass Valley, NSW (fractured rock system)

CS2 Location

The Yass Valley is located in the southern tablelands of NSW (Figure CS2.1). The Yass River flows north-west from the Australian Capital Territory border until it enters the backwaters of the Burrinjuck Dam. Its catchment area covers 159,000 hectares.

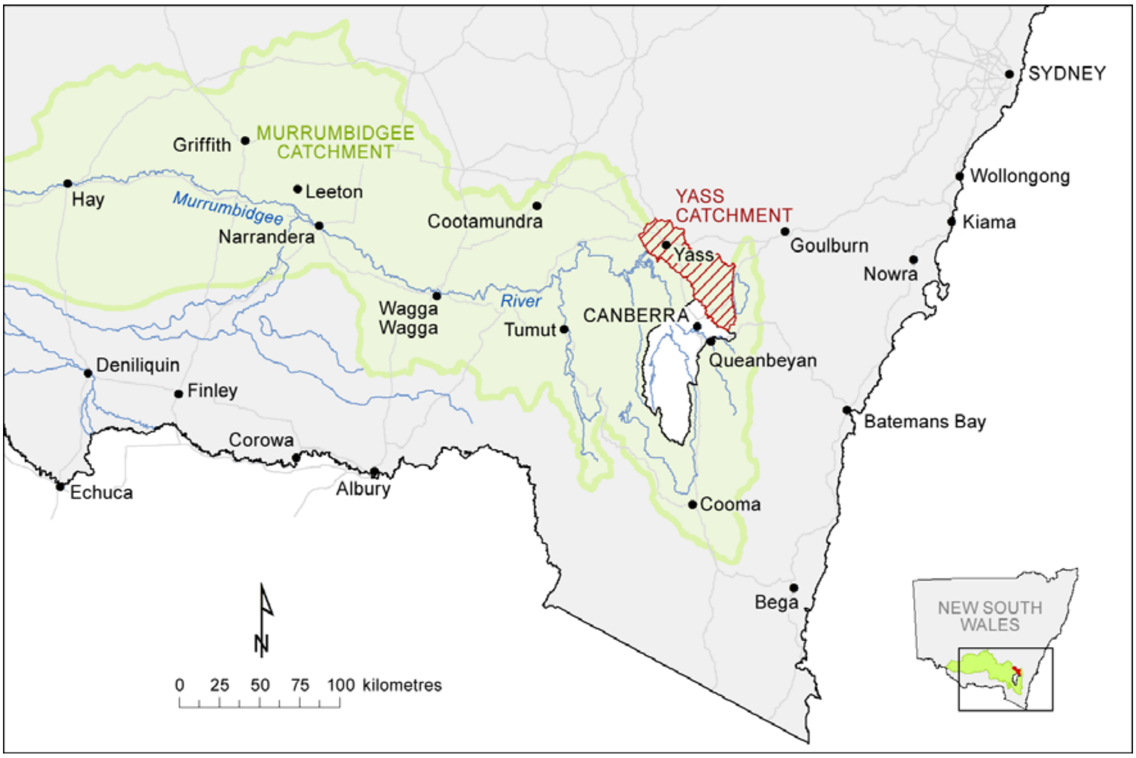


Figure CS2.1. Map of Yass River catchment location (prepared by the Spatial Products and Services Unit, Department of Water and Energy, Queanbeyan).

CS2 Climate and land use

The area has a Mediterranean climate with an average annual rainfall of 648 mm. Mid-winter to mid-spring is the period with the highest average monthly rainfalls, and monthly rainfall usually exceeds pan evaporation in June and July. The average daily temperature ranges from 13°C to 27°C in summer and 1°C to 13°C in winter.

Land use in the Yass catchment has changed considerably over recent years. Department of Land and Water Conservation (DLWC) published a detailed land use study and mapping program in 2000 (Scown 2001). This report was based on aerial photography from the 1997/98 period and so provides a recent picture of land use across the catchment. The land use is summarised in Table CS2.1.

Table CS2.1. Yass Catchment land use (after Scown 2001).

Total estimated area cropped	= 5,127 ha or 3% of the catchment area
Total estimated area grazed	= 124,679 ha or 78% of the catchment area
Total estimated area irrigated	= 642 ha or 0.4% of the catchment area
Total area of native trees	= 27,012 ha or 17% of the catchment area
Total area of pine plantations	= 741 ha or 0.5% of the catchment area
Total number of dams	= 7,153 (estimated total storage of dams = 20,682 ML)
Proportion of cleared riparian zone	= 72%

CS2 Geological setting

The Yass Valley is dominated by metamorphosed sediments and acid volcanics of the Lachlan Fold Belt. The mid- to upper-catchment area comprises mainly early to mid-Palaeozoic metasediments (interbedded sandstone, siltstone, shale and minor black shale chert) with isolated granite and granodiorite. The lower catchment area mainly comprises Silurian and Devonian acid volcanics (Figure CS2.2). These consist of fine to coarse, rhyolitic to dacite crystal tuff, andesite, dacite, and rhyolite (Cramsie et al. 1975).

The bedding and cleavage of the metasediments have a general north to north-east strike with dips generally being greater than 50 degrees (Abell 1992). There are a number of north–south striking faults, with the major faults being the Queanbeyan and Sullivans Line Faults.

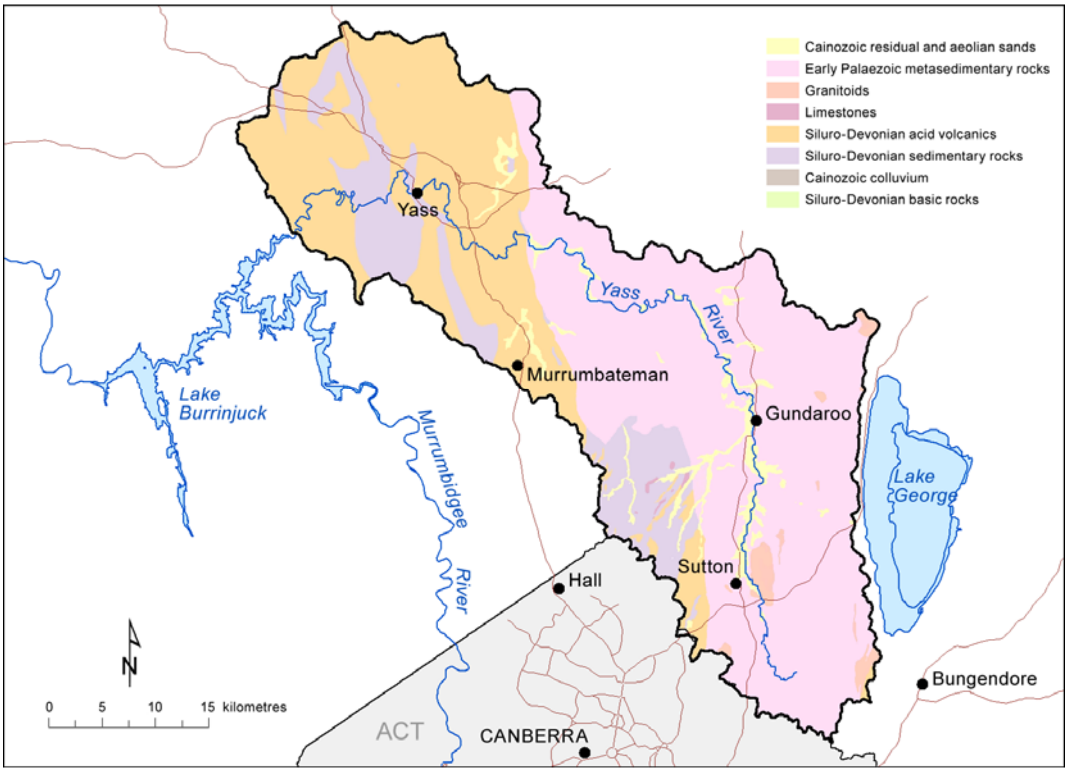


Figure CS2.2. Geology of the Yass Catchment (prepared by the Spatial Products and Services Unit, Department of Water and Energy, Queanbeyan; after Brown and Stephenson 1991).

CS2 Hydrogeology

Fractured rock aquifer systems, particularly in the metasediments and volcanics, provide the main groundwater resources in the catchment. There are small aquifers in shallow, Quaternary alluvial deposits associated with the Yass River and some minor tributaries. However, they are generally not of sufficient thickness to enable supply of usable amounts of water for human or commercial consumption.

In the elevated areas, the shallow watertable aquifer has a higher head than the deeper groundwater in the fractured rocks. However, in the lower valley slopes, the deeper groundwater has a higher head (Turner et al. 1992). Consequently, springs can occur on the lower slopes where either the deeper groundwater under pressure finds a pathway to the surface, or where shallow lateral flow emerges with a sudden shallowing of the topographic gradient.

Turner et al. (1992) found that there were similar isotopic and major ion compositions in the deep fractured rock aquifers in adjacent sub-catchments. It is therefore possible that discharge from these aquifers does not necessarily result from recharge in the same sub-catchment and that they may behave as intermediate to regional scale aquifer systems.

CS2 Groundwater–stream interaction

Turner et al. (1992) identified that neither shallow nor deep groundwater formed a substantial component of the stream flow during rainfall-runoff events in the Williams Creek sub-catchment, located in the upper eastern area of the Yass catchment. However, further analysis is required to identify if the Williams Creek sub-catchment processes are in any way representative of the broader Yass catchment. The Yass River may be reliant on some springs at the top of the catchment and groundwater baseflow during periods of low flow.

In recent years, the effects of the prevailing dry climate, combined with the increased use of stock and domestic bores and dams, have caused reductions in groundwater levels in the fractured rock aquifers, leading to smaller spring flows.

The stream–groundwater relationships along the Yass River are presently not well understood. There is uncertainty regarding which reaches of the river are losing and gaining. In the reaches that are known to be gaining, it is uncertain what proportion of subsurface flow can be attributed to lateral flow, or flow from the fractured rock aquifer system.

CS2 Groundwater development and impact on streams

The Yass River supplies the urban water requirements for the township of Yass and surrounding villages of Bowning and Binalong. Growth in Yass and surrounding areas has placed increasing pressure on the Yass water supply. Accentuated by dry climate conditions, this has resulted in the imposition of severe water restrictions on local residents in four of the last six years.

An embargo on the issuing of new surface water irrigation licences in the Murray–Darling Basin has resulted in a proliferation of groundwater licences. This dramatic increase in groundwater use is exemplified in the Yass Valley

(Figure CS2.3). The graph in Figure CS2.3 shows the number of bore licences issued per year, both for stock/domestic and irrigation bores. It also shows the cumulative increase in the allocation of groundwater associated with these bores (Franklin and Parker 2004).

There is a variety of consumptive uses of groundwater in the Yass Valley. Uses include viticulture, rural residential development, domestic and stock, and pasture.

Groundwater in the Yass catchment is predominantly used for rural residential purposes. Increased use of groundwater for rural residential development in recent years has resulted in significant localised areas of extraction where the sustainable groundwater yield is exceeded. The effect of this on the Yass River stream flow has not been quantified.

The large numbers of private dams now existing in the catchment may significantly restrict surface runoff to the Yass River. However, this is yet to be scientifically validated.

The Yass River was evaluated against a range of environmental thresholds in the 'Stressed Rivers Assessment Report' (DLWC 1998) and concluded to be in the 'heavily stressed' category.

CS2 Management status

The Yass Valley groundwater management area is one of a number of fractured rock groundwater sources in NSW. It forms part of a macro water-sharing plan currently being developed in NSW as part of the implementation of the Water Management Act 2000. The planning process for Yass Valley has included the assessment of the current level of development, level of allocation, and the sustainable yield of the management area. When completed, the Yass Valley water management plan will aim to ensure the sustainable management of the resource for licence holders and the environment.

CS2 Data

Table CS2.2. Summary of available data sets and data collection methods in the Yass Valley.

Data sets	Period of data record	Field or data collection methods
Yass snapshot on sustainability (Franklin and Parker 2004)	1949–2003	Desktop
Stressed rivers assessment report (DLWC 1998)	Uncertain	Desktop
Yass catchment: an integrated project to assess land use and catchment condition in the Murrumbidgee Catchment (Scown 2001)	Uncertain	Desktop
Stream flow	Early 1900s to present	Stream gauges
Groundwater levels	2000 to present (approximately)	Field measurements
Water licences (surface and groundwater)	1912 to present	Dept of Natural Resources Licence Administration System

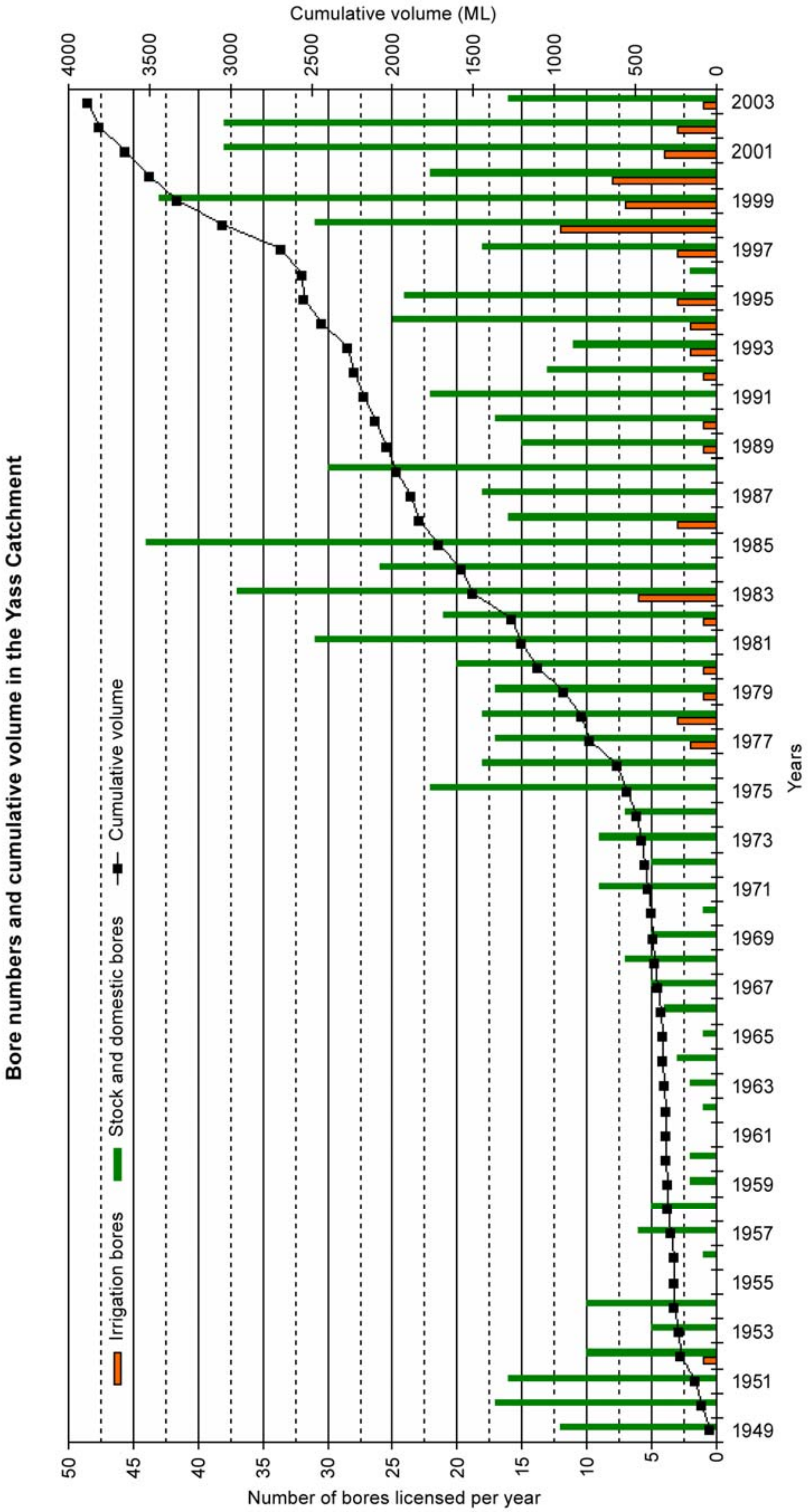


Figure CS2.3. Summary of bore installation and estimated cumulative groundwater extraction in the Yass Catchment (after Franklin and Parker 2004).

CS2 Groundwater–stream interaction classification

Table CS2.3. Classification of Yass Valley using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to Yass Valley for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as low.

Type of characteristic	**Attribute**				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Case study 3: Upper Nepean, NSW (layered or complex system)

CS3 Location

The Upper Nepean River catchment is located to the south-west of Sydney and includes the Dudewaugh Creek and Stockyard Swamp sub-catchment in the eastern resource area. The study area forms part of the Groundwater Management Area for the Wollondilly–Nepean Aquifers. Figure CS3.1 shows the location of the study area. The area has been extensively studied in recent years and interested readers should refer to the list of references at the end of this case study.

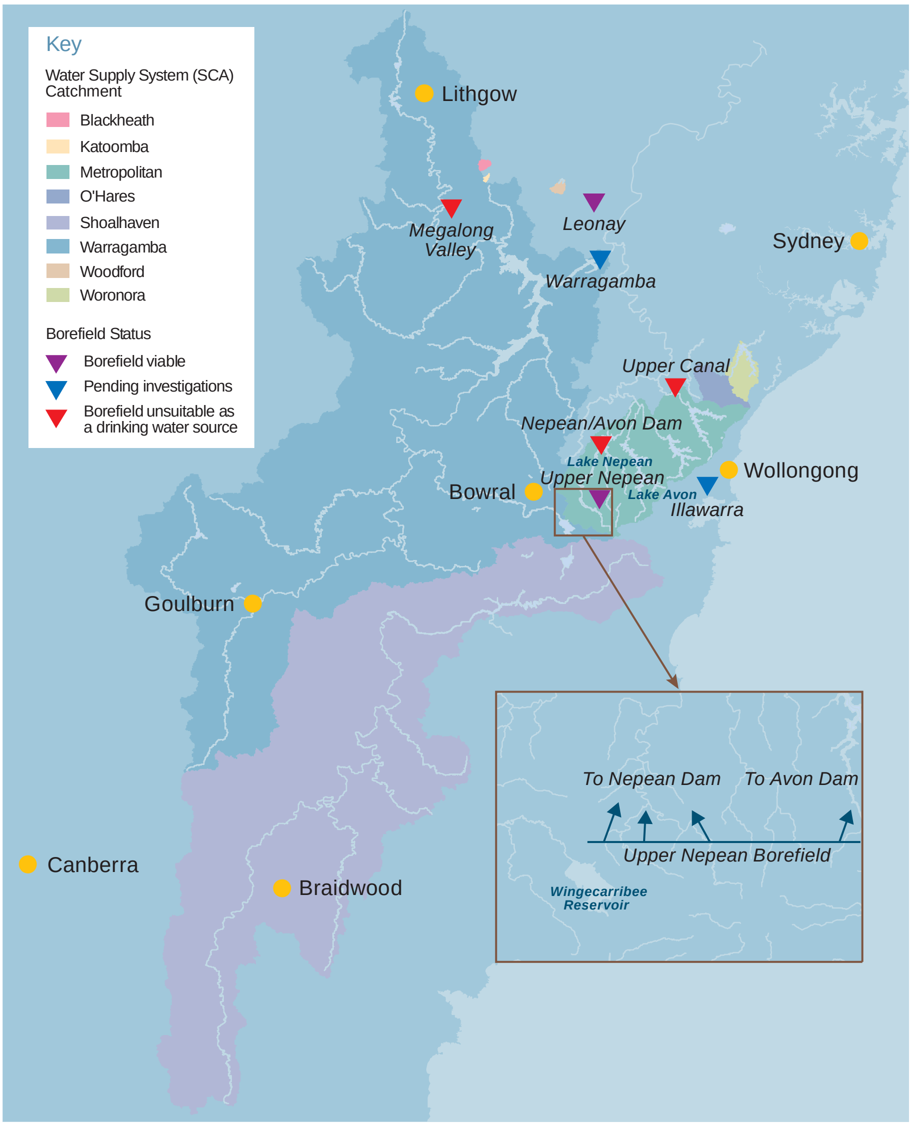


Figure CS3.1. Location of the Upper Nepean River catchment area with the priority investigation areas in the Sydney region (after SCA 2006b).

CS3 Climate and physiography

Annual long-term local rainfall data taken from 15 rainfall stations show that considerable spatial variation in average long-term rainfall is evident in this area, with rainfall in the east being around twice as high as that in the west. Annual long-term variability is between 300 and 2200 mm/year. The average rainfall recorded in the Bureau of Meteorology's Moss Vale (Hoskins Street) station, which has the longest record, is 973 mm/year. The relative magnitude of annual rainfall for the 15 stations compared with rainfall volume recorded at the Moss Vale station ranges from 0.92 to 2.20.

Digital elevation data on a 200 m grid for the regional area show that the Upper Nepean catchment is bounded to the south by a topographic ridge just north of Robertson, and to the north by Lakes Nepean and Avon and their associated drainage channels. The area has undulating topography ranging from over 800 m AHD on the ridge to below 400 m AHD in the vicinity of the lake dam walls. Ground elevations in the vicinity of the Upper Nepean study area range between 550 m AHD and 650 m AHD with gently rolling hills extending northwards for several kilometres where ground levels begin falling more markedly. Rivers and creeks are slightly incised into the local topography by around 0 to 15 m. Incisions deepen markedly several kilometres to the north towards the lakes. Most of the study area is located within the Special Area of the Sydney Catchment Authority (SCA).

CS3 Geological setting

Geologically, the Southern Highlands are located on the south-west margin of the Sydney Basin. The Basin was formed by extensive sedimentation as a consequence of a predominantly compressional tectonic regime, driven by foreland loading from the Lord Howe Rise and the 'Gerringong Volcanic Ridge'. Sedimentation was contemporaneous with tectonism throughout the Late Carboniferous to Cainozoic periods.

The geology across the Southern Highlands region is variable. However, this can be simply divided into three broad categories, as follows:

1. the Palaeozoic basement rocks comprising the Ordovician to Devonian volcanics, granites and sediments of the Lachlan Fold Belt,
2. the overlying Triassic Hawkesbury Sandstone and associated sedimentary deposits of the Sydney Basin sequence, and
3. younger Tertiary basalt of the elevated highland areas.

The geology of the Upper Nepean area comprises a gently deformed sequence of Triassic sandstones and shales that form the upper sequence of the Sydney Basin sediments. The surface geological unit exposed throughout much of the Upper Nepean catchment area is the Triassic aged Hawkesbury Sandstone. This overlies the sandstones and siltstone of the Triassic Narrabeen Group and the Permian Illawarra Coal Measures.

The Hawkesbury Sandstone is the primary target for the Sydney Catchment Authority groundwater investigation program. It varies in thickness from 160 m in the Mittagong region to approximately 250 m in the Sydney region. It is overlain in the area by the Mittagong Formation and Wianamatta Group.

In areas of the middle slopes, the Ashfield Shale, the basal unit of the Wianamatta Group, lies beneath the surficial soil cover. The Tertiary aged Robertson Basalt overlies the Wianamatta Group and caps the high areas in the Kangaloon–Robertson area.

