Conjunctive management of groundwater and surface water resources in the Upper Ovens River Valley

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Abstract

The Upper Ovens River catchment is located in the Victorian high plains of Australia. With an absence of major storages or weirs, the flow regime of the Upper Ovens River is close to its natural magnitude and frequency. Water extraction from rivers has the potential to negatively impact on environmental flow requirements and management of extraction is required to maintain flows to the river, especially over the low flow summer periods. The Upper Ovens River has been shown to have a high connectivity between groundwater and surface water, and for effective protection of stream flow, it is proposed that groundwater and surface water are managed conjunctively by a government legislated Water Management Plan. Environmental stream flow objectives have been identified, but no method exists to link these to groundwater objectives. Without this link, water resource managers cannot develop management methods or plans for management of groundwater to achieve surface flow objectives.

Existing data commonly available to water resource managers was analysed to develop a method to link stream flow objectives to groundwater management objectives, and investigate the groundwater-surface water relationship and water cycle in the Upper Ovens catchment. A water balance for a well defined sub-catchment was developed for the period between 1975 and 2005 to investigate the water cycle and magnitude of fluxes between groundwater in the unconsolidated sediments of the valleys and surface water. Darcy's law and statistical regression analysis of commonly available historic data were used to develop the understanding of the groundwater-river level relationship and produce a method for relating environmental river flow targets to groundwater levels. A set of conjunctive management principles for resource managers was produced based upon the sound scientific understanding of groundwater-surface water interactions.

The mean water balance shows a clear seasonal pattern for movement of water between surface water and groundwater. Groundwater levels have remained steady, with average annual groundwater recharge from rainfall and the river of 9,773 ML nearly equal to average annual discharge of 9,584 ML from the aquifer as baseflow or evaporation in the

dry season. Generally extraction of groundwater and surface water (3,200 ML/yr) and fluxes between groundwater and the river (2,626 ML/yr), are only minor components of the water balance (560,000 ML/yr) and do not affect the flow patterns in the Ovens River. However, in years with very low flows over the Summer/Autumn period, extraction from the river can significantly reduce flow in the river. Management of river flow at this time is the focus for water resource managers.

Field measurements and regression relationships showed a rapid rate of flux between groundwater and the river with the time lag (for rises in river level to subsequent rises in groundwater levels) increasing with distance of the aquifer from the river to be 14-20 days at the maximum measured distance of 750 metres from the river. With the narrow width of the unconsolidated sediment aquifer (less than 3000 metres) extraction of groundwater from these aquifers is expected to impact on stream flows within the summer period (90 days).

Regression analysis produced equations for relating Ovens River levels to groundwater levels with a high correlation. These equations can relate stream flow objectives to corresponding groundwater management that can be used by resource managers with a high level of confidence. Groundwater and surface water, in the form of river flows, are intrinsically linked and to protect flows in the Ovens River during times of low flow, groundwater has to be managed in line with surface water. Four principles have been identified for conjunctive management in the Upper Ovens, and resource managers should set management rules based on the following principles:

1) Groundwater and surface water are hydraulically connected, manage as one;
2) Restrict groundwater extraction in line with surface water restrictions;
3) Manage groundwater to minimum groundwater levels; and
4) Manage groundwater in the unconsolidated sediments as one aquifer.

Declaration

This is to certify that

(i) the thesis comprises only my original work towards the Masters except where indicated;

(ii) due acknowledgment has been made in the text to all other material used;

(iii) the thesis is less than 50,000 words in length, inclusive of footnotes, but exclusive of tables, maps, appendices and bibliography

Daniel Martin Lovell

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Table of Contents

List of Figures

List of Tables

Acronyms

ET Evapotranspiration

ET_c calculated crop evapotranspiration

ET_o Reference crop evapotranspiration

FAO Food and Agriculture Organisation

GMA Groundwater Management Area

PCV Permissible Consumptive Volume

SDL Sustainable Diversion Limit

SOBN State Observation Bore Network

GW-SW Groundwater-Surface Water

WSPA Water Supply Protection Area

Chapter 1: Introduction

1.1 Problem description

In the Victorian high plains of Australia, the Ovens River flows from the heights of Mt Hotham through narrow alluvial valleys and onto the broader floodplains where it joins up with the Murray River. The Upper Ovens Catchment is the highland area and is defined as the drainage area of the Ovens River and tributaries upstream of the town of Myrtleford. The catchment encompasses mountainous regions and also has narrow alluvial valleys which support a variety of agriculture and several rural towns.

The Upper catchment is still highly forested and the absence of major storages or weirs means that the flow regime of the Upper Ovens River is close to its natural magnitude and frequency. As a result, human influences on the flow regime are minor and the river has maintained the environmental values associated with a natural flow regime.

Although the flow regime of the Upper Ovens River is generally unchanged, water extraction for human use is increasing stresses on the riverine environment in periods of low flow over the drier summer period. Environmental flow requirements are critical in times of low flow and this coincides with the greatest extraction for human uses, primarily summer irrigation.

Management of human extraction from the river at low flows is proposed to reduce stress during these periods and provide higher environmental flows through reduced extraction. It is proposed that the management will be in the form of a government legislated Water Management Plan (Victorian Government 2004).

During periods of low river flow, baseflow from groundwater is the primary source of water (Cartwright et al. 2005). Groundwater is also extracted for human uses in the catchment and has been identified as a possible alternative to direct stream extraction. In areas with a strong hydraulic connection between aquifers and the river, groundwater extraction can lead to lowering of groundwater levels and a reduction of baseflow from groundwater. In extreme cases, baseflows can be reduced to an extent that the flow regime of the river catchment is fundamentally changed and rivers can shift from a perennial flow regime to an ephemeral flow regime (Glennon 2002).

The Upper Ovens River has been shown to have a high connectivity between groundwater and surface water (Sinclair Knight Merz 2006a; Sinclair Knight Merz 2007a). For effective protection of stream flow, especially in times of low flow, groundwater extraction has to be managed conjunctively with stream flows.

Numerical modelling of a small number of extraction bores in a discrete segment of the alluvial aquifer of Upper Ovens River catchment has indicated that in the long term (10 years), groundwater extraction from the modelled bores will be sourced from stream flow (Sinclair Knight Merz 2006a). However, for management, a gap lies in the understanding of the influence of the alluvial groundwater system on river flows and bulk water movement through the catchment. Further to this, an understanding of the groundwater-surface water relationship and how the fluctuations of groundwater and stream levels influence the magnitude of fluxes of water between the two is also missing.

Environmental Stream Flow objectives have been developed using a scientific methodology (Sinclair Knight Merz 2006d), however, a method to link stream flow objectives to groundwater management objectives is required. Without this link, water resource managers cannot develop management methods or plans for management of groundwater to achieve surface flow objectives. A conjunctive management plan that has not developed its management principles based on a robust scientific understanding of the interactions between groundwater and the river has the potential for not meeting management aims and faces the possibility of unfairly impacting on water users.

1.2 Aim

To develop conjunctive management principles for the protection of low flows in the Upper Ovens River based on the relationship between groundwater levels and river flow.

1.3 Thesis structure

The first two chapters examine the literature to detail knowledge on both the groundwater and surface water resources in the Upper Ovens River catchment. Chapter 2 gives background into the physical hydrology and hydrogeology of the catchment. It also outlines human water use in the catchment and impacts of water extraction on natural river flows and the environment. Current management practices are discussed as are the proposed new management aims to protect environmental flows. The need for conjunctive management to effectively achieve these outcomes is shown. Gaps in the current understanding of groundwater – surface water interaction are explored and summarised as key research questions to focus the study. Chapter 3 uses a water balance to develop understanding of the timing and magnitude of water movement through the hydrological cycle. Particular emphasis is placed on the movement of water between the groundwater and surface water systems. A model is developed, to show seasonal patterns of water fluxes between the groundwater and surface water systems, to inform management. Chapter 4 uses Darcy's law and statistical regression analysis of commonly available historic data to develop understanding of the groundwater-river level relationship and produce a method for relating environmental river flow targets to groundwater levels. The understanding of groundwater-river relationships are used to develop an idealised conjunctive management option, including principles for managers in Chapter 5. Implications for groundwater users are also discussed and several alternative options for conjunctive management are given. Conclusions are drawn in Chapter 6.

Chapter 2: The Upper Ovens River Catchment Study Area

The important points highlighted in the introduction were, the need to manage groundwater and surface water conjunctively to effectively protect low flows, and the requirement to determine a method for linking groundwater management objectives to river flow objectives. To ensure appropriate management decisions are made it is important to relate, or put in perspective, the current and historic water use and management into the existing knowledge of the hydrological cycle of the area. This perspective will determine the critical information required to enable the shift to conjunctive management.

This chapter examines the existing literature and understanding of the hydrological cycle, water use and management in the Upper Ovens Catchment. First, climate, geological setting, hydrology and water use are outlined. To determine the critical information required for conjunctive management. The current understanding of the interactions between the groundwater and surface systems is then examined, along with current impacts of groundwater extraction on these interactions. Current management practices are outlined and then implications of proposed new conjunctive management on existing users are examined. Finally, the critical information required for conjunctive management is summarised as key research questions.

2.1 Location, climate and physiography

The Ovens River is located in south eastern Australia in the state of Victoria. It starts in the Victorian Alpine area and flows inland 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 is the alpine part of the catchment with an area of approximately 1,500 km^2. It is defined as the Ovens River catchment upstream of the confluence with Buffalo River near Myrtleford, as shown in Figure 2-1.

The Upper Ovens River catchment receives varying rainfall depending primarily on elevation. Averaged over the whole catchment the approximate annual rainfall is 1200mm, with average monthly rainfall fluctuating between 57 mm in February and 181 mm in July. Average potential annual evaporation is 1170 mm with average monthly evaporation ranging between 22 mm in June and 228 mm in January (Australian Bureau of Meteorology 2001). Mean annual rainfall varies with elevation with mean annual rainfall on Mt Buffalo, at an elevation of 1350 metres of 1850 mm compared to 900 mm of rainfall in the valley at Myrtleford, with an elevation of 223 metres (Australian Bureau of Meteorology 2008). 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 through the entire Upper Ovens catchment (Australian Bureau of Meteorology 2008).

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

2.2 Geology of the Upper Ovens

2.2.1 Geological setting

The regional geology in the Upper Ovens catchment is dominated by early Paleozoic (lower-middle Ordovician) marine sedimentary rock (Pinnak Sandstone) intruded with several granite plutons of Silurian and Devonian age. Alluvial processes have incised into the Ordovician and granite fractured rock, creating deep, narrow sided valleys in which unconsolidated alluvial and colluvial sediments have been deposited (VandenBerg et al. 2004). The surface geology of the catchment is outlined in Figure 2-1 which is interpreted from geological maps (Geological Survey of Victoria 1974; Tickell 1978).

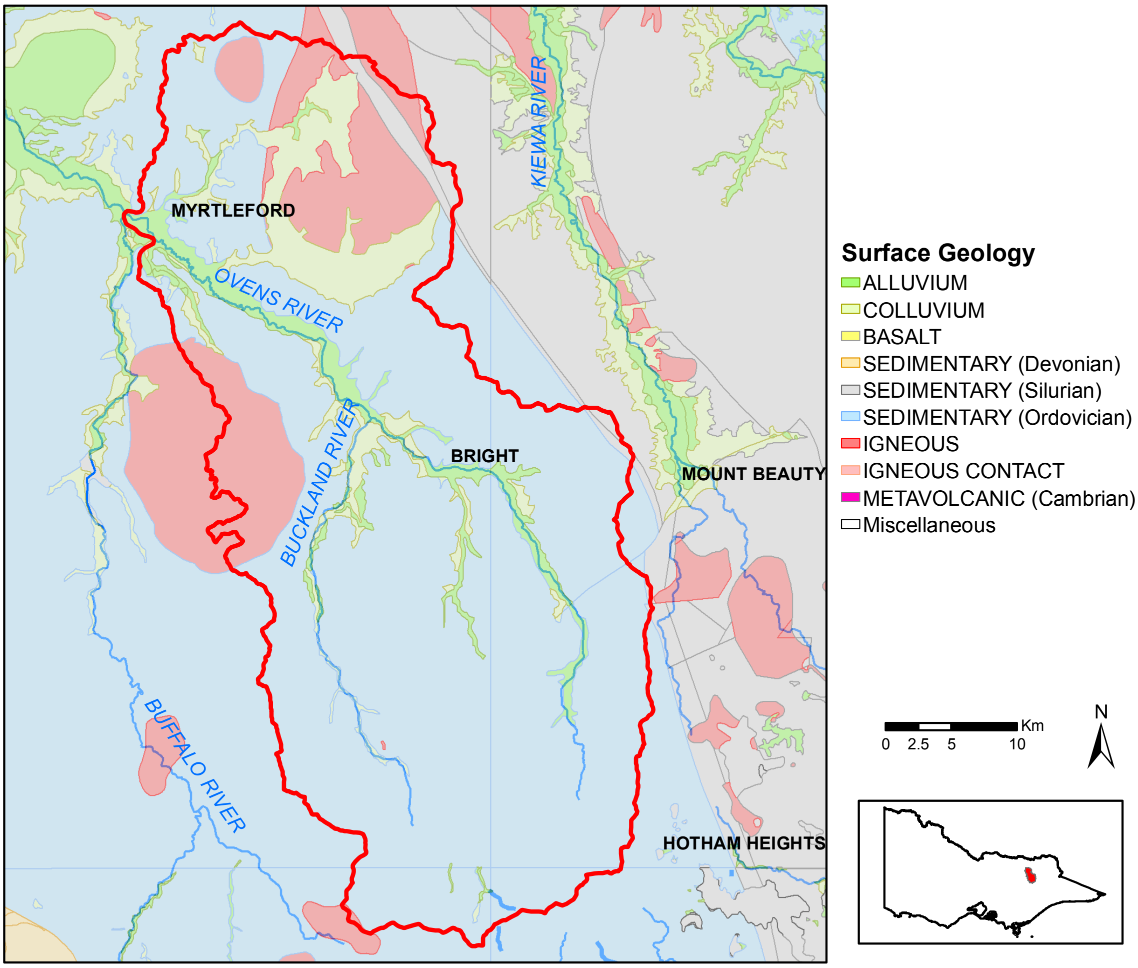

Figure 2-1: Location and Geology of the Upper Ovens River Catchment (Geological Survey of Victoria 1974)

2.2.2 Geomorphology

Alluvial processes have been the dominant factors in forming the landscape and defining the aquifer systems of the Upper Ovens catchment. VandenBerg et. al. (2004) classify the landscape elements of the area into five categories depending on total relief and slope steepness. In the Upper Ovens catchment, three landscape categories are of interest in terms of hydrogeology and will have an influence on hydrology of the area.

The dominant landscape elements are deeply dissected highlands ranging in height between 1000 and 1600 metres above sea level. These are a network of steeply sloping spurs (300-400 m/km) and drainage lines cut in to form the river valleys as can be seen in Figure 2-2. The spurs are intersected by V shaped valleys infilled with alluvium in the centre and colluvium on the slopes. The areas of deeply dissected highlands roughly follow the Ordovician sedimentary area shown on Figure 2-1.

Low relief foothills and intermontane basins form the next landscape element and are the more gently sloping sides of the mountainous valleys, with slopes of less than 150 m/km. In the Upper Ovens catchment this element is the Colluvial fans in the upper river valleys and tributaries. It is represented in Figure 2-1 as the colluvial areas of the Ovens River valley upstream of Bright and the Upper Buckland river valley.

The final landscape elements are the River flats which extend along the Ovens River and major tributaries and are represented by the alluvial areas in Figure 2-1. The valley floor is dominated by the river flats with meanders and billabongs across its reach. Generally the river floor is easily distinguishable as it is bordered by the steep Ordovician hill slopes. This landscape element is the most impacted by human activities in the catchment.

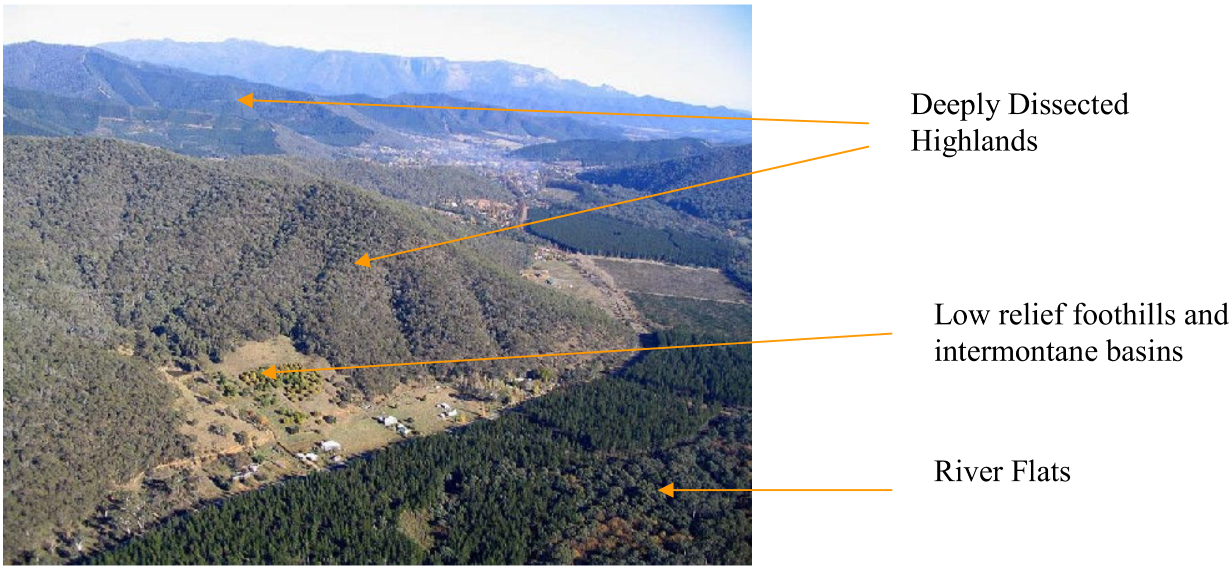

Figure 2-2: Major Ovens Valley geomorphology elements (looking down valley towards Bright) (University of Melbourne 2004)

2.2.3 Stratigraphy

For conceptualisation of aquifers in the Upper Ovens it is useful to consider stratigraphy in terms of the hydrogeology and possible aquifers. Landscape formation processes influenced aquifer formation and definition and the hydrogeological units of the area can be split into two main categories. The first type of aquifer are the porous aquifers of the unconsolidated sediments that include the alluvial sediments of the valleys and lateral terrace deposits/colluvial deposits from landslide erosion and slope wash. Underlying and surrounding the unconsolidated materials is the second aquifer type, Fractured Rock aquifers of the consolidated Ordovician marine sediments and granite that forms the mountain ranges and valley bases (Shugg 1987a; VandenBerg et al. 2004; Sinclair Knight Merz 2007a).

Shugg (1987) attempted to transpose the stratigraphic units of the Murray Basin to the Upper Ovens valley, and acknowledged that this was problematic due to the differences in geological unit formation process between these areas. As limited work has been completed on mapping stratigraphy of the alluvial sediments, this terminology has persisted and led to some confusion of naming and defining the alluvial stratigraphy. VandenBerg et al. (2004) have outlined the processes that have formed the unconsolidated hydrogeological units and this formal stratigraphic interpretation will be used.

2.2.3.1 Ordovician Fractured rock and Granite

The Ordovician Pinnak Sandstone formation consists of thinly bedded siltstones with interbedded mudstones, slate and occasional sandstones, and is typical of a sub-marine fan environment. (VandenBerg et al. 2004). This unit forms the primary underlying fractured rock of the Upper Ovens catchment (Geological Survey of Victoria 2004).

Intruding into the Pinnak Sandstone are Devonian granite intrusions. These formations are only a minor part of the catchment with the most noticeable feature being Mount Buffalo (Geological Survey of Victoria 2004).

2.2.3.2 Unconsolidated sediments deposition process

The process for deposition of the unconsolidated sediments occurred in two cycles. In the first cycle the older alluvial sediments of the Wunghnu Group (Shepparton and Calivil formations) were deposited in the Pliocene to Pleistocene time with the Calivil deposit followed by the Shepparton Formation. This group in-filled the valleys to 20-30m above the level of present day alluvial flats (VandenBerg et al. 2004). At some stage late in the Pleistocene period erosion increased, possibly due to lowering sea levels and a trench was cut through the Wunghnu group. This removed nearly all of the Shepparton formation and a large part of the Calivil formation, to an unknown depth. During the Holocene, the second depositional period occurred with the recent valley alluvial sediments were deposited, infilling the trench (VandenBerg et al. 2004).

Analysis of bore logs shows the difficulty of differentiating between the Wunghnu and Holocene sediments. The river depositional and anastomosing processes have had a large influence on the stratigraphy of the alluvium (Schumm et al. 1996). The alluvial processes lead to difficulty in differentiating the stratigraphy from bore logs as highlighted in the cross sections and bore logs shown in Appendix 6. In the cross sections at Ovens the general bore log descriptions are clayey sandy gravel with lenses of clays and gravels from alluvial processes and no differentiation between units can be made. At Bright the geology is more complex with lenses of different formations. Shugg (1987a) has identified Calivil sediments in the bore logs at this location, however differentiation is not apparent in the cross section descriptions.

2.2.3.3 Calivil Formation

The Calivil Formation forms the deeper parts of the alluvial sequence, however, its thickness and continuation across the valley is unclear. It does not outcrop and thus has only been identified in bore logs. In bore logs the formation is difficult to distinguish from the Shepparton and recent Holocene alluviums (VandenBerg et al. 2004). In the Upper Ovens valley the Calivil Formation is not the same as in the Lower Ovens valley, with rounding and sorting much poorer indicating less stream action. Composition is poorly sorted gravels with numerous sandstone clasts and some angular to sub rounded quartz clasts. Generally the colour is yellow-orange to grey, similar to the Pinnak sandstone but different in colour to alluvium attributed to the Calivil Formation in the Lower Ovens and greater riverine plain (generally grey with quartz).

2.2.3.4 Shepparton Formation

The Shepparton Formation has been almost completely removed with only a few deposits remaining in the tributaries and on isolated terraces of the Ovens River main alluvial valley (VandenBerg et al. 2004). The composition of the formation is interbedded channel conglomerate grading up to sand with loosely scattered pebbles. There are usually also clay layers from flood sediments.

2.2.3.5 Recent Alluvium

As indicated by VandenBerg et al (2004), other authors (Shugg 1987a; Sinclair Knight Merz 2007a) generally group the Quaternary alluvium into the Coonambidgal formation based on its age. Due to lithological differences in the geographically scattered alluvial sediments of the Upper Ovens Valley, Vandenberg (2004) and the Geological Survey of Victoria (2004) leave the Quaternary alluvium undifferentiated in their maps.

The lithology of the recent alluvium is generally only known from bore hole records with a few rare cuttings in low terrace deposits. Recent alluvium overlays the older Wunghnu group but bore drilling logs record them very similarly and thus it is not easy to distinguish between the units. There is also very little continuity of rock types across the valley sequence. This reflects the fluvial environment where discrete units relating to river processes, such as channel lag deposits, point bar deposits and flood plain deposits are all present in any valley cross section (VandenBerg et al. 2004).

Lithology of the recent alluvium varies considerably with location and the river process that formed it. A typical description can be found in a road cutting near Happy Valley which shows interbedded gravel and sand with good sorting and varying rounding. The pebbles are mostly hornfels from the Pinnak siltstone and the sand is generally from granite. This structure is reflected in other bore log records showing gravels through to cobbles interspersed with silt and sand and some lenses of clay/silt.

2.2.3.6 Colluvium

Fan sediments are known as colluvium and fringe most of the transitions between the ranges and the alluvial flats and many of the drainage lines. In the Lower Ovens below

Myrtleford, older fan sediments are evident as higher terraces to the level of Shepparton Formation. However, in the Upper Ovens there is less height difference and it is hard to distinguish between the older and younger colluvium.

Composition and textures vary but mostly consist of a generally poorly sorted mixture of clasts in a matrix of sand, silt and some clay. Clasts are poorly rounded and range up to tens of centimetres in size but those in excess of 1cm rarely make up greater that 25 percent of the rock (VandenBerg et al. 2004).

2.3 Groundwater hydrology

2.3.1 Aquifer units

Groundwater is present in both the fractured rock and the unconsolidated sediments in the Upper Ovens catchment and these units make up the two separate groundwater flow systems (Shugg 1987a). An extensive groundwater system exists as a fractured rock aquifer in the Ordovician sandstones and granite intrusions. The second aquifer system is the complex unconsolidated sediment aquifers within the unconsolidated sediments of the alluvial and colluvial valley deposits. The porous groundwater aquifers comprise the major groundwater resource with the fractured rock aquifers mainly used for domestic and stock and small scale developments (Shugg 1987a).

2.3.1.1 Fractured rock

The majority of the fractured rock aquifer is in the Ordovician sandstone. It is an unconfined aquifer and rainfall infiltrates into the aquifer through the weathered zone which is up to 30m thick. Rapid direct infiltration also occurs through fractures and joints in the upper layers. The high rainfall of the area ensures that the aquifer water is of good quality and Total Dissolved Solids (TDS) are generally less than 200-300mg/L (Heislers 1993). Estimated hydraulic properties are Transmissivity (k) of 0.01-1 m/day, storativity (S) of 1% and Specific yield (Sy) of 0.5%. Generally bore yields average approximately 0.1 ML/day (Heislers 1993).

Areas of granite intrusion are minimal in the Upper Ovens area and there is little information on the nature of the aquifer. As they are elevated landforms in high rainfall areas there is potential for high infiltration however bore yields are slightly less than the Ordovician aquifer (Heislers 1993). Given their geographic location (Figure 2-1) the chance for management of interactions with streams is minimal with inputs to flow from springs and fractures being accounted for as baseflow in stream flow gauging. Thus for this project they will be grouped into the Ordovician fractured rock aquifer and not considered separately.

2.3.1.2 Unconsolidated Sediments

As described in the stratigraphy section (2.2.3), it is very difficult to differentiate between the unconsolidated alluvial and colluvial sediments of the valley. Previous attempts (Shugg 1987a; Sinclair Knight Merz 2007a) to differentiate the sediments into aquifer units have been problematic, as the extent of formations within the sediments have not been mapped and continuity through the system is not known. Given the complexity of the unconsolidated sediments and the depositional processes, different formations exist as heterogeneous shoestring layers and discrete units rather than layers extending across the valley. Although separate aquifers may be identified within the unconsolidated sediments, the interconnection between the aquifers is hard to define (Sinclair Knight Merz 2007a).

Water quality of the alluvial aquifers is of a quality fit for all uses with low salinities, generally less than 200mg/L TDS, and some areas have groundwater high in iron that may require aeration before use (Heislers 1993; Sinclair Knight Merz 2007a).

Reports of aquifer parameters vary widely and are generally reported as representing an individual aquifer (e.g. Calivil) based on the interpretation of bore logs. Depth of the bore screen is generally used as the primary indicator for the aquifer and as such, aquifer parameters may be assigned incorrectly if information is lacking (See Appendix 6).

In the coarser sand and gravels of the deeper alluvials, which is commonly referred to as the Calivil aquifer, yields are around 0.1-1 ML/day. Hydraulic conductivity values are around 1-15m/day but can be as high as 60m/day, transmissivity varies between 17-140m/day and specific yield values are in the order of $1x10^{-4}$ (Sinclair Knight Merz 2007a).

The recent (or uppermost) alluvial sediments, sometimes called the Coonambidgial or Shepparton Formation, have a high porosity of 15-30%. Other aquifer parameters vary depending on the nature of the sediments. In coarse gravels or sands, hydraulic conductivities are high around 21-65 m/day. In contrast, sediments dominated by clay and silts have a low hydraulic conductivity of 0.5-8 m/day (Sinclair Knight Merz 2007a).

There has also been considerable dredging of the top 40m of the alluvial sediments in the search for gold with the areas shown on geological maps (Geological Survey of Victoria 2004). The dredging process involves disturbance of the shallow sediments by successive excavation, mixing, re-constitution and re-deposition. This process removed the natural depositional formation, moved fines and often resulted in changed hydraulic conductivities (Sinclair Knight Merz 2007a).

Differentiation of the unconsolidated sediments into separate aquifers has implications for management concerning groundwater-surface water interaction. If confining layers exist there may be the potential for groundwater extraction from the deeper aquifer without impacting on stream flow. Decisions for management of the potential unconsolidated sediment aquifers will have to consider the contradictions in the literature regarding their interactions with the river.

2.3.2 Groundwater behaviour

2.3.2.1 Groundwater flow

Groundwater levels loosely follow topographic contours and flow follows these gradients. The fractured rock aquifer is the large regional aquifer, with little known about its groundwater movement and behaviour. Groundwater flows from the fractured rock aquifer into the alluvial aquifer both directly and via the colluvial aquifer. The flow of groundwater in the alluvial aquifers is complex with local and regional flow cells, which is conceptualised in Figure 2-3 . In general regional terms, the greatest flow of groundwater is horizontally towards the river which acts as a drain. Using Darcy flux analysis it has been calculated that only a small proportion (200 ML) of the alluvial aquifer recharge of 42,600 ML, flows down the valley through the alluvial aquifers (Sinclair Knight Merz 2007a).

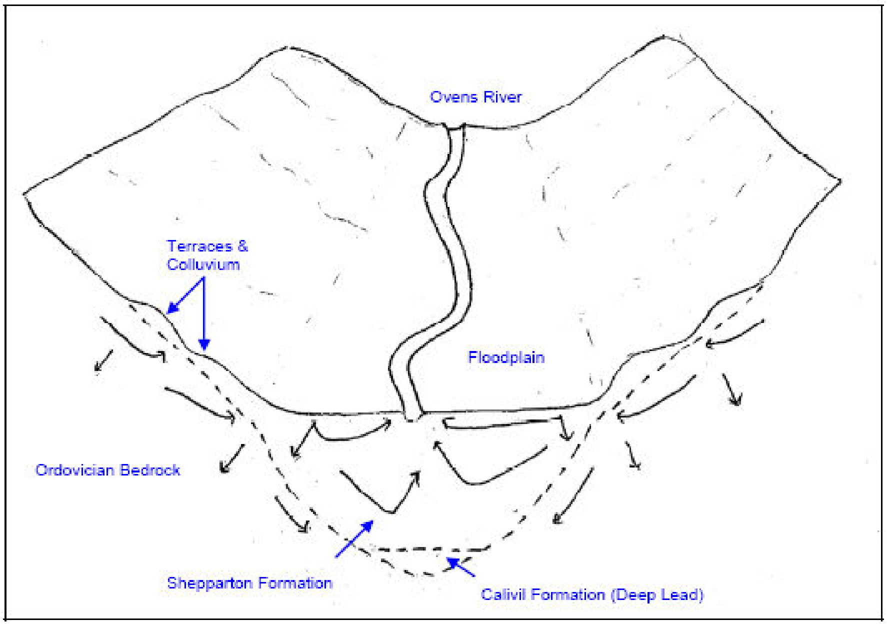

Figure 2-3: Conceptualisation of groundwater flow (Sinclair Knight Merz 2007a)

2.3.2.2 Groundwater levels

Groundwater levels are monitored using a Victorian government owned bore network called the State Observation Bore Network (SOBN). Groundwater levels are measured at set intervals with the data held in a central database. In the Upper Ovens catchment only one observation bore directly monitors the fractured rock aquifer and as such there is very little information on groundwater level trends. In contrast, there are 33 bores available for monitoring the alluvial aquifer. Generally these are shallow but there are 9 bores screened to greater depths. Hydrographs were constructed for all 34 observation bores in the Upper Ovens catchment. Similar trends were seen in all bores and rather than show all bores a small selection of groundwater bores has been used to represent the general trends in the groundwater levels. Locations of these bores are shown in Figure 2-4 and bore information with depth and screen details outlined in Table 2-1. These bores were chosen as a representative sample with different depths in the unconsolidated aquifer sampled by two nested sites, and geographical distribution taken into consideration by using bores at four different locations down the valley.

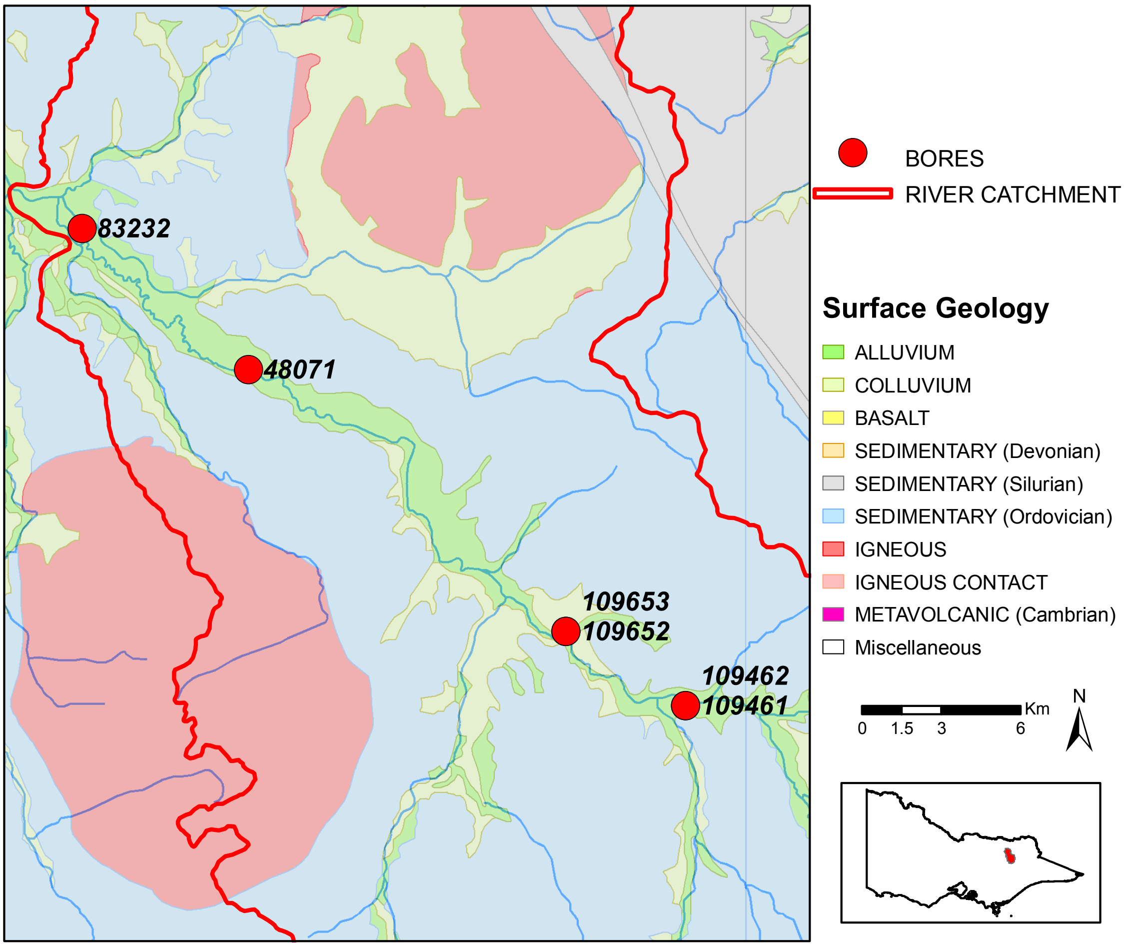

Figure 2-4: Locations of selected observation bores

Bore	**Depth (m)**	**Screen interval (m)**	**Aquifer**	**Location**
83232	13	6 - 12	Unconsolidated sediment	Myrtleford
48071	12	5 - 11	Unconsolidated sediment	Ovens/Barwidgee
109652	60	11 - 15	Unconsolidated sediment	Porepunkah
109653	60	39 - 42	Unconsolidated sediment	Porepunkah
109461	51	11 – 15	Unconsolidated sediment	Bright
109462	51	45 - 51	Fractured rock	Bright

Table 2-1: Details of selected observation bores

Groundwater levels show an annual seasonal variation but have otherwise remained steady for the period of record (Figures 2-5 to 2-7). Annual groundwater level fluctuation is in response to rainfall and rises in river level, with recharge over the winter months increasing groundwater levels. Groundwater levels drop over summer in response to discharge to the river, higher evapotranspiration and extraction for human uses. Aquifer behaviour is consistent for the whole unconsolidated sediment aquifers of the Ovens River valley with observation bores showing the same trends (Figure 2-5). For the selection of bores shown in Figure 2-5, variation in depth below natural surface levels is most likely due to variation in surface topography and the bore's situation in the valley landscape, such as proximity to the river.

The same seasonal response was seen in bores at all depths in the unconsolidated sediment aquifer and a representative example can be seen in Figure 2-6 which shows the hydrographs for a nested site at Porepunkah. Bore 109653 is screened in the deep unconsolidated sediment aquifer (39-42m) and bore 109652 screened in the shallow aquifer (11-15m). SKM (2007) have classified bore 109653 as being screened in the Calivil formation and used this as justification that there is high interconnectivity between the aquifers. A high interconnectivity at all depths in the unconsolidated sediment aquifer is also indicated by the similarity of hydrographs of deeper and shallow bores, however, there may be areas where confining sequences exist as there are only a few deeper monitoring bores. The classification of a Calivil aquifer at this location is questioned. Bore records from the groundwater management system show no differentiation between the gravels in the screened layer and gravels at other depths. There is also no indication of a confining or separating layer that could be expected if the gravels were part of the Calivil Formation.

A lag between groundwater responses in the Calivil and shallow aquifer of 2-4 months has been published but no details of the bores used to determine this lag were given (Heislers 1993). Hydrographs of nested sites at Porepunkah (Figure 2-6) and bores at Bright show no lag, indicating a high level of interconnectivity in the unconsolidated sediment aquifer at all depths and formations.

One bore 109462 exists in the fractured rock aquifer; this is a nested site with bore 109461. Hydrographs of these two bores in Figure 2-7 show that the groundwater levels in the fractured rock aquifer are the same as in the alluvial aquifer. Seasonal fluctuations are identical which would indicate that the fractured rock system has a high level of interconnection with the unconsolidated sediment aquifer. However, the weathered part of fractured rock can be up to 30m deep and as the bore is possibly screened in this section this could be the reason for such a strong relationship. Poor bore construction is another possible reason. As there is only one bore in the fractured rock, there is not enough information to conclusively determine trends and in any case, a single bore does not necessarily show trends for fractured rock aquifer as a whole, especially for deeper fractures.

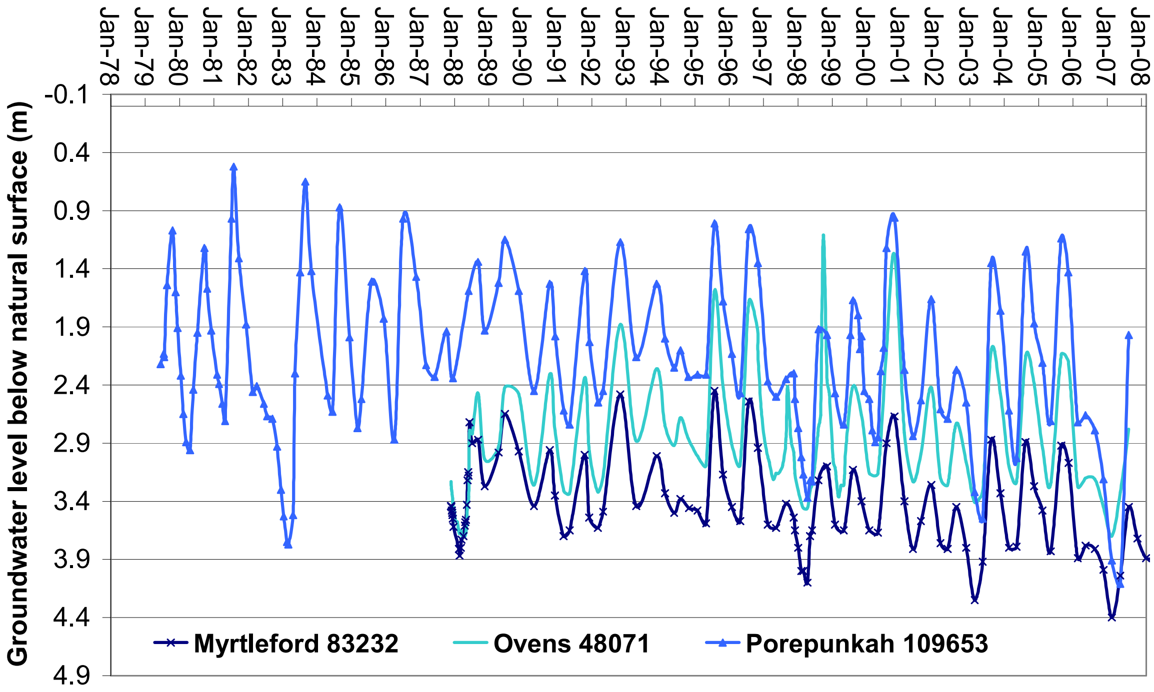

Figure 2-5: Down valley bore hydrographs showing the similar water level fluctuations of the unconsolidated sediment aquifer

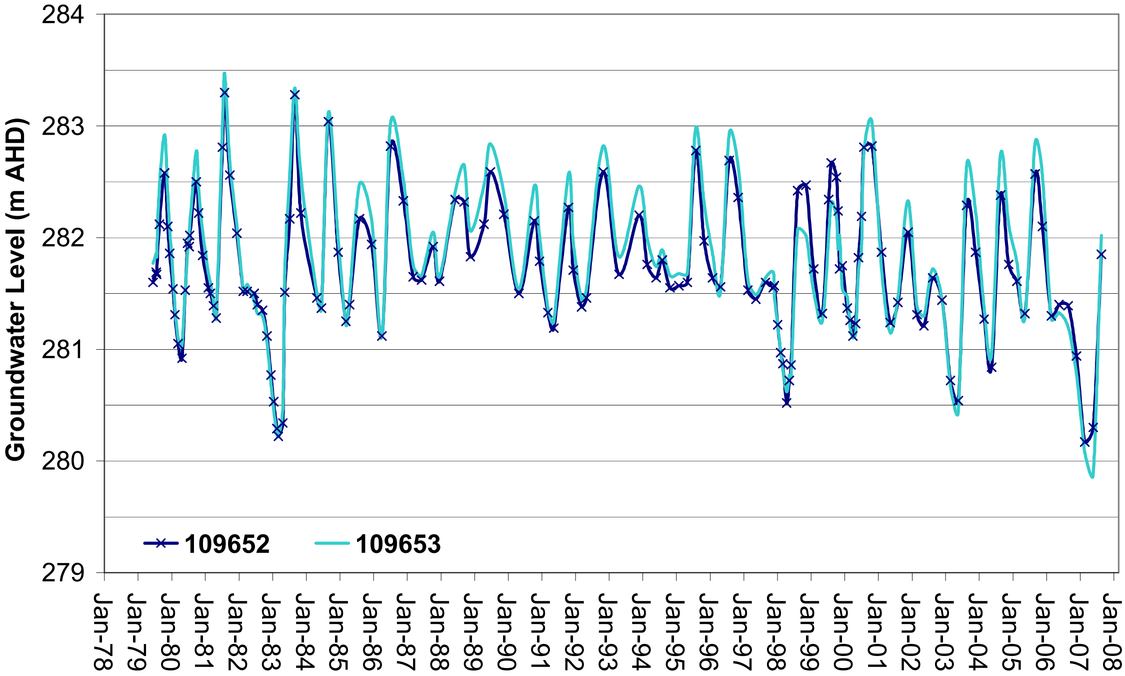

Figure 2-6: Nested Bores at Porepunkah showing connectivity between the shallow unconsolidated sediment aquifer (Bore 109652) and the deep unconsolidated sediment aquifer (Bore 109653)

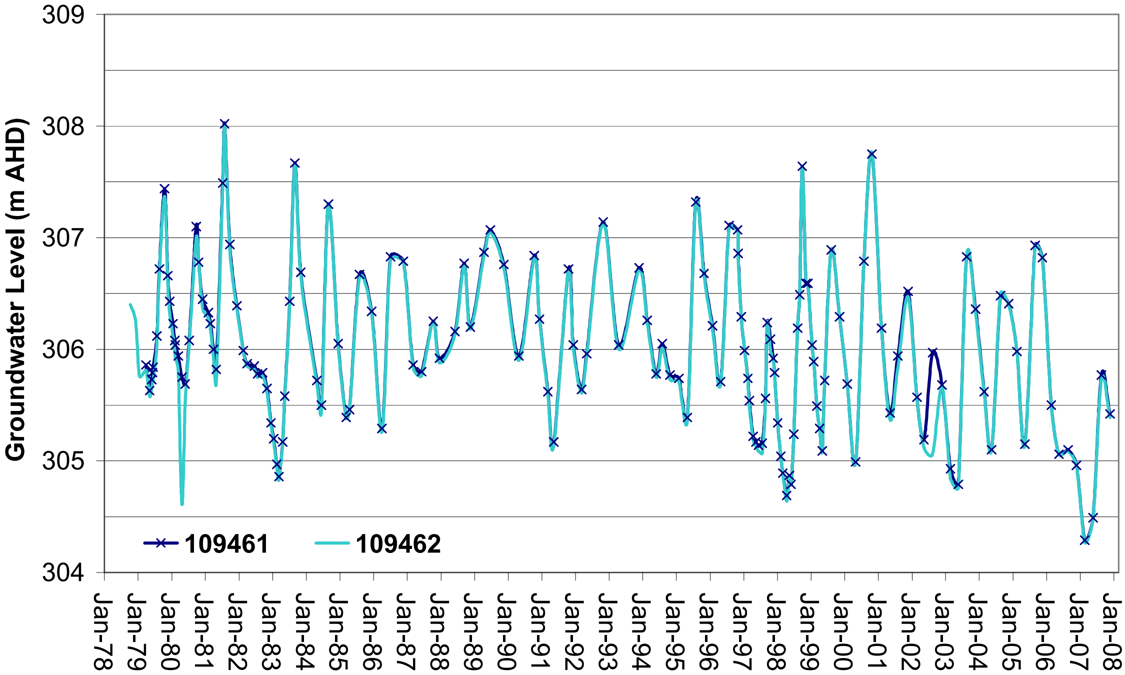

Figure 2-7: Nested bores showing aquifer level responses in the unconsolidated sediment (Bore 109461) and Fractured Rock aquifers (Bore 109462)

2.4 Surface water hydrology

The Upper Ovens River is an unregulated river without major storages. High flows are close to natural frequency and magnitude. The major flow related threat to river health is extraction from the river during low flow periods (Cottingham et al. 2001; Liang and Xie 2003; CSIRO 2008). The annual flow for the Upper Ovens River is measured at Gauge 403210 (adjacent to bore 83232 in Figure 2-4) which captures all flows from the Upper Ovens River catchment and all of its tributaries except for Barwidgee and Happy Valley Creeks. On average, the annual flow is 584,000 ML/yr but this has been as low as 69,000 ML in 2006. Flow statistics for gauge 403210 between 1961 and 2007 show that lowest flows occur over the late summer/autumn months, between February and April, and the highest flows are recorded during winter and the start of spring (September) with snowmelt (Table 2-2; Figure 2-1).

Month	**Median Flow ML/day**	**90th Percentile Flow ML/day**	**Minimum Flow ML/day**
January	291	42	0.9
February	178	30	0*
March	133	47	0*
April	166	82	0*
May	298	125	89
June	844	228	110
July	1320	327	139
August	2650	673	225
September	2730	725	181
October	1880	506	57
November	1140	306	15
December	592	95	1
Overall	**596**	**104**	**0**

* Recorded in 1968

Table 2-2: Daily Flow statistics for gauge 403120 at Myrtleford, 1961 - 2008

Low flows are common over the summer months and can occur for extended periods. Flows of 2 ML/day or less were recorded for the whole period of December to March in the summers of 1967/68, 1982/83, 2002/2003 and 2006/07. Zero flows were recorded from February to April in 1968, however, this may have been related to the gauge not recording flows less than 1 ML/day rather than no water in the river. Anecdotal accounts record surface flows in some points of the river during this time (Goulburn Murray Water 2003). When the gauge is recording zero flow there is some water in the river at the gauge and in January 2007 the gauge zero datum at 403210 was lowered by 1m to more accurately record low flows.