CS3 Groundwater–stream interaction

The main lithological units forming the major aquifers are the Tertiary Basalt and Hawkesbury Sandstone. The Wianamatta Group shales and minor sandstones form a confining unit in many areas and this unit generally behaves as an aquitard in this area.

Groundwater flow in the Hawkesbury Sandstone (the main regional aquifer) is generally from the south-south-west to the north-north-east and locally follows the topography. Generally, the sandstone water levels are higher than the water level in creeks, providing baseflow discharge during most of the drought periods. Recharge to the groundwater system is mainly by rainfall infiltration and occurs a small distance upstream from the Dudewaugh Creek and Stockyard Swamp area. Discharge occurs at escarpments, rivers and as evapotranspiration at some wetlands. The Wianamatta Group and Hawkesbury Sandstone each contain multiple hydraulic conductivity zones. For the sandstone, the zonation reflects the effect of the weight of overlying rock and structural deformation.

The available evidence of groundwater–surface water interaction shows that baseflow discharge dominates the pristine environment during most of the year, including drought periods. However, high borefield extraction rates will induce stream leakage, assuming that hydraulic connection is maintained between surface water and groundwater in the sandstone. It is expected that leakage will occur to the shallow aquifer system in the sandstone. Figures CS3.2 and CS3.3 broadly conceptualise groundwater flow and stream interaction in the study area, respectively prior to and following borefield development.

CS3 Groundwater development and impact on streams

The Upper Nepean catchment has been selected for groundwater development after initial water resource investigations in 2005. The whole area possesses very good groundwater resources and there is potential for a large borefield development of up to 15 GL/year. However, the proposed study area is an area of likely groundwater–stream interaction and this will require a greater degree of understanding at several locations.

Groundwater extraction from the borefield may commence in 2007/08. Significant groundwater drawdown is expected at localised points with the cone of drawdown extending out from the borefield a predicted distance of approximately 2000 m in all directions (Figure CS3.4).

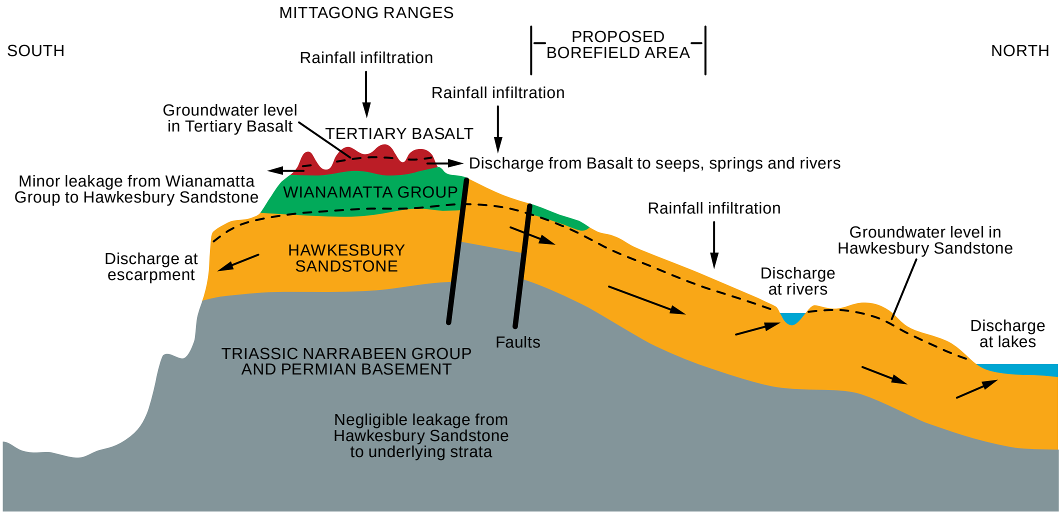


Figure CS3.2. Geology and conceptual groundwater flow model – natural system (after SCA 2006a).

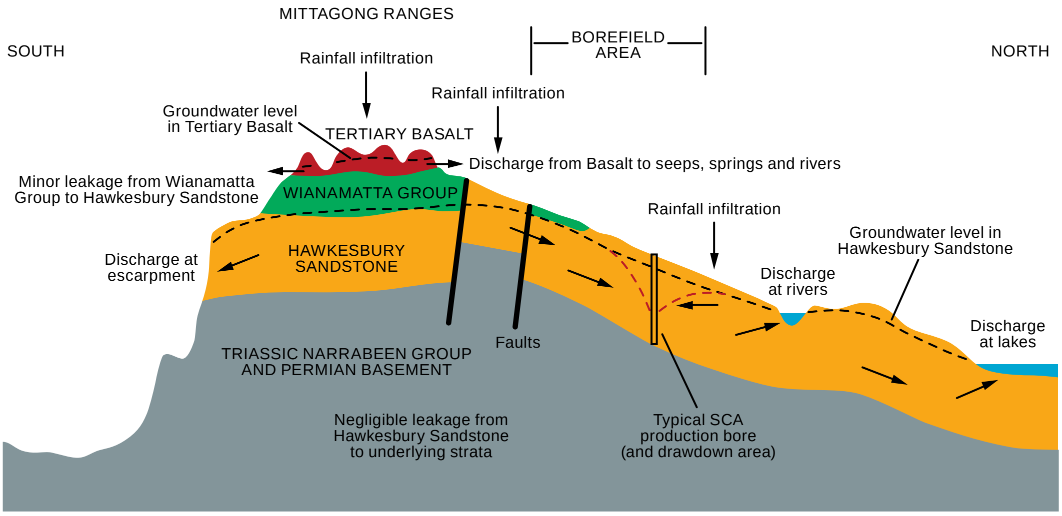


Figure CS3.3. Geology and conceptual groundwater flow model – borefield development (after SCA 2006a).

It has been assessed that some groundwater-dependent ecosystems (GDEs) will be impacted by groundwater extraction. Five potentially relevant types of GDE have been identified in the Upper Nepean catchment and they are: wetland, river base flow system, terrestrial vegetation, terrestrial fauna and aquifer ecosystem.

Given the significance of groundwater–stream interaction and GDEs, the sustainability and impact of extension of the proposed borefield in this area is uncertain and, therefore, a greater understanding of the interaction processes needs to occur in advance of the commitment to develop production bores.

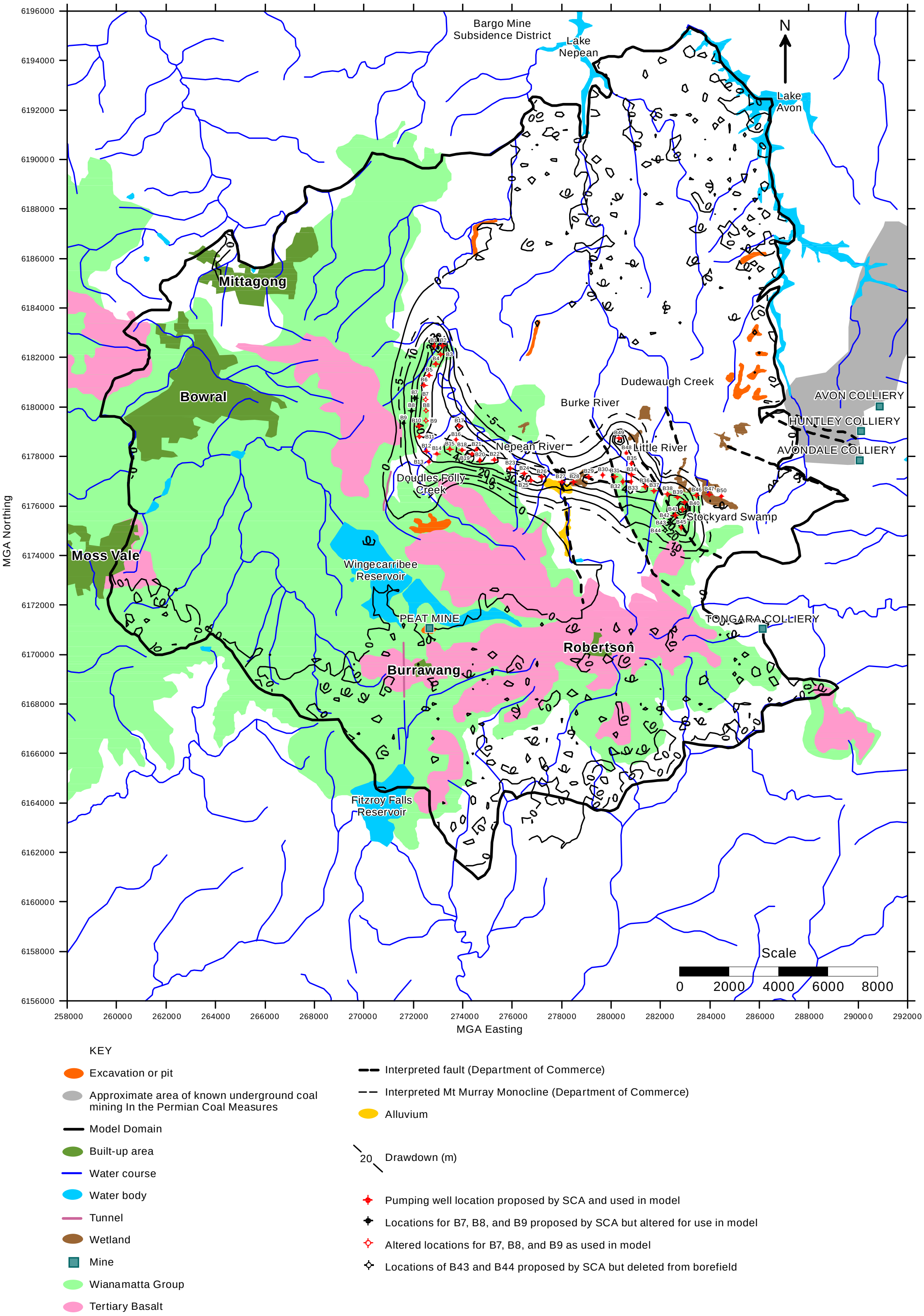


Figure CS3.4. Predicted extent of groundwater drawdown around the proposed SCA production borefield in the Hawkesbury Sandstone (after Coffey Geosciences 2006, Figure 13).

CS3 Management intervention and status

There is no management intervention at present. The area is suspected to be a groundwater discharge or throughflow area providing baseflow to the local creek system but could potentially become an induced recharge area if production bores were located close to the ecosystems associated with these features. A preliminary monitoring program is in place to monitor temporal changes in water level, groundwater flow direction and interaction between surface water and groundwater (Figure CS3.5). However, additional investigation, monitoring and analysis will be required prior to mining or borefield development in this area.

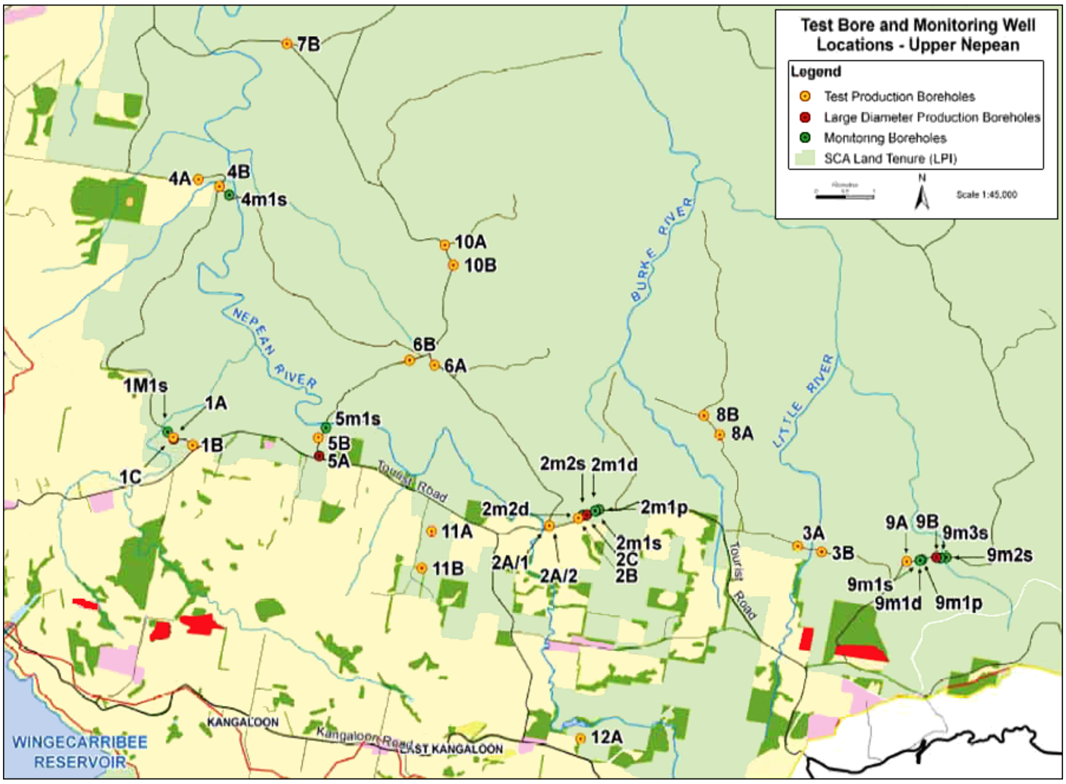


Figure CS3.5. Location of test and monitoring boreholes in the Upper Nepean River catchment (after SCA 2006b).

CS3 Data

Table CS3.1. Accumulated data sets and applied field and data collection methods for conceptualisation of groundwater–stream interaction in the Upper Nepean catchment.

Data sets	Period of data record	Field or data collection methods
Topography	2006	Digital elevation model (DEM)
Geophysics	2006	Aerial geophysics – magnetic and radiometric surveys targeting structural geology – maps, report in preparation
Geology/soils, groundwater resources, aquifer thickness	2005–2006	Drilling, existing maps have been upgraded; cross sections; geophysical/geological logs
Ecology	2006	Groundwater-dependent Ecosystem (GDE) evaluation – maps, reports
Aquifer parameters	2005–2006	Pumping tests, continuous groundwater level monitoring – reports
Water Quality, detailed groundwater chemistry, residence time, recharge–discharge zones	2005–2006	Hydrogeochemical and stable/radioactive isotope survey – report
Hydrogeological modelling	2006	Groundwater flow, groundwater–surface water interaction, assessment of pumping impact on groundwater system, sustainability – model, report
Surface water	1970–2006	SCA data base contains long-term gauging stations flow data; new gauging stations will be installed in 2007
Artificial recharge	2006	Report in preparation
Detailed hydrogeochemical, isotopic and tracer studies	2007–2008	Project will start in 2007

CS3 Groundwater–stream interaction classification

Table CS3.2. Classification of Upper Nepean using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to the Upper Nepean for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as medium.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Case study 4: Hodgson Creek, Qld (layered or complex system)

CS4 Location

The Hodgson Creek catchment is located on the eastern Darling Downs, Queensland, in the headwaters of the Murray–Darling Basin (Figure CS4.1). It borders the southern boundary of Toowoomba City and is bounded by the Great Dividing Range in the east. Surface water drains towards the west and south to the Condamine River, with a catchment area of 566 km^2 behind the Balgownie gauging station (Figure CS4.2).

Figure CS4.1. Location of Hodgson Creek Catchment within the Murray–Darling Basin.

CS4 Climate and physiography

The climate is subtropical with a moderately dry winter (Bureau of Meteorology 2004). The areal annual average rainfall is 738 mm, with a range of 687 mm at Balgownie West in the south-west to 952 mm in the ranges near Toowoomba in the north. About 60% of the annual rainfall occurs during October to March. Annual average pan evaporation was 1731 mm, ranging from 1638 mm in Toowoomba to 1796 mm at Balgownie West. The areal mean monthly maximum temperature varies from 18°C in winter (Jun–Aug) to 29°C in summer (Dec–Feb).

Relief ranges from 700 m AHD in the north-east to 400 m AHD at the confluence with the Condamine River. Two main creeks join Hodgson Creek in the centre of the catchment – Umbiram Creek from the north-west in the vicinity of Southbrook, and Emu Creek from the east in the vicinity of Greenmount (Figure CS4.2). As the distance down the valleys increases, there is a progression from steep-sided valleys underlain by volcanic rocks, to more mature, broad alluvium-filled valleys. The alluvium forms a relatively narrow, flat strip on the floor of these valleys. Streams vary between incised channels and broad depositional/in-filled areas with discontinuous gully heads and pools. Valley infilling increased as a result of extensive sheet, rill and gully erosion after agricultural development.

The Hodgson Creek catchment has a long history of agricultural development relative to most other areas in Queensland. Predominant land uses are grazing (45%; 18% under woodland) and cropping (51%) (Rattray et al. 2002) and have been reasonably stable since at least the 1960s.

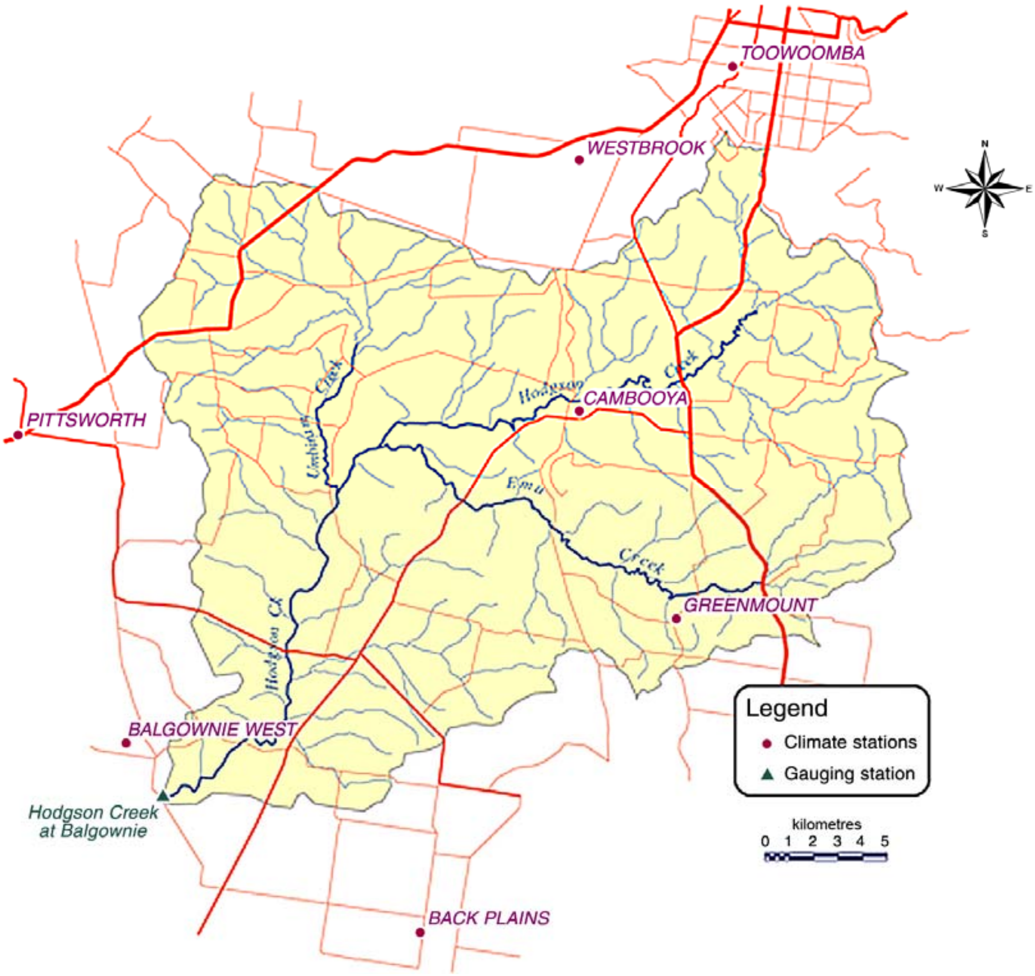


Figure CS4.2. Hodgson Creek map showing towns with climate stations, drainage lines, sub-catchments, main roads and gauging station.

CS4 Geological setting

Cranfield and Schwarzbock (1971) mapped and described the geology of the region (Figure CS4.3). Hughes (1986) described the geology of the Darling Downs, as it relates to salinity. Willey (1992) mapped and described the geology of the Hodgson Creek catchment. The geology of the majority of the catchment is Main Range Volcanics (Tertiary age), predominantly composed of basalts, but may also contain inter-bedded sediments including fluvial gravels and sands (Willey 1992). The Walloon Coal Measures (Jurassic period) underlie the basalts and outcrop in the south-west of the catchment (approximately 100 km^2). This unit contains medium to fine sandstone, shales, coal and mudstone. The catchment also contains alluvium of the Quaternary period along the valley floors and at the confluence with the Condamine River. Aquifers mostly occur in the underlying basalt, although small areas of shallow sand/gravel aquifers may occur, such as at the Condamine River confluence.

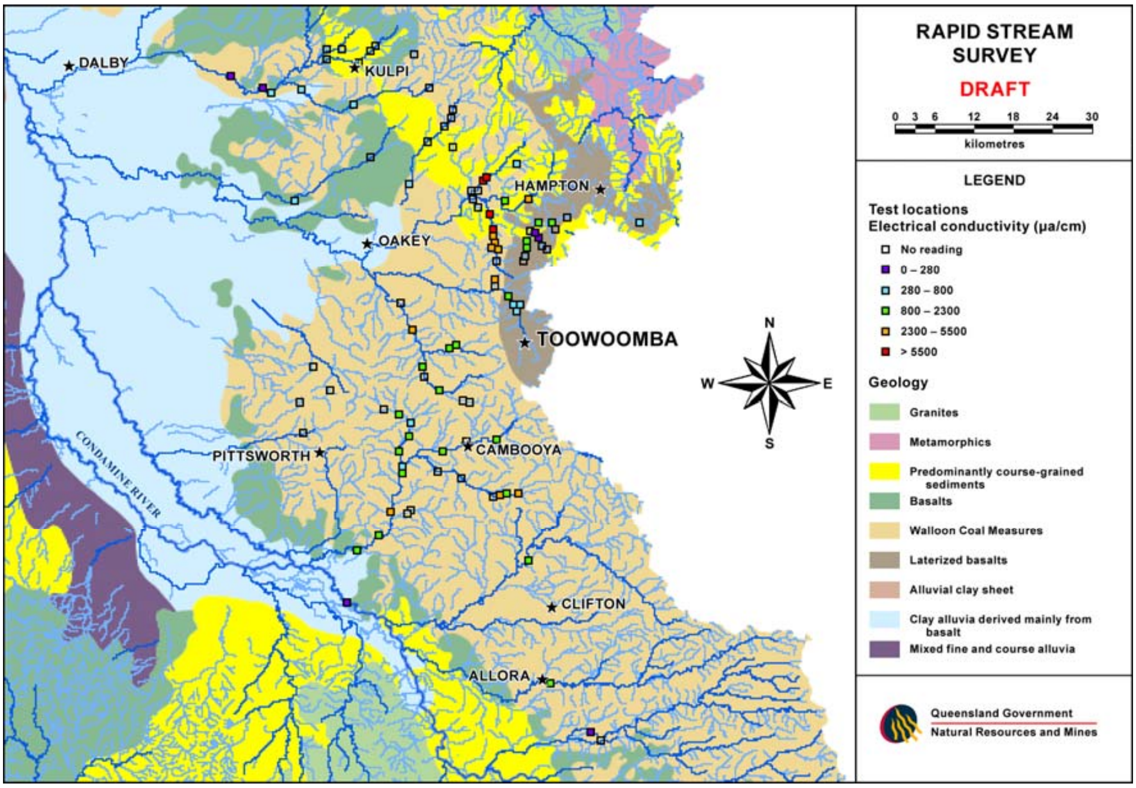
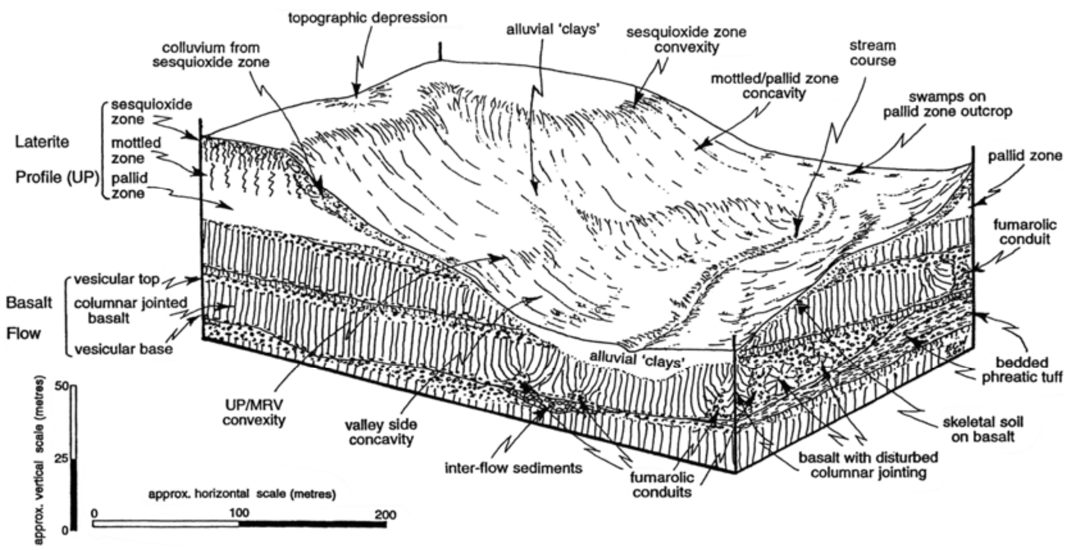


Figure CS4.3. Geology of the central eastern Darling Downs, Queensland (after Cranfield and Schwarzbock 1971). Hodgson Creek flows through Cambooya. The map also shows stream sites (open squares) with groundwater discharge in winter after a dry period in 2004; this is indicated by high electrical conductivity readings (orange and red fill).

The basalts may extend to over 100–200 m depth, becoming thinner towards the west and south. They often contain multiple aquifers in decomposed or ‘honeycomb’ layers separated by harder, partially/variably fractured layers related to the roughly horizontal lava flows (Figure CS4.4). Volcanic vents also occur, where decomposed layers may be absent but fractures still occur.

CS4 Groundwater–stream interaction

Hodgson Creek is a ‘gaining stream’, although streamflow provides some groundwater recharge in dry periods, in some locations. Baseflow was estimated as 5–9 mm/yr, or 10–17% of flow. Silburn et al. (2006) and Dutta and Silburn (2005) found that groundwater levels occur at shallow depths (e.g. <5 m) in much of the alluvia, and have done so since the late 1960s at least. While the creek has no flow at the gauging station for about 12% of the time, groundwater is generally not far under the creek bed. The presence of baseflow spatially (Figure CS4.3) is related to the depth of stream incision.



Baseflow no longer occurs in several streams (where it once did), for example, in Hodgson Creek downstream of Cambooya, below the area of greatest

Figure CS4.4. Schematic of the Toowoomba Main Range Volcanics (Source: Willey 2003). Note: some surface features apply to the Toowoomba plateau, however the underlying layered basalts apply in the Hodgson Creek catchment. Vertical exaggeration ~ 250%.

groundwater use. A transect of monitoring bores in the alluvium near the gauging station indicate groundwater and surface water interact strongly at that site.

There are several sites with monitoring bores in the upper aquifer beside the stream, including the gauging station site. The bores were constructed to determine the down-valley groundwater heads/gradient and the head relationships to the stream. The Queensland Department of Natural Resources and Water (NRW) now has dataloggers on several monitoring bores beside the stream. Other stream sites with stable controls have some records of stage but were not rated. These sites could later be set up with stream and groundwater dataloggers. Cresswell et al. (2006) installed several new bores in the upper and lower aquifer beside Umbiram Creek. They sampled various strata and streams for ionic chemistry and isotopes, and have made an initial assessment of groundwater–stream interactions in Hodgson Creek.

CS4 Groundwater development and impact on streams

Significant use of groundwater for irrigation occurs in the Upper Hodgson Creek Groundwater Management Area (GWMA), surrounding and north and east of Cambooya, as well as in alluvial areas in Umbiram and Emu Creeks (Figure CS4.5). Thus, there is a component of recharge that is pumped onto and evaporated from sprinkler-irrigated crops and will not contribute to stream flow. Dutta and Silburn (2005) estimated that pumping for 1997–2002 (including irrigation, domestic and stock) averaged an equivalent of 14 mm/yr (10–18 mm/yr range) for the GWMA and about 8 mm/yr for the entire Hodgson Creek catchment. This is approximately equal to the difference between estimates of net recharge and baseflow. Groundwater chloride mass balance (chloride data from 476 bores) yielded an average recharge rate of 14 mm/yr in the GWMA and 13 mm/yr for the entire catchment. Approximate average groundwater balances (Dutta and Silburn 2005; Silburn et al. 2006) are:

- GWMA – recharge 14 mm/yr, baseflow 0 mm/yr, pumping 14 mm/yr;
- entire catchment – recharge 13 mm/yr, baseflow 5 mm/yr, pumping 8 mm/yr.

CS4 Management status

Pumping from irrigation bores in the declared GWMA has been monitored (quarterly) since 1997. Future management emphasis will be on metering of groundwater use, except for stock and domestic purposes, and managing pumping so that water use equals recharge in the long term.

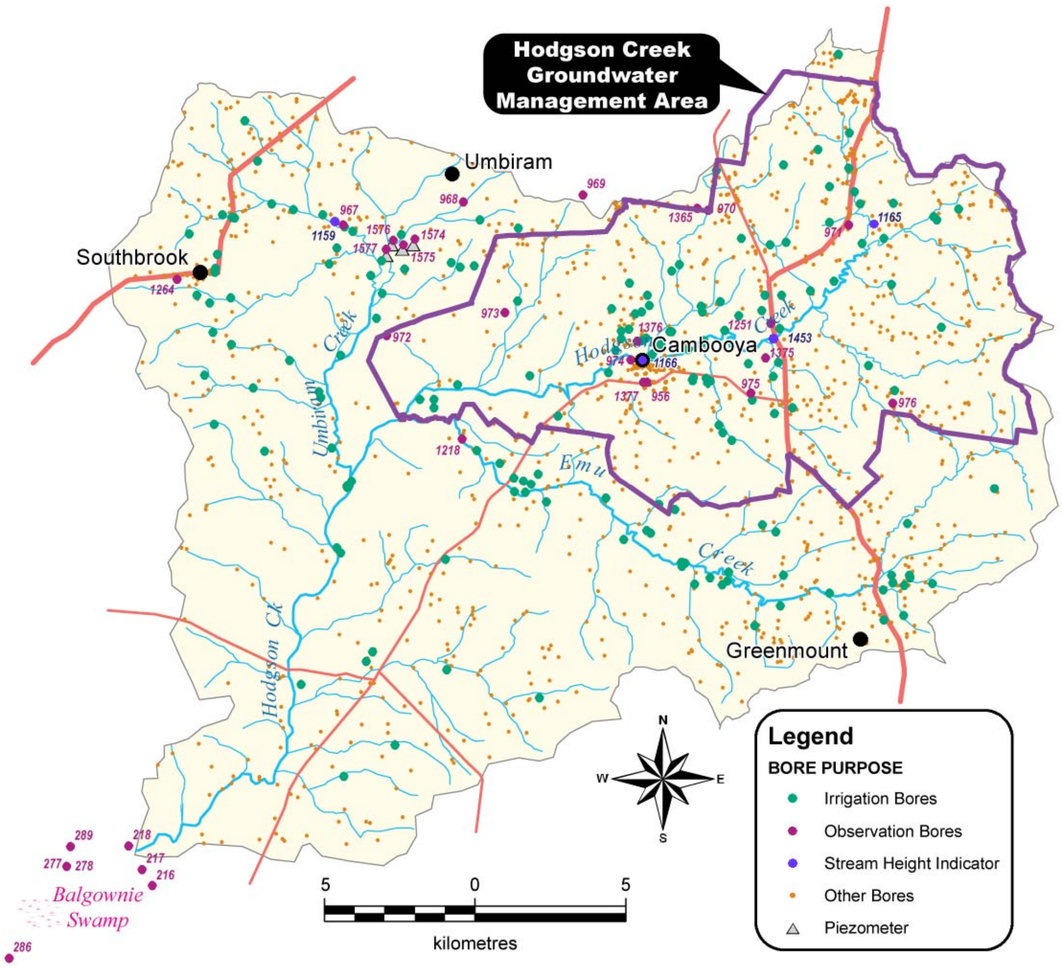


Figure CS4.5. Locations of bores used for monitoring, irrigation and other purposes, and Upper Hodgson Creek Groundwater Management Area (GWMA).

CS4 Data

Many aspects of hydrology, hydrogeology and salinity in the Hodgson Creek catchment were investigated by Dutta and Silburn (2005), Silburn et al. (2005; 2006) and McNeil and Silburn (2005). These included calculating stream salt loads, catchment salt balance, a spatial survey of baseflow and salinity in a dry season, interpretation of bore hydrographs and rainfall patterns, and estimation of groundwater recharge, pumping and baseflow rates. Hydrogeochemistry and isotopes were investigated by Cresswell et al. (2006). Several indicators suggest that the catchment is undergoing hydrologic change as a result of agricultural development. For example, salt load in streamflow is several times greater than in rainfall, and baseflow is more persistent spatially and temporally than in many Queensland Murray–Darling Basin streams. The catchment water and salt processes were modelled using the 2CSalt model (Silburn and Owens 2005). Stream water has been sampled during several flood events and analysed for major ions; this and continuation of the work by Cresswell et al. (2006) will be used to separate baseflow from surface runoff. Several sampling sites have monitoring bores in the upper aquifer beside the stream, including the gauging station site.

Table CS4.1 summarises the accumulated data sets and applied field and data collection methods for conceptualisation of groundwater–stream interaction in the case study area.

Table CS4.1. Summary of available data sets and data collection methods in Hodgson Creek.

Data sets	Period of data record	Field or data collection methods
Streamflow	1987 onwards	NRW gauging station
EC autosensor	1993 onwards	NRW gauging station
Baseflow survey	2004 winter	Visual observations and hand sampling EC measurement spatially within Eastern Darling Downs
DEM		
1:100,000 scale soils map		
Radiometrics	2006	Airborne
1:250,000 scale groundwater flow system map and attributes		Desktop analysis and expert consultation
Groundwater levels	Since mid-1970s	Manually read each 3 months
Groundwater levels	2005–06 onwards	Daily data loggers in 5 bores
Groundwater chemistry	Since mid-1970s	Approx 650 ionic chemistry samples
Groundwater chemistry	2005/2006	Ionic chemistry and isotopes on selected bores and streams

Logging of groundwater levels will continue and be expanded during 2007. If the site is adopted as a National Water Initiative surface–groundwater interaction site, stream water level loggers will be installed near stream-side bores and low-flow rating will be performed.

CS4 Groundwater–stream interaction classification

Table CS4.2. Classification of Hodgson Creek using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to Hodgson Creek for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as high.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Case study 5: Pioneer Valley, Qld (contained alluvial valley system – coastal)

CS5 Location

The Pioneer Valley is located on the north-eastern coast of Queensland, directly to the south and west of the city of Mackay. The management area for both surface water and groundwater resources is the Water Resources Planning (WRP) area, as shown in Figure CS5.1. The WRP area includes the Pioneer River, Bakers Creek, Sandy Creek, and Alligator Creek catchments, and a part of the Plane Creek catchment, covering an area of some 2,400 km^2. Groundwater is extracted mostly from alluvial sediments, but also from fractured rock aquifers such as those of the Mt Vince block (Figure CS5.1).

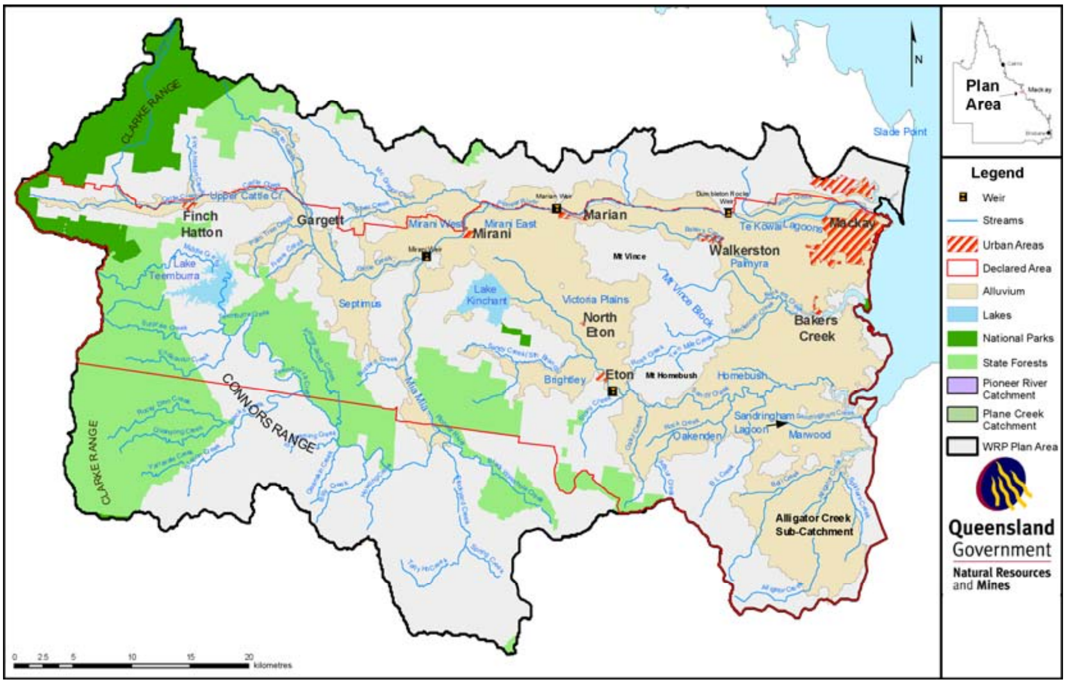


Figure CS5.1. Location of the Pioneer Valley case study area (Werner et al. 2006b).

CS5 Climate and physiography

The Pioneer Valley experiences a humid, wet, tropical climate with a summer-dominated rainfall pattern. Rainfall varies across the study area, with average annual rainfall ranging from less than 1,100 mm in the south to over 2,000 mm in the headwaters of Cattle Creek in the west, where the topographic effects of the Clarke and Connors Ranges lead to higher, orographic rainfall. The average annual rainfall for the Pioneer Valley is approximately 1,600 mm. Mean daily temperatures for Mackay varied from 13.9°C (June) to 30.0°C (December/January) for the years 1959 to 2004. Mean monthly humidity between 1961 and 1990 varied from 65% in October to 80% in April (information sourced from http://www.bom.gov.au/silo/). Evaporation measurements (Class A pan evaporation) from the Bureau of Sugar Experimental Stations (BSES) Te Kowai Research Station indicate that the mean annual evaporation for Mackay is approximately 2,000 mm per annum.

The alluvial sediments of the Pioneer Valley are dissected by a mid-valley high, which rises to a maximum height of 255 m AHD at Mt Vince and to 160 m AHD at Mt Homebush, and segregates the alluvial deposits into the coastal plains to the east and the Victoria Plains, Upper Pioneer and Cattle Creeks to the west. The western portion of the valley containing the Cattle Creek catchment has a moderate slope, while the Victoria Plains area and the coastal plains are relatively flat. The main surficial features of the alluvial aquifer area include the Pioneer River (1,489 km^2 catchment area), Sandy Creek (367 km^2), Bakers Creek, Sandringham Creek and Alligator Creek. Sandy Creek and Bakers Creek drain the major portion of the lower Pioneer Valley through areas thought to be the floodplain of previous Pioneer River courses and now drained by these two lesser streams (Gourlay and Hacker 1986).

CS5 Geological setting

The regional geology and hydrogeology of the Pioneer Valley area have been described by Jensen (1972), Bedford (1978a, 1978b) and Murphy et al. (2005). The geology of the WRP area to the south of Upper Cattle Creek and the Lower Pioneer River is predominantly a Cainozoic alluvial sedimentary basin overlying the Permian Carmila Beds, the Carboniferous to Mesozoic Urannah Complex, and the Upper Devonian and Lower Carboniferous Campwyn Beds. Alluvial sediments deposited from the Pioneer River, Cattle Creek, Sandy Creek, and Bakers Creek dominate the unconsolidated sediments, which comprise Quaternary-aged inter-bedded sequences of clays, silts, sandy clays, sands, clayey sands, and gravels overlying mostly Palaeozoic rocks. Alluvial deposits have been intersected by post-deposition streams, which have subsequently been in-filled by channel deposits of coarse to fine sands, and gravels. These infill deposits are common across the coastal plains and are also prevalent in sections of incised paleochannels in the underlying basement. Alluvial sediments range in thickness from 5 to 40 m, and average about 18 metres.

The rocks of the Lower Permian Carmila Beds are exposed in the central valley basement exposure commonly known as the ‘Mt Vince Block’, and these consist of mainly tuff, lithic greywacke, and freshwater sediments with less abundant acid volcanics (Jensen 1972). Sodic soils have been identified to be associated with weathered volcanics exposed on the lower slopes. A geology map of the WRP area adapted by Murphy et al. (2005) from Jensen (1972) and Bedford (1978a; 1978b) is shown in Figure CS5.2.

CS5 Groundwater–stream interaction

Significant hydraulic connections exist between the streams and aquifers of the WRP area. Generally groundwater discharges into streams where the stream bed level is below the local groundwater level, although reversals of flow (i.e. stream to groundwater) are common during significant stream flow events. In the WRP area, the main streams considered to be receiving significant groundwater discharge are the Pioneer River and Cattle, Finch Hatton, Owens, Sandy, Bakers and McGregor Creeks (Murphy et al. 2005). Murphy et al.(2005) outlines the hydrological and hydrogeological evidence of stream–aquifer interaction, including the extent and temporal variability of groundwater

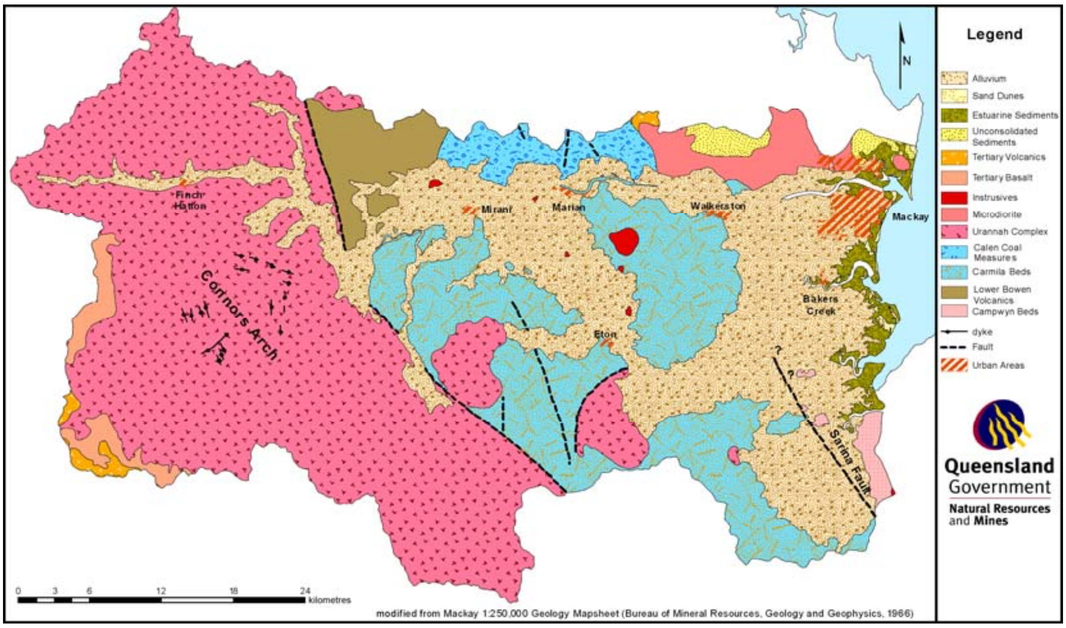


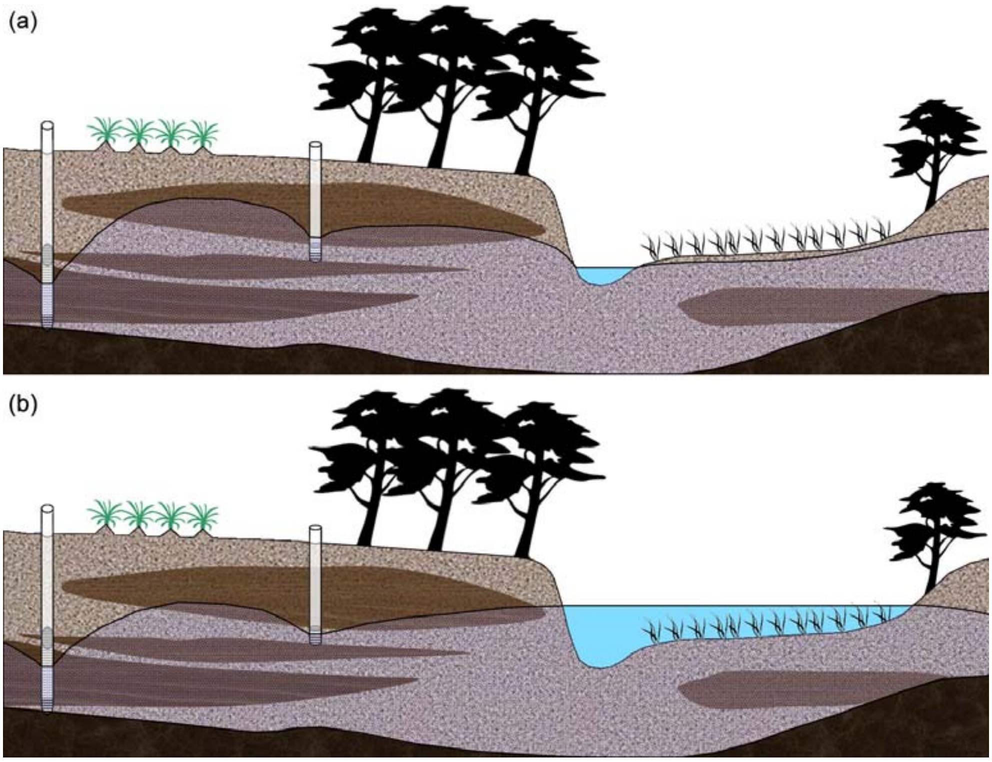
Figure CS5.2. Geology of Pioneer Valley case study area (Werner et al. 2006b).

discharge to and recharge from the main surface water features of the Pioneer Valley area. Only the stream–aquifer interaction in the Sandy Creek area is included in this case study.