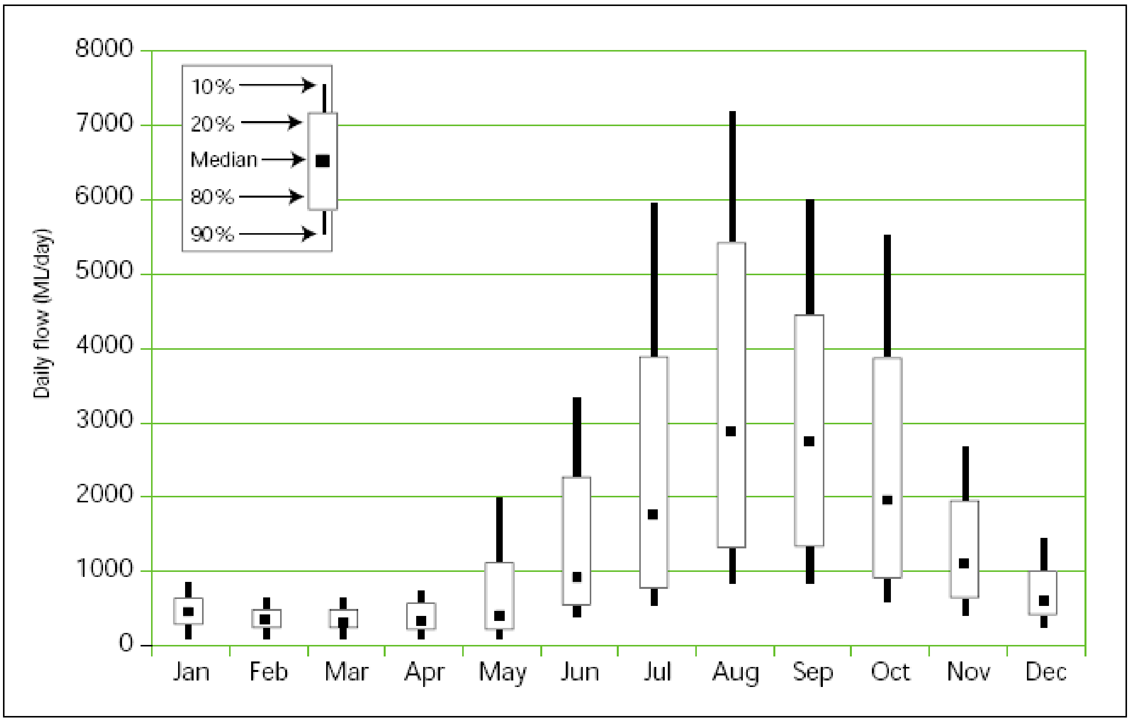

Figure 2-8: Box plot of daily flows showing flow exceedence percentiles for each month at the Myrtleford flow gauge 403210 (1965-1998). (Goulburn Murray Water 2003)

Although the river may not have actually stopped flowing, low flows over summer are posing an issue for irrigators and water users who rely on the river to maintain production over summer months (Rural Water Commission of Victoria 1986; Goulburn Murray Water

2003). It is also an issue for river health as reduced flows have implications for water quality and reduced habitat for in-stream biota (Cottingham et al. 2001).

2.5 Groundwater- stream interaction

Nearly every surface water feature, such as rivers and lakes, will interact with groundwater (Winter et al. 1998; Sophocleous 2002). Where they are connected, groundwater and surface water interact in the hydrologic cycle and changes in one, e.g. human extraction of groundwater, will impact on the other. For effective management of water resources an understanding of the basic principles of the interactions between groundwater and surface water is needed (Winter et al. 1998; Sophocleous 2002; Evans 2007)

The mechanisms and different types of groundwater-surface water interaction have been covered in detail in publications by Winter et al. (1998), Sophocleous (2002) and Brodie et al. (2007). The current literature on groundwater – surface water interaction in the Upper Ovens River will be combined with general literature on interactions in other regions to determine knowledge gaps and information lacking in the Upper Ovens.

Interactions between groundwater and surface water are complex and vary depending on climate, landform and geology. Groundwater movement occurs along flow systems, or flow paths, which occur on a local, regional or intermediate scale. Flow paths are used to help conceptualise groundwater movement with different flow path timeframes shown in Figure 2-9. In general, local flow systems are classified as those with a timeframe of days to years, intermediate systems would be years to centuries and regional systems would be in centuries to millennia. The scale of the groundwater system(s) will influence interactions with surface water features, as will the context of the features in the landscape. Thus it is important to understand the scale of the flow system, its interaction with other flow systems, and effects of topography, geology and climate (Winter et al. 1998; Sophocleous 2002). Lag times or flow times become important for understanding interactions and also have a large influence on management decision timeframes (Figure 2-9).

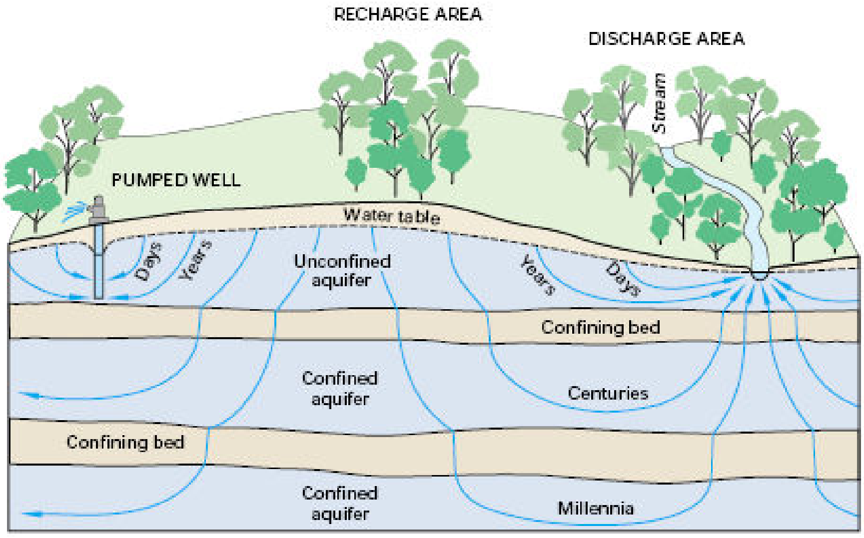

Figure 2-9: Temporal scales of groundwater movement and interactions with surface water (Winter et al. 1998)

Potentiometric groundwater surface maps of the Upper Ovens catchment show that groundwater levels and flow are dominated by surface features with groundwater gradients loosely following surface feature topographical gradients (Sinclair Knight Merz 2007a). In topography controlled systems the groundwater can move in a series of predictable patterns and the interaction with surface water features are governed by the positions of the feature with respect to groundwater flow systems, geologic characteristics of their beds and the climatic settings (Winter 1999; Sophocleous 2002). All three of these components must be taken into account for a thorough understanding of the hydrology of the Ovens River and its interactions with groundwater.

In the Upper Ovens catchment a regional flow system exists in the fractured rock aquifer. Intermediate and local flow systems occur in the unconsolidated sediment aquifers of the valleys and this is the interface where the interactions between the Ovens River and all of the groundwater flow systems occur. A generalised simplified representation of this interaction interface is described by Winter et al. (1998) and is shown in Figure 2-10. The unconsolidated sediment aquifers of the valleys are also where the majority of water extraction occurs and is the area where the understanding of groundwater-surface interactions is required for management.

Interactions between the fractured rock aquifer and the Ovens River occur through springs at the break of slopes on the valley walls (Shugg 1987a). This flow system may also have indirect interactions through influences on the intermediate and local flow systems of the unconsolidated sediment aquifers of the valleys. The temporal scale of these interactions is unknown. The fractured rock aquifer is an unknown element and will require consideration in the research but will not be a focus.

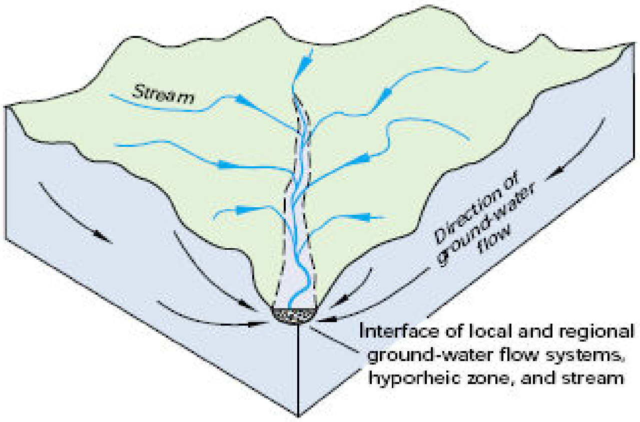

Figure 2-10: Simplification of Groundwater flow systems of the Upper Ovens Catchment (Winter et al. 1998)

2.5.1 Interaction between alluvial groundwater and the Ovens River

There is a high level of interaction between the shallow alluvial groundwater and the Upper Ovens River (Cox 1989; Sinclair Knight Merz 2006a). The Ovens River is hydraulically connected to the alluvial groundwater aquifer of the valleys via a continuous saturated zone (Sinclair Knight Merz 2007a) and can be defined as either connected (Winter et al. 1998), or contiguous (Brodie et al. 2007). Connected streams will can gain or lose water to the groundwater depending on the gradient between the water table (groundwater level) and the height of water in the river (river stage). When the groundwater level is higher than the river stage, groundwater will flow into the river and the river will be classified as gaining (condition A. Figure 2-11). Conversely when groundwater level drops below the river stage the river will lose water to groundwater (condition B Figure 2-11) .

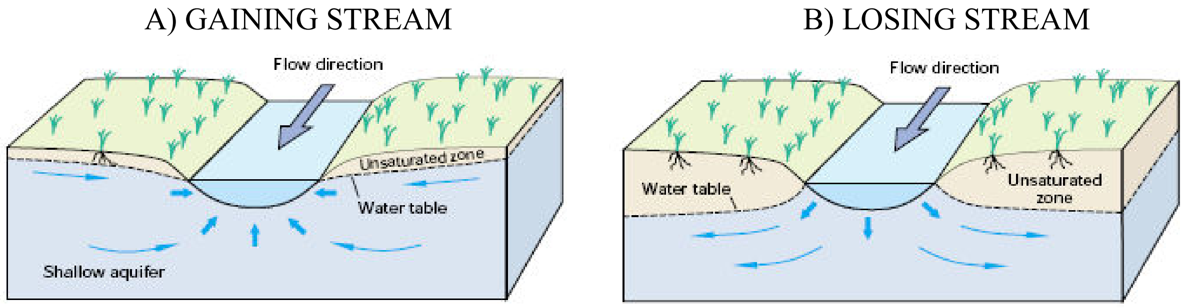

Figure 2-11: Representation of gaining and losing conditions in a connected stream (Winter et al. 1998)

Water flow direction between the alluvial aquifer and the river is not constant spatially and can vary along the length of a river, depending on channel bed morphology, aquifer hydraulic conductivities and geomorphology. Precipitation events and seasonal patterns alter the hydraulic head in both groundwater and river and thereby induce changes in flow direction (Sophocleous 2002). Combining these factors means that the direction of water flow between groundwater and the river varies spatially and also in time. Understanding how the above factors influence water flow direction is critical for effective management.

Under normal climatic conditions and for most reaches, the Ovens River is gaining from the alluvial aquifer (Rural Water Commission of Victoria 1986; Shugg 1987a; Heislers 1993; Sinclair Knight Merz 2007a), however, it can become losing in some sections (Shugg 1987a). The majority of studies in the Upper Ovens have focused on average flow and climate conditions and there is some evidence of the river becoming losing in reaches during periods of low flow in times of drought. A monthly surface water balance of the 1982/83 drought year found between 1 and 26% of monthly flows were lost to groundwater over summer in the Ovens River reach between Bright and Myrtleford (Rural Water Commission of Victoria 1986). The methodology used for that water balance is vague but no reference to consideration of groundwater levels or stream morphology was found.

The need to understand the impacts of channel morphology on the direction of water flow is highlighted at Myrtleford where there is a streamflow gauge and groundwater monitoring. Comparisons of river stage to groundwater levels have shown that the river height is approximately 1.5 metres higher than groundwater levels and thus it could be considered that the river is losing to groundwater at all times (Figure 2-12). Stream bed morphology has been indicated as the reason for the difference in heights and that although the river is losing at this point it is still considered gaining in the general Myrtleford area (Sinclair Knight Merz 2007a). Site investigations reveal the reason for the discrepancy. Gauge 403210 is located where the river intersects the fractured rock on the valley side. Even though the gauge site is only 300 metres from the bore, the river bed at the gauge is approximately 1.5 metres higher than the river bed adjacent to bore 83232. The localised variations in stream morphology would have implications on flow cells and losses from the river and the impacts of these variations require consideration when analysing interactions at this site.

The RWC (1986) water balance used gauge 403210 to calculate the flows at the end of the reach. The influence of the fractured rock high, large drop in channel bed height and high permeability of the aquifer, means that water may be flowing through the aquifer at the gauge rather than in the river. If this is the case, the flows recorded at the gauge would be less than the flows immediately downstream. As such the calculated loss may be a localised loss specific to the site, rather than a loss occurring over the whole reach.

Hydrographs in Figure 2-12 shows that groundwater and river show the same seasonal responses, and indicate that they are connected. Previous studies by SKM (2007) and the RWC (1986) that reflect the current understanding of groundwater-surface fluxes in the Upper Ovens River, were limited to bulk water balance calculations and estimations of average fluxes of water between groundwater and the river in terms of losses in the water balance. For a complete understanding of volume of fluxes between groundwater and the river, investigations that include the influences of spatial factors (channel bed morphology, aquifer hydraulic conductivities, geomorphology) and temporal factors (precipitation events and seasonal patterns) is required. The SKM (2007) study utilised modelling to reproduce flows. Errors in the reproduction of low flows were acknowledged due to the difficulty in accurately modelling groundwater interactions that are important at low flows. A water balance using gauged flows rather than a modelled flow series will overcome this issue.

Of key importance to understanding the mechanisms of fluxes of water between groundwater and surface water is whether a relationship can be defined to show when the

Ovens River switches from gaining to losing in a given reach. This relationship will also be critical for management as without it, no decisions can be made regarding groundwater level management targets.

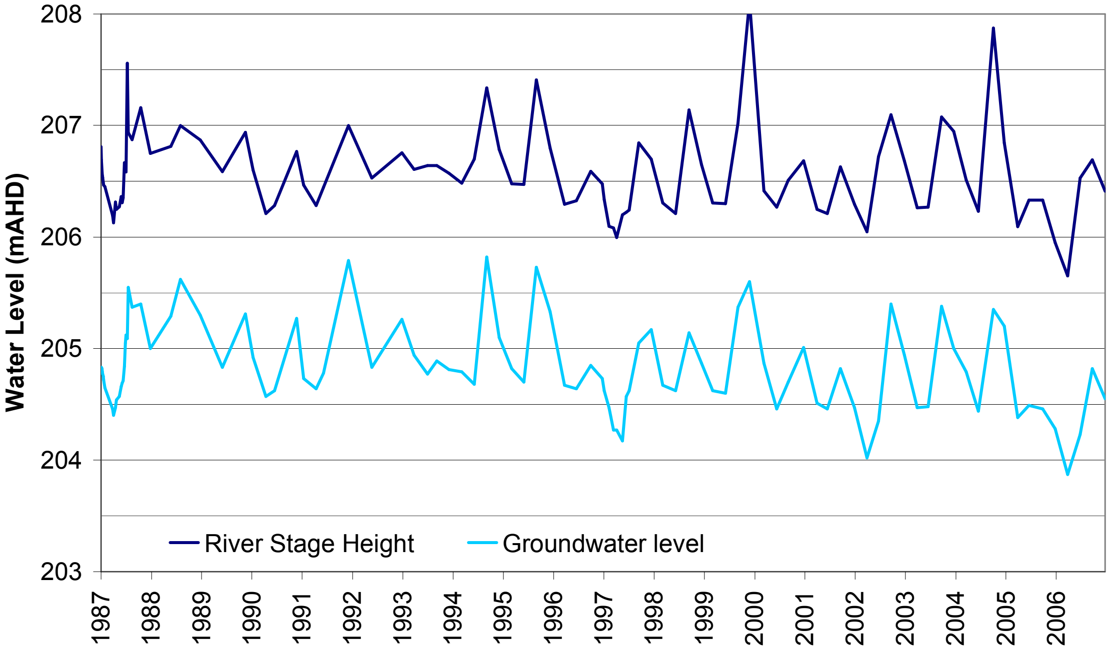

Figure 2-12: River stage height (gauge 403210) and groundwater levels (Bore 83232) at Myrtleford

2.5.2 Groundwater development and impacts on streams

Groundwater pumping near a river creates a gradient that captures some of the water that would have discharged as baseflow to the river. If extraction becomes sufficiently large the declines can induce flow out of the river into the aquifer (Sophocleous 2002). In connected systems such as the Ovens valley, pumping can have a significant effect on the movement of water between the river and groundwater. A group of bores will usually impact at a local groundwater flow scale, however, with sufficient bores and extraction the effect can be at a regional scale (Winter et al. 1998). At its extreme the regional impacts can become so large that it actually changes the flow regime of the stream. In Arizona (USA), the flow regime of Santa Cruz River has been altered from a perennial gaining stream to an ephemeral stream and resulted in large environmental impacts, such as species loss and desertification. In the greater Arizona region, groundwater pumping has lowered the groundwater table to such an extent that 90% of Arizona's perennial streams have dried up or degraded (Glennon 2002).

Even small changes in the gain loss relationship can have large environmental impacts. In California's last, large, unregulated river, the Consumnes River, groundwater pumping has increased the interval where the river remains dry. This occurs because the lowered groundwater table means the streambed must become fully saturated before the river will flow, often delaying full river flows for several months (Glennon 2002). To adequately manage groundwater-surface water interactions, an understanding of the possible implications to the flux relationship from pumping and impacts to the environment is required. These examples show that the impacts of groundwater pumping are often not realised until it is too late and impacts are too large to easily reverse.

In this regard it should be noted that the impacts of groundwater pumping cannot be just turned off. Timeframes for reversal of pumping effects are dependent on the lag time required for recharge, both directly from rainfall and from surface features, to return the groundwater to pre-pumping levels. Depending on the recharge rates and aquifer parameters this can take days to centuries (Winter 1999).

In the Upper Ovens the majority of groundwater extraction is from the shallow aquifer with high transmissivity. This extraction has the potential to rapidly influence groundwater-river fluxes. Preliminary test pumping and numerical modelling in the Upper Ovens near Bright found that groundwater extraction did rapidly impact on river flows (within hours) and that the degree of interaction was dependent on the extraction rates (Cox 1989; Cox 1990).

A rudimentarily calibrated finite difference model (MODFLOW) covering a 6 km reach of the Upper Ovens catchment near Ovens, was developed to investigate the impacts of groundwater extraction fluxes from the Ovens River (Sinclair Knight Merz 2006a). The modelling confirmed the very high level of interaction and found that in the long term (10 years) all of the groundwater extracted would be sourced from stream flow depletion. More importantly, they found that there was the potential for substitution of direct stream flow extraction to groundwater extraction to provide slightly increased flows over the summer low flow period. It was noted that the slight increase was short term and that due to short lag times between groundwater extraction (days to months) and the related streamflow depletion, there was a risk that in years of low flow for extended periods (months) that the groundwater extraction may actually negatively impact on the stream flows.

The risk of groundwater extraction is that once the groundwater is taken, impacts on streamflow depletion cannot be turned off. The lag between extraction and streamflow depletion is potentially unknown for management. In systems such as the Ovens River with periods of river flow dependant on baseflow, groundwater extraction early in the baseflow dependant period may actually reduce baseflows and groundwater levels to such an extent that the river dries out. Understanding the time lag is critical for managers to set decisions around groundwater pumping and restrictions.

The amount of groundwater extraction is unknown in the Upper Ovens valley and understanding the volume of extraction in relation to its impacts on the volume and timing of fluxes between groundwater and the Ovens River is also an important issue for management. Impacts of groundwater pumping on stream flows are largely unknown, modelling has shown water taken from groundwater will come from the stream, but also that substitution could increase flows in low flows but with possible risks depending on lag times for impacts (Sinclair Knight Merz 2006a). A better understanding of lag times is required.

These issues have led to this research seeking to understand fluxes between groundwater and the Ovens River and lag times for interactions.

2.6 Water use and management in the Upper Ovens Valley

In Victoria, water extraction and use is managed under the Water Act 1989. Extraction from unregulated rivers and aquifers, such as the Upper Ovens River Catchment, requires a licence which gives the licence holder rights to extract a volume of water (entitlement). The majority of water users have a licence managed by a Rural Water Authority. All licences have a set volumetric limit and may have special conditions that limit where and when water can be taken. In addition to licences, Water Authorities hold entitlements for water extraction called Bulk Entitlements. In the Upper Ovens, there are several Bulk Entitlements for the supply of water to towns. The management of Bulk Entitlements is the responsibly of the Authority holding the Entitlement, however, compliance is monitored by the Victorian Government. Bulk Entitlements often have strict conditions on when and where water can be taken.

In areas where resource availability issues have developed, community consulted management plans are used to share resources equitably between users. This also includes the environment (but not always). The Upper Ovens catchment has been identified as one area where the flow regime is stressed and has been prioritised for management plan development (Victorian Government 2004). As strong connectivity is known to exist between groundwater and surface water, the area has been identified for the first conjunctive water management plan in Victoria.

2.6.1 Water use in the Upper Ovens

Agriculture in the Upper Ovens valley is focused on river flats and gentle slopes of the valley side. The largest land use is grazing and dry land farming, however, there is also a large amount of irrigation of pasture, tobacco, hops, vineyards, nuts and orchards (Goulburn Murray Water 2003). The steeper slopes and mountain areas are either state forest or national parks and thus retain native vegetation, primarily in the form of Mountain Eucalypt varieties. However there are large areas of pine plantations including on the alluvial flats around Bright.

Irrigation is primarily summer based, is reliant on river flows and most water is extracted directly from the river using pumps. Flows in the Ovens River are such that there is water available for extraction in most years, with only one year in ten where reduced availability is predicted (Rural Water Commission of Victoria 1986). As shown in Figure 2-13, demand for irrigation varies seasonally, maximum extraction averages around 25 ML/day with peaks over 35 ML/day in the summer months (Goulburn Murray Water 2003). Demands for town and household use are around 6 ML/day. Over summer when flows are low the demand cannot be met by stream flows and extraction from the river may be restricted or banned. This can be an issue for irrigators as no access to water means reduced crop yield and even possible complete crop loss. Many irrigators have both a groundwater and surface water licence and use the former as a backup to irrigate crops in times of restriction or bans on extraction from the river (Rural Water Commission of Victoria 1986). This use of groundwater as a backup supply, combined with the topography of steep valley walls and narrow alluvial floodplain, means there are few farm dams or storages in the main valley.