In general, the Sandy Creek system is considered to comprise both gaining (groundwater sink) and losing (groundwater source) reaches, with flow directions dependent on groundwater levels, stream water levels and physiography (Cook et al. 2004; Murphy et al. 2005; Werner et al. 2006a). A geological conceptual diagram of the interaction between Sandy Creek and adjacent alluvial aquifer system is given in Figure CS5.3.

Sandy Creek is perennial, though some sections of the stream do cease to flow and recede to a series of waterholes during dry seasons. Under dry conditions, flow between waterholes occurs through the sand and gravels of the streambed. In periods of low water table elevations, Sandy Creek appears to contribute stream water to the northern aquifer in the Homebush area (downstream of the Sandy Creek stream flow gauge 126001A, see http://www.nrm.qld.gov.au/watershed/precomp/126001a/126001a.htm). Sandy Creek rarely breaks the banks during peak stream flow events, and over-bank flows are considered insignificant, and not a major source of groundwater recharge (Murphy et al. 2005).

Murphy et al. (2005) present groundwater flow contours that illustrate regional trends in the direction of stream–aquifer interaction during both high watertable and low watertable conditions. Their interpretations of regional groundwater levels and river water levels indicate that the average annual groundwater discharge to Sandy Creek was 4,100 ML/annum for the period 1991–2003 and 5,200 ML/annum during 1998–2003 (annual figures are given in Werner et al. 2005). Murphy et al. (2005) also outline the results of a manual base flow separation method, from which they estimated Sandy Creek base flow to be



about 7,600 ML/annum for 1998–2003. The results of groundwater flow modelling of the Pioneer Valley groundwater basin (Kuhanesan et al. 2005)

Figure CS5.3. Conceptual representation of the interaction between Sandy Creek and the adjacent unconfined alluvial aquifer: (a) during low flows in Sandy Creek, and (b) during high flows.

using the MODFLOW code indicated that the average monthly groundwater discharge to Sandy Creek follows a seasonal pattern, as illustrated in Figure CS5.4. The average groundwater discharge to Sandy Creek of 3,400 ML/annum for the period 1998–2003 from MODFLOW modelling is somewhat less than the estimates of Murphy et al. (2005). It should be noted that base flow estimates from the base flow separation by Murphy et al. (2005) were included in the calibration of the Pioneer Valley MODFLOW model undertaken by Kuhanesan et al. (2005), and therefore correlation between the two results is expected. Subsequent modelling of Sandy Creek stream–aquifer interaction using the MODHMS code indicated that the average annual groundwater discharge to Sandy Creek was 1,700 ML/annum for the period 1998–2003. An additional base flow separation method, which used a hydrograph filtering approach, was carried out by Werner et al. (2005) and an average stream base flow of 50,000 ML/annum was produced. The more rigorous approach of Werner et al. (2006b), who developed a coupled stream–aquifer model using the code MODHMS is probably the more accurate calculation of groundwater discharge to Sandy Creek. Nonetheless, the high variability of estimates between the various methods of stream–aquifer interaction assessment indicates that further investigation of the applicability of these methods is warranted.

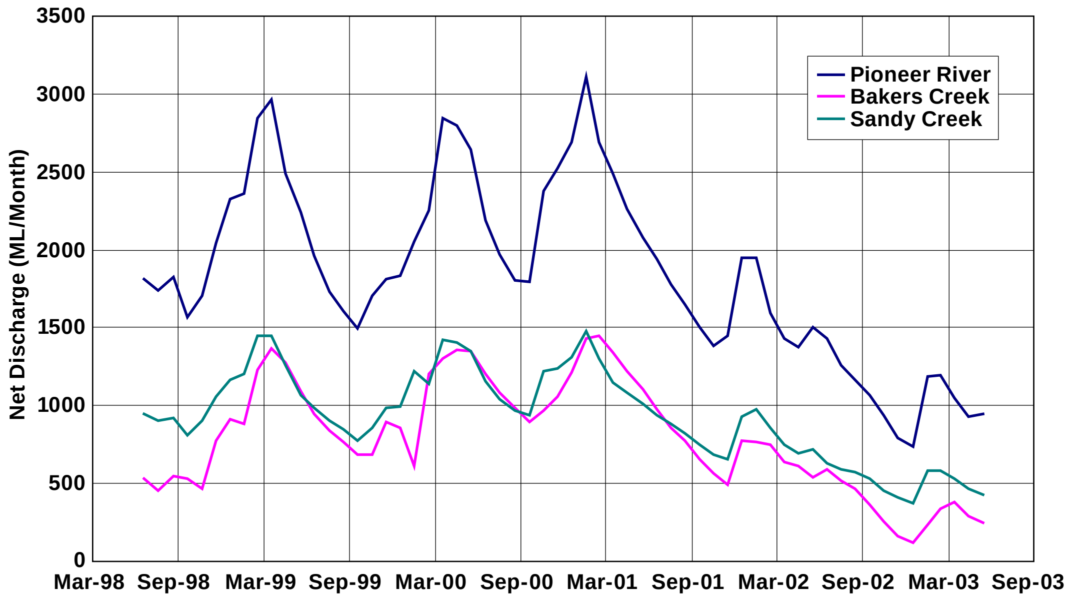


Figure CS5.4. Average monthly groundwater discharge to Pioneer River (top), Sandy Creek (middle) and Bakers Creek (bottom) for the period 1998–2003 (adapted from Murphy et al. 2005).

CS5 Groundwater development and impact on streams

Groundwater has been an important source of water in the Mackay area since the late 1800s. Currently, in the modelled area, 4,650 groundwater extraction bores are utilised for agricultural, industrial, and urban supplies. Of these, an estimated 2,905 are in use for domestic water supply and 1,466 as irrigation bores. Thirty-seven industrial bores are utilised by sugar mills and other industries, with the remaining 231 bores in the district nominated as stock watering bores. Figure CS5.5 shows the level of groundwater development within the area. The installation of flow meters on major production bores was undertaken between 1997 and 1998. There are currently 525 metered irrigation, industrial and town water supply bores in the area. Metered use data for the period 1998–2003 given by Murphy et al. (2005) indicates high variability in Pioneer Valley groundwater extraction, ranging from 3,400 ML/annum in 1998/1999 to 45,700 ML/annum in 2002/2003.

The impact of groundwater abstraction on Pioneer Valley streams is difficult to quantify. Historical pumping rates are not well-documented, and the large seasonal variability in stream flow (associated with the tropical climate) masks any gradual base flow reductions that might have occurred with increases in groundwater abstraction. While NRMW have undertaken various modelling scenarios of groundwater management approaches using the stream–aquifer interaction model originally developed by Werner et al. (2006b), simulations aimed at ascertaining the reduction in base flow, compared to an 'undeveloped state' of the system, have not been constructed at the present time. Given the proximity of a large number of irrigation bores to Sandy Creek (Figure CS5.5), some level of groundwater pumping-induced stream depletion is highly likely.

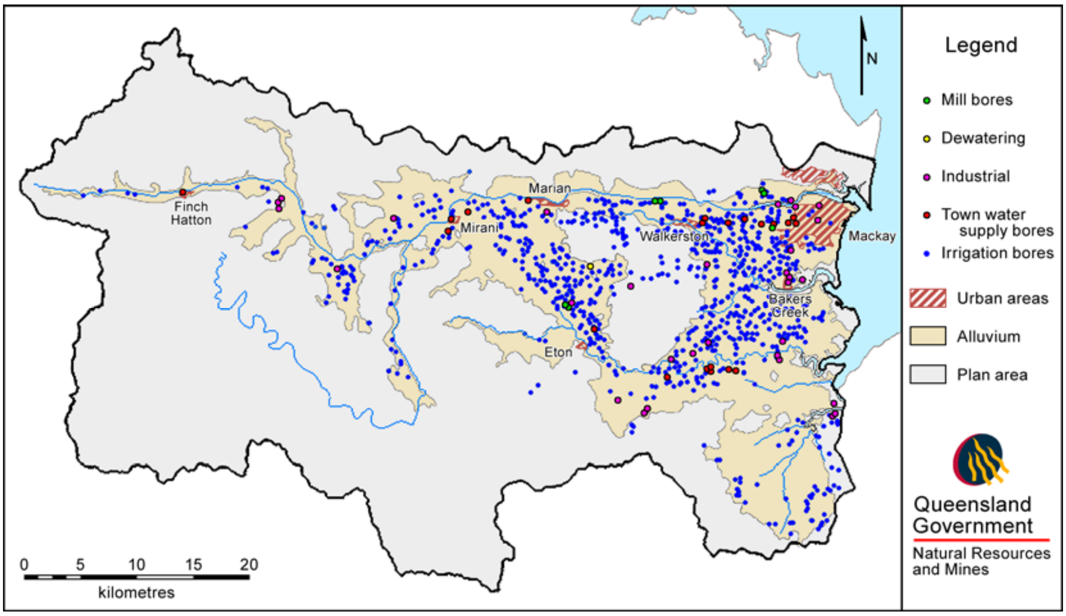


Figure CS5.5. Location of groundwater bores in the Pioneer Valley case study area (Werner et al. 2006b).

CS5 Management intervention and status

The Queensland government (Department of Environment and Resource Management) are presently developing water resource management policy through the WRP and Resource Operation Planning (ROP) framework. Background information on WRP and ROP objectives can be found at : http://www.nrw.qld.gov.au/wrp/pdf/general/understanding_wrp_09.pdf. The interaction between groundwater and surface water is of particular importance in the WRP and ROP agendas, due to current inconsistencies between management approaches applied to inter-linked groundwater and surface water resources.

It is not possible to speculate on pending changes to water resource management approaches in the Pioneer Valley prior to the formation of any WRP legislation, which is soon to be publicly released. However, it is anticipated that specific policies will be devised for the management of near-stream groundwater pumping, based on the current understanding of stream–groundwater interaction. These policies will aim to protect riverine environmental assets and groundwater-dependent ecosystems in general, and take into account groundwater pumping impacts on supply reliabilities of downstream surface water users.

CS5 Data

Table CS5.1 summarises the accumulated data sets and applied field and data collection methods for conceptualisation of groundwater–stream interaction in the case study area.

Table CS5.1. Summary of available data sets and data collection methods in the Pioneer Valley.

Data sets	Period of data record	Field or data collection methods
Topography	2005	Digital elevation model (DEM)
Geology and soils, groundwater resources, aquifer thickness, etc.	1976–2005	Various drilling programs, soil profiling, cross sections, geophysical/geological logs
Ecology and groundwater-dependent ecosystems (GDEs)	2004	Groundwater-dependent ecosystem (GDE) evaluation – maps, reports
Computer modelling of groundwater and surface water hydrology and seawater intrusion	2004–2006	Groundwater flow, groundwater–surface water interaction, assessment of pumping impact on groundwater system, sustainability – model, reports
Surface water	1916–present	HYDSYS database containing gauging stations data from as early as 1916

CS5 Groundwater–stream interaction classification

Table CS5.2. Classification of Pioneer Valley using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to Pioneer Valley for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as medium.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Case study 6: Mid-Murrumbidgee, NSW (contained alluvial valley system)

CS6 Location

The Mid-Murrumbidgee Groundwater Management Area (GMA) is located in the south-eastern riverine plains of NSW along the alluvial valley of the Murrumbidgee River between Gundagai, Wagga Wagga, and Narrandera (Figure CS6.1). The management area also includes the alluvial sediments of Tarcutta and Kyeamba Creeks where the Lachlan Formation is present.

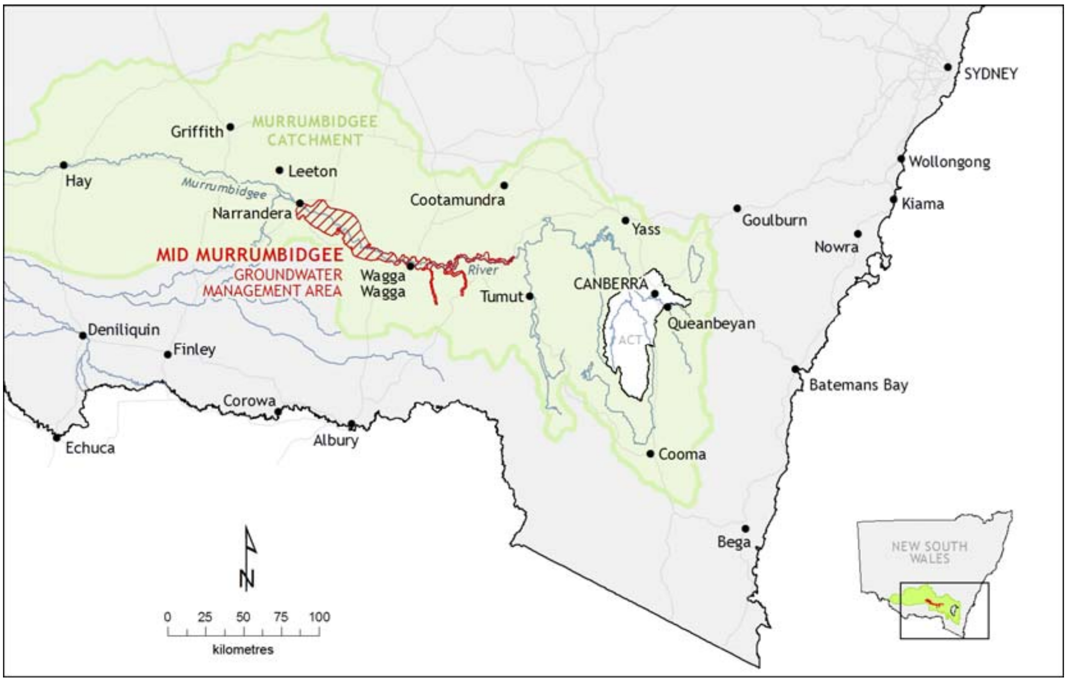


Figure CS6.1. Location of the Mid-Murrumbidgee GMA, NSW south-eastern Riverina (prepared by the Spatial Products and Services Unit, Department of Water and Energy, Queanbeyan).

CS6 Climate and physiography

The area has a Mediterranean climate with a mean annual rainfall of 575 mm. Mid-winter to mid-spring is the period with the highest average monthly rainfalls, and monthly rainfall usually exceeds pan evaporation in June and July. The average daily temperature ranges from 16°C to 31°C in summer and 3°C to 14°C in winter.

In the Gundagai to Wagga Wagga reach of the Murrumbidgee River, the alluvial valley ranges in width from approximately 1 km to 8 km, with an average width of approximately 2 km to 3 km. West, or downstream of Wagga Wagga, the landscape flattens out and the alluvial system is up to 10 km wide or more, with an average width of 6 to 7 km.

CS6 Geological setting

The alluvial system consists of two aquifers – the Cowra Formation (alternatively known as Shepparton Formation) and the Lachlan Formation (Figure CS6.2). The system increases in thickness from approximately 20 m in the east at Gundagai to 160 m in the west at Narrandera.

The Cowra Formation comprises clay, sand, gravel and cobbles. The grain size of the deposits decreases from east to west, with the formation being characterised by clay and coarse sand in the west of the study area. The formation ranges from approximately 20 m to 40 m in thickness.

The Lachlan Formation is characterised by thick, grey quartz sands and gravels with grey clay bands. The formation extends from approximately 20 km upstream of Wagga Wagga to downstream of Narrandera in the Murray–Darling Basin. The total formation thickness ranges from a few metres to approximately 120 m in the study area.

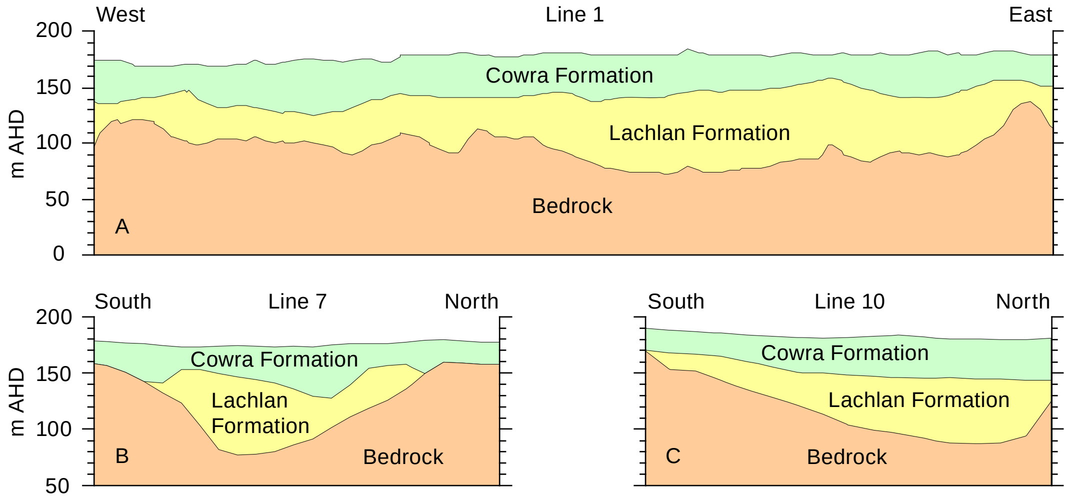


Figure CS6.2. Cross-sections of the alluvial aquifer system in the vicinity of Wagga Wagga. A : East–west section from the Malebo Range to Oura. B: North–south section near Malebo Range. C: North–south section near Forest Hill.

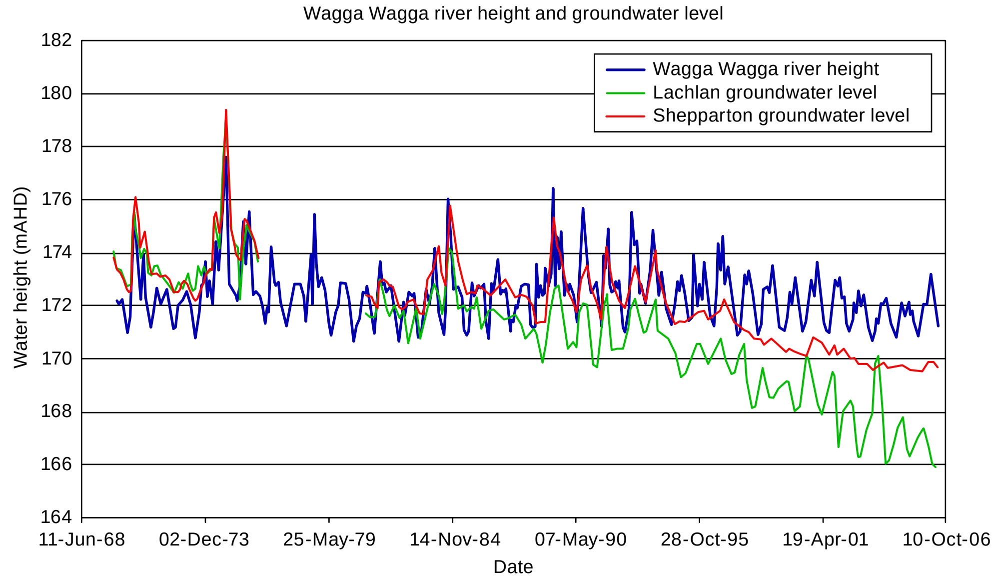
CS6 Groundwater–stream interaction

The Cowra Formation is an unconfined aquifer which overlies the semi-confined to confined aquifer of the Lachlan Formation. Recharge to the Lachlan Formation occurs via vertical leakage from the Cowra Formation and groundwater throughflow. The rate of vertical leakage is dependent on the lithology of the Cowra Formation, the connectivity between the two formations, and the hydraulic conductivity of the Murrumbidgee River bed.

Previous groundwater studies in the area by Woolley (1972), Kalf and Woolley (1977), Webb (2000), and Braaten and Gates (2002) concluded that the Murrumbidgee River and the Mid-Murrumbidgee alluvial aquifer system are highly connected.

Figure CS6.3 shows comparative groundwater and river hydrographs in two parts of the Mid-Murrumbidgee Valley. For the river reach between Gundagai and Wagga Wagga (top chart in figure), the hydrographs indicate a close relationship between the groundwater level in the Cowra Formation (shown as Shepparton Formation) and the river level/flow. Between Wagga Wagga and Narrandera, it is not clear from the hydrographs (bottom chart in Figure CS6.3) whether significant interaction occurs between the aquifer system and the river.

The NSW Department of Natural Resources (now Department of Water and Energy) has conducted a numeric modelling study of the aquifer system in the Wagga Wagga area (Mitchell and O'Neill 2006). It revealed a relationship between the Murrumbidgee River, the Cowra Formation, and the Lachlan Formation. The modelling indicates that there is recharge of the Cowra and Lachlan Formations following flood events, and that a portion of this recharge returns to the river. Groundwater extraction from the Lachlan Formation was shown to have increased the vertical hydraulic conductivity between the Cowra and Lachlan Formations, which is predicted to lead to additional leakage from the Murrumbidgee River (Mitchell and O'Neill 2006).



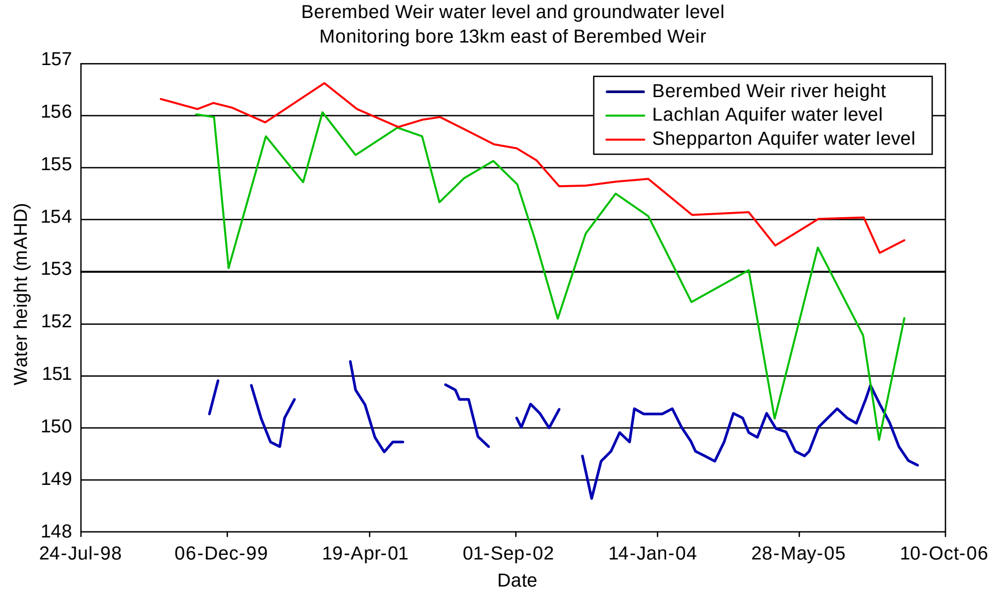


Figure CS6.3. Murrumbidgee River and groundwater hydrographs at Wagga Wagga (top panel) and Berembed Weir (bottom panel) (after Mitchell and O'Neill 2006).

CS6 Groundwater development and impact on streams

There is a variety of consumptive groundwater use in the alluvial aquifers along the Murrumbidgee River between Gundagai and Narrandera. The groundwater is used for urban water supply for Wagga Wagga and the surrounding towns, and for irrigation of crops and pasture, horticulture, rice and vegetables.