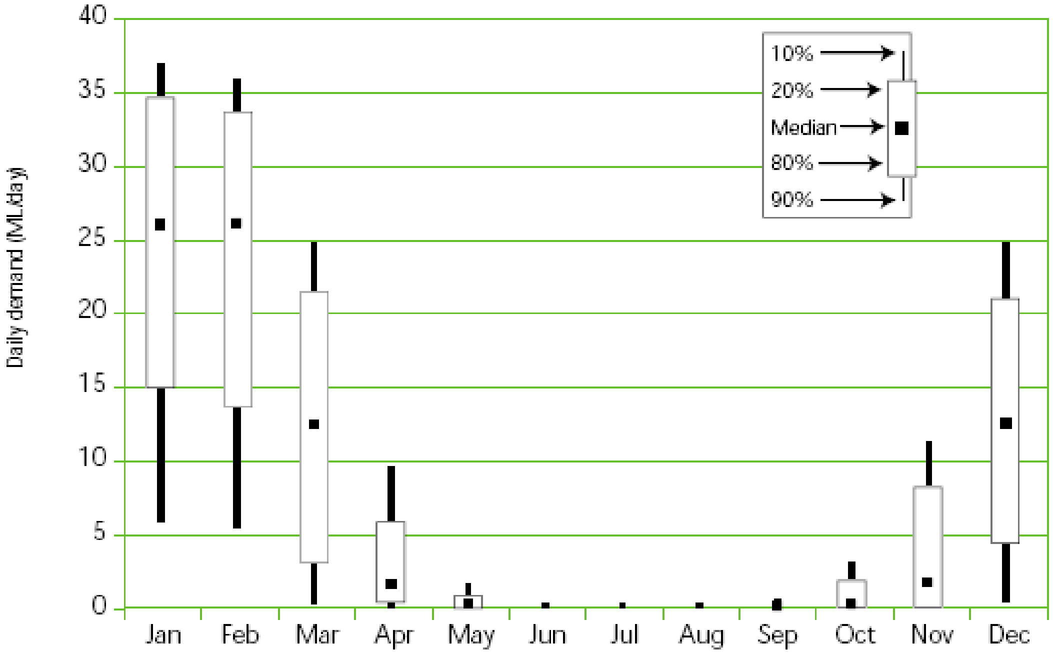

Figure 2-13: Estimated range of daily direct irrigation diversions from the Upper Ovens catchment (Goulburn Murray Water 2003).

Volumes of licenced entitlement for extraction of water in the Upper Ovens catchment are given in Table 2-3. There is 8,292 ML of licenced entitlement for irrigation and other uses (including domestic and stock) as direct extraction of water from the Upper Ovens River and its tributaries (Goulburn Murray Water 2003). The majority of extraction is between Bright and Myrtleford (Figure 2-15). Extraction is metered and this has shown that not all of the water is used each year. Between 1996 and 2005 an average of 37% (3048 ML) of entitlement has been metered as being used (Goulburn Murray Water 2003). Towns (Urban use) are licenced (in the form of Bulk Entitlements) to extract a further 3,385 ML of water. Urban usage is around 2,000 ML/yr (Goulburn Murray Water 2003).

Licence type	Volume (ML)	Average Use (ML)	Maximum Use (ML)	Usage calculation method
River Extraction	8,292	3,048	3,791	Metered (1996-2005)
Catchment Dams	1,851	Unknown	Unknown	
Groundwater	3,727	1,130	1,868	Modelling (SKM)
Bulk Entitlement	3,385	1,716	2,011	Metered (1996-2005)
Total	17,255	5,894	7,670	

Table 2-3: Entitlements to water and use in the Upper Ovens Catchment

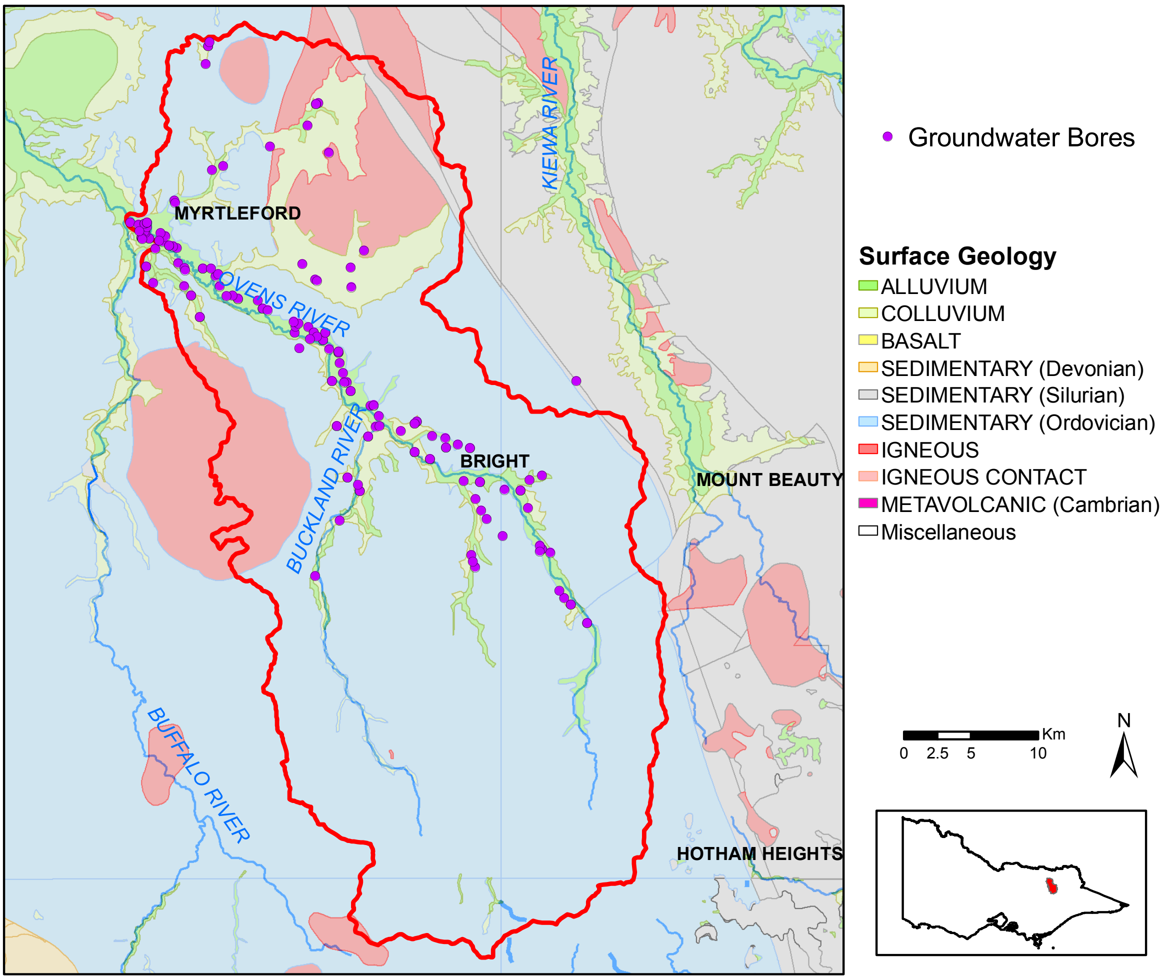

Figure 2-14: Location of groundwater bores

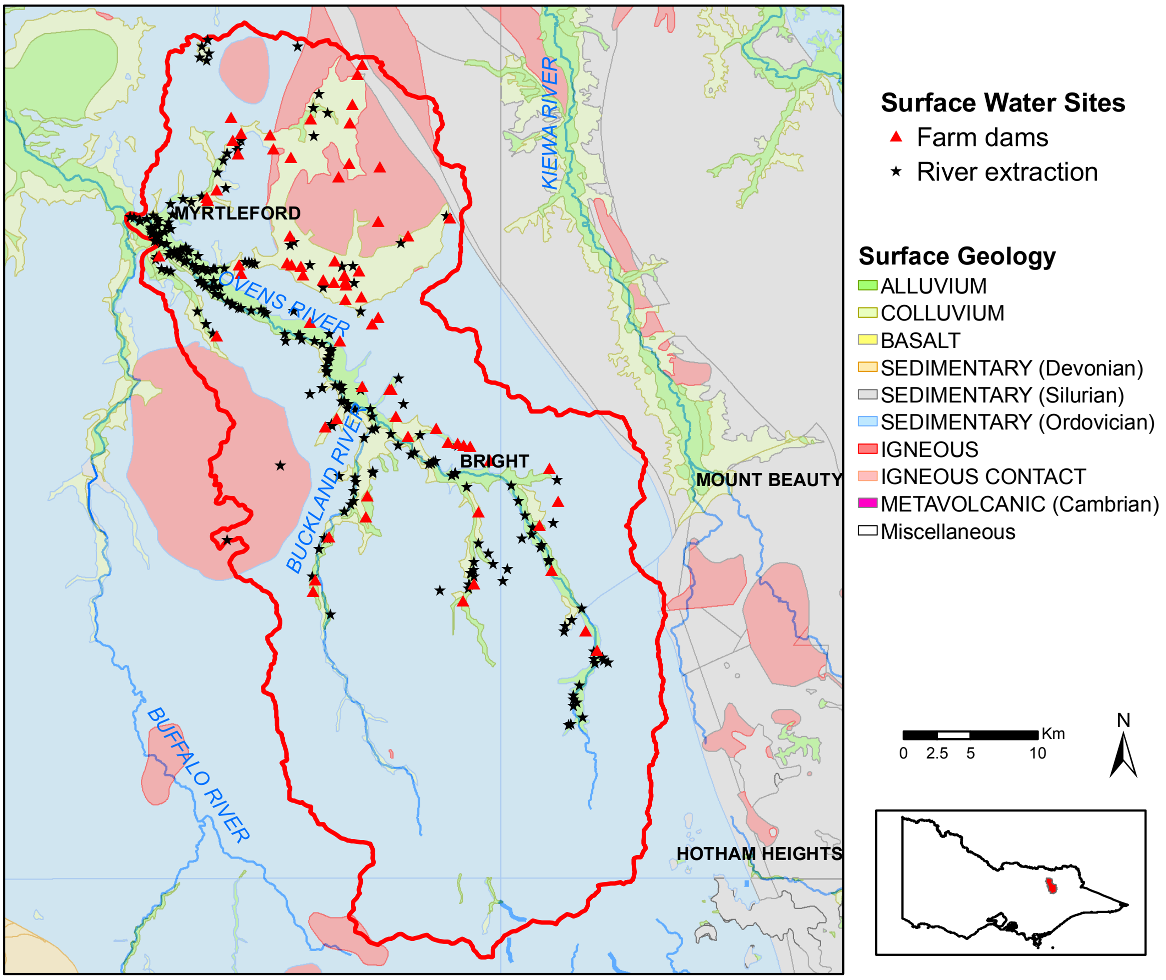

Figure 2-15: Location of licence surface water extraction sites

2.6.2 Groundwater management

All groundwater in the Upper Ovens catchment is part of the recently declared (2008) Upper Ovens Water Supply Protection Area (WSPA). The Permissible Consumptive Volume (PCV) was set in 2008 at 4,010 ML per annum for all formations below the surface (Holding 2008). The PCV sets a maximum cap on the volume of licenced groundwater entitlement and means that no new licences may be issued for the area. New development for groundwater can only occur via temporary trades of water where the groundwater user can trade their water requirements for one season.

The PCV was set based on the existing amount of entitlement (3727 ML in Table 2-3), plus the existing commitment of licence applications (283 ML) within the boundary. Thus it is a precautionary value, rather than a scientifically based rigorous resource assessment. As to why the precautionary extraction volume was set, we have to look the history of groundwater management in the Ovens valley and also the whole of Victoria. In other Victorian aquifers, entitlement has been granted without reference to sustainable extraction levels. In some areas, where entitlement exceeds the sustainable extraction level, falling groundwater levels have led to Groundwater Management Plans being developed to restrict groundwater use. This occurred in the Katunga and Campaspe WSPA's in North Central Victoria.

In the early 1990s, the Victorian government conducted preliminary resource assessments to determine sustainable groundwater extraction volumes based on recharge calculations. In the Ovens River catchment area, the Murmungee GMA was previously the management area for the alluvial sediments to 25m deep. This boundary included areas outside the Upper Ovens catchment but covered the majority of the alluvial aquifer within the Upper Ovens catchment. The sustainable extraction volume for the Murmungee GMA was derived by subtracting the average discharge to the Ovens River from the calculated rainfall recharge (Reid 2004). In December 1999, approximately 88% of sustainable extraction volume in the defined Murmungee GMA had been allocated and as a precautionary measure Goulburn-Murray Water (G-MW) placed a moratorium on the allocation of any additional groundwater licences in the GMA.

The Murmungee GMA boundary did not cover all of the alluvial aquifer area and the depth restriction to 25m meant that deeper aquifers in the Calivil and Shepparton formation were not included. Added to the inadequacy of the boundary, an audit report also noted that calculations of recharge were not appropriate and more resource may be available (Reid 2004). A proliferation of new groundwater licences in the alluvial aquifers just outside the boundaries further highlighted the inadequacy of the boundary and inequity for possible groundwater users. Problems with the boundary led to the formation of the Upper and Lower

Ovens GMA's which covered all the surface water catchment boundaries and ensured all of the alluvial aquifers were covered.

Uncertainties over the recharge calculation in terms of sustainable extraction volumes, and also the unknown influence of groundwater pumping in regard to groundwater-surface water interaction, and the impact on base flows has led to the water resource manager, Goulburn-Murray Water, issuing the PCV at current groundwater licence volumes.

Groundwater levels are used by water managers to observe trends in aquifer volumes. With groundwater levels steady in the Upper Ovens catchment (Figure 2-5) there has not been considered to be an unsustainable use of the aquifer. No restrictions on groundwater pumping have been implemented beyond keeping extraction to licenced volumes.

Historically, groundwater licences have not been required to be metered within the Upper Ovens catchment and as such there is no record of use. Preliminary studies of groundwater use indicate only low level of extraction (Sinclair Knight Merz 2006b). An understanding of possible impacts of increased groundwater extraction on baseflow to the river is not known but is considered to be a risk that will be considered in the proposed water management plan.

2.6.3 Surface water management

There are two types of surface water licence managed by the Rural Water Authority, a direct licence allows water to be pumped from a waterway at any time but is generally used for summer irrigation. A winter fill licence allows water to be harvested or used in the winter period between July and October inclusive. The Bulk Entitlements in the Upper Ovens allow extraction from the Ovens River and its tributaries and usage is in line with town demands.

Direct licences are over committed in the Upper Ovens and in low flow periods there is not enough water to meet demand (Goulburn Murray Water 2003). No new direct licences can be issued, however, they can be traded into the area under certain rules. Generally the rules only allow trade downstream thus there is limited potential for further trade into the Upper Ovens catchment. Sustainable diversion limits (SDL) for volumes of winter licences have been set for all Victorian catchments based on average flows over a pre-determined environmental flow volume (Department of Sustainability and Environment 2008). The SDL for the Upper Ovens catchment is approximately 62,000 ML, with total surface water licence volumes less than 15,000 ML (Table 2-3) and the level of winter fill licences is not over committed. As a result, new winter fill licences can be allowed up to the Upper Ovens Catchment SDL. In all cases no new licence entitlement is created, the required volume must be traded from other sources.

Because the Upper Ovens River is unregulated the only way to vary flows is to manage extraction from the river. As direct licences are overcommitted during low flow periods the water resource manager is required to implement water sharing rosters and restrictions on water extraction. When flows decline below set flow trigger levels, rosters are implemented which restrict extraction volumes from the river. As flows decline the roster (restriction) level increases. When flows hit a minimum level, a ban on extraction from the river is introduced. Current management is based on a 1983 drought response plan (HydroTechnology 1993). Levels for restrictions are based on flows at the Bright Gauge 403205 and the flow levels and restrictions in extraction volume are outlined in Table 2-4. Once seven day average flow increases above the trigger level, the rosters are removed or lifted.

Flow level at Bright (ML/day)	Roster Level	Reduction in pumping volume
40	1	Water sharing
30	2	25%
20	3	50%
10	4	75%
<4	5 - Ban	Direct irrigation Ban

Table 2-4: Rostering schedule for the Upper Ovens River (Goulburn Murray Water 2003)

2.6.4 Proposed conjunctive management plan

The Victorian Government has legislated that a conjunctive management plan will be implemented for the area. Initially the area was identified for a stream flow management plan to provide for increased flows for the environment (Victorian Government 2004). Due to the high connectivity between groundwater and surface water, a conjunctive plan will now be developed. The aim of the plan is to recognise the environment as a legitimate water user and provide a plan that shares water between all users.

An environmental flows assessment which analyses the flow patterns and determines environmental flow requirements based on set environmental flow objectives has been completed. Recommendations from this analysis highlight magnitudes and timings of river flow events required to maintain or improve the environmental condition of the river (Sinclair Knight Merz 2006d). The report emphasises that water extraction generally only has an impact on the environmental flow regime under summer low flow conditions. As this also coincides with the period of time where the river is already overcommitted for human uses, the plan will need to focus on this period for negotiated outcomes.

The recommend minimum summer environmental flow is 137 ML/day and this equates to the 80th percentile flows (Sinclair Knight Merz 2006d). As the river is unregulated the recommendation is that all extraction should cease when this flow level is reached. Flows may drop below this figure but only if that would happen naturally. This figure greatly exceeds the flow thresholds in Table 2-4 and is a recommendation only. The final environmental flow trigger will be determined within plan negotiations between stakeholders.

Although the final actual negotiated environmental flow figure is unknown, given the flow recommendation it will most probably be higher than current management levels and have an impact on reliability of supply for irrigators. Extraction bans at the current 3 ML/day have an occurrence of less than 10 times per 100 years with an average duration of 2 weeks. A ban for an environmental flow at 137 ML/day has an occurrence of over 70 years per 100 years with an average duration of around 6 weeks. Halving the flow at 66 ML/day sees irrigation bans 35 years in 100 with average duration of 4 weeks (Goulburn Murray Water 2003). Reduced access to water will mean irrigators will be required to look for alternative sources of water such as on-farm storage or groundwater in times of the extraction ban.

Groundwater could provide an alternative supply of water in a low flow period, however, with its strong connection to the river there is risk of adverse impacts to river flow. Numerical modelling has indicated that there may be a possibility that switching to groundwater extraction in low flow years may provide short term flow benefits, but there is also the recognition that with short lag times this actually may reduce flows late in the season if rain is delayed (Sinclair Knight Merz 2006a). Hence the need to conjunctively manage the resources.

SKM (2007a) proposed that the unconsolidated sediment aquifers area be managed in two zones. In the near river zone (Zone 1) groundwater would be managed consistently with surface water licences. In Zone 2 licences would be managed as groundwater, recognising delayed lag of impacts of groundwater extraction on stream flow.

These zones were based on modelling showing that 100% of groundwater extracted from a bore 10m from the river is sourced from the river within one irrigation season, but from a bore 300m from the river only 65% of groundwater extraction is sourced from the river within one season (Sinclair Knight Merz 2006a). There was no attempt to link the groundwater management objectives to stream flow objectives or consider the impacts of the extraction outside Zone 1 on the environmental flow objectives.

To develop a conjunctive management plan, an understanding of timing and volumes of fluxes between groundwater and surface water and the impacts of groundwater pumping on these fluxes is required. Currently river flow objectives are known however there is no method to link these to groundwater management to ensure environmental flow objectives are achieved.

If interactions can be adequately evaluated possible impacts of extraction volume on the resource, especially at low flows, can be considered and a bulk sustainable groundwater extraction volume determined.

For an effective conjunctive management plan scientific research needs to investigate whether groundwater extraction can be managed to provide increased security of supply without compromising river flow objectives.

2.7 Summary

The Upper Ovens River Catchment is in a mountainous area with a wet winter/spring period and dry summers. River flow follows the climate patterns with peak median monthly flows of 2730 ML/day (Table 2-2) after the wet period and with spring snow melt and low median monthly flows (133 ML/day) over the dry summer.

Two major aquifer systems exist in the Upper Ovens catchment. A regional flow system occurs in the larger fractured rock aquifer of the Ordovician marine sediments. The fractured rock aquifer has good quality water with a TDS generally less than 300 mg/L but low bore yields of around 0.1 ML/day mean use from the aquifer is limited to domestic and stock use (Heislers 1993). The second aquifer system occurs in the unconsolidated sediments that have in-filled the valleys by alluvial processes. It is hard to differentiate the sediments into aquifer units from bore logs, different formations exist as heterogeneous shoestring layers and discrete units rather than layers extending across the valley. Generally the water quality is good with TDS less than 200 mg/L and higher yields in some of the coarser sediments of up to 1 ML/day lead to use of water in these areas for irrigation.

Groundwater levels in the unconsolidated aquifers show seasonal variation and response to river levels with high levels in the wet winter and low levels in the summer (Figure 2-5). Similar responses are shown at all depths of the unconsolidated aquifer suggesting a high connectivity between possible aquifer units and the river (Figure 2-6). Only one fractured rock observation bore exists and shows the same water level response as the unconfined aquifer (Figure 2-7), however issues with the bore, outlined in section 2.3.2.2, suggest that it does not represent the aquifer as a whole.

The unconsolidated aquifer is hydraulically connected to the Ovens River via a continuous saturated zone. As outlined in section 2.5.1, studies have found that primarily the Ovens River gains water from the aquifer, however, this relationship can vary temporally and spatially and will depend on the relative river and groundwater levels. The RWC (1986) found that in the 1982/83 drought the Ovens River lost to groundwater with monthly losses varying between 1 and 26% over summer. Further understanding the timing and magnitude of fluxes between groundwater and the river is required for conjunctive management. Key research question one is focused on this understanding.

In connected systems, groundwater pumping creates a groundwater gradient away from the river and captures base flow, or in extreme cases, reverses the gradient and water can flow from the river. If groundwater pumping in the Upper Ovens occurs in the summer period with low flows, there is the risk that the river will dry out (Section 2.5.2). To effectively manage this risk an understanding of whether the river naturally loses water is required and hence key research question number two.

Although there is the risk of groundwater pumping reducing flow in the river, SKM (2006a) showed that switching extraction from the river to groundwater can lead to short term flow increases. Flow benefits arise through the lag time between groundwater pumping and subsequent river losses, however, if the lag period is such that the impacts occur in low flow periods they may increase risks to the environmental flow. If groundwater can be used as an alternative to river extraction this will have benefits for irrigators and for achieving environmental flows, hence key research question number three.

In Victoria, water extraction is licenced to set volumes. The Upper Ovens has 17,255 ML of licences for extraction directly from rivers, from groundwater or by capturing surface runoff in dams (Table 2-3). On average less than 6000 ML is extracted from the river or groundwater each year. This extraction is only a small amount of the mean annual flow of

584,000 ML and for the majority of time does not have a large influence on the flow regime. However, daily demand can peak at over 35 ML/day (Figure 2-13) and in low flow periods users are restricted on how much and when they can take water. Restrictions are based on flow trigger levels set out in Section 2.6.3. Currently extraction is banned when flows drop below 4 ML/day, but, it is proposed to increase this restriction flow level to provide for environmental flows. Environments flow requirements are calculated to be 137 ML/day and although the final trigger level is to be negotiated with users it is envisaged that it will be higher than the current level, reducing user access to water.

It is proposed that due to the high connection between the river and groundwater that groundwater extraction is managed to protect environmental flows. As there is the potential for groundwater extraction to reduce flows, restrictions on groundwater use may be required in extreme low flow events. Currently there are no restrictions on groundwater use apart from keeping to licence volumes so any management will reduce groundwater user's access to water. A method to link river flow objectives to groundwater levels is required to set groundwater management objectives as outlined in key research question four. A groundwater extraction volume that does not compromise the flow objectives would also be of benefit to managers and is investigated by key research question five.

This chapter has highlighted gaps in the understanding of groundwater – surface water interaction in the Upper Ovens and outlined information required for managers to develop conjunctive management principles for the protection of low flows in the Upper Ovens River. A series of key research questions have been developed to focus the investigations in this study.

2.7.1 Key research questions

1. What are the magnitudes of the fluxes between groundwater and surface water and is there a pattern or trend for these interactions?
2. What are the natural conditions under which the flux of water switches between the river gaining from groundwater to losing to groundwater?
3. Can groundwater extraction be used as an alternative supply to surface water for irrigators without compromising environmental flow objectives?.
4. Can a groundwater-river level relationship be defined to link groundwater levels to stream flow objectives?
5. Can a bulk annual sustainable groundwater extraction volume be calculated?

Chapter 3: Water Balance

The need for a robust scientific understanding of the timing and magnitude of fluxes between groundwater and surface water systems for managers to determine principles for conjunctive management was outlined in the last chapter. Water balances, also known as water/hydrologic budgets, are used to understand the movement of water through the hydrological cycle and have been used to estimate groundwater and surface water interactions (Todd and Mays 2005; Krause et al. 2007). A monthly water balance is used to explore the movement of water through the hydrological cycle in the Upper Ovens Valley, with special attention paid to the terrestrial cycle, which is the movement of water in the surface and groundwater parts of the cycle. A time series of the water balance is used to investigate the timing and quantities of water movement between the groundwater and surface water systems.