The earliest development of the groundwater occurred in the mid-1970s with the establishment of four bore fields in the vicinity of Wagga Wagga for urban water supply. The extraction of water from these bore fields has had a noticeable influence on the groundwater levels in the Wagga Wagga area, as shown in Figure CS6.3 (top chart).

Significant development of the resource for irrigation and other commercial enterprises did not occur until the late 1990s and early 2000s. This has resulted in significant groundwater level declines in the Lachlan and Cowra Formations (Mitchell and O'Neill 2006).

The State Water Corporation annually calculates the unaccounted losses and gains in the river system. The data from the previous five years suggests that with the growth in the construction of bores for commercial and irrigation developments, there has been a noticeable increase in losses from the river system. The majority of the growth in the development of the resource has occurred between Wagga Wagga and Narrandera. It is in this river reach that the most significant increase in flow losses has been observed.

CS6 Management status

The Mid-Murrumbidgee GMA is one of a number of significant alluvial groundwater sources in NSW. It forms part of a macro water-sharing plan currently being developed as part of the implementation of the NSW Water Management Act 2000. The plan development process for the Mid-Murrumbidgee has included the assessment of the current level of development, level of allocation, and the sustainable yield of the management area. The completed management plan will aim to ensure the sustainable management of the groundwater resource for licence holders and the environment.

The Department of Natural Resources is also currently developing a numerical groundwater model for part of the GMA in the vicinity of Wagga Wagga (Mitchell and O'Neill 2006). This model will assist in improving knowledge of the sources of recharge to the aquifer systems, their temporal variability, and the influence of groundwater extraction on aquifer system behaviour.

CS6 Data

Table CS6.1. Accumulated data sets and applied field and data collection methods for conceptualisation of groundwater–stream interaction in the Mid-Murrumbidgee area.

Data sets	Period of data record	Field or data collection methods
Mid-Murrumbidgee status report	2000	Desktop
Numerical model – Wagga Wagga area	1975–2005	Desktop
Groundwater level monitoring network	Early 1970s to present	Field measurements of water levels
Stream gauges at Gundagai, Wagga Wagga, Berembed Weir, and Narrandera	Early 1900s to present	Field measurements
Groundwater usage	2000 to present (additional data for Wagga Wagga town water supply back to 1975)	Field data collection and user return cards
Regulated river operating spreadsheet	2000 to present (may be able to locate earlier data)	User orders and gauging stations
River usage	1990s to present (possibly earlier data available)	Field data collection
IQQM	1900–2000 (approximately)	Desktop

CS6 Groundwater–stream interaction classification

Table CS6.2. Classification of Mid-Murrumbidgee using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to the Mid-Murrumbidgee for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as medium.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	# Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Unregulated flows in the tributaries of Kyeamba and Tarcutta Creeks

Case study 7: Upper Ovens Valley, Vic (contained alluvial valley system)

CS7 Location

The Ovens River is located in North East Victoria and flows in a north-westerly direction from the northern slopes of the Mount Hotham Alpine National Park, until its confluence with the Murray River near Yarrawonga. The Upper Ovens River catchment has an area of approximately 1,500 km² and is defined as the Ovens River catchment upstream of the confluence with Buffalo River near Myrtleford (Figure CS7.1). Groundwater in the catchment is extracted mostly from shallow alluvial sediments, but also from deeper alluvial and fractured rock aquifers.

CS7 Climate and physiography

The Upper Ovens Valley receives varying rainfall depending primarily on elevation. Averaged over the whole catchment, the approximate annual rainfall is 1,200 mm with, average monthly rainfall fluctuating between 57 mm in February and 181 mm in July. The average annual evaporation is 1,170 mm with average monthly evaporation ranging between 22 mm in June and 228 mm in January. Temperatures vary widely but generally the summers are warm and dry with winters being cold and wet. In summer, temperatures above 35˚C are not uncommon and in winter, snow can fall over the entire Upper Ovens catchment.

The Upper Ovens Basin lies on the northern slopes of the Eastern Highlands and is mostly mountainous with narrow alluvial plains. The area includes the major tributaries of the Buckland River, Barwidgee Creek and Morse Creek with areas of 435, 240 and 135 km^2 respectively.

CS7 Geological setting

The surface geology of the Upper Ovens catchment comprises broadly 3 units. (Figure CS7.2). The bedrock consists of Devonian granite, which forms Mount Buffalo, and consolidated Ordovician sediments in the surrounding ranges. These rocks have been dissected by fluvial processes, creating deep, narrow-sided valleys in which unconsolidated alluvial sediments of Quaternary and Tertiary age have been deposited (SKM 2006b).

The alluvial deposits in the Upper Ovens catchment consist of, from oldest to youngest, the Calivil Formation, Shepparton Formation and Coonambidgal Formation. In many places it is difficult to distinguish between these alluvial formations. The maximum recorded thickness of alluvial sediments in the Upper Ovens catchment is approximately 70 m (Shugg 1987). Extensive dredging undertaken during gold exploration has disturbed the alluvial sediments in several places over the full depth of alluvium.

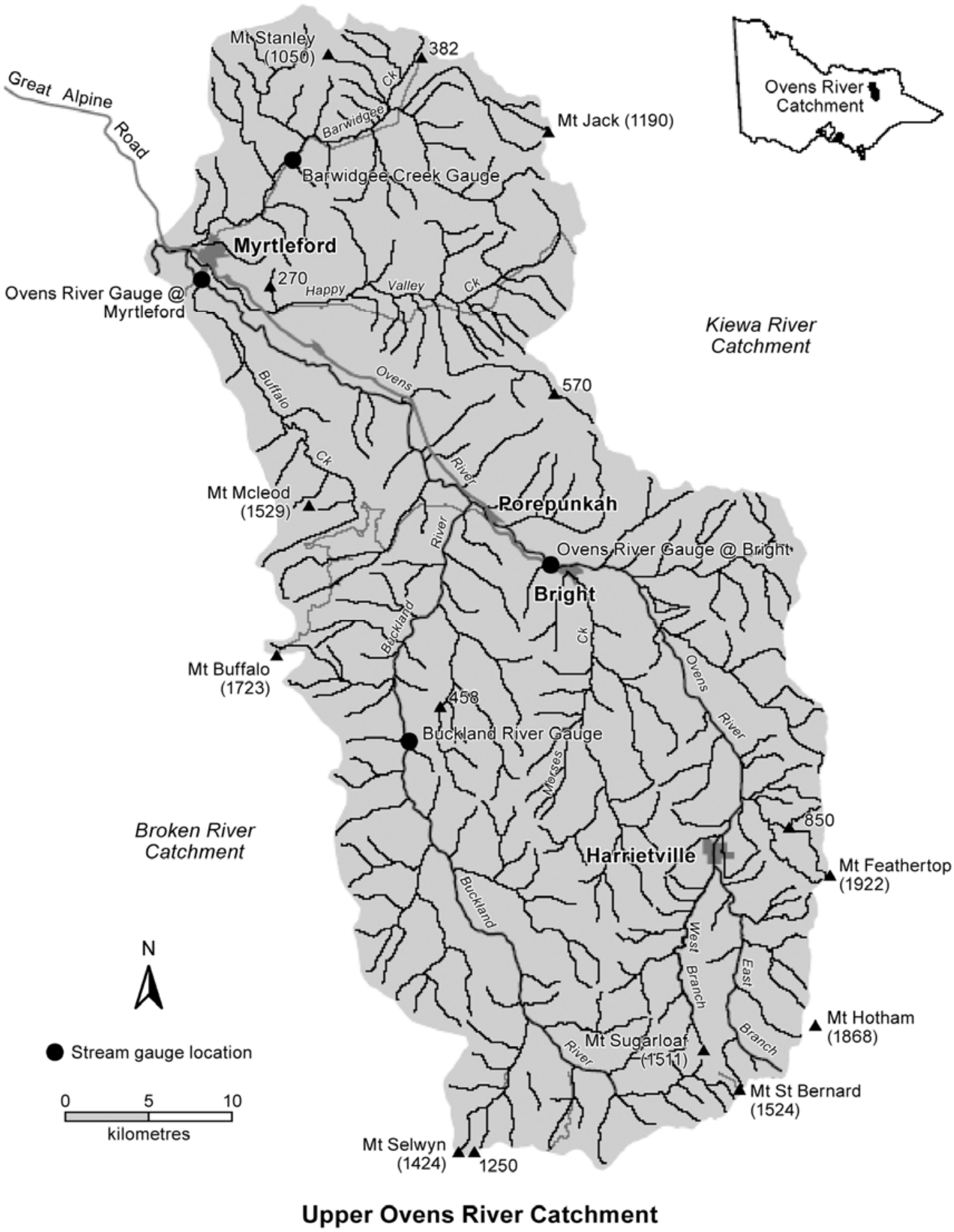


Figure CS7.1. Upper Ovens Water Management Area (after Goulburn–Murray Water 2003).

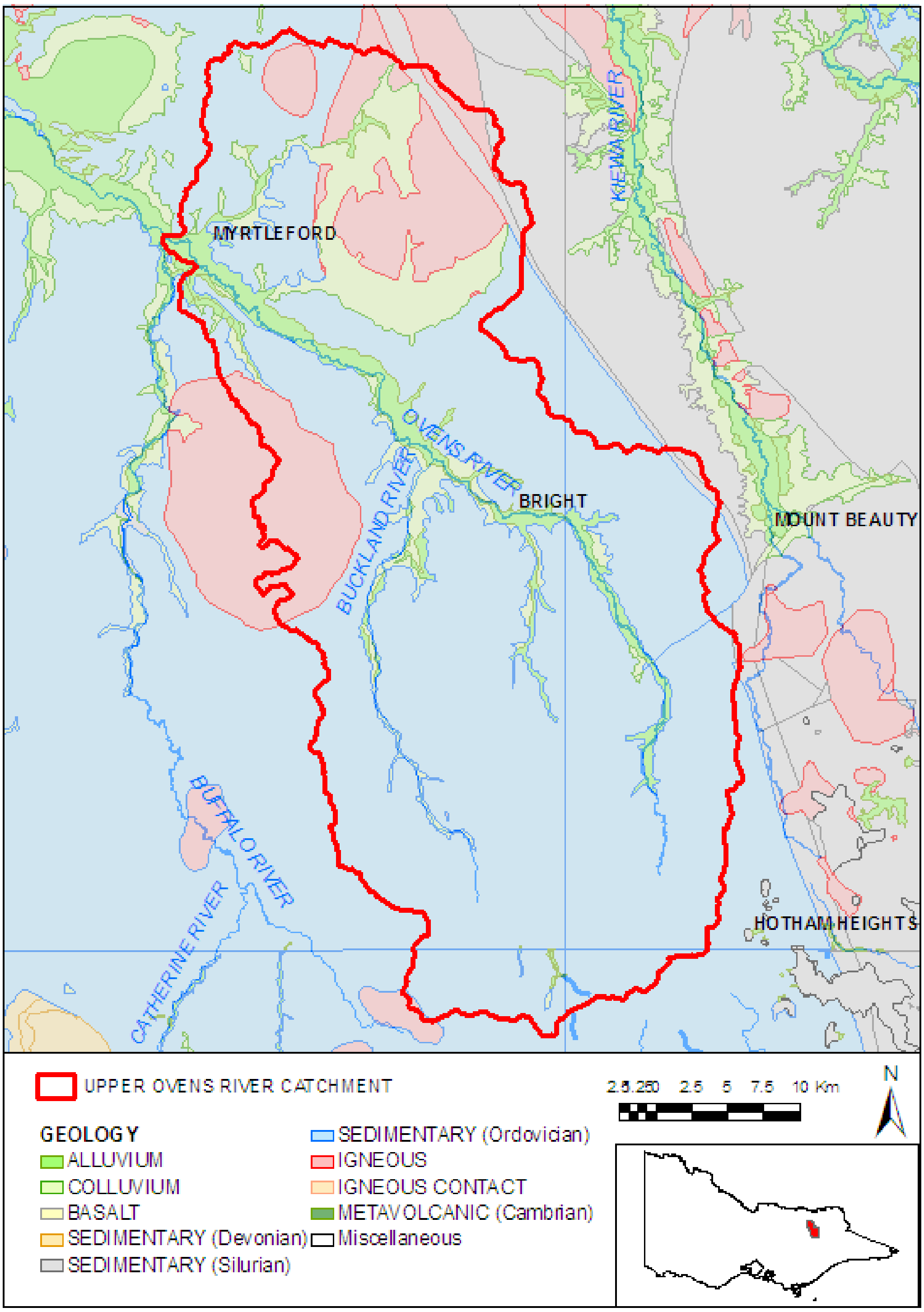


Figure CS7.2. Surface geology of Upper Ovens catchment (modified from SKM 2006b).

An extensive aquifer system exists in the bedrock, with groundwater contained in fractures and joints in the Ordovician shales and sandstones. A complex aquifer system operates within the alluvial sediments but SKM (2006b) have concluded that there is generally hydraulic connectivity between aquifer units in the alluvial sequence. The alluvial aquifer system is commonly utilised for irrigation and is the major groundwater resource. The fractured rock aquifers are mainly utilised for domestic and stock purposes and small-scale commercial developments.

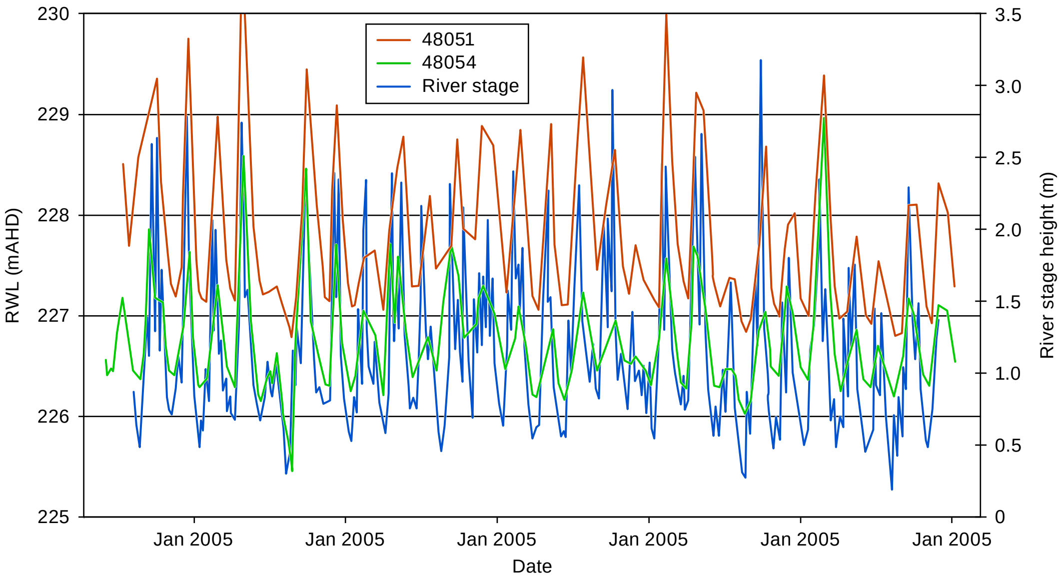


Figure CS7.3. Relationship between river level (lowest trace) and two groundwater bore levels (after SKM 2006a).

CS7 Groundwater–stream interaction

Strong interaction has been observed between the shallow alluvial groundwater and the Upper Ovens River (Cox 1989; Shugg 1987; SKM 2006a). Groundwater hydraulic gradients are steep at the top of the valley and shallow in the base of the valley where groundwater levels are close to stream levels (Shugg 1987). The groundwater–stream relationship is demonstrated in Figure CS7.3, which shows groundwater levels in two observation bores closely following river height trends.

Groundwater movement is generally towards the Ovens River (Tickell and Humphrys 1986), although the dredged areas of alluvium (or draglines) produce local groundwater flow anomalies (Shugg 1987). The vertical component of groundwater movement is downward (Tickell and Humphrys 1986). The Ovens River is generally a gaining stream, receiving contributions through bank storage, interflow and groundwater discharge (Shugg 1987). There exists a delicate balance of recharge and discharge where maintenance of surface water flow is significantly dependant on groundwater supply from the alluvial or bedrock aquifers (SKM 2006a).

In general, the alluvial aquifer system is essentially unconfined at all depths and interacts closely with the stream (SKM 2006b). The system-wide hydraulic communication may be accentuated in areas disturbed by dredging.

The Ovens River incises bedrock highs at Bright and Rocky Point in the upper catchment area. Hydrographs indicate that these bedrock highs may influence the level of interaction between groundwater and the river. In times of low flow, the recorded river flows at the Bright Gauge are higher than those at the downstream gauge at Myrtleford. This could indicate that dredging of the shallow alluvium between Bright and Myrtleford is already impacting on river flow and causing it to become a losing stream at times of low flow. An alternative theory is that downvalley flow of groundwater is forced up (under hydraulic head) at the Bright bedrock high and becomes baseflow (Shugg 1987; SKM 2006b). A conceptual model has been developed that holistically describes the stream–aquifer system in the Upper Ovens catchment (SKM 2007). Further research is continuing into the direction, timing and magnitude of groundwater–stream fluxes.

CS7 Groundwater development and impact on streams

In the Upper Ovens Catchment, there is a total volume of approximately 3,200 ML of allocated groundwater licences. The magnitude of the impacts on stream flow from groundwater use is unknown as groundwater extraction has been unmetered. However, SKM (2006b) have concluded that all groundwater extraction in the Upper Ovens Valley alluvial aquifers will ultimately, if not already, impact to some degree on stream flow. Impacts are dependent on lag time and this is dependent on distance from the river, geology, human impacts (e.g. dredging from draglines) and physiography. Field studies are currently being undertaken by G-MW and the Department of Sustainability and Environment to quantify lag times and aid the development of management strategies for the conjunctive use of groundwater and surface water.

The majority of groundwater used in the Upper Ovens catchment is extracted from the shallow aquifers via draglines. Generally, these are large holes or trenches in the shallow alluvium that allow easy pumping of shallow groundwater. The strong interaction between groundwater and stream flow has been recognised for decades and the impact of draglines close to streams has been managed by treating draglines within 200 m of a major stream as surface water. In this respect they are subject to the same rules and restrictions as surface water. As such, these particular draglines are not included in the 3,200 ML of groundwater licence volume mentioned above.

CS7 Management status

The Murmungee (Ovens) Groundwater Management Area (GMA) was established to protect the alluvial aquifers in the Upper (and Lower) Ovens Valley and its major tributaries. Based on total licensed allocations and estimates of sustainable yield, approximately 88% of the estimated available resource in the defined Murmungee GMA has been allocated (SKM 2006b). Therefore, as a precautionary measure, Goulburn–Murray Water (G-MW) has imposed a moratorium on the allocation of any additional groundwater licences in the GMA. The moratorium has recently been extended to cover the entire Upper Ovens catchment and now incorporates bedrock and colluvial aquifers.

Under the Victorian Government's White Paper, 'Securing Our Water Future Together' (Victorian Government 2004), G-MW will project manage the development of a Water Management Plan for the Upper Ovens Catchment. This plan will provide for conjunctive management of surface and groundwater in the plan area. The draft groundwater and surface water management plan will be developed by a consultative committee, which includes community representatives from all relevant stakeholder groups. It is envisaged that the plan will seek to formalise current management practices and manage both water resources to minimise impacts to the environment.

Before the management plan can be developed, a sound understanding of the groundwater system and groundwater stream interaction is required. Theoretical, broad-scale management strategy options have been evaluated and recommendations have been made using the Upper Ovens catchment as a case study (SKM 2006b). Further technical work is underway to verify the findings of this desktop study. A metering program is being implemented for the Upper Ovens catchment and it is expected that this will provide an accurate estimate of groundwater usage and aid in quantifying the interaction of groundwater with the Upper Ovens River.

CS7 Data

Table CS7.1 summarises the accumulated data sets and applied field and data collection methods for conceptualisation of groundwater–stream interaction in the case study area.

Table CS7.1. Summary of available data sets and data collection methods in the Upper Ovens catchment.

Data sets	Period of data record	Field or data collection methods
Topography	2007	Digital elevation model (DEM)
Geology/soils, groundwater resources, aquifer thickness	Early 1900s to present	Drilling logs, bore completion reports, government and consultant reports, geology and soil maps
Ecology	1990s to 2006/07	Wetland area surveys (reports in progress). Stream health indices (report).
Aquifer parameters	1980s to present	Pumping tests, continuous groundwater level monitoring (reports)
Water quality, detailed groundwater chemistry, residence time	2005–2006	Hydrogeochemical and stable/radioactive isotope survey (report)
Hydrogeological modelling: recharge–discharge zones; cross sections	2007	Conceptual groundwater model
Surface water	1972–2007	Victorian Data Warehouse holds historical flow records for gauges in the area.
Groundwater levels	1980s to present	State observation bores monitored quarterly (database)

CS7 Groundwater–stream interaction classification

Table CS7.2. Classification of Upper Ovens Valley using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to the Upper Ovens Valley for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as medium.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Case study 8: Chowilla Floodplain, SA (regional system)

CS8 Location

The Chowilla Floodplain is on the northern side of the River Murray, and is located near the borders of South Australia, New South Wales and Victoria (Figure CS8.1). Most of the floodplain lies in South Australia, with a section extending into New South Wales. It covers 17,700 ha, forming the largest floodplain complex in the lower River Murray (MDBC 2002).

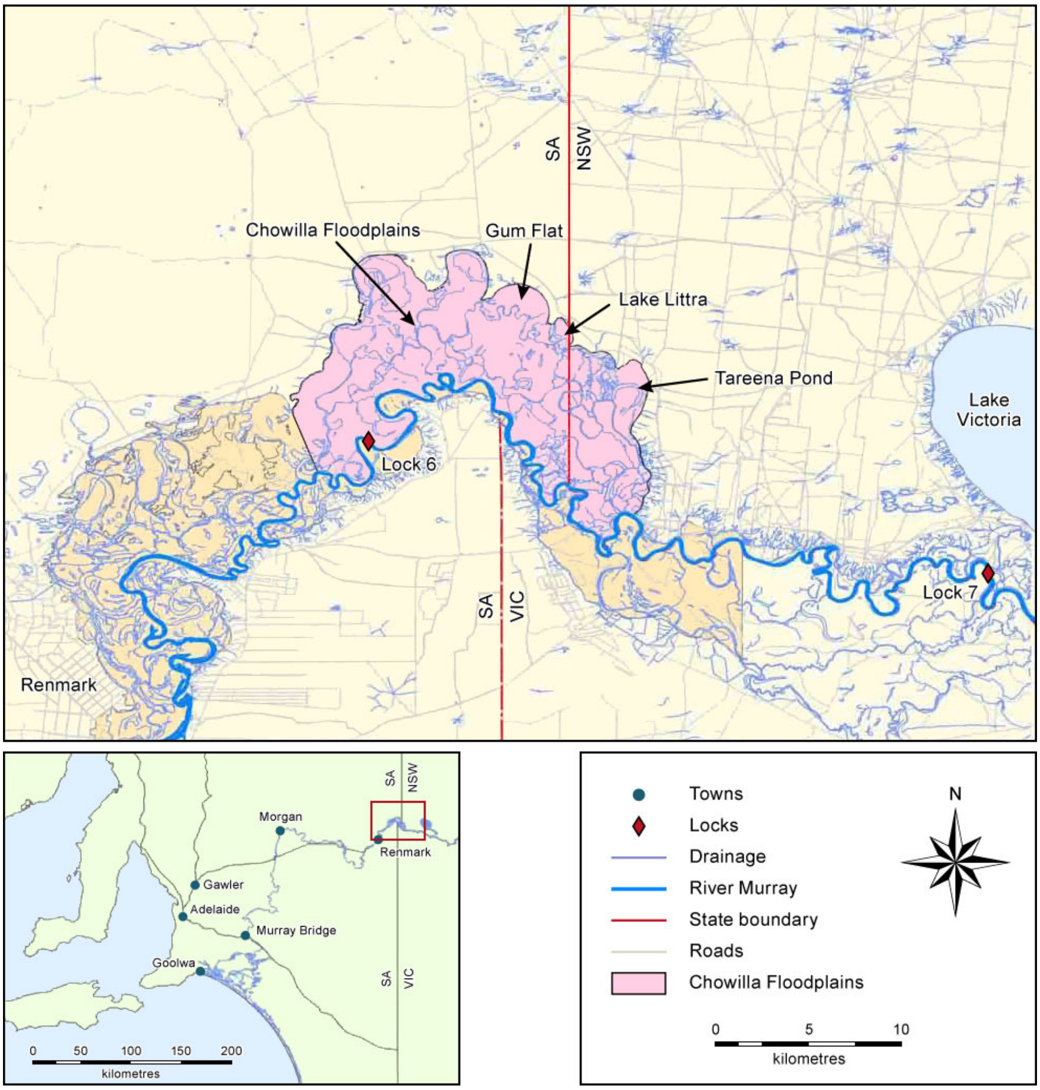


Figure CS8.1. Location of the Chowilla floodplain case study (after Yan et al. 2005).