In this chapter, Section 3.1 investigates the literature and defines the scope and general methodology for the water balance. Justification for completing a water balance for a sub catchment (the study area), rather than the whole catchment, is provided in this section, along with a conceptualisation of the water balance components in the Upper Ovens. The methodology for calculating each of the individual water balance components is detailed for the surface water system in Section 3.2 and for the groundwater system in Section 3.3. In Section 3.4 the monthly water balance models are defined and the results shown. A river reach balance is calculated first to investigate the river flow patterns. The groundwater and surface water systems are balanced and investigated separately and then combined to give a whole of system balance. The results of the whole of system water balance are analysed to describe the hydrological cycle and define the seasonal pattern of fluxes between the groundwater and surface water systems. A sensitivity analysis of critical water balance components is undertaken in Section 3.5 to understand how the variation of components, or errors in the data, may affect the magnitude or pattern of fluxes. The results of the water balance analysis are then summarised.

3.1 Water balance conceptualisation and method

The water balance investigates the surface water and groundwater components of the hydrological cycle for the Upper Ovens. Recorded field data readily available to water resource managers, were used as the primary source to describe each component. For components with no recorded data, modelling using simple calculations was used for quantification. For many groundwater components, recorded field data was not available (e.g. recharge rates), furthermore many of these groundwater components can't be recorded directly in the field (Scanlon et al. 2002). This is the case in the Upper Ovens. In contrast, recorded data are available for many of the surface system components (e.g. flow, rainfall) and a higher level of confidence can be given to the surface water balance for the Upper Ovens. The groundwater – river flux has not been measured in the field. By quantifying all of the other components of the surface water balance, the groundwater-surface flux can be estimated from the unaccounted volume differences in the surface water balance (Braaten and Gates 2003). Due to the lack of field data, a groundwater balance using the level fluctuation method is used. Comparison of the groundwater balance to the calculated surface water balance determines if flux calculated by the surface water balance is correct and also gives the system (or whole of catchment) water balance. A time series of the water balance is used to investigate the timing and quantities of water movement.

Previous attempts at completing water balances for the Upper Ovens have been on either an individual surface water system or groundwater system basis (Rural Water Commission of Victoria 1986; Sinclair Knight Merz 2006a). No attempt has been made to complete a whole system water balance. In the 1982/83 drought, a river reach water balance was carried out and found losses from the Ovens River of up to 26% of monthly river flow (Rural Water Commission of Victoria 1986). However this balance was only based on gauged flows and metered river diversions and did not consider evapotranspiration. Also, as the focus was to determine river losses, during any periods where the river reach gained water, such gains were considered to be zero. By ignoring gains in a reach, the loss figures would be larger than actual.

River flow modelling of the catchment has been completed using the REALM modelling software (Sinclair Knight Merz 2006b). The purpose of this work was to generate time series of river flow under natural conditions (pre-human development) and also for different levels of development. Outputs of this model could be used to generate a water balance for the area, however, this work has not been completed. REALM modelling attempts to simulate flow patterns and as a result modelled flows for a given time period may not accurately represent the actual values, causing errors in the water balance. The modelling does take into account river losses and also attempts to quantify fluxes from the river to/from groundwater, however, no quantification of these calculated values has been documented. The time series generated from this model provides background data to complement measured data and provide modelled data series for components of the water balance when no recorded data is available. The models application is described later in this chapter.

Sinclair Knight Merz (2007a) completed a preliminary steady state (inflow = outflow) groundwater system balance quantified using rudimentary bulk assessments. This can be used as a guide to the magnitudes of the groundwater balance components. Numerical modelling of a small area of the unconsolidated aquifer was also undertaken to investigate conjunctive management options (Sinclair Knight Merz 2006). Although not a water balance, the numerical modelling quantified the unconsolidated aquifer’s through flow as one to two orders of magnitude higher than the through flow calculated using Darcy’s flux analysis at Bright and Myrtleford (Sinclair Knight Merz 2007a). This study concluded that the discrepancy is due to boundary effects of the small numerical model and that extending the model could determine this component with more confidence (Sinclair Knight Merz 2007a).

Generally, hydrogeologists must consider an open system balance where the whole of the aquifer area is not constrained by no-flow boundaries and groundwater flows into and out of the area. In an open system balance quantification of the components becomes a mass balance and the change in storage of the system is equal to the inputs minus the outputs (Todd and Mays 2005). Evans (2007) argues that for a complete understanding of water movement in a system and to have a chance of understanding connectivity and interactions between groundwater and surface water, a whole of catchment closed water balance is required. Given the hydrogeology of the Ovens catchment (Chapter 2) a closed whole of catchment water balance could be appropriate as the catchment boundary acts as a closed system with no lateral inflows of groundwater into the area. The fractured rock aquifer levels follow topography and groundwater will be flowing down the valley, both in the unconsolidated and fractured rock aquifers (Figure 3-1).

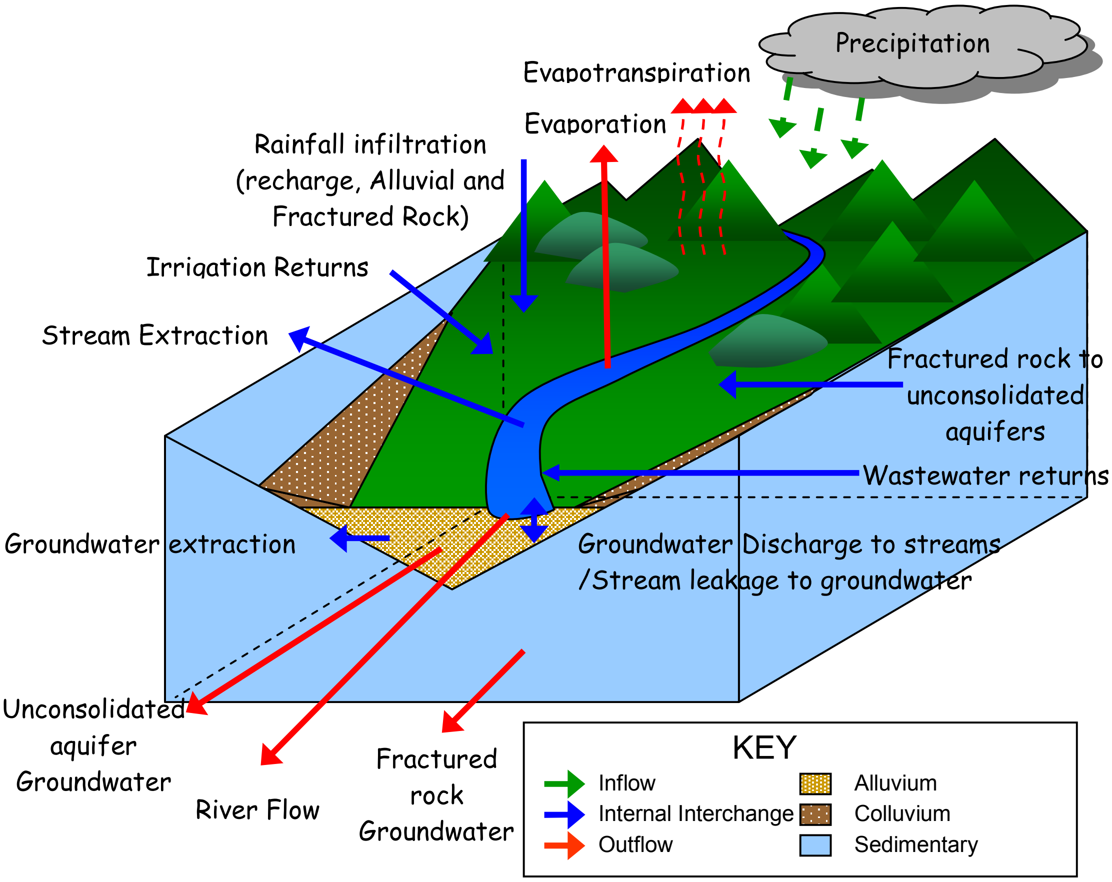

Figure 3-1: Conceptualisation for whole of catchment closed water balance

A conceptualisation of a whole of system closed water balance has been developed for the Upper Ovens catchment and is outlined in Figure 3-1. The change in storage (ΔS) is calculated by subtracting the inputs from the outputs. In this case as the system is closed, the number of input and outputs are reduced. The components classified as internal interchange will not influence the change in storage but quantification is required for an understanding of water movement in the catchment. In this case the water balance is represented by Equation

1 where the only input is precipitation (*P*) and outputs are evapotranspiration (*ET*), surface water evaporation (*Ev*), river/surface flow out (*Qout*), alluvial groundwater flow out (G_{Al}), fractured rock groundwater flow out (G_{Fr})

$$P - Et - Ev - Q_{out} - G_{Al} - G_{Fr} = \Delta S \qquad (1)$$

An absence of monitoring bores in the fractured rock aquifer limits the accuracy with which interactions of the unconsolidated aquifer and this aquifer can be determined. When considering the whole catchment, volumes of rainfall and evaporation are on much larger scale than the volumes fluxes between groundwater and surface water. For the catchment area (1500 km^2) and based on average values of *P* and potential *ET* of around 1200mm/yr (Section 2.1) there would be approximately 1,800,000 ML of rainfall per annum (*P*) and an equivalent volume of Evapotranspiration (*ET*) for the area. Average annual flow out of the catchment is approximately 584,000 ML suggesting a rainfall/runoff coefficient of 0.3 and that *P* is not equal to actual *ET*. Preliminary estimates of fluxes between the river and the alluvial aquifer are around 36,000 ML per annum (Sinclair Knight Merz 2007a). This means that at a catchment scale, the error bounds of the major water balance components are likely to be much greater than the estimated groundwater to river fluxes and would make differentiation of fluxes from the errors very difficult.

One of this study's key research questions is to determine the timing and magnitude of water fluxes between the Ovens River main stem and the intermediate flow cells of the unconsolidated sediment aquifers. The lack data of on the fractured rock aquifer, one of the major components of the water balance, combined with errors in calculating components such as runoff from ungauged areas and *ET* in forested areas, hinders the calculation for a whole of catchment water balance. As a result the water balance will be calculated for a well constrained sub-catchment (the study area) in the area of interest.

3.1.1 Study area conceptualisation

Reducing the water balance to the chosen sub-catchment (study area) makes the surface system water balance into, essentially, a river reach balance. In the study area there is little information on aquifer behaviour and parameters, in particular recharge values. In areas with little information on aquifer parameters, determination of the groundwater components in the groundwater balance may have large errors (Scanlon et al. 2002). River reach balances can be used to estimate groundwater-surface water fluxes by estimating them from the unaccounted volume differences in the surface water balance (Braaten and Gates 2003). In concept, this is similar to the method used by Krause et al (2007) where the modelled fluxes from numerical groundwater models were compared to losses from stream gauging between reaches. Groundwater level data are available for the unconsolidated aquifer and all bores in the study area show similar trends and difference in groundwater fluctuation, however, the information on aquifer parameters varies widely. Instead of numerical modelling, measured groundwater level fluctuations and the water level fluctuation method are used to determine groundwater fluxes into the surface system. Comparison between the surface system water balance results and the groundwater hydrograph fluctuation fluxes will enable verification of aquifer parameters.

A further benefit of the constrained study area is the accuracy of surface flow measurement, with numerous gauging stations reducing the area needing rainfall runoff calculations and reducing the associated error. Groundwater inputs from the fractured rock aquifer into the sub-catchment from the area outside the sub-catchment are also captured as baseflow to streams measured in the gauged flows or in the unconsolidated aquifer level fluctuations. To focus the water balance on fluxes between the river and unconsolidated sediments, the study area has been split into two components based on the geology. The first area is the unconsolidated sediments outlined by the areas of Colluvium and Alluvium and the second is the fractured rock areas outlined as Ordovician Sandstone in Figure 3-2. This differentiation constrains evapotranspiration and rainfall components of the water balance to represent their contributions only to the unconsolidated sediment aquifers.

3.1.2 Study area

The study area boundary covers the topographic catchment for the main stem of the Ovens River between Bright and Myrtleford and is highlighted in Figure 3-2. This area has the benefit of containing the majority of the irrigation licences and covers the main reach where fluxes between groundwater and surface water occur. Measurement of surface water flow is also comprehensive with all flows out of the study area measured by the Myrtleford gauge (403210). Flows into the study area come from the Buckland River and the Ovens river main stem, both of which are measured by flow gauges 403233 and 403205 respectively. Buffalo Creek enters the study area just upstream of the Myrtleford gauge and flows are not currently measured. Two major tributaries, Barwidgee and Happy Valley Creeks join the Ovens River downstream of the gauge. Barwidgee Creek catchment is left out of the study as it should have only minor inputs into the groundwater-surface water interactions of the main valley. Happy Valley Creek may have some influence on the main valley aquifers as it flows parallel to the Ovens River main stem in the alluvial valley for nearly 6 km.

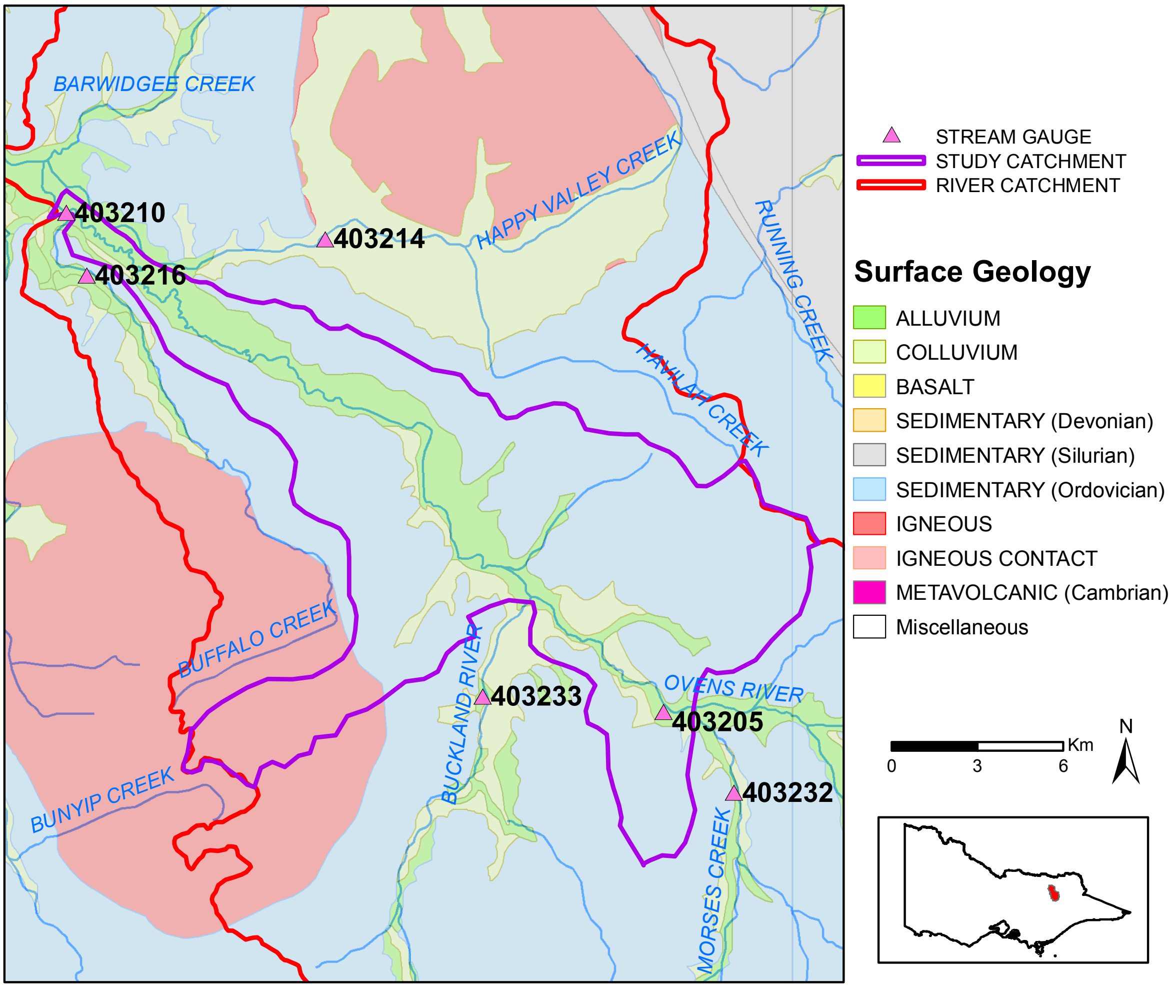

Figure 3-2: Map of Ovens River area with study area

3.1.3 Study area water balance conceptualisation

Components of the study area water balance are outlined in the three dimensional representation in Figure 3-3. The majority of surface water system components are measured directly, or can be calculated using known methods. Groundwater system components are highlighted in italics. These are not measured directly and require calculation or modelling to quantify. This conceptualisation is based on the water balance of the unconsolidated sediments outlined by the areas of Colluvium and Alluvium in Figure 3-2. Fluxes between groundwater and the Ovens River have been excluded from the conceptualisation as these were not quantified individually but rather were inferred as the unaccounted difference in the surface water system balance and value of the groundwater system balance.

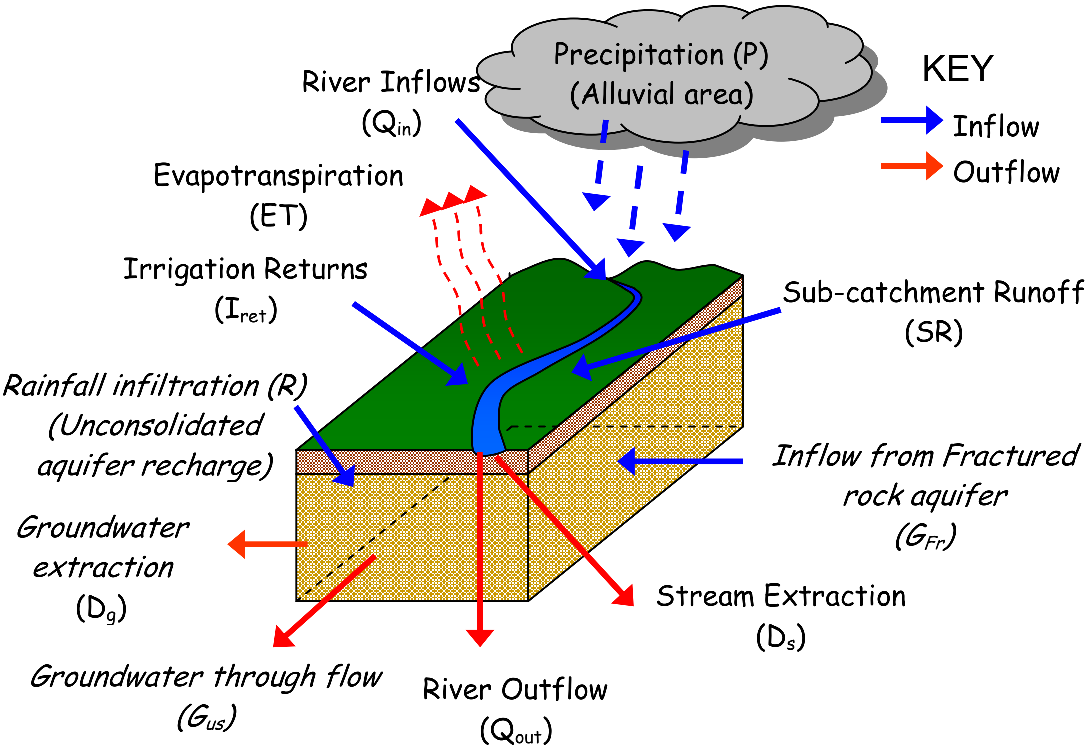

Figure 3-3: Conceptualisation of the study area water balance components

The fractured rock area was excluded from *ET* calculations as it was assumed that *ET* in this area does not affect the fluxes between the unconsolidated aquifer and the Ovens River. Rainfall onto the fractured rock area was treated the same way as *ET* with the assumption rainfall from the fractured rock area is captured in the form of runoff into the unconsolidated aquifer area. Rainfall and *ET* for the unconsolidated aquifer area were considered in full.

3.1.4 Model type and period

The water balance for the study area was an open system balance and quantification of components formed a mass balance to show the change in storage volume over time. Where they were available, measured data were used for components of the water balance in the upper Ovens River catchment. Methods detailing calculation of the individual components are outlined in Section 3.2.

A 30 year period between 1 January 1973 and 30 July 2005 was used for the water balance. This period has a large coverage of the key data, namely river flow records, climate data and groundwater level readings. All surface water components have been measured or calculated on a daily time step. Due to constraints in groundwater data availability, this component was aggregated to a monthly time step. This time step is also considered appropriate to represent the groundwater balance.

Where a daily data series was developed, this was aggregated to monthly data. Missing daily data from sites in the study area were in-filled using data from nearby sites that have been modified using regression relationships to fit data from sites in the study catchment.

Preliminary groundwater inputs/outputs into the water balance were calculated using hydrograph analysis. A representative bore (Section 3.3.1) has been used and groundwater fluctuations extrapolated for the whole alluvial aquifer. Fluctuations were cross referenced across several bores to ensure that the representative bore was consistent with other bores in the aquifer. Groundwater data are generally recorded quarterly but have a varied recording time step at some sites. To develop a monthly series, a linear regression between recordings has been used to estimate groundwater levels. This is possibly a large source of error as the groundwater levels can fluctuate considerably over short periods (days) in the upper catchment. The unconsolidated aquifer is taken as the area on the geology map shown as Alluvium and Colluvium, as identified by the dark and light green areas on Figure 3-2.

3.2 Development of study area water balance data – Surface system

As there was continuous yearly data series an opening balance is not required as monthly changes in volume was captured in the continuous series.

3.2.1 Precipitation (P)

Varied topography, combined with the large catchment area means that there will be spatial and temporal variation of rainfall across the catchment (Li. M. H et al. 2006). The mountainous terrain also means that orographic and rain shadow effects may introduce another source of spatial variability and simple approaches for estimating basin rainfall may not be appropriate. (Li. M. H et al. 2006)

The study area still has large variation of topography but the reduced area also reduces the spatial and orographic effects on the recorded rainfall. To further reduce spatial variation, the Thiessen polygon method has been used to create a representative rainfall series in the study area (Sinclair Knight Merz 2006b). The Thiessen polygon method doesn't weigh or constrain the rainfall series based on elevation and thus doesn't specifically account for orographic effects. However, the rainfall sites chosen to represent the study area have similar elevations to the study area (Table 3-1), thus helping to take into consideration some of the orographic effects.

A rainfall series for the study area was developed using the Thiessen polygon method for the REALM model and this series is used to represent rainfall for the study area in the water balance (Sinclair Knight Merz 2006b). These data were prepared using two rainfall gauges located within the study area, and one outside, as outlined in Table 3-1. Recorded daily rainfall at the sites was used as base data, missing data were infilled or extended by using regression equations determined from neighbouring sites with a complete rainfall record. The modified records were then de-trended using a site with high quality rainfall data.

Thiessen weightings were then applied to the infilled point recorded rainfall series at the three sites to give representative rainfall for the study area (Table 3-1). Further details of the methodology can be found in SKM (2006b).

In the alpine areas precipitation falling as snow is another factor that needs to be taken into consideration. The delayed effects of snowmelt on rainfall runoff were accounted for by using gauged stream flows into the study area.

Station name	Station number	Period of record	Elevation (mAHD)	% Missing Data (after infill)	Thiessen weighting
Myrtleford Post Office	082034	1897-1969	223	1%	0.22
Bright Post Office	083005	1881-1969	319	0.1%	0.74
Dandongadale	083008	1904-2003	344	2%	0.04

Table 3-1: Rainfall site information and Thiessen weighting (Sinclair Knight Merz 2006b)

3.2.2 Evapotranspiration (ET)

Evapotranspiration (*ET*) is a complex factor to calculate. Evapotranspiration and rainfall are the two major components of the water balance and required accurate estimates to close the water balance. There are many methods for calculating evapotranspiration, however, the Food and Agriculture Organisation (FAO) Penman-Monteith method is considered the international standard for calculating reference crop evapotranspiration (Chiew et al. 1995; Allen et al. 1998).