The floodplain is the largest remaining area of natural riverine forest in South Australia and is included within a 'Riverland Wetland of International Importance' under the UNESCO RAMSAR Convention. The floodplain is typical of those in the lower reaches of the River Murray in that it is underlain by saline groundwater at depths of two to four metres (Overton and Jolly 2004b).

CS8 Climate and physiography

The region has a semi-arid climate with a mean annual rainfall of about 260 mm/yr and a potential evaporation of about 2,000 mm/yr. Annual rainfall is highly variable, ranging from less than 100 mm to over 500 mm. Monthly rainfall averages are reasonably uniform with only a slight winter dominance.

The Chowilla Floodplain consists of a network of streams that flow from the River Murray upstream of Lock 6 and across the 6–8 km wide floodplain. They eventually join together to form Chowilla Creek which discharges back into the River Murray downstream of Lock 6. Prior to the installation of Lock 6, the floodplain streams were ephemeral and flowed only during times of flood (Jolly et al. 1994). The construction of Lock 6 in 1930 on the River Murray resulted in permanently higher water levels on the adjacent streams and higher groundwater levels (Sharley and Huggan 1995).

CS8 Geological setting

A typical cross-section of the Chowilla Floodplain is shown in Figure CS8.2. The Pliocene Sands forms a regionally extensive unconfined to semi-confined aquifer into which the channel of the ancestral River Murray is incised. Within this channel (the Murray Trench), the Monoman Formation and the overlying surficial sediments of the Coonambidgal Formation were deposited, and it is within this sequence that the channel of the modern River Murray is incised (Yan et al. 2005). Underlying the entire region is the Murray Group limestone aquifer, which is confined by the Bookpurnong Beds (micaceous and glauconitic sands and marls) and the Winnambool Formation (marls, glauconitic marly limestone, and marly clays) (Jolly et al.1994).

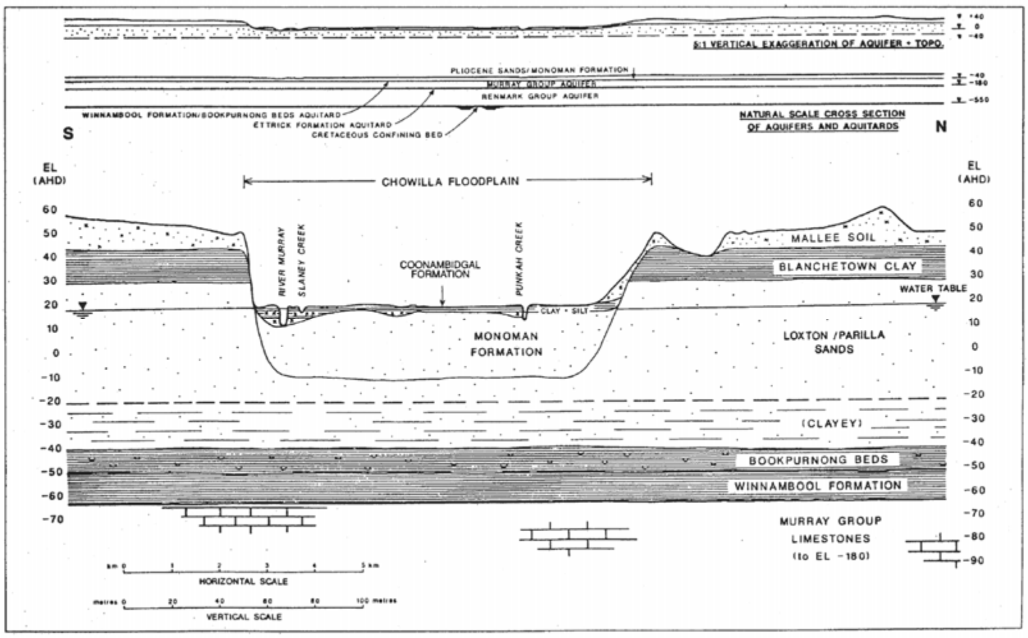


Figure CS8.2. Cross-section of the hydrogeology of the River Murray floodplain in the vicinity of Chowilla (after Yan et al. 2005).

The Pliocene Sands and the Lower Monoman Formation are considered to be in direct hydraulic communication. The Monoman Formation and the Pliocene Sands have a total combined thickness of 50 m. In the floodplain, the water table occurs within the Coonambidgal Formation (Yan et al. 2005).

CS8 Groundwater–stream interaction

Saline groundwater enters the Chowilla Floodplain by lateral flow from the Pliocene Sands, and by slow vertical leakage through the Bookpurnong Formation from the underlying regional, confined Murray Group Limestone. Saline groundwater (25,000–50,000 mg/L TDS) enters the River Murray by direct inflow, and via the flux of groundwater entering the anabranch creeks that then deliver the salt load to the river (Yan et al. 2005).

The hydraulic communication between the Monoman Formation and the anabranch creeks is an important factor controlling salt movement on the Chowilla Floodplain. The flux of saline groundwater entering the creeks is determined by the hydraulic conductivity on the sides and bottom of the creeks, and the head difference between the water table and the stage of the creeks. Measurements of the groundwater level in the aquifer and the stage of the creeks at a similar time are critical for understanding the conductance between them. This data can then be used to calculate the flux of saline groundwater entering the creeks, and consequently, the total salt load being delivered to the River Murray (Yan et al. 2005).

It is also believed that Lock 6 and Lock 7 impart hydraulic impacts on the Chowilla Floodplain groundwater system. Controlled pool levels above the locks have resulted in the elevation of the water table across the Chowilla Floodplain (Figures CS8.3a and b), and altered flows in the Anabranch Creek system that occurs on the floodplain. In parts of the floodplain, the elevated water table has resulted in increased salt accumulation and this has resulted in severe consequences for vegetation health. It has generally been accepted that there has been an increase in the flux of saline groundwater entering the anabranch creeks (occurring in response to the elevated water table), and this has resulted in an increased salt load being delivered to the River Murray. On average 130 tonnes/day of salt enters the Chowilla Floodplain with groundwater inflow. After extended dry periods and low flows in the River Murray, the salt load entering the anabranch creeks from the aquifer system (and thus the river) is 40–60 tonnes/day. The maximum peak of 1,800 tonnes/day followed the 1974 flood.

CS8 Groundwater development and impact on streams

Groundwater development is currently insignificant and has limited impact on streams. However, a groundwater modelling study was carried out by Yan et al. (2005) to investigate the impact of salt interception schemes (SIS) on groundwater levels and salt load being delivered to the River Murray. The modelling results indicated that groundwater pumping could significantly lower water tables across the Chowilla Floodplain and consequently reduce saline groundwater entering the streams (Figure CS8.4). The reach of the River Murray adjacent to the floodplain above Lock-6 could become a dominantly losing stream.

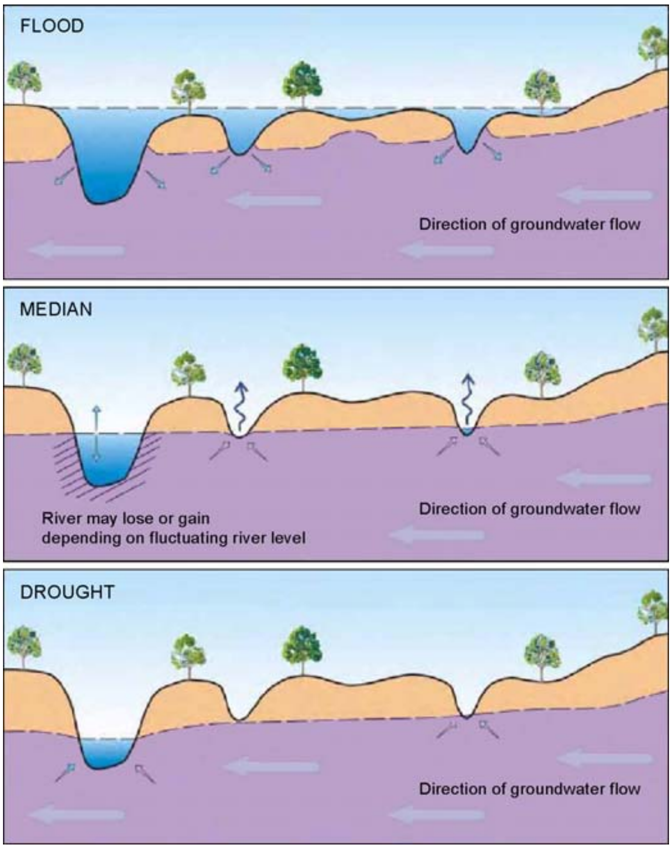


Figure CS8.3a. The river, creek and groundwater interaction prior to river locking (after Yan et al. 2005).

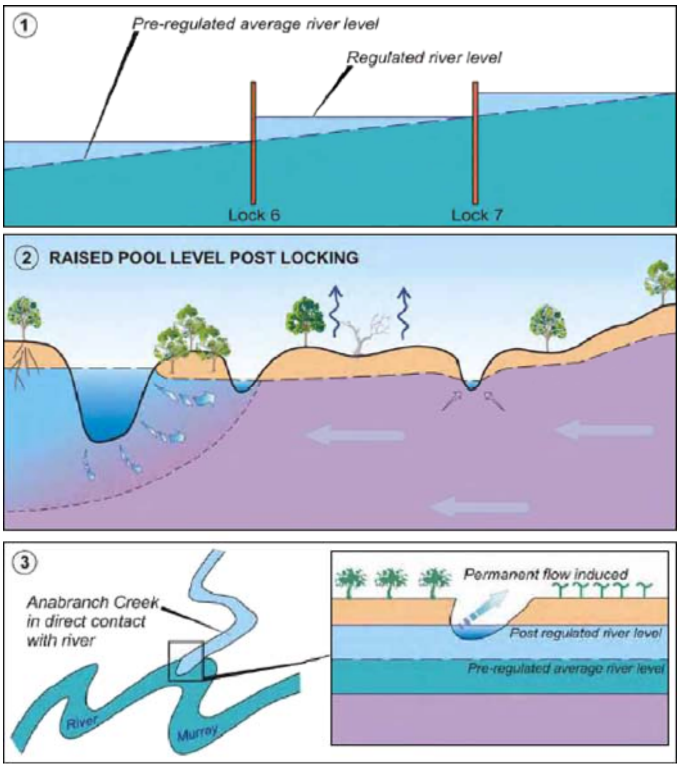


Figure CS8.3b. The river, creek and groundwater interaction after river locking (after Yan et al. 2005).

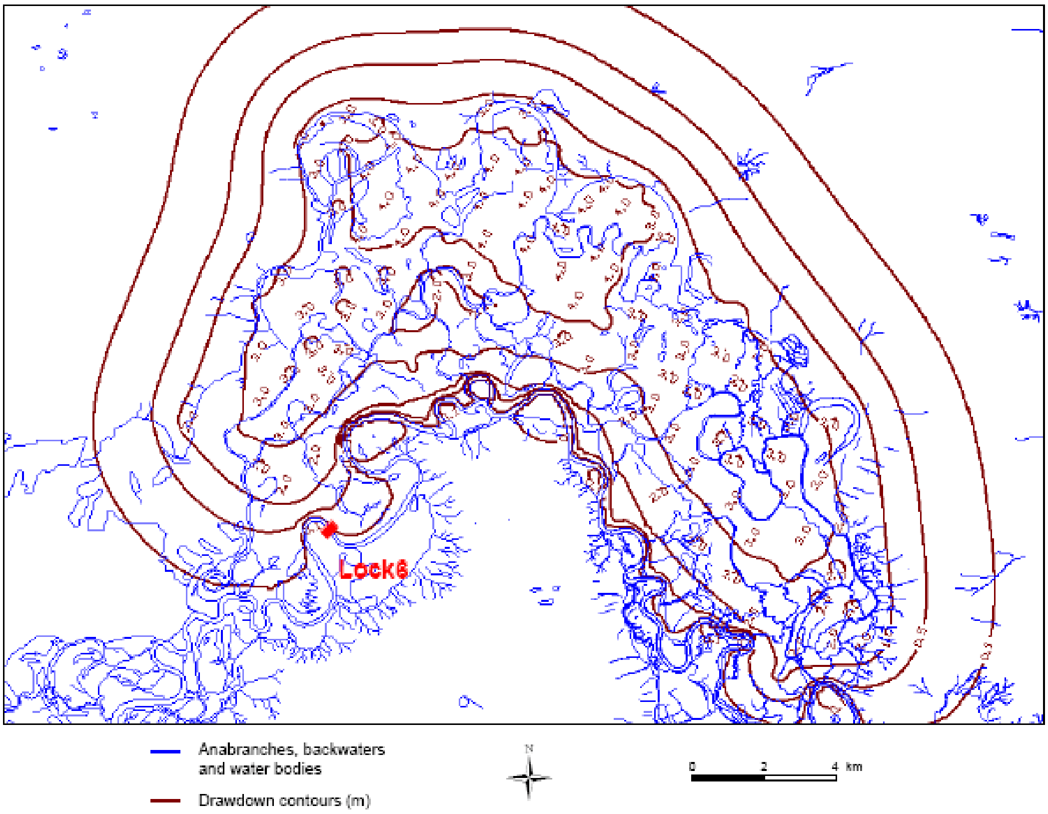


Figure CS8.4. Modelled drawdown contours (m) after 5 years of operation of a SIS comprising 119 production wells (after Yan et al. 2005).

CS8 Management intervention and status

Rising groundwater levels, reduced flood frequency, rapid flood recession, and stable weir pool levels are the main hydrological causes of environmental problems at Chowilla Floodplain. Actions that could improve the environmental condition of Chowilla Floodplain include increasing the frequency and duration of flows, and improving groundwater and salinity management (Overton and Jolly 2004a). Also, improved land management activities such as reducing stock grazing pressure, removing feral animals and controlling over-abundant native species would probably lead to improved environmental health (MDBC 2005). Important actions implemented include:

- Integrated catchment and salinity management. In 1992, after a period of intensive research and public consultation, an integrated resource management plan for Chowilla Floodplain was developed by South Australia focusing on saline groundwater management and rehabilitation of floodplain biodiversity;
- Enhancement of natural floods to increase their peak or duration using water releases from storages.

A major program is underway (Yan et al. 2005) to design and construct a groundwater management scheme that will either:

- Control groundwater levels in targeted areas on the Chowilla floodplain and control the flux of saline groundwater entering the anabranch creeks, i.e. a salt interception scheme (SIS), or:
- Control groundwater levels below evapotranspiration extinction depth in targeted areas on the Chowilla floodplain, which will:
  a. Allow the regeneration of the natural vegetation across the floodplain.
  b. Control the flux of saline groundwater entering the anabranch creeks.

CS8 Data

There have been extensive field investigations carried out at the Chowilla Floodplain over the last 50 years. Good summaries of the available data can be found in Overton and Jolly (2004a), Overton et al*.* (2005), Clark (2005) and Yan et al*.* (2005). The data sets summarised below are those most relevant to groundwater–stream interaction.

Table CS8.1. Accumulated data sets and applied field and data collection methods for conceptualisation of groundwater–stream interaction in the Chowilla Floodplain.

Data sets	Period of data record	Field or data collection methods
Flood masks (33, 42, 47, 62, 70, 77, 82, 98, 101 GL/day floods)	N/A	From Chowilla GIS modelling work as a component of the Chowilla Resource Management Plan (Sharley and Huggan 1995).
Flood inundation model		Developed by SA Water and the MDBC to predict the extent of inundation from flows at every 1 GL/day step (Overton et al. 1999; Overton 2005).
Groundwater depth	Intermittent. DWLBC and CSIRO Land and Water have been collecting data from late 1980s onwards. DWLBC currently have a monitoring network. CSIRO collected data presented in Jolly et al. (1992), McEwan et al. (1994) and McEwan et al. (1995). Maps of groundwater depth presented in Overton and Jolly (2004a) and Overton et al. (2005).	Manual water level readings and some logged data.
Groundwater salinity/chemistry	Intermittent. DWLBC and CSIRO Land and Water have been collecting data from late 1980s onwards. Not routinely measured in DWLBC monitoring network. CSIRO collected data presented in Jolly et al. (1992), McEwan et al. (1994) and McEwan et al. (1995). Maps of groundwater salinity presented in Collingham (1990a and 1990b), Overton and Jolly (2004a), Overton et al. (2005) and Sharley and Huggan (1995). Study of hydrochemistry carried out by Vader et al. (1994).	Manual EC readings and full laboratory chemistry analyses.

Data sets	Period of data record	Field or data collection methods
Aquifer parameters	Over the last 50 years and still continuing. Results published in Barling (1999), Howles and Marsden (2003), Johnson et al. (1960), and Watkins (1992)	Numerous pumping tests
Topography	1993 2005	DEM developed from spot heights by Noyce and Nicolson (1993). LiDAR-based high resolution DEM
Soil types	1990	Field and aerial photo geomorphological mapping of landscape units by Hollingsworth (1990). Overton and Jolly (2004a) produced a simplified soil map based on Hollingsworth (1990) maps, Landsat imagery and surface topography
Soil salinity	Intermittent measurements by CSIRO Land and Water and Flinders University between 1989 and 1996. Results published in Eldridge et al. (1993), McEwan et al. (1991), McEwan et al. (1994), McEwan et al. (1995), Thorburn (1993) and Zubrinich (1996)	Chloride in soil solution, gravimetric water content, matric suction
Recharge areas	1990 to 2004–5	Maps of potential maximum recharge rates developed by Overton et al. (2005) based on simplified soil map, Landsat NDVI imagery, and Helicopter TEM survey
Helicopter TEM survey	2005	Transient Electromagnetic Induction survey targeting recharge areas, aquifer salinities and geology
Landsat satellite imagery	1983, 1984, 1988, 1994, 1995, 2002, 2003, 2004	Landsat Multi-Spectral Scanner and Landsat Thematic Mapper
Salt loads from Chowilla to River Murray	1974–present	Measured difference in EC upstream and downstream of where Chowilla Creek enters River Murray. Results summarised in Sharley and Huggan (1995) and Stace and Greenwood (2004)
Flows and salt loads within Chowilla	Intermittent measurements from 1972 to present	Field measured flow and EC. Results summarised in Sharley and Huggan (1995) and Stace and Greenwood (2004)

CS8 Groundwater–stream interaction classification

Table CS8.2. Classification of Chowilla Floodplain using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to the Chowilla Floodplain for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as high.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Case study 9: Lower Murrumbidgee, NSW (regional system)

CS9 Location

The Lower Murrumbidgee Groundwater Management Area (GMA) lies within the eastern Riverine Plains province of the Murray–Darling Basin. It is located between the towns of Narrandera, Booligal, Balranald and Jerilderie and is bounded by Billabong Creek and the Edwards River in the south, the Lachlan River to the north-west, and exposed Palaeozoic bedrock to the east (Figure CS9.1). It covers an area of approximately 33,000 km^2.

CS9 Climate and physiography

Rainfall exhibits a generally decreasing pattern towards the west. Average annual rainfall figures range from about 440 mm at Narrandera to 320 mm at Balranald. Annual evaporation within the area is also variable and ranges approximately between 1600 and 2000 mm.

The area is generally flat with a very shallow gradient to the west. Ground elevations range from 162 m in the east at Narrandera to about 56 m at Balranald. The Murrumbidgee River enters the Riverine Plain at Narrandera and flows in a westerly direction through the central part of the area. Other minor rivers and creeks run mainly along the edges of the area and include the Lachlan River, Billabong Creek, Edward River, Yanco Creek and Colombo Creek.

CS9 Geological setting

The Lower Murrumbidgee GMA lies within the eastern Riverine Plains province of the Murray–Darling Basin and is underlain by semi-consolidated to unconsolidated flat-lying Cainozoic sediments of mainly continental origin. Deposition of the sediments began some 50 million years ago (early Palaeocene). The maximum thickness varies from 170 m in the east (at Narrandera) to about 400 m at Balranald (western end of GMA). The sediments overlie Palaeozoic and Mesozoic rocks that form the basement (Kumar 2002). Within the GMA, the sedimentary deposits have been subdivided into three main units or layers. From youngest to oldest, these are Shepparton Formation, Calivil Formation and the Renmark Group. Figure CS9.1 shows three geological sections across the GMA.

The Shepparton Formation forms the uppermost aquifer and is of Late Pliocene to Pleistocene age. It directly overlies the Calivil Formation and is a complex assemblage of clays, silts and sands that was deposited in a fluvio-lacustrine (streams and lakes) environment. The proportion of sand in the sequence is highly variable but mostly about 20 to 30%, occurring predominantly in the top third of the formation. The formation thickness is variable and averages around 65 m.

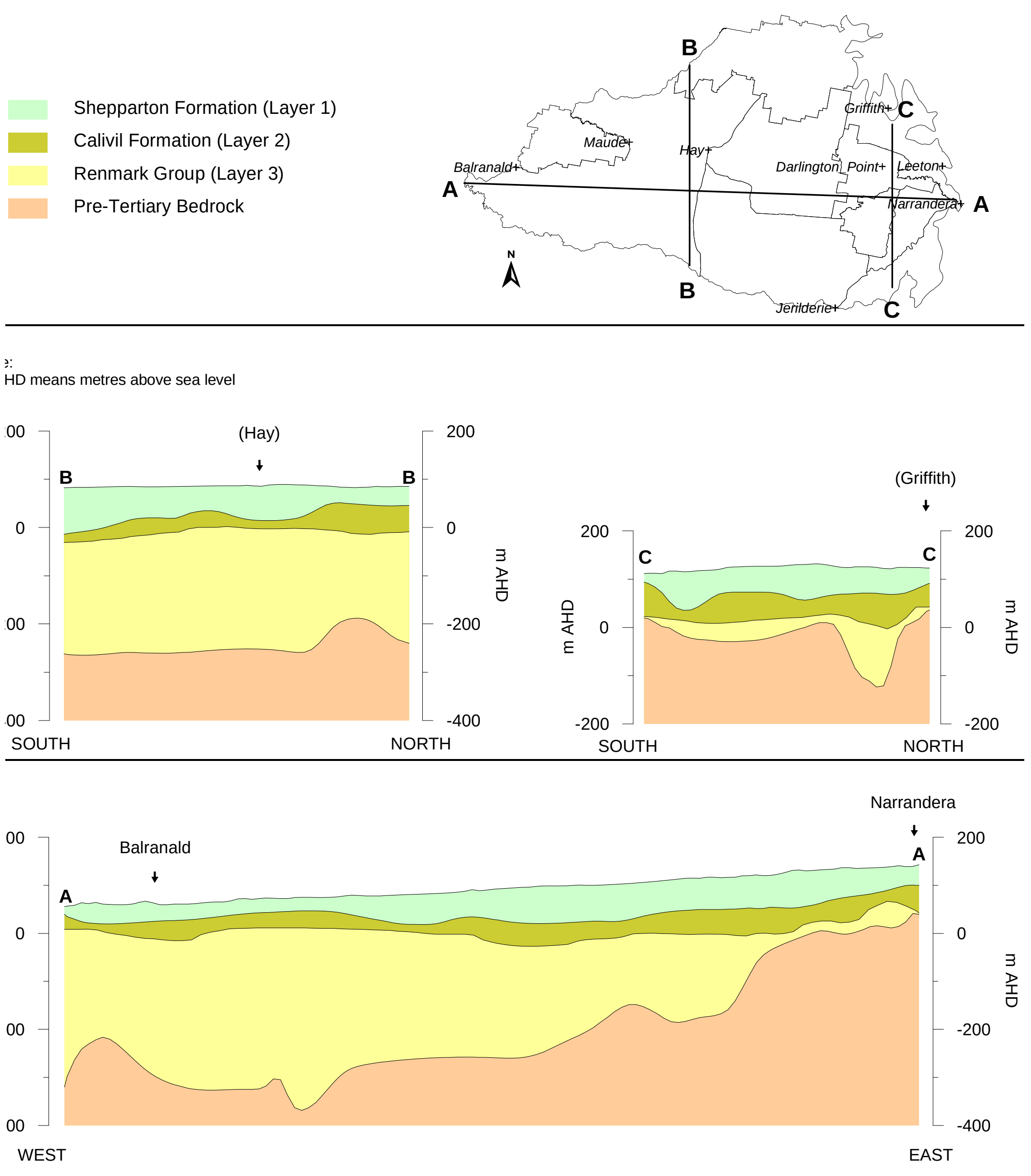


Figure CS9.1. Location plan and geological sections AA, BB and CC (after O'Neill 2005).

The Calivil Formation forms the semi-confined to confined middle aquifer and was deposited during the Late to Middle Miocene period (5–15 million years ago). It is dominated by pale grey, coarse quartz sand with lenses of pale grey to white kaolinitic clay. Its higher proportion of sand, typically 50–70%, makes it the most productive aquifer within the Lower Murrumbidgee GMA. The thickness of the Calivil Formation ranges between 50 and 70 m in the eastern part of the management area with a maximum of about 90 m.

The Renmark Group forms the basal confined aquifer. It is characterised by dark grey to black carbonaceous clay and dark brown lignite units but also contains thick sequences of grey, medium-grained quartz sand, which commonly comprise 30–50% of the entire unit. Its thickness is variable and peaks at a recorded 366 m.

CS9 Groundwater–stream interaction

Recharge to the Shepparton Formation Aquifer (shallow aquifer) occurs through rainfall infiltration, leakage from the Murrumbidgee River, leakage from Yanco and Colombo Creeks, and infiltration from applied irrigation water (both surface and groundwater). The deeper aquifers are recharged primarily through vertical leakage from the Shepparton Formation and throughflow from upstream of Narrandera, to the east of the area (Figure CS9.2; O'Neill 2005).

Low salinity groundwater (<500 mg/L TDS) in the Shepparton Formation occurs close to the Murrumbidgee River and sporadically within irrigation areas and areas where prior streams existed. It is usually in these areas, mostly to the east of Hay, where there is good vertical hydraulic connection allowing recharge to the Calivil Formation.

Modelling work to date by the Department of Natural Resources (O'Neill 2005) suggests that the river leakage contribution to the groundwater system is largely independent of the rate of groundwater extraction from the Calivil Formation and Renmark Group aquifers.

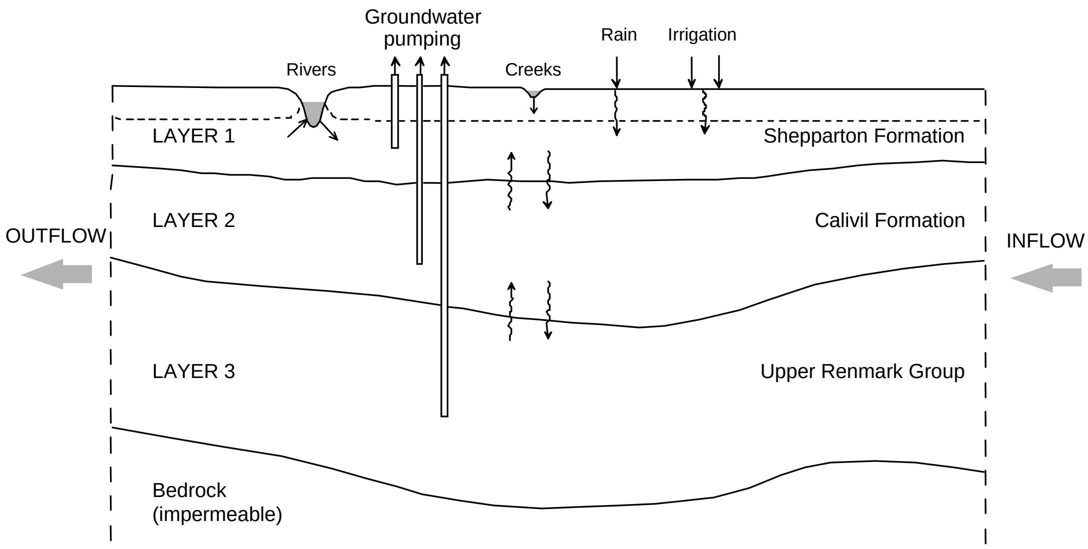


Figure CS9.2. Conceptual model of Lower Murrumbidgee groundwater sources (after O'Neill 2005).

CS9 Groundwater development and impact on streams

Large amounts of fresh groundwater have been extracted in the Lower Murrumbidgee GMA, particularly from the Calivil Formation and Renmark Group aquifers, which are the main groundwater sources for irrigation. There are approximately 178 licensed users of the Calivil Formation and Renmark Group aquifers, sometimes collectively referred to as the Calivil–Renmark Aquifer. These aquifers commonly yield fresh groundwater with the best quality groundwater in the Calivil Formation (<1,000 mg/L TDS) occurring east of Hay (Kumar 2002). The use of groundwater from these aquifers for irrigation purposes has been recorded since the early 1980s. Significant increase in usage was observed during the 1994/1995 irrigation season (>100,000 ML). The figures rose above 200,000 ML during the 1997/1998 season and peaked at 381,405 ML during the 2002/2003 season. Figure CS9.3 shows annual extractions for the Lower Murrumbidgee.

The Shepparton Formation Aquifer is the main source for stock and domestic supply. The groundwater salinity is generally higher (1,500 to 7,000 mg/L TDS) and more variable than that of the Calivil Formation and Renmark Group. At present there are some 400 licensed stock and domestic users and possibly a similar number of unlicensed users. Groundwater usage is not monitored but is estimated to be around 8,000 ML/yr. There are also a small number of licensed users extracting groundwater from the Shepparton Formation for irrigation within the Murrumbidgee and Coleambally Irrigation Areas. The use for irrigation is estimated at around 2,000 ML/year (Kumar 2002).

Groundwater generally flows from east to west across the Lower Murrumbidgee GMA under gentle hydraulic gradients. Groundwater levels across the GMA showed gentle rising trends until the late 1980s to early 1990s. However, levels have been falling significantly since the early to mid 1990s (Figure CS9.4). This is attributed to the significant increase in groundwater usage since the 1994/1995 irrigation season (over 230,000 ML/year after 1997/98). The continued declining trend since the mid-1990s indicates that extractions are taking place at rates higher than the rate of aquifer replenishment. The lack of seasonal groundwater level recovery around Hay, Carrathool and Steam Plains is a further indication of this.

Groundwater extraction is concentrated in areas between Hay and Narrandera. This has caused development of local ‘hotspots’, or areas with large observed seasonal or long-term drawdowns in groundwater level, particularly around Darlington Point, Gundaline and Steam Plains (Kumar 2002). In areas such as this, the deep pumping stresses have induced downward leakage of more saline groundwater from the Shepparton Formation causing some salinisation of the Calivil Formation (Timms et al. 2002).

Hydrographs in Figure CS9.4 show that seasonal groundwater responses to extractions have been occurring since the late 1970s and early 1980s in the eastern part of the GMA, where groundwater development for irrigation began early. Seasonal responses to extractions further west, around Hay, have occurred much later (during mid-1990s), as expected, with groundwater development occurring later in this area.

Groundwater pumping from the Calivil Formation and Renmark Group aquifers has an impact on Shepparton Formation watertables. This is possibly due to the presence of hydraulically connected prior stream and ancestral river deposits. However, the drawdown in these deep aquifers is not translated into equivalent drawdown in the Shepparton Formation Aquifer, either spatially or temporally, and there is a considerable time lag between impacts of deep pumping on groundwater levels in the deep aquifers and the Shepparton Formation. The impact of the pumping on the Murrumbidgee River is not yet evident but may be delayed due to the size and complexity of the Lower Murrumbidgee groundwater–stream system (Khan et al. 2000; Kumar 2002; O’Neill 2005).

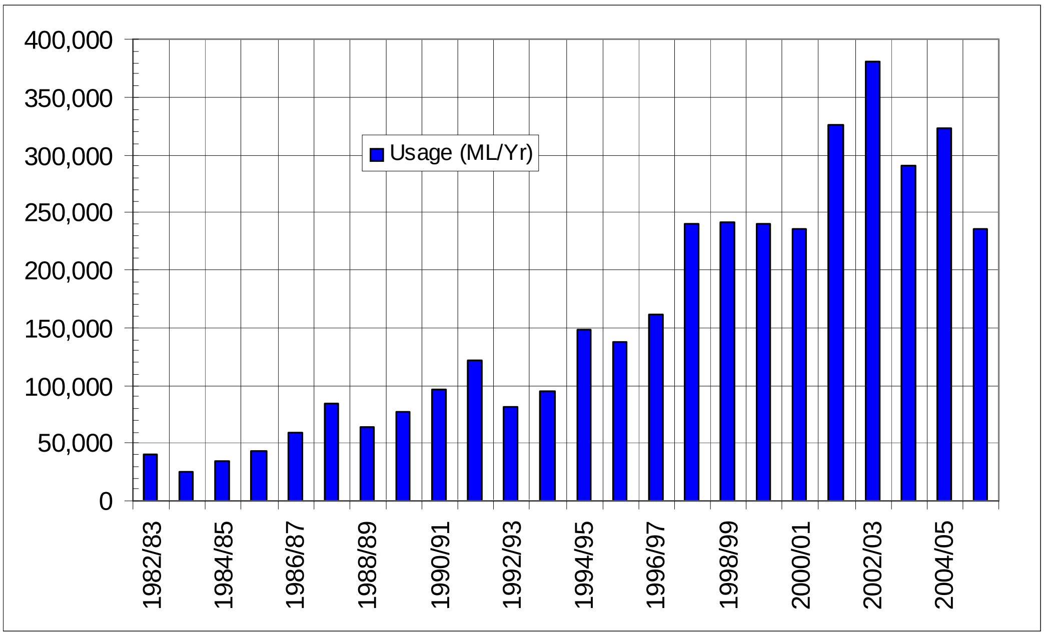


Figure CS9.3. Annual groundwater extractions in the Lower Murrumbidgee GMA (source: P. Kumar, Department of Water and Energy 2007).

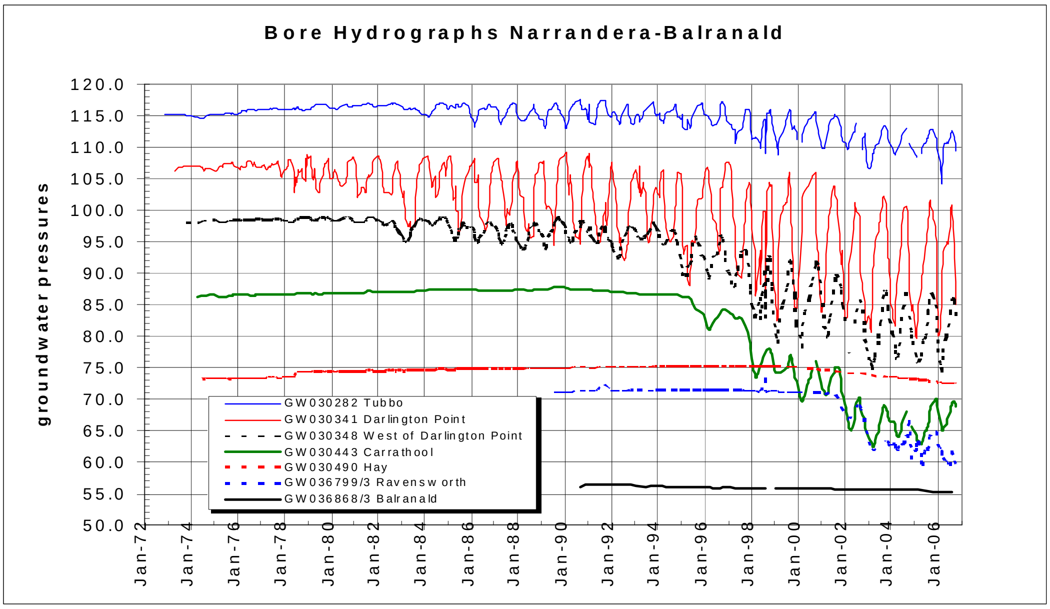


Figure CS9.4. Groundwater hydrographs of bores in Calivil Formation and Renmark Group aquifers (source: P. Kumar, Department of Water and Energy 2007).

CS9 Management intervention and status

Summaries of the groundwater management history and rules governing groundwater extraction in the Lower Murrumbidgee Valley are provided in Tables CS9.1 and CS9.2.

Table CS9.1. Groundwater management history in the Lower Murrumbidgee GMA.

Period	Description
1955	All water bores constructed required a license. Licenses were issued in perpetuity with no area or volume based restrictions.
1972–1984	Licences became renewable on a 5-year basis and were issued initially based on authorised area for irrigation, and later on a volumetric basis.
1984–1991	Licences in the Lower Murrumbidgee Groundwater Management Area were issued on a revised volumetric allocation basis
1991–1997	Licences in the Lower Murrumbidgee Groundwater Management Area were issued on a further revised volumetric allocation basis
1997	A 12-month moratorium preventing the issue of groundwater entitlement for irrigation use was put in place in September 1997 for the Lower Murrumbidgee Groundwater Management Area.
1998	The moratorium was extended for an additional 18 months in September 1998.
1999	The above moratorium was replaced by a statutory embargo in September 1999.
2000	In May 2000 a moratorium was placed on all new bore licenses for irrigation and Industrial purposes. This prevents the drilling of additional bores even where entitlements still exist.
2001	Conjunctive bore licenses converted to fixed groundwater entitlements
2003	Water Sharing Plan for Lower Murrumbidgee Groundwater Sources was developed.
2006	Water Sharing Plan for Lower Murrumbidgee Groundwater Sources was implemented on 1 October 2006. Groundwater entitlement in the deep source was reduced to the sustainable yield under the Achieving Sustainable groundwater Entitlements Program.

Table CS9.2. Groundwater extraction rules in the Lower Murrumbidgee GMA

Period	Access limit	Purpose
pre-1982	Unlimited or not specified	Low level of groundwater usage
1982/83 – 1990/91	Access to 100% of entitlement	Low level of groundwater usage
1991/92 – 1997/98	Access to 150% of entitlement	Relatively low level of groundwater usage and rising pressures
1998/99	Access to 100% of entitlement	Prevent over-use
1999/00	Access to 95% of entitlement	Prevent over-use
2000/01 – 2001/02	Access to 90–100% entitlement, based on zones	Prevent over-use
2002/03 – 2005/06	Access limited to share of extraction limit or maximum history of use	Manage within the extraction limit of the system
2006/07	100% of new reduced entitlement	Manage within the extraction limit of the system

CS9 Data

Table CS9.3. Summary of available data sets and applied field and data collection methods for conceptualisation of groundwater–stream interaction in the Lower Murrumbidgee Valley.

Data sets	Period of data record	Field or data collection methods
Lower Murrumbidgee Status Report	2002	Desktop
Numeric model – Lower Murrumbidgee	1975–2002	Desktop
Groundwater level monitoring network	Early 1970s to present	Field measurements of water levels
Stream gauges at Yanco, Gogelderie, Hay, Maude, and Balranald Weirs	Variable depending on station, 1950s to present (time series). Some earlier field measurements available	Field measurements
Groundwater usage	1982 to present	Field data collection
Regulated river operating spreadsheet	Mid-1990s to present (earlier, approximate data may be available)	User orders and gauging stations
River usage	1990s to present (possibly earlier data available for the Irrigation Areas)	Field data collection
IQQM	1980 to 2004 (approximate data) 2004 to 2006 (validated data)	Desktop

CS9 Groundwater–stream interaction classification

Table CS9.4. Classification of Lower Murrumbidgee using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to the Lower Murrumbidgee for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as medium.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

Case study 10: Western Macintyre and Weir River alluvia, Qld (regional system)

CS10 Location

The western Macintyre and Weir River alluvia are located in the Border Rivers catchment, between Goondiwindi and Mungindi, in southern inland Queensland and in northern inland NSW (Figure CS10.1). The Border–Moonie Salinity Audit (Biggs et al. 2005) identified this area as having the highest risk of salinity affecting valuable assets in the region. This was concluded to be due to the relatively shallow groundwater levels, the extreme salinity of groundwater, large irrigation development (with evidence of rising groundwater levels), low slopes, permeable red soils in the upper landscape, and the intensity of development close to streams.

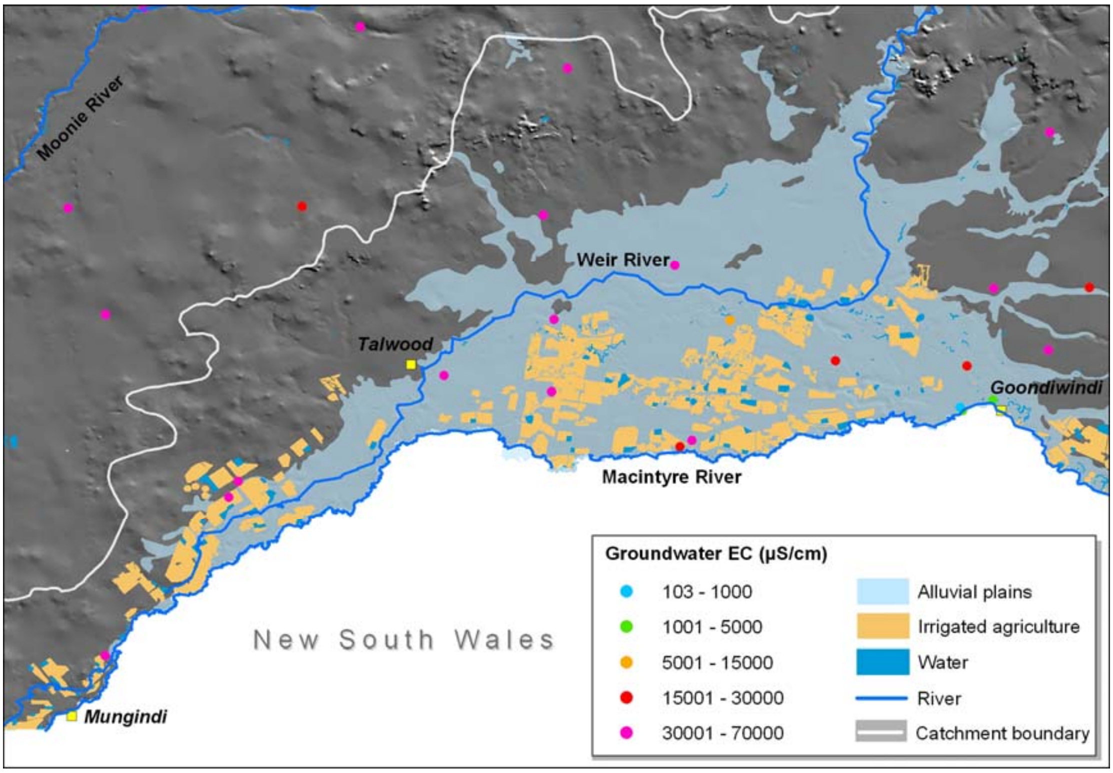


Figure CS10.1. Location of the western Macintyre (Barwon) River and Weir River alluvia between Goondiwindi and Mungindi. The region is in the Border Rivers catchment, Queensland. Note red dots (electrical conductivity (EC) 15,000–30,000 µS/cm) and pink dots (EC 30,000–70,000 µS/cm).

CS10 Climate and physiography

The climate is semi-arid to sub-tropical and rainfall is summer-dominant and strongly episodic. Long-term average annual rainfall is 614 mm at Goondiwindi and 504 mm at Mungindi. Potential evapotranspiration is about 2,000 mm/year.

Land use. Prior to the 1960s, land use in the area was grazing of sheep and cattle. Dryland cropping, mainly wheat, expanded from 1960 onwards, and the main land uses are now irrigation, dryland cropping and grazing. Irrigation commenced in the area in 1979 with the main crop being furrow-irrigated cotton. The main irrigation water sources are the Macintyre River, Weir River and captured overland flow.

In the year 2000, approximately 15,400 hectares were irrigated. Average water application rates in the 1999/2000 cotton season varied from 8 to 10 ML per hectare for furrow-irrigated cotton. In contrast, the water application rate for trickle-irrigated cotton was less than 5 ML per hectare.

Soils. Soils on the alluvia are mainly heavy clays (Vertosols and Sodosols) with occasional sand ridges; it is unknown if these ridges sit on top of clays. To the north on the Griman Creek Formation sandstones, red soils (Chromosols, Dermosols, Kandosols) occur in the upper landscapes. These soils have low water-holding capacity and permit potentially high recharge, particularly under cropping (Yee Yet and Silburn 2003; Robinson et al. in prep.).

Land use practices and deep drainage. Considerable research has been carried out in recent years, including direct measurement of deep drainage using lysimeters and measurement of soil chloride movement (Tolmie et al. 2003). This has illustrated the increase in deep drainage that occurs when native vegetation is cleared and replaced by crops. Deep drainage under native vegetation on clay soils is very low by comparison. Practices such as long-fallow wheat cropping can lead to increases in deep drainage up to 10 mm/year on Vertosols and 50 mm/year or more on the red soils. Under furrow irrigation, deep drainage is typically 100 to 200 mm/year (Silburn and Montgomery 2004), but can vary from 20 to 800 mm/year – this is highly dependent on irrigation management practices. Leakage may also occur from water storages and channels (Dalton et al. 2001).