For the study, the FAO Penman-Monteith methodology was used to determine evapotranspiration as it allows for the potential to alter *ET* estimates for different crop types. The Australian Bureau of Meteorology (BOM) has produced potential areal evapotranspiration maps for Australia. These maps are based on Mortons (1983) complementary relationship which is based on the Priestly-Taylor equation (Australian Bureau of Meteorology 2001). They have been based on 30 years of data between 1961 and 1990. Interpreting these maps gives the average potential evapotranspiration which can be approximated to the Penman-Monteith ET_o. From these maps the average ET_o for the area is 1100 mm per year. This value is used to verify the ET_o calculated using the FAO Penman-Monteith method.

The definition of reference crop evapotranspiration is as defined by the FAO and is the rate of evapotranspiration from a hypothetical grass reference crop with specific characteristics and which is not short of water (Allen et al. 1998). Evapotranspiration rates vary between plant species and also vary for different times of the year and different stages in a plants growth. To account for these variations the reference evapotranspiration (ET_o) is multiplied by a variable crop factor (k_c) to give a particular crop evapotranspiration (ET_c) as shown in Equation 2.

$$ET_c = k_c \times ET_o \tag{2}$$

Detailed methodology and assumptions used in this study to calculate the ET_o are outlined in Appendix 1. The method for conversion of the calculated ET_o series into evapotranspiration for the sub-catchment is outlined below

Crop factors (k_c) have been determined by field experiments and have been compiled and are provided for most crops by the FAO. There is a time component which relates to the crop growing period and a transpiration component that alters with the different growth stages. As these are generalised, crop factors developed specifically for the Upper Ovens region were developed in December 2005 in a meeting comprising the local water authority (G-MW), irrigators, government extension staff and Tobacco industry representatives from the region. Crop areas were also developed at this meeting. Specific crop factors and areas determined in this meeting were used in the development of a flow model for the Upper Ovens (Sinclair Knight Merz 2006b). Crop factors used in the SKM (2006b) study were compared to those available from the FAO, The length of growing season and crop factor were comparable and are shown in Figure 3-4. Areas of crop under irrigation are outlined in Table 3-2.

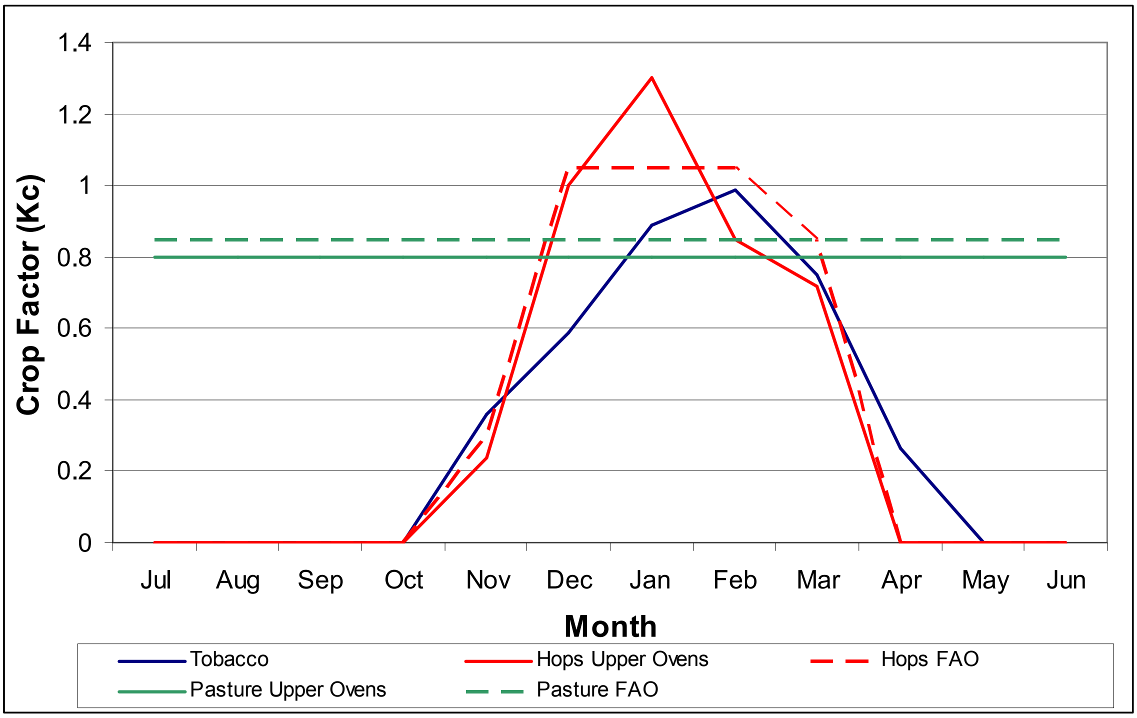

Figure 3-4: Comparison of SKM (2006b) and FAO Crop factors

Tobacco	Hops	Perennial Pasture/ Lucerne	Grapes	Orchard	Summer crop or Millet	Nuts	Annual Pasture	Total
315	180	20	20	20	20	40	20	635

Table 3-2: Areas of crops under irrigation (hectares)

3.2.2.1 Calculation of study area evapotranspiration

Evapotranspiration for the study area was only calculated for the area covered by the unconsolidated sediment aquifer. All irrigation occurs on the unconsolidated sediments of the valleys. Crop *ET* was calculated by multiplying the calculated ET_c by the areas shown in Table 3-2. *ET* for the remainder of the alluvial area not under irrigation was assumed just to have reference crop evapotranspiration. The majority of the area is unirrigated pasture with little information available on vegetation types, thus ET_o was assumed to be a good estimate of *ET*.

3.2.3 Stream extraction (D_s)

There are several types of human extraction from the river. Depending on the use, the timing and volumes of extraction will vary, as does the amount of data available for each. Extraction can be classified into three main categories. The first is urban use in the larger towns. Licenced extraction for irrigation is the second category and extraction for other uses, such as licenced industry or unlicenced use for domestic and stock (D&S) are all grouped into the third category.

Farm dams are also a form of extraction but mainly affect rainfall runoff into streams. As the water balance is considered on a continual time series, the delayed effect of annual changes in storage volume will be taken care of in the time analysis. Volumes of extraction used for irrigation are metered and included in the irrigation extraction.

3.2.3.1 Irrigation extraction

Although there is a large volume associated with licences, not all of the licenced volume will be extracted in a given year. All licences that have viable extraction points (i.e. ability for pumping) have been metered, so usage volumes are known. Metered use was available from 1997 with the amount of data increasing over time. Data are available on an annual timestep with some intermediate readings at non standard intervals. To create a monthly timestep interpolation of the metered data would be required or modelling of crop requirements.

For the water balance the modelled irrigation extractions developed for the REALM model was the primary source for the irrigation demand series. Irrigation demands were modelled on a daily timestep using a crop water requirement demand model (PRIDE). The model used known crop areas and modelling results were calibrated to match annual metered usage, thus representing expected farm use and not actual crop demands (Sinclair Knight Merz 2006b). For unmetered users the same percentage entitlement use was assumed and added to total volumes. PRIDE crop factors were calibrated based on crop area and usage. This series is available as a daily series for the modelling period.

3.2.3.2 Urban extraction

No extraction for urban centres exists in the study area. Extraction upstream will be covered in the gauged inputs into the study area.

3.2.3.3 Extraction for other uses

Of the other uses in the study area, extraction for domestic and stock (D&S) is the largest use. D&S use is licenced but not metered, licences are generally given for 2 ML/year and it is assumed that the whole 2 ML is used each year. If a property abuts a watercourse the property owner can legally take water for D&S use without a licence. The number of licences and volume of water taken under this right is unknown but is assumed to be less than the licenced amount (<100 ML). As such, it is assumed to have minimal influence on the water balance and has been excluded from the calculations.

Other uses included licences for industry and commercial uses. There is only a small amount of this licence volume in the sub-catchment and for the water balance it is assumed that the whole volume is extracted annually. These demands have been assumed to be consistent throughout the year and a daily time series has been created by dividing the licenced volume by 365.

3.2.4 Irrigation returns (I_{ret})

Irrigation occurs primarily on the alluvial floodplains and valleys. Limited irrigation encroaches onto the valley sides, with plantings in the colluvium mainly limited to fruit trees and vineyards that are primarily irrigated through drip or spray.

Areas of irrigation have not been recorded historically however, they have recently been estimated based on anecdotal evidence and licenced crop areas held by G-MW. Areas were then calibrated against metered use using PRIDE modelling (Sinclair Knight Merz 2006b).

Recharge from irrigation has been estimated to be 75 and 110 mm per year depending on the type of irrigation (Tickell 1978). Modelling in the Campaspe River Catchment (Victoria) has determined that approximately 15% of irrigation water reaches the shallow water table (Chiew and McMahon 1991).

In previous modelling and water balances for the Upper Ovens River catchment, an additional 550 mm/yr (5.5 ML/ha) has been added to total rainfall to account for irrigation in irrigated areas. A factor of 15% was then assumed as the proportion of all applied water (rain and irrigation) reaching the groundwater table through infiltration (Sinclair Knight Merz 2006a; Sinclair Knight Merz 2007a). However, there is no justification of where this figure came from or basis for use except that it is similar to the figure determined by modelling in the Campaspe catchment. The large differences in soil profile and shallow groundwater systems between the two areas could preclude use of this figure without further studies to determine its appropriateness.

Given the uncertainties, the value of 15% return of the irrigation diversions was used for the base case. An irrigation return series was calculated by multiplying the estimated percentage of return by the irrigation extraction series.

As there is no differentiation between crop types was significant error was expected in this simple approach. The sensitivity of the water balance to this factor was tested by varying the percentage of return value.

3.2.5 Study area runoff (SR)

All of the rainfall falling on the unconsolidated sediments will become part of the water balance for the unconsolidated aquifer and river. Rainfall in this area will be depleted by evapotranspiration or captured in the soil or the unconsolidated aquifer and flow into the river as base flow or flow directly into the river as direct runoff. Thus the whole volume of rainfall on this area will be included in the water balance.

The water balance is trying to reduce the error bounds of rainfall and evapotranspiration and focus on the fluctuations between the unconsolidated aquifer and Ovens River. For simplification it is assumed that only a proportion of the rainfall falling on the fractured rock areas will flow into the unconsolidated aquifer area and rivers. The runoff will be the proportion of rainfall that is not lost through evapotranspiration or infiltration into the fractured rock aquifer. Quantification of the runoff is through a simple equation multiplying the volume of rainfall by a runoff coefficient.

Rainfall-runoff modelling using SIMHYD has calculated the runoff coefficient at 24% for the study area (CSIRO 2008). Other sub-catchments within the Upper Ovens catchment with higher elevations had runoff coefficients up to 49%. For comparison, the data were aggregated to create monthly rainfall for 2004. The monthly rainfall was then multiplied by the catchment area to give the total inflows for 2004. Calculated volumes totalled 1,217 GL. River outflows at gauge 403210 which captures runoff from the equivalent area totalled 427 GL. Runoff as a percentage of rainfall is thus 35% for 2004. Based on average rainfall (1170 mm) for the catchment and average flows at 403210 (598 GL), runoff is approximately 45% of rainfall. As this calculated figure is for the whole Upper Ovens catchment and includes runoff from the upper sub-catchments with much higher CSIRO (2008) calculated rainfall-runoff coefficients (up to 49%) than the study area, it is an average figure.

The CSIRO (2008) runoff value for the study area (24%) will be used as the base value for calculations in this study, however, using a single coefficient may not be sufficient for shorter timeframes as it can underestimate runoff in wet periods and overestimate in dry periods. To allow for this, the coefficient was varied to check its sensitivity in the water balance and also to preceding rainfall on a 7 day period.

3.2.6 River inflows (Q_{in})

Surface water flow into the study area is via the Ovens River, Buckland River and Buffalo Creek and, as shown in Figure 3-2, flows are measured on gauges 403205, 403233 and 403216 respectively. The Bright gauge (403205) and the Buckland River gauge (403233) have a long history of recorded flows and have a complete flow series for the water balance period. These flow series will be used to represent the quantified flow series for the water balance for these rivers.

Gauge 403216 has only a partial flow history with flows recorded between 1971 and 1983. A daily flow series has been modelled using SIMHYD for the whole water balance period

(Sinclair Knight Merz 2006b). The modelled series was compared to the recorded flows and found to over represent the recorded monthly flows by 21%. To represent flows from Buffalo Creek the modelled series was multiplied by 0.83 to give a daily flow series.

River inflows into the study area (Q_{in}) are the sum of all of these components as shown in Equation 3. Where Q_{403205} is the flow at the Bright Gauge, Q_{403233} is the flow at the Buckland River gauge and Q_{403216} is the flow at the Buffalo Creek gauge

$$Q_{in} = Q_{403205} + Q_{403233} + Q_{403216} \tag{3}$$

3.2.7 River outflows (Q_{out})

The Myrtleford stream flow gauge (403210) is on the downstream edge of the study area boundary and the daily flow series measured at this gauge is used to represent river outflows. Average daily stream flow data are available from 1967 to current, however, the series is incomplete for the period of record. Missing data are due to the gauge not being rated for flows over 9000 ML/day. For periods without recorded flow, the flow was assumed to equal the inflows into the study area and was calculated using Equation 4. When flows are at this level the river is flooding and the accuracy of the gauges is low. Also, periods of high flow are not the focus of study, thus this approach should allow for these periods not to impact on the water balance with undue errors.

$$Q_{403210} = Q_{in} + SR \tag{4}$$

Where Q_{in} are the measured inflows into study area and SR is the surface runoff in the study area.

3.2.8 Assumptions about non quantified components

3.2.8.1 Evaporation

Like rainfall, evaporation varies spatially, especially in alpine areas, where changes in topography can cause variations. Calculation of evaporation from water bodies is difficult and although there are several methods to calculate evaporation, unlike ET_o there is no internationally recognised standard procedure (Grayson et al. 1996).

In the sub-catchment there are no major surface water storages and generally the largest volume of surface water will be held in the rivers. Determining the surface area of rivers is problematic as the area varies depending on flow. Determination of evaporation from rivers is also problematic and prone to large errors (Chiew et al. 1995).

Given the issues with the calculation of both the surface area extent and the lack of an recognised standard for calculating direct evaporation from water bodies, evaporation was assumed to be included in the evapotranspiration equation which assumes ET_o for the whole of the unconsolidated alluvial area. This will capture evaporation from all surface bodies regardless of their extent.

Evaporation from the soil profile and unconsolidated groundwater aquifer system was also considered to be part of evapotranspiration

3.2.8.2 Urban Wastewater returns

North East Water manages the wastewater treatment plants in the Upper Ovens River Catchment. Within the sub-catchment there is only one wastewater treatment plant which treats sewerage from the towns of Bright and Porepunkah.

The treatment plant utilises evaporation ponds to dispose of treated waste water. In periods of low evaporation or high rainfall, water may be discharged into the river. Total volume discharged is less than 5 ML/day and as these discharge times would be related to high flows they are considered to have negligible impact on the flow balance and have not been included in the water balance.

The treatment ponds are clay lined to prevent seepage into the unconsolidated aquifer. In addition the aquifer surrounding the ponds is monitored to ensure that they are not leaking. Thus seepage is considered to be negligible and has been excluded from the water balance.

3.3 Development of study area water balance data – Groundwater System

Components for the groundwater system water balance are shown in italics in Figure 3-3. Quantification of monthly variations in these components is problematic due to the limited aquifer parameter data for all aquifers and the absence of groundwater level information for the fractured rock aquifer. Measured level data is available for the unconsolidated sediment aquifer and a time series using these measured fluctuations was created. Calculation of the potential volume of fluctuations of groundwater was developed from the series and compared to the surface water balance to determine seasonal patterns. This series represented changes in the unconsolidated system as a whole and did not separate the contributions of individual components. A secondary analysis was completed using the limited data to estimate the components individually.

Previous attempts by SKM (2007a) to quantify the individual components for the groundwater balance of the unconsolidated aquifer system have estimated that groundwater fluxes with the river (36,000 ML/yr) are the largest outflow component (total groundwater balance 42,600 ML/yr). Groundwater extraction could be a large component based on entitlement however estimated extraction figures by SKM were 1,800 ML. Groundwater through flow was calculated at 400 ML/yr at Myrtleford (Sinclair Knight Merz 2007a). The study also concluded that rainfall recharge (33,000 ML/yr) and bedrock inflows (9,000 ML/yr) were the largest inflow components of the water balance in the unconsolidated sediment aquifers.

3.3.1 Development of Groundwater fluctuation series

The monthly time series showing volume fluctuations in the unconsolidated sediment aquifer represents the groundwater balance, which is the sum of groundwater system outputs minus the sum of inputs (shown in italics in Figure 3-3). In addition to the input/output components of the groundwater system balance (rainfall infiltration, extraction, through flow and fractured rock inflows), the balance also represents the fluxes of interactions between the river and unconsolidated sediment aquifer. Any possible evapotranspiration from the aquifer is also included, as groundwater levels are close to the surface and there is the possibility that deeper rooted plants may use water from this aquifer.

In the study area, groundwater levels of the unconsolidated aquifer were shown to have consistent seasonal variation and similar seasonal response at all depths (Section 2.3.2). Spatial extrapolation of groundwater bores, with individual bores representing an area of aquifer, was initially considered to be a way to calculate groundwater fluctuation. However, level readings in bores are not taken over the same time periods or with the same time step. Thus considerable estimation or modelling of levels through infilling and extending of data would be required to create a time series for individual bores. Comparison of bore hydrographs in Figure 3-5 show similar magnitudes in level fluctuations and to minimise data extrapolation it was considered that one bore could be used to represent the groundwater levels for the whole aquifer. Given the variation in aquifer parameters, in particular storativity which ranges between 0.0001 and 0.26 (Appendix 2), the influence of this variation when estimating groundwater volumes was considered to be much greater than possible errors from using a single bore as representative of groundwater fluctuations.

Bore 48048, located near Ovens and shown in Figure 4-9, has the longest period of data and highest frequency of level readings. It is in the middle of the study area and also in the middle of the valley cross section, approximately one kilometre from the river. Hydrographs of all bores were compared to the hydrograph for this bore and hence it was considered to give a good representation of groundwater level fluctuations for the whole aquifer. It matched hydrographs for almost 80% of bores in the catchment. Only bores near Myrtleford did not have as much fluctuation in terms of winter recharge, however, summer lows and seasonal patterns were almost identical, as shown in Figure 3-5. All bores in Figure 3-5 are bores in the centre of the valley cross sections and are at different locations moving up the valley (see Figure 2-4 and Figure 4-9).

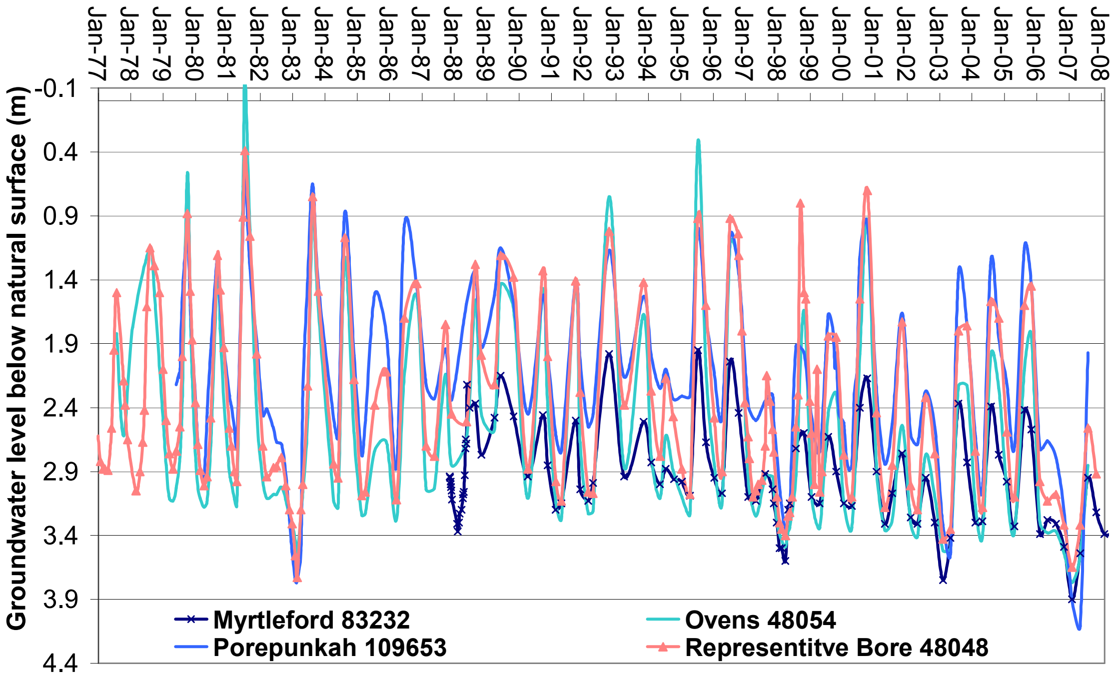

Figure 3-5: Hydrographs of bores in comparison to bore 48048

To check bore 48048's representativeness, standard deviations for water level readings were calculated for each bore. Standard deviations are an indication of the range of fluctuations from average water levels in each bore. For all bores the average standard deviation was 0.69 and for bore 48048 it was 0.73. The F test can be used to test if the difference between standard deviations of two populations of a certain size is significant, with F values further from the value of 1 providing evidence against the hypothesis of equal standard deviations (Moore and McCabe 1993). The F value was calculated to be 1.069, with the degrees of freedom for bore 48048 of 171 and for all bores of 110. Using the F tables (Moore and McCabe 1993) the calculated F (1.069) is less than the critical F value 1.28 (p=0.1) and the difference is not significant. As the results of the F test (difference between population standard deviations) are not significant there is no reason to suspect unequal population standard deviations. It can be concluded that groundwater fluctuations of bore 48048 are representative of average fluctuations for all bores in the study area.

Groundwater level readings were not available for every month and to complete the series for bore 48048 monthly values were interpolated between readings to in-fill the data. Figure 3-6 shows the series of recorded levels and the in-filled series.

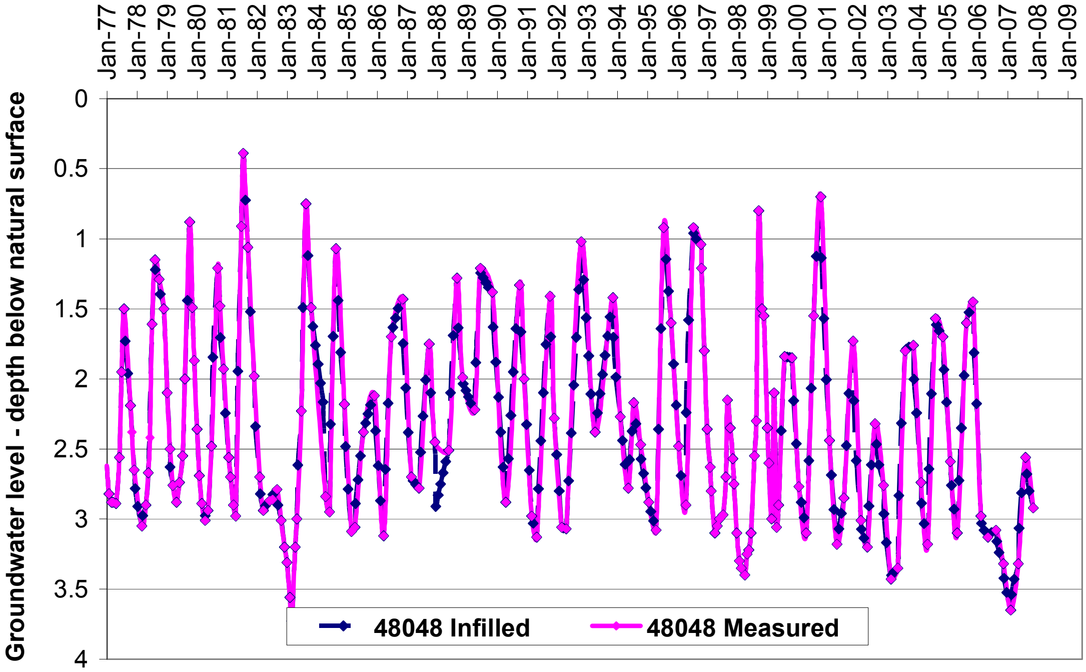

Figure 3-6: In filled representative bore data series

Groundwater level fluctuations were volumetrically quantified by multiplying the unconsolidated aquifer area by the groundwater fluctuation by the aquifer Storativity (*S*). As groundwater level is recorded as depth below natural surface level, a negative reading meant a decrease in groundwater levels and thus loss from the system. A positive change in level meant a rise in groundwater levels and a system gain. The fluctuation is calculated from the change in groundwater level where monthly fluctuation (*F*) in metres for month (*n*) is the change in groundwater level (*L*) in metres from the previous month (*n-1*) as per Equation 5.

The volume of monthly groundwater fluctuation (ΔGW) in cubic metres is calculated by multiplying the fluctuation (F_n) by the unconsolidated aquifer surface area (*A*) in square metres and the aquifers storativity (*S*) as shown in Equation 6. The groundwater fluctuation can be converted to Mega litres (ML) by dividing the result of Equation 6 by 1000.

$$F_n = L_{n-1} - L_n \tag{5}$$

$$\Delta GW = F_n \times A \times S \tag{6}$$

Appendix 2 outlines all of the aquifer parameter data from the literature as the result of pump and field tests. Specific yield for the unconsolidated aquifer ranges between 0.001 and 0.26. For the base case a specific yield of 0.26 is used as this is consistent with values used by Shugg (1987) and SKM (2007a) and allows direct comparison between the studies. It is the largest value and as such groundwater fluctuations are shown at their highest possible magnitude. It is also consistent with the specific yield for gravely sand and coarse gravel (Todd and Mays 2005). The groundwater balance is sensitive to the storativity value; an analysis of this sensitivity is included.

3.3.2 Groundwater extraction (D_g)

Groundwater is currently not extracted for urban use, however in the past, small volumes were used to supplement Myrtleford during drought periods. Currently there are only licenced bores and unlicenced domestic and stock bores (D&S) in use. Bores/draglines have only been metered since 2006 and this only applies to licences greater than 20 ML. Licences less than 20 ML and D&S bores are registered so the numbers of bores, their uses and licenced entitlements are known.

There are approximately 2000 ML of entitlements in the study area. However, currently very little metered data is available. As an example of extraction, one property owner with a licence of 600 ML can only extract less than 100 ML per year from two draglines. Given the amount of metered data, extraction is estimated using groundwater entitlement, the area of land and licence status (currently actively using water or not) provided by G-MW.

SKM (2006b) developed daily series of groundwater demands based on licenced volume and status of licence given by G-MW. Licenced crop areas were used as a basis to determine water requirement. Extraction was limited by potential aquifer yields as determined by MODFLOW modelling (Sinclair Knight Merz 2006a). This series was used as a basis for the quantification of this component. As estimates are based on crop water requirements it will give an indication of seasonal variability.

3.3.3 Rainfall infiltration into aquifers (R)

Many methods exist for quantification of aquifer recharge and their accuracy is generally limited by the amount of aquifer parameter and monitoring data (Scanlon et al. 2002). Groundwater fluctuation and water balance methods are used to determine the recharge. Groundwater level data are fairly accurate and groundwater level fluctuations are consistent for the whole unconsolidated sediment aquifer (Section 2.3.2.2).

Aquifer recharge is quantified but separating rainfall recharge from river recharge and fractured rock inputs is difficult and based on estimates.

To calculate the rainfall recharge a percentage of rainfall onto the alluvial aquifer is assumed to infiltrate into the aquifer. Using the rainfall series (Section 3.2.1) multiplied by the percentage of recharge creates the time series for groundwater recharge. The base case uses the literature quoted value of 5% (Sinclair Knight Merz 2006a) of rainfall.

3.3.4 Regional fractured rock flows into the unconsolidated sediment aquifer (G_{Fr})

There are limited fractured rock exposures into the lower reaches of Ovens River and tributaries, which limits the extent of direct interaction between surface water flow and fractured rock, however, spring action at break of slopes and in colluvial areas can be important (Sinclair Knight Merz 2007a).

Based on the limited information, it is assumed that groundwater gradients are always higher in the fractured rock aquifers than the unconsolidated aquifers (Sinclair Knight Merz 2007a). As a result, only estimates of inflows from fractured rock to unconsolidated aquifers are included. Based on Darcy flux equations, SKM (2007a) estimates that groundwater flows from fractured rock aquifers to the unconsolidated aquifers equate to approximately 9000 ML per year, for the whole of Upper Ovens River catchment. For the study area this reduces to 2400 ML/yr.

The water balance has assumed that contributions are constant throughout the year and thus the estimated 2400 ML/yr is averaged over the timestep period to give a time series for this groundwater component.

3.3.5 Down valley groundwater flow (G_{us})

Numerical modelling (SKM 2006b) shows alluvial aquifer through flow as a major component, whereas using Darcy flux analysis at Bright and Myrtleford alluvial cross sections, SKM (2007a) showed through flow as only a minor component. The Darcy flux analysis is considered a reasonably accurate method for calculating down valley flow (Todd and Mays 2005). The SKM (2007a) analysis estimated inflows into the sub-catchment to be 1400 ML/yr using a cross section at Bright, outflows were estimated at 400 ML/yr using a cross section at Myrtleford. Aquifer parameters were similar

This study used Darcy's equation and the down valley groundwater gradient between Bright (Bore 51737 in Figure 4-11) and Myrtleford (bore 83232 in Figure 4-6) in August 2005, and the through flow was calculated to be 980 ML. The SKM estimates are considered to be reasonable and from the Darcy analysis, gains into the study area are approximately 1000 ML/year. This will be modelled as an input into the system and averaged over the year to create monthly series.

3.4 Monthly system water balance models

This section investigates water balances of the river, groundwater, and surface water systems in order to quantify fluxes between groundwater and surface water. A river reach balance is prepared first to investigate the trends in surface flow. Surface water and groundwater system balances are calculated separately and then combined to give a whole of system water balance. The water balances are completed on a monthly time step for the whole 32 year modelling period and the monthly results averaged to give an average annual water balance.

To calculate the balance, and hence unaccounted flows, inflow totals are subtracted from the outflow totals. Negative balance values mean inflows are greater than outflows and either one of the inflow components is over estimated, or at least one outflow component is underestimated. Conversely, a positive balance means one of the outflow components is over estimated or an inflow component is under estimated. Non-included components could also be sources for error in the balance

3.4.1 River reach balance

A river reach balance has been completed to investigate and describe trends in the river reach in terms of flow. The unaccounted difference is the quantified volume of river outflows (Q_{out}) and stream diversions (D_s) minus river inflows (Q_{in}) and sub-catchment runoff (SR) as shown in Equation 7.

$$Balance = (Q_{out} + D_s) - (Q_{in} + SR) \qquad (7)$$

The definition and explanations for each of the components are outlined in Section 3.2. The river balance was completed using the base data and parameters, where surface runoff was 24% of rainfall (CSIRO 2008). Inflows and outflows were totalled on a monthly basis and the results are shown in Figure 3-7, where the bars show the total monthly flows and the balance is represented by the green line. The balance line can be viewed as being similar to a hydrograph with the change in volume being equivalent to a change in river flow. A five year period is represented to show trends.

Monthly averages were calculated for the 32 year period (Figure 3-8). Standard deviations for total inflows and outflows are represented by error bars and show the large variation in annual flows.

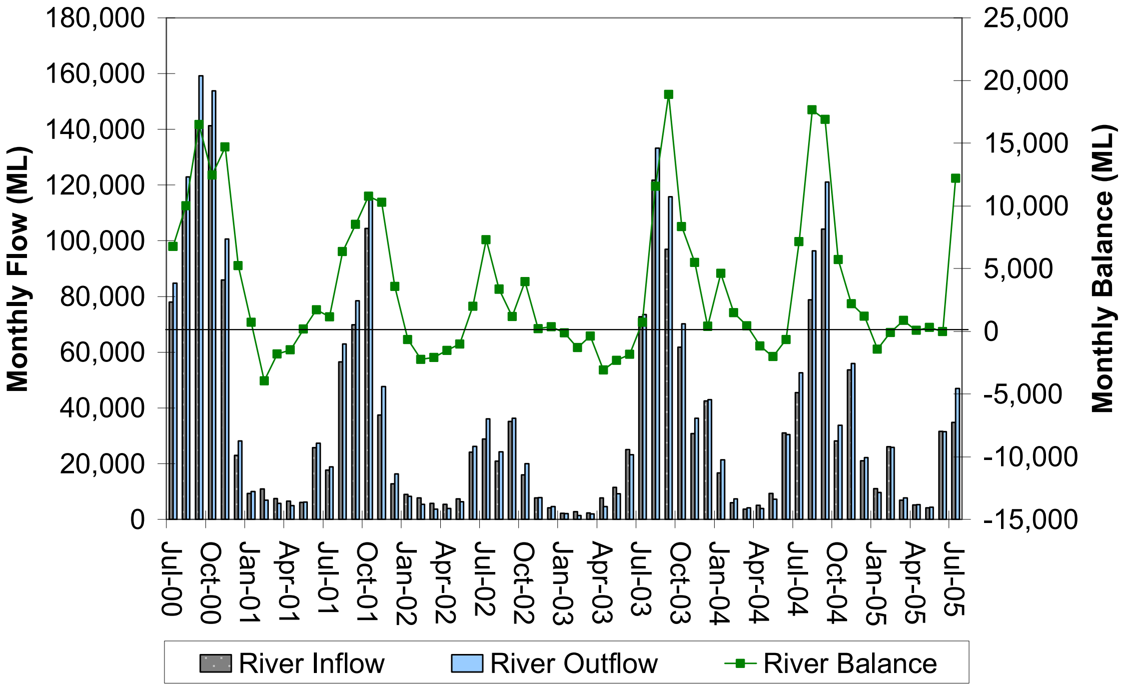

Figure 3-7: Monthly river reach balance results (July 2000 to July 2005)

Average monthly river reach balance values show that in the Ovens River reach between Bright and Myrtleford outflows generally exceed inflows in the winter and spring (i.e. there are unaccounted-for gains) and inflows exceed outflows in summer and autumn (i.e. there are unaccounted-for losses). If this pattern is related back to fluxes with groundwater then the river reach balance infers that the river gains from groundwater over winter and spring and loses to groundwater summer and autumn when groundwater tables have dropped below streambed height.

This observation runs contrary to observed trends where the river is gaining from groundwater for most of the year (Shugg 1987a) and indicates that an error may exist in the river reach water balance calculated in this study. Gauge errors excluded, the largest input is sub-catchment runoff from the fractured rock area. Using a 24% generic runoff coefficient means that the value is averaged for the year and may underestimate runoff in the high rainfall periods (winter/spring) and over estimate runoff in the dry months (summer/autumn) and account for the error trends. Influences of runoff calculation errors on the water are investigated in further detail later in the chapter to examine the causes of the differences between the two studies.

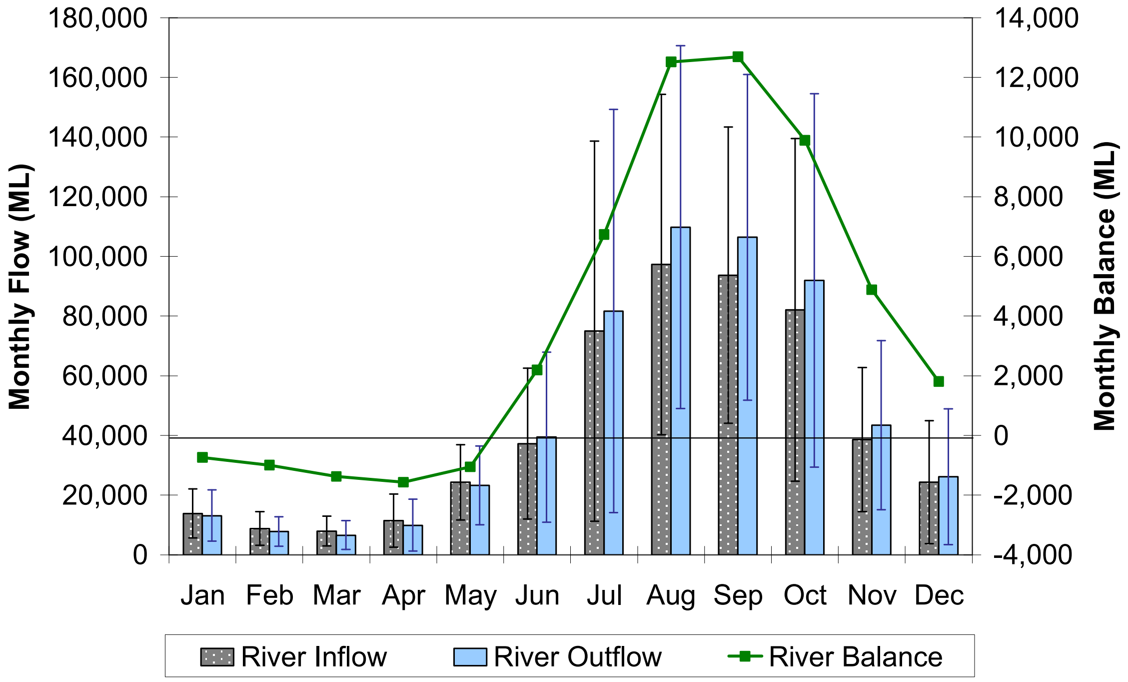

Figure 3-8: Average monthly river reach balance with error bars showing standard deviations of each component (1973 -1995).

The average annual volumes of the individual inflow and outflow components of the river reach balance are show in Figure 3-9. The simplified reach balance does not include *ET* or rainfall which may also account for the variation in the river balance. Use of the river reach balance may be too simplistic and have too larger error to quantify fluxes with groundwater.

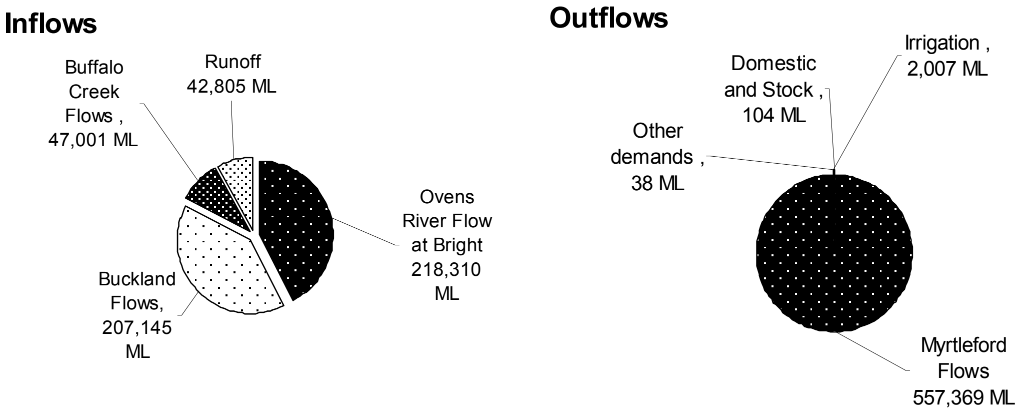

Figure 3-9: Average proportion of components in the river balance (1973 -1995)

3.4.2 Surface Water System Balance

A water balance for the surface water system has been calculated by incorporating rainfall (*P*) and evapotranspiration (*ET*) into the river reach balance (Equation 7) as shown in Equation 8. The general condensed components shown in the catchment water balance conceptualisation (Figure 3-3) have been broken down and are shown in the sub-catchment schematic of Figure 3-10.

$$Balance = (Q_{out} + D_s + ET) - (Q_{in} + SR + P) \qquad (8)$$

Incorporating rainfall (*P*) and *ET* into the surface water system balance effectively closes the water balance for the surface system. In this respect the balance or unaccounted difference should be sourced from, or contributed to, the groundwater system. Not including errors, the unaccounted difference would be from groundwater fluxes with the river. Changes in volume of the groundwater system are represented by the groundwater fluctuation series. The fluctuations are the change in aquifer volume on a monthly basis, a negative fluctuation means the aquifer has lost water whereas a positive figure indicates the aquifer has recharged in the month. The groundwater fluctuations have been calculated separately and are included for comparison to the surface water balance.

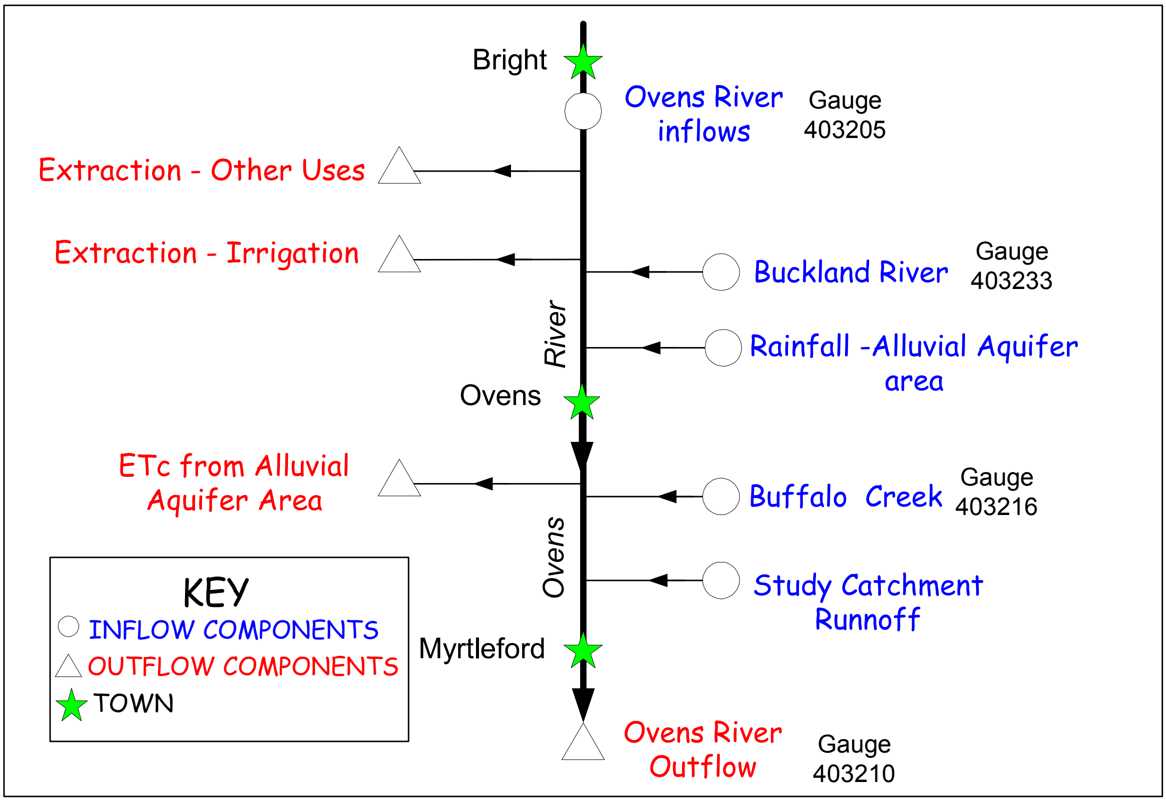

Figure 3-10: Schematic for study catchment surface water balance

The monthly data series (Figure 3-11) shows that that the addition of ET and rainfall causes more variation in the balance when compared to just the river flow data (Figure 3-7). Although still partially evident in the surface water balance, the patterns of the river reach balance having inflows exceeding outflows over winter and outflows exceeding inflows over summer is not as clear.

Again the 32 year average monthly values are a much clearer representation of trends for water movement in the sub-catchment (Figure 3-12). Looking at surface flows only, the average monthly balance shows inflows exceeding outflows over wetter months and outflows exceeding inflows over between April and June. Groundwater fluctuations generally mirror the surface water balance and indicate that groundwater becomes a river inflow, particularly over the summer period.

Maximum balance errors occur over the high flow periods where the groundwater system is gaining water and surface outflows exceed inflows. Balance errors at this time could be due to a combination of losses to groundwater, runoff calculation errors and gauge errors at large flows. Variations in lower flow months and loss months could be due to other errors in runoff calculations and gains from groundwater. Evapotranspiration is generally overestimated by the Penman -Monteith calculation and could be a reason for the excess outflow in summer (Allen et al. 1998). Countering the ET overestimation could be the overestimates of runoff in summer; these will be further investigated later in the chapter.

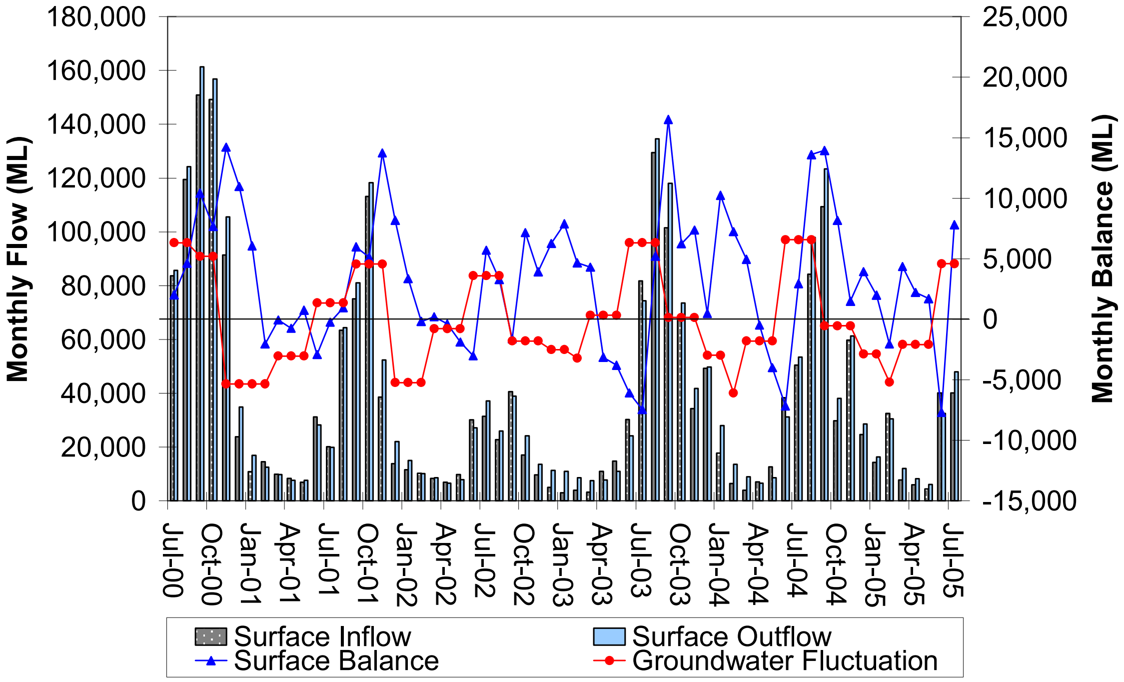

Figure 3-11: Monthly surface water system balance results (July 2000 to July 2005)

A breakdown of the average proportions of the individual surface water balance components are outlined in terms of inflow and outflows in Figure 3-13. River flows in and out of the catchment make up the greatest proportion of the water balance and have the greatest influence on water movement. In comparison to river flow, ET and extraction for human uses are less than 10% of the yearly outflow balance, and thus changes in these values will have little effect overall on the water balance. Average monthly results shown as a breakdown by individual components are available in Appendix 3. In low flow periods of summer and autumn ET becomes a much large component and nearly equals river outflows. Human extraction becomes a larger component however this is still under 10%.