CS10 Geological setting

The lower Weir River and lower Macintyre River alluvia both sit on top of the Griman Creek Formation, which is composed of Cretaceous fine-grained sandstones that tend to be deeply weathered. This formation occurs west of the Goondiwindi Fault and outcrops to the north of the alluvia. The alluvia are generally made up of clay overlying sand. Figure CS10.2 provides a simplified geological cross-section through the area.

The depth to basement (Griman Creek Formation) is typically 20–30 m in the east of the area and 10–20 m in the west. Depth to basement is progressively deeper to the south (Biggs et al. 2005 and 2006).

CS10 Hydrogeology

Please et al. (2000) from the Bureau of Rural Sciences (BRS) conducted a detailed assessment of groundwater and surface water chemistry at 30 sites within the Border Rivers alluvia. This included measurement and analysis of major ions, trace elements, metals, nutrients, pesticides and isotopes. They found that frequently very saline, and sometimes acid, water occurs either in the bottom of the basal alluvial sand layer (sitting on top of the Griman Creek

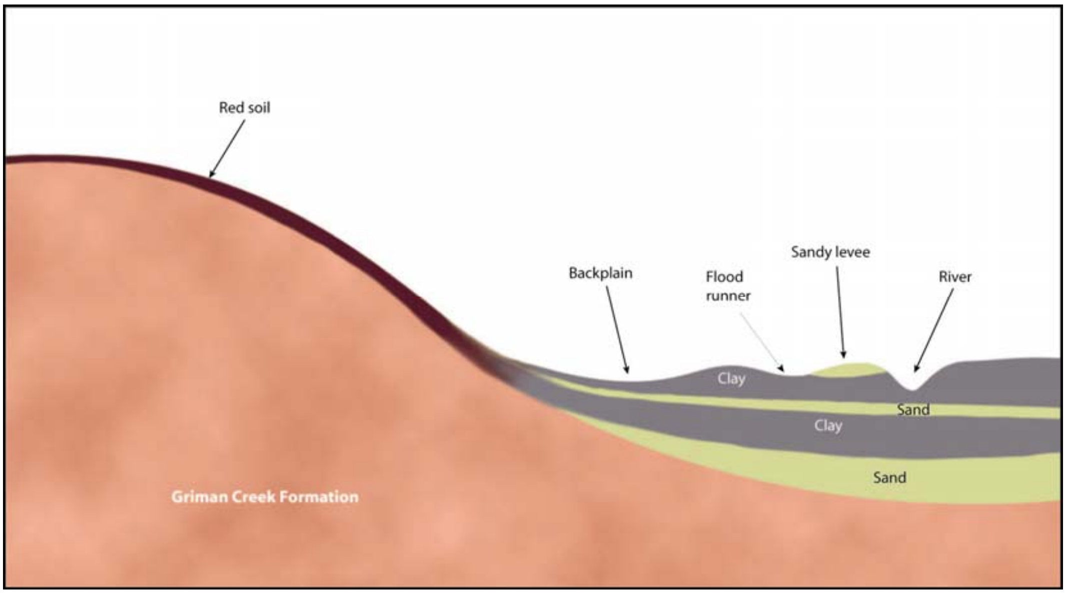


Figure CS10.2. Conceptual geological cross-section showing the western Macintyre River alluvia (Andrew Biggs, QNRM, pers. comm. 2006). It is not known if the alluvial sand layers are spatially continuous.

Formation), or in the upper parts of the Griman Creek Formation. Perched watertables with varying water quality sometimes occur in the alluvia, for example, in an interbedded sand layer between two clay layers. The mean electrical conductivity (EC) of groundwater in the area is 30,000 µS/cm, with recorded values exceeding 60,000 µS/cm (Biggs et al. 2005 and 2006).

Groundwater levels in bores located away from irrigated areas have typically shown little change over time. In contrast, two bores near irrigated areas have recorded rising groundwater levels. Figure CS10.3 provides a comparison of the hydrograph of one of these bores with a hydrograph of a bore in a dryland area (Biggs et al. 2005 and 2006).

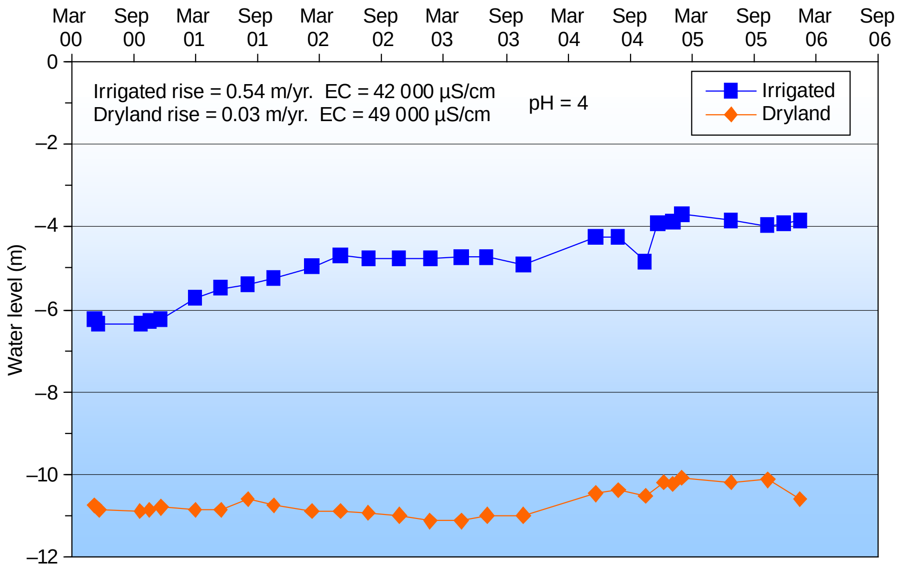


Figure CS10.3. Groundwater levels in two bores, 'irrigated' and 'dryland'. They are located close to and away from, respectively, irrigated fields and infrastructure on the Macintyre River alluvium (Biggs et al. 2005; 2006).

CS10 Groundwater–stream interaction

Groundwater levels are typically greater than 10 m below the surface, except under some irrigated areas, and are thought to be mostly below the bed of the streams. However, a detailed survey of the elevation of the streambed is required to validate this.

BRS (2005) found some indications from in-stream electromagnetic (EM) resistivity surveys conducted by Allen (2005) (Figure CS10.4) that the alluvial sand aquifers intersect the Macintyre River streambed at the upstream (Goondiwindi) end of the river. BRS (2005) concluded from these that 'The Macintyre/Barwon River appears to be underlain by uniform sediment in comparison with other Murray–Darling Basin rivers, with only minor conductivity variation evident'. It further concluded that 'Most transverse variation is evident in the South Callandoon image where the river intersects, at numerous locations, the sides of a swath of recent river palaeochannels, which are recessed into the broad scale floodplain. However, in the Macintyre/ Barwon River reach at Mungindi, salinity increases and is quite uniform in the sediment' (Figure CS10.4).

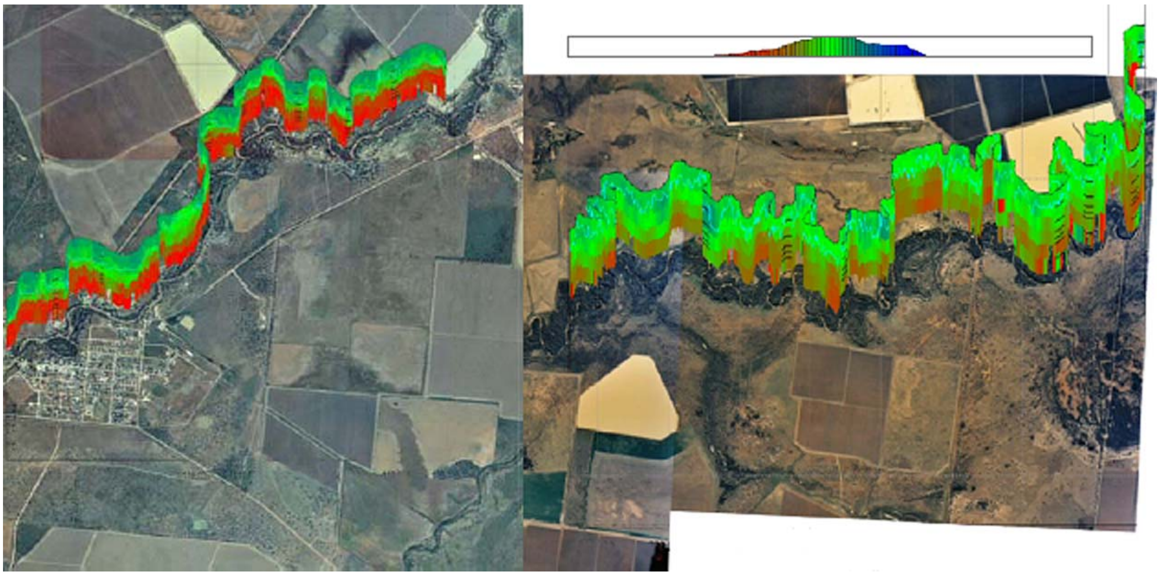


Figure CS10.4. Electrical conductivity (EC) ribbon images from an electromagnetic resistivity survey conducted along the Macintyre River (Allen 2005). Ribbon images show apparent EC to a depth of 40 m beneath the Macintyre River along two reaches: (i) South Callandoon, immediately downstream of Goondiwindi (right), and (ii) upstream from Mungindi (left). Stream flow is from right to left. Blue represents low EC, green is moderate, and red is high. The survey results show a steady increase in groundwater salinity beneath the river in a downstream direction, particularly below Goondiwindi (Allen 2005; BRS 2005).

CS10 Groundwater development and impact on streams

Groundwater in the western Macintyre and Weir River area is mostly too saline to use for water supply, except in small areas recharged from the rivers. However, there are other types of human activity and other significant factors that have influenced, or will influence, the impact of groundwater on streams. The most notable of these are:

- shallow depths to basement and/or groundwater;
- groundwater is consistently very saline and sometimes acid;
- extensive amount of irrigated land and channels and storages;
- the area is on a low-sloping plain with low groundwater discharge capacity;
- extensive clearing and cropping, and high rates of deep drainage on outcropping Griman Creek Formation, upslope of the alluvia;
- the time lag for drainage to fill the unsaturated zone soil moisture deficit is unknown, but creates a false sense of security;
- rising groundwater levels; these will cause increases in salt discharge to the Macintyre and Weir Rivers, or to lower parts of the land surface, which will impact on the valuable assets of the streams and agricultural land.

CS10 Management status

It is intended to involve irrigators in the monitoring and investigation of the groundwater–stream interaction issues through avenues such as land and water management plans, sub-catchment planning and the Cotton Best Management Practice program (Biggs et al. 2006). A series of workshops was held across the area in 2006 to initiate this process.

To better inform and assist implementation of land and water management plans in the future, processes are underway to improve the integration of information across the Queensland and NSW sections of the Macintyre and Weir River alluvia. In addition, further investigations are being planned to achieve a good working knowledge base of the following:

- Geology and hydrogeology, including the extent of the alluvial sand aquifers and their hydraulic connectivity with the rivers (drilling programs and possible airborne EM survey).
- Groundwater levels and trends near, or under, irrigated and non-irrigated areas (more monitoring bores and use of data loggers).
- Stream bed elevations.
- The moisture capacity and status in the unsaturated zone under irrigation, dryland cropping and native vegetation.
- Recharge during the occasional but extensive flooding that occurs over the alluvia.
- Spatial and temporal variation of deep drainage, recharge and groundwater responses, and their relationships to the rivers (groundwater modelling).

CS10 Data

Table CS10.1 summarises the accumulated data sets and applied field and data collection methods for conceptualisation of groundwater–stream interaction in the case study area.

In recent years, the NSW Department of Natural Resources (DNR) completed drilling as part of the salinity audit and commenced daily to sub-daily groundwater level monitoring. Groundwater loggers (with telemetry) were installed near the river at one site. Loggers were installed in the four 'Fresh-as-a-daisy' bores in Queensland in 2006 (Biggs et al. 2005; Biggs et al. 2006; Free et al. 2001). A monitoring bore construction program and land surface surveying program will occur in 2007. Proposals have also been developed for further boat-based surveying of the streambed elevation and electrical resistivity surveying beneath the streambed.

Table CS10.1. Summary of available data sets and applied field and data collection methods in the western Macintyre and Weir River area.

Data sets	Period of data record	Field or data collection methods
Stream flow	1917 onwards 1949 onwards	QNRM gauging station 416201A on Macintyre River at Goondiwindi Weir and various sites upstream, and on the Weir River. DNR NSW Barwon River at Mungindi
EC autosensor	Not known	Barwon at Mungindi
Boat based resistivity survey	2006	David Allen for BRS, sections in upper and lower Macintyre River
Soils		1:250,000 scale
Radiometrics	2006	Airborne
Groundwater flow system map and attributes		1:250,000 scale (Biggs et al. 2005)
Groundwater levels (manual)	Qld – since 2000 NSW – since 1993	Manually read each 3 months Manually read several times per year
Groundwater levels (automated)	Qld: 2006 onwards NSW: recent years	Sub-daily data loggers in 4 bores Sub-daily data loggers in some bores
Groundwater chemistry	Since mid-1970s 2005/06	QNRM, BRS (Please et al. 2000) Ionic chemistry and isotopes on selected bores and streams

CS10 Models

Deep drainage for the soils, climate and land uses in the area was modelled by Yee Yet and Silburn (2003) and Briggs et al. (2006).

Whiting (2007) constructed a MODFLOW model of the alluvia between Goondiwindi and Talwood and between the Macintyre and Weir Rivers. This indicated that there was groundwater mounding associated with irrigation. The shallowest groundwater levels were shown to occur adjacent to the Macintyre River, commonly 4 m below ground, and in one location, 2 m below ground. The time scales for the groundwater rise were reasonably long, with some rise evident at 25 years, and continuing out to 250 years. Assumptions about hydraulic conductivity, storage and permeability under sand ridges were influential to the model outcomes. The model was constrained by uncertainties due to limited topographical, geological, hydraulic and hydrogeological data.

CS10 Groundwater–stream interaction classification

Table CS10.2. Classification of Western Macintyre and Weir River alluvia using the Table 10.3 template (see Chapter 10.3). The highlighted boxes are the attributes interpreted to be applicable to the case study area for each type of groundwater–stream interaction characteristic. The classification confidence level is rated as medium.

Type of characteristic	Attribute				
A. Aquifer system	Fractured rock	Layered or complex	Contained alluvial valley	Regional	
B. Aquifer scale	Local (maximum flow length <5 km)	Intermediate (maximum flow length 5–50 km)	Regional (maximum flow length >50 km)		
C. Aquifer width	Narrow (<5 km)	Broad	Variable		
D. Recharge	Rainfall	Stream	Riverine/ flood	Throughflow/ interflow	Artificial (including irrigation returns)
E. Discharge	To stream	To floodplain or groundwater-dependent ecosystem	To sea	Throughflow/ interflow	Groundwater pumping / subsurface drainage
F. Floodplain	Narrow and/or incised	Broad	Terraced	Variable	
G. Stream flow	Regulated	Unregulated	Mostly reliable	Variable	Intermittent
H. Stream–aquifer relationship	Dominantly gaining	Dominantly losing (saturated connection)	Dominantly losing (unsaturated connection)	Variably gaining and losing (spatially or temporally)	Unconnected
I. Aquifer connectivity or confinement status	Unconfined	Semi-confined	Confined		
J. Hydraulic conductance	High	Medium	**Low	Unsaturated connection	
K. Long-term pumping impact on stream flow	High (> 15%)	Medium (5–15%)	Low (1–5%)	Very low (<1%)	No impact

** In this case, 'low' refers to the infiltration capacity of the unsaturated zone material

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Glossary

AHD. Australian Height Datum. Mean sea level for 1966–1968 at 30 Australian tide gauges – see http://www.ga.gov.au/geodesy/datums/ahd.jsp.

Alluvium. A sediment deposited from transport by stream flow.

AMLRNRM Board. Adelaide and Mount Lofty Ranges Natural Resource Management Board, http://www.amlrnrm.sa.gov.au.

Anabranch. A stream branch that leaves the trunk stream and re-enters it further downstream.

Aquifer. A water-bearing geological formation capable of yielding useful quantities of water via bores or other extraction facilities.

Aquitard. A saturated, but poorly permeable stratum which impedes the movement of groundwater (e.g. clay).

Baseflow. That part of streamflow that is derived from groundwater seeping into the river channel. Typically, it is the low flow in a stream over the dry season in Australia.

Bedrock. Unweathered or partially weathered hard rock that is at the base of soils or other unconsolidated surficial material.

BMR. Bureau of Mineral Resources. Now Geoscience Australia, http://www.ga.gov.au.

Bore. A hole in the ground that is constructed using a drilling plant and lined with tubing (usually steel or PVC), which allows the inflow of groundwater.

Confined aquifer. An aquifer (see above) that is overlain by a low permeability confining layer (aquitard or aquiclude), such as clay.

CRC. Cooperative Research Centre.

CSIRO. Commonwealth Scientific and Industrial Research Organisation. http://www.csiro.au.

DEM. Digital elevation model.

DIPNR. NSW Department of Infrastructure, Planning and Natural Resources, http://www.dipnr.nsw.gov.au. Became Department of Planning (http://www.planning.nsw.gov.au) and Department of Natural Resources (http://www.dnr.nsw.gov.au), and thence Department of Water and Energy, http://www.dwe.nsw.gov.au.

Discharge. Flow or evaporation of groundwater from an aquifer to the earth surface/stream/atmosphere.

Discharge area. An area in which groundwater intersects the ground surface and/or there is an upward hydraulic gradient. In such an area, groundwater can escape via a spring or seep, or by evaporation and transpiration.

Drawdown. The vertical decline in the watertable surface or groundwater potentiometric surface caused by extraction of groundwater.

Dryland salinity. A form of land degradation in which the discharge of groundwater causes formerly productive non-irrigated soils to become unproductive.

DLWC. NSW Department of Land and Water Conservation. Now part of the NSW Department of Water and Energy, http://www.naturalresources.nsw.gov.au and http://www.dwe.nsw.gov.au.

DNR. NSW Department of Natural Resources. Now part of the NSW Department of Water and Energy (DWE), http://www.naturalresources.nsw.gov.au and http://www.dwe.nsw.gov.au.

DWLBC. South Australian Department of Water, Land and Biodiversity Conservation, http://www.dwlbc.sa.gov.au.

EC. Electrical conductivity (of water; provides an approximate measure of salinity).

Environment Australia. Became Australian Government Department of the Environment and Heritage; then Department of the Environment and Water Resources; then Department of the Environment, Water, Heritage and the Arts, http://www.environment.gov.au. (See http://www.anbg.gov.au/anbg/anbg-admin.html.)

EPA. NSW Environment Protection Authority. Became part of the Department of Environment and Conservation; later the Department of Environment and Climate Change, http://www.environment.nsw.gov.au.

Evaporation. The physical process by which liquid water is converted to its gaseous phase (water vapour).

Evapotranspiration. The sum of water loss from the soil by evaporation and by transpiration from plants.

Fluvial. Belonging to a river; the physical products of river action.

GDEs. Groundwater dependant ecosystems, which are defined as the ecosystems that are dependant on groundwater for their existence and health.

GMA. Groundwater Management Area

Hydrogeology. The study of the interrelationships of geologic materials and processes with water, especially groundwater.

Hydraulic gradient. The difference in groundwater pressure head over a set distance. Water will naturally move from high to low pressure positions.

Hydraulic conductivity. A quantitative measure of the ease with which water moves through the soil or geological strata – expressed as metres/day.

IAH. International Association of Hydrogeologists, http://www.iah.org.au.

Infiltration. The flow of water downwards from the land surface into and through the upper soil layers.

Interflow. Lateral movement of water through the soil. Interflow often takes place above a less permeable layer in the soil profile.

Lithology. (Science of) the nature and composition of rocks or geological strata.

mAHD. Metres above the Australian Height Datum (see AHD).

LWRRDC. Land and Water Resources Research and Development Corporation, aka Land & Water Australia, http://www.lwa.gov.au.

MDB. Murray–Darling Basin.

MDBC. Murray–Darling Basin Commission, http://www.mdbc.gov.au.

MLR. Mount Lofty Ranges.

NGC. National Groundwater Committee, http://www.environment.gov.au/water/environmental/groundwater/ngc.html.

NLWRA. National Land and Water Resources Audit, http://nlwra.gov.au.

NWC. National Water Commission, http://www.water.gov.au.

Outcrop. Exposure of bedrock or strata projecting through the overlying cover of regolith or soil.

Palaeochannel. Buried, ancestral alluvial valley or channel.

Permeability. A qualitative measure of the relative ease with which a porous medium can transmit a fluid.

Piezometer. A non-pumping well, generally of small diameter, that is used to measure the elevation of the watertable or potentiometric surface. A piezometer generally has a short well screen through which water can enter.

Potentiometric surface. An imaginary surface representing the total head (or pressure) of groundwater and defined by the level to which water will rise in a well.

Recharge. Infiltration/percolation into an aquifer – which may be natural or induced.

Recharge area. An area in which there is a downward hydraulic head. In such an area, infiltrated water moves downwards into an aquifer.

REM. Resource and Environmental Management, http://rem.net.au. Now part of SKM, http://www.skmconsulting.com.

Runoff. Lateral movement of water through the landscape. May occur over the surface (surface runoff or overland flow) or above a less permeable layer in the soil (inflow).

RWL. Reduced Water Level. The height of the groundwater level above the Australian Height Datum (see AHD).

Salinity (water quality). Normally the total quantity of dissolved salts in water, expressed as milligrams per litre (mg/L) or parts per million (ppm).

Saturated zone. The subsurface zone in which all pore-space openings are full of water.

SCA. Sydney Catchment Authority, http://www.sca.nsw.gov.au.

SCC. Scott Creek Catchment.

Semi-confined aquifer. An aquifer in which the upper confining layer is leaky, but still contributes significantly to the flow in the aquifer. Such aquifers normally produce a delayed yield or delayed drainage effect when pumped, or leakage through the semi-confining layer only becomes significant after the head of the aquifer has been altered.

SKM. Sinclair Knight Merz, http://www.skmconsulting.com.

Subcrop. Sub-surface expression of bedrock or layered rock strata.

Subsidence. Movement of a structure due to change in the structural properties of the underlying material. The change in groundwater level could lead to movement (collapse) of the soil.

Unsaturated zone. The zone between the land surface and the watertable that contains both water and air.

URS. URS Corporation, http://www.ap.urscorp.com.

USGS. United States Geological Survey, http://www.usgs.gov.

WAP. Water allocation plan.

Waterlogging. A temporary or permanent saturation of the soil or land surface whereby water stands at, just below, or just above the land surface.

Watertable. The surface of a groundwater body in an unconfined aquifer at atmospheric pressure, as distinct from groundwater in a confined aquifer, which may be under greater pressure.

Weathering. Physical and chemical disintegration, decomposition and alteration of rocks and minerals.