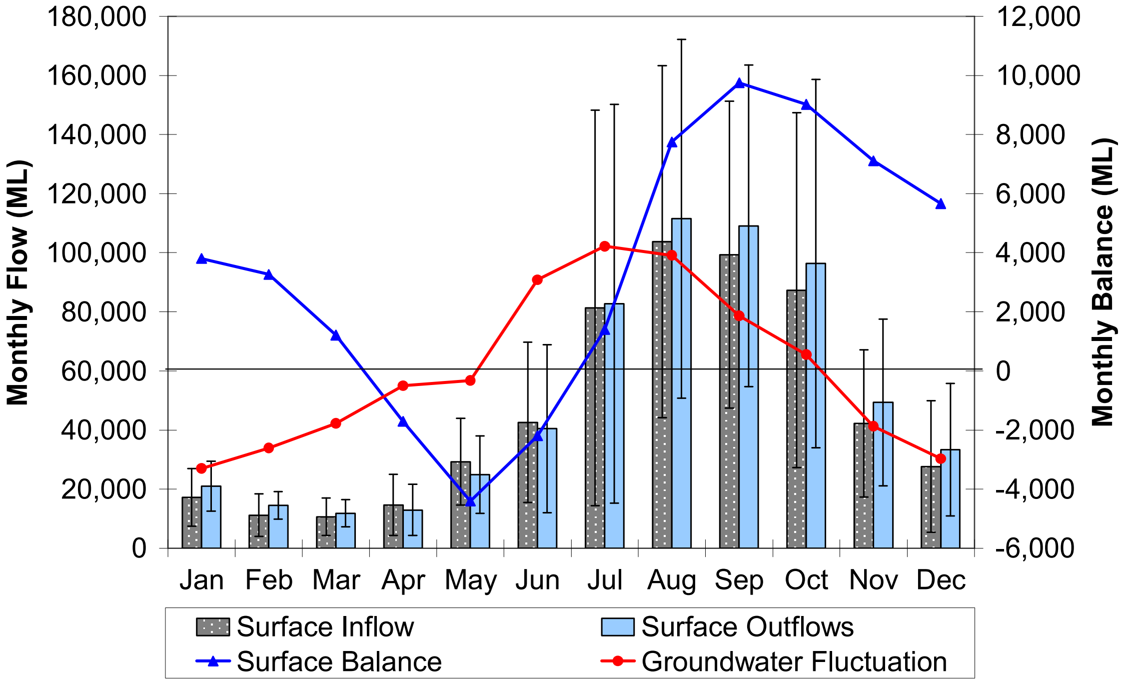

Figure 3-12: Average monthly surface water system balance with error bars showing standard deviations (1973 -1995)

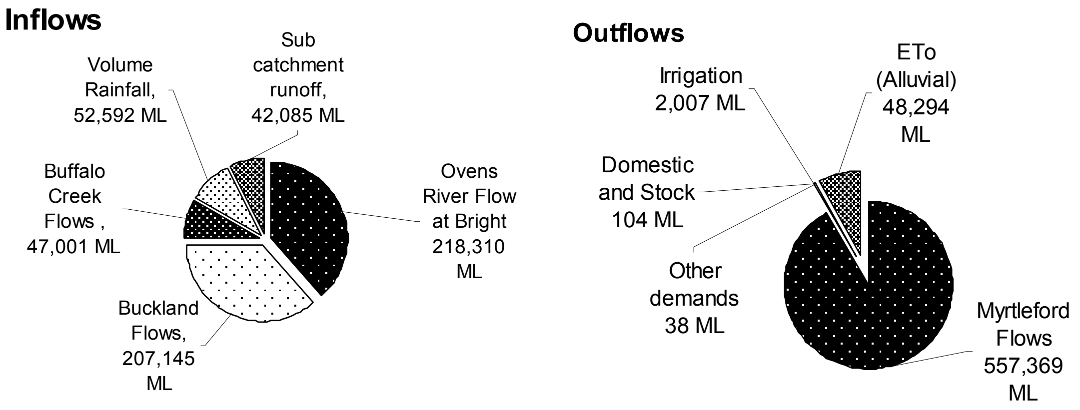

Figure 3-13: Average annual proportion of components in the surface water system balance (1973 -1995)

3.4.3 Groundwater Components

The groundwater fluctuation series is represented in the monthly and average annual series shown in Figure 3-11 and Figure 3-12 in the surface water balance section. Quantification of the average annual trends corresponds with the long term groundwater level hydrographs for the unconsolidated aquifers in that they both have a cyclic pattern with levels fluctuating with seasons. Trends show that on average the groundwater system is losing from November through to May and recharging from June to October, with peak recharge between June and August.

To separate the fluxes between groundwater and the river from the groundwater balance the other components of the groundwater were estimated and a groundwater balance was attempted using Equation 9. By subtracting the outflows from the inflows the balance would represent the interactions with the river. The balance (or flux) will still include any potential evapotranspiration however this will be considered in the surface water balance as part of the whole of system balance. The outflow components are groundwater through flow out (G_{out}) and groundwater extraction (D_g). Inflows are the sum of groundwater throughflow in (G_{in}), rainfall infiltration (R) and fractured rock inflows (G_{Fr}),

$$Flux = \left(G_{out} + D_g\right) - \left(R + G_{in} + G_{Fr}\right) \qquad (9)$$

Results from the balance show that inflows are always exceeding outflows and that the flux would always be from the groundwater aquifer to the river (Figure 3-14). Recharge calculations are very simple and have been set as 15% of rainfall when the preceding 7 days of rainfall exceeds 30mm and thus would have a large margin of error. Fractured rock inputs are also expected to have a large error due to the absence of level data. The equation does not take into account positive and negative fluxes from the surface water system and thus it is used only as an indication of magnitudes of the relevant inputs from groundwater resources.

Quantification of the components (Figure 3-15) show that recharge and inflows from fractured rock are the major component of inflows to the unconsolidated sediment aquifer.

Fractured rock inputs are constant thus they can be disregarded as having significant monthly variation and impact on water balance. Throughflows in and out of the study area are also minor when considering the balance as a whole, and differentiating them from the total balance would be difficult as they would be within error bounds of calculations. The results also imply that on average the flux is from groundwater to the river with most of the groundwater inflows into the study area leaving as fluxes to the river and evapotranspiration from the shallow groundwater. This is in line with the observations by Shugg (1987a).

A better indication of the groundwater recharge and discharge process is shown in Figure 3-16 where the annual total recharge and discharge is calculated. The values assume a specific yield value of 0.26 which would be the maximum groundwater volume. Note the very low recharge in 1982 and 2006; these were the years with the longest period of low stream flows indicating a relationship between recharge and summer low flows.

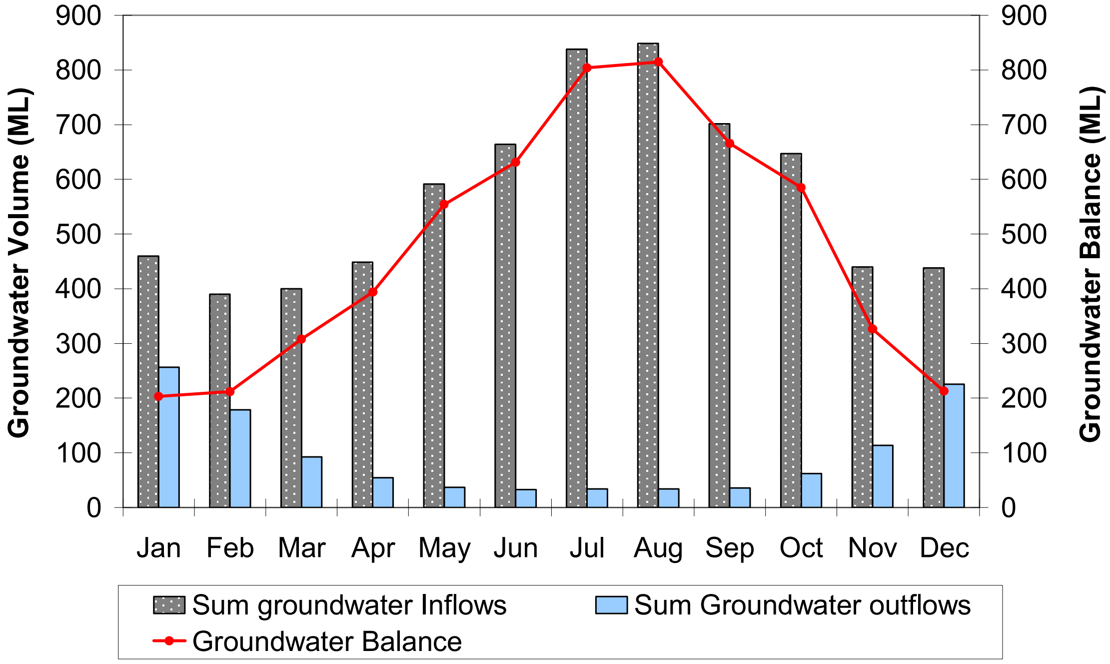

Figure 3-14: Average monthly groundwater water system balance (1973 -1995)

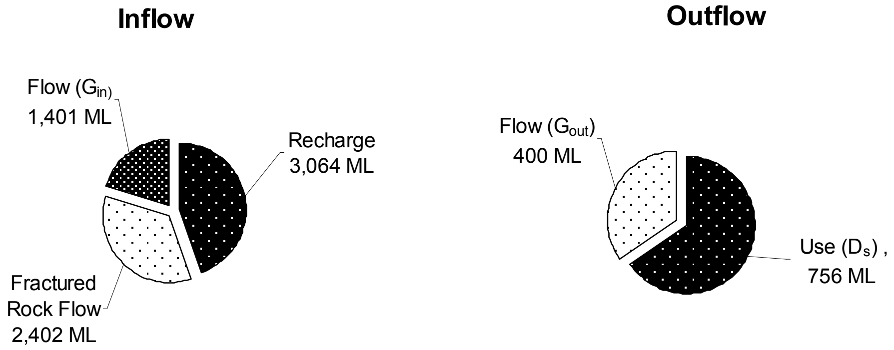

Figure 3-15: Average annual proportion of components in the groundwater system balance (1973 -1995)

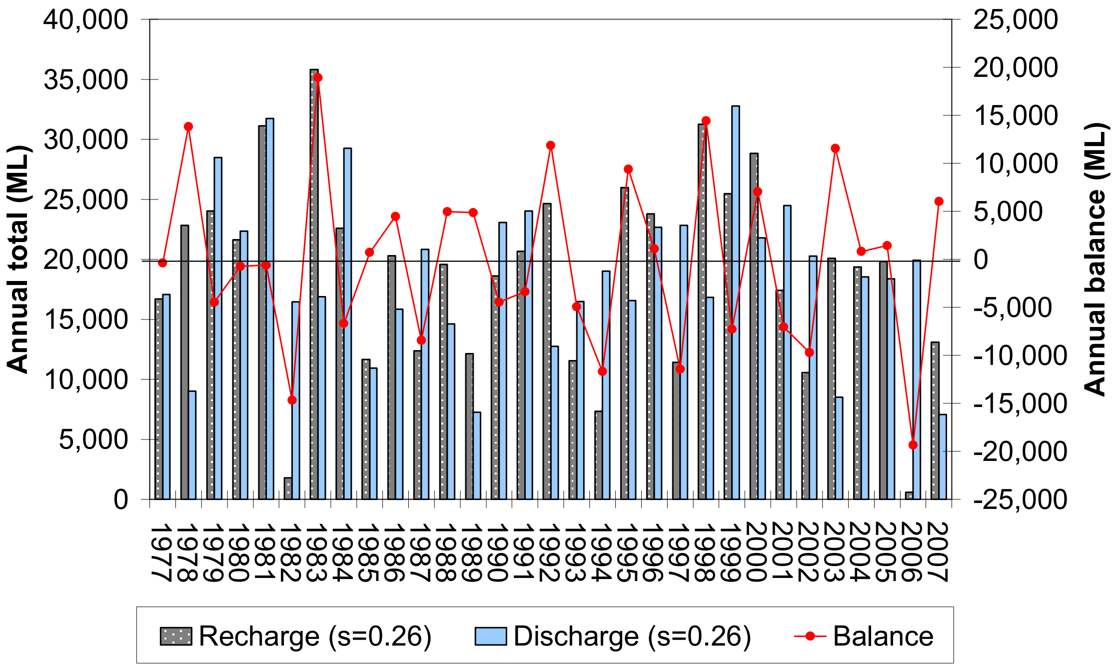

Figure 3-16: Annual Recharge and discharge totals for the groundwater flux

The cyclic seasonal nature of groundwater fluctuation means that on average, yearly recharge is equal to yearly discharge and thus the system is in equilibrium as demonstrated by the hydrographs in Section 2.3.2. Years with low recharge volumes generally have a following year with recharge exceeding discharge. The relationship of rainfall and flows to this recharge may be related to high rainfall and flow years following low rainfall years. It is conceivable that consecutive years of low rainfall and flow may throw the balance into a new equilibrium with lower discharge to the river and lower groundwater levels, but a numerical model is needed to test this scenario.

Uncertainties in calculation of the components of the groundwater system balance mean that it is better to use the groundwater fluctuation series for the whole of system balance. With this approach groundwater recharge is unable to be separated into rainfall and river components.

3.4.4 Whole of system water balance

Uncertainties with the calculation of the groundwater flow component means the measured groundwater fluctuation has been used for the whole of system balance. The whole of system water balance was calculated by combining the groundwater and surface water balances, as shown in Equation 10. In the equation, groundwater is added as it is taken as an inflow into the system. A negative fluctuation means the groundwater is losing to the surface system whereas a positive value means that it is gaining from the surface system.

$$Balance = \left[(Q_{out} + D_s + ET) - (Q_{in} + SR + P)\right] + \Delta GW \qquad (10)$$

The whole of system quantification is shown in Table 3-3 and the whole of system balance error (40,943 ML) is nearly identical to that of the surface system balance (40,680 ML). This is due to the cyclic groundwater fluctuation meaning the annual balance change is near zero. The effect on the whole of catchment balance is to distribute the balance errors to different months. This is shown graphically in the average monthly values for the whole of system water balance in Figure 3-17. Adding groundwater reduces the balance errors in November through to March. In these periods, groundwater fluctuations are negative and, if the water balances are correct, this fits with the conceptual understanding that the groundwater system is providing water to the surface water system at these times. The groundwater system could be providing water to the surface system through contributions to streamflow or losing to the *ET* component of the water balance.

May and June seem to be the change over months where the surface water system may be either gaining from, or losing to, the groundwater system. Large uncertainties in May are disproportionate to flows, probably due to the large variation in groundwater flows and the switching of the stream from gaining to losing. This error will be investigated later in the chapter. June seems to be a period where consistently the surface water system is losing to the groundwater system through recharge. This could either be direct rainfall infiltration or seepage from the river. The wet periods have an excess of outflows and may be due to gauge error or errors in the runoff calculation; these are investigated later in the chapter.

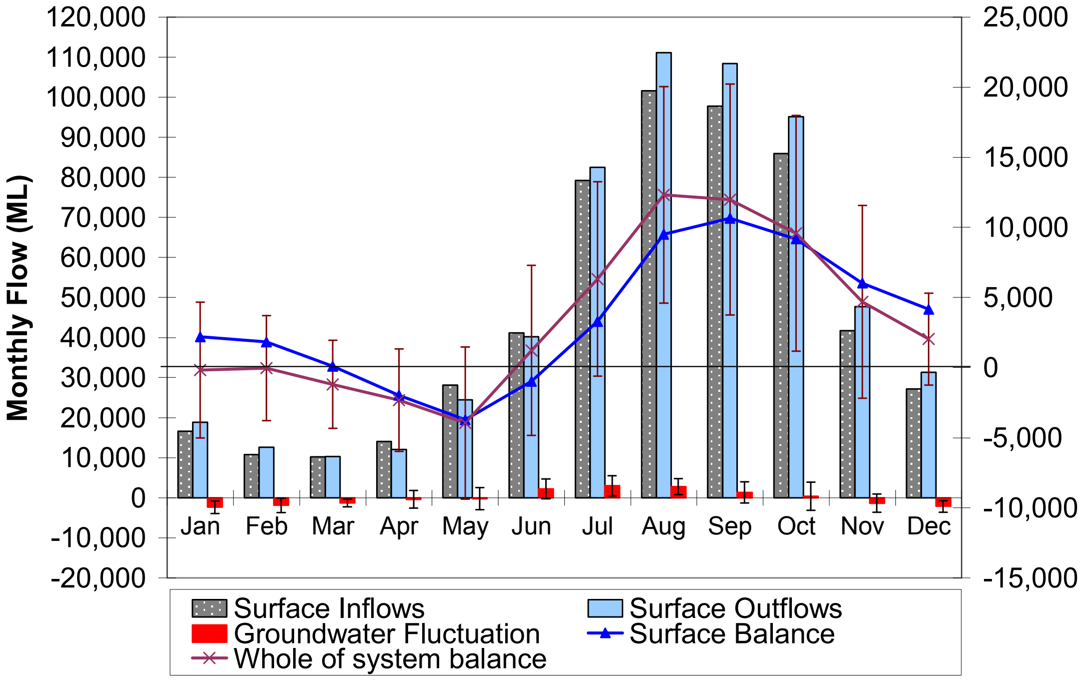

Figure 3-17: Average monthly whole of system water balance (1973 -1995)

Large standard deviations for the balance are shown in Figure 3-17 and are due to the large seasonal variation in surface flows and rainfall. In the summer months where flows and rainfall are most consistent, the water balance seems to even out and the fluxes between groundwater and surface water are a better match.

On average, fluxes between groundwater and surface water are minor in terms of the yearly water balance. However, in individual years they may become important in the summer months where groundwater contributions make up a larger part of the water balance. Groundwater contributions are largest at the start of summer with peak contributions in December January and February. In March contributions are less, probably due to groundwater draining out of the catchment. April and May are the gaining/losing change over months and have a large variation. On average, the groundwater system recharges in June and the water balance is near zero at this time. In the high rainfall months, errors in the water balance have outflows exceeding inflows for the surface system. Groundwater is also recharging at this time, adding to the excess error. In November the groundwater system switches and starts losing to the surface system.

Month	**Surface Inflows**	**Surface Outflows**	**Surface Balance**	**Groundwater Fluctuation (S=0.265)**	**Whole of system balance**
Jan	17,206	21,014	3,807	-3,305	502
Feb	11,201	14,467	3,266	-2,610	655
Mar	10,592	11,805	1,213	-1,779	-566
Apr	14,613	12,906	-1,707	-503	-2,211
May	29,286	24,876	-4,410	-327	-4,736
Jun	42,618	40,421	-2,197	3,082	884
Jul	81,336	82,736	1,399	4,220	5,619
Aug	103,772	111,528	7,756	3,916	11,672
Sep	99,349	109,104	9,754	1,862	11,616
Oct	87,295	96,316	9,021	552	9,572
Nov	42,232	49,346	7,114	-1,874	5,240
Dec	27,631	33,296	5,665	-2,970	2,695
Annual Sum	**567,133**	**607,813**	**40,680**	**263**	**40,943**

Table 3-3: Average monthly water system balance values (1973-2005)

Analysis of the averaged whole of catchment water balance results shows, that on average, there is a clear cycle for the surface water balance with large surface water balance gains (outflows exceeding inflows) in the catchment over the high rainfall periods (August – October). The magnitude of the gains then drops in proportion to rainfall and flows in November through to March, and the system reverses to a net loss (inflows exceeding outflows) in late summer/autumn.

The groundwater fluctuation cycle in Figure 3-17 shows the aquifer recharging quickly at the onset of the high rainfall season (June – October). After initial high recharge the aquifer seems to reach saturation with recharge volumes reducing late in the season. The aquifer starts losing water (ET and losses to river) in November with the volume of loss peaking between November and March and then reducing later in the season.

3.5 Sensitivity analysis

This section investigates the sensitivity of the components of the water balance to variations in parameters and also uncertainties in calculations. Runoff calculations, gauge errors and *ET* are analysed to determine the sensitivity of the balance to these components. As the water balance is to be used to determine the fluxes between groundwater and the river, any errors will reduce confidence in the magnitude of the calculated values.

3.5.1 Low flow (drought) years

Investigation of drought years was undertaken to show the trends and magnitude of the surface water and groundwater system balances in these critical periods. All years were ranked according to annual flow and the five lowest flow years were included in the analysis. The five lowest flow years were 1976, 1977, 1982, 1997 and 2002.

Average monthly flows and balances for the five low flow years (Figure 3-18) follow the same seasonal pattern as was observed for the average data series for the complete modelling period (Figure 3-17). In the low flow years, balance figures for the higher flow months were less than the values for the complete modelling period, suggesting less gauge error at lower flows. In low flow years rain generally does not come until later in the season and in April the surface water system is gaining from the groundwater system. Groundwater to surface water fluxes also show a more stable relationship with groundwater supplying the surface system for a longer period than the average relationship. There are only two months (July and August) where both systems are gaining. In other months there is a complementary relationship. In the low flow years, the pattern of fluxes between groundwater and surface water systems are very similar, however, contributions from groundwater are of a higher magnitude than those for the complete modelling period.

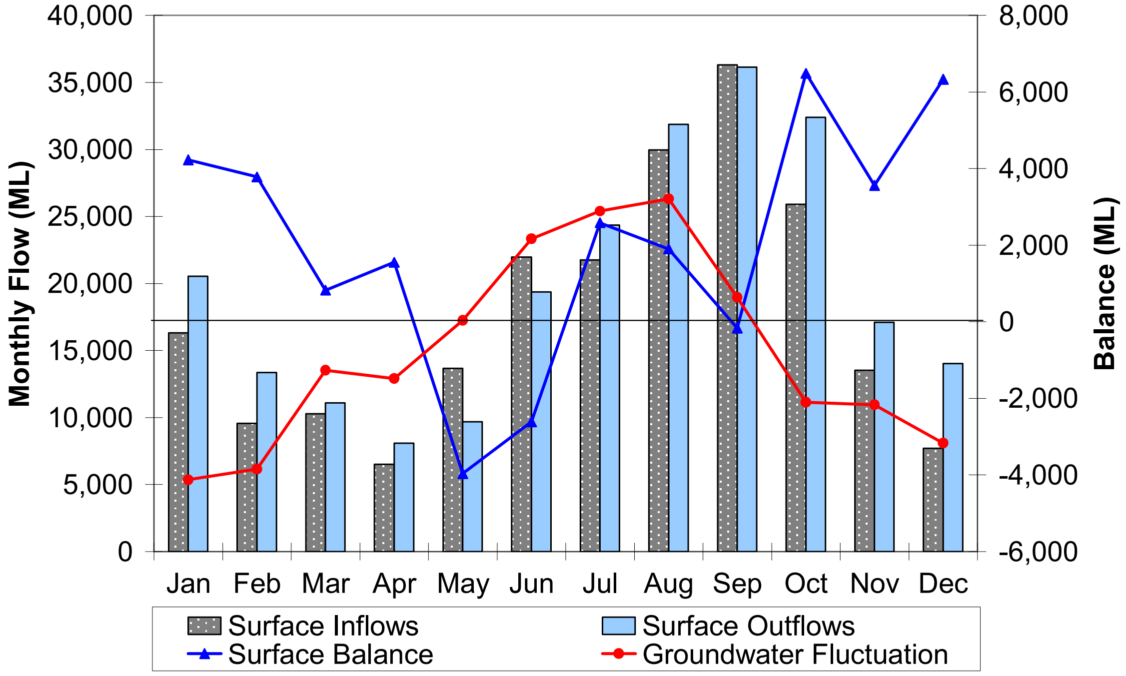

Figure 3-18: Average monthly water balance for dry years

Comparison of the 2002/03 year river reach balance (Figure 3-20) to the surface system balance (Figure 3-19) shows that the between November and March the river inflows and outflows of the river balance are roughly equal. In comparison, the surface balance shows that surface water system outflows are greater than inflows over this period. As rainfall (and runoff) is negligible it is estimated that *ET* is causing the balance to shift. Groundwater fluctuations in this period show the groundwater system losing water. It is most likely that groundwater is supplementing *ET*, either by supplementing flow in the river to cover riparian ET or direct evaporation from the river, or directly to *ET* from vegetation in the unconsolidated aquifer. The magnitudes of groundwater fluxes in proportion to *ET* suggest that *ET* is being overestimated in dry years.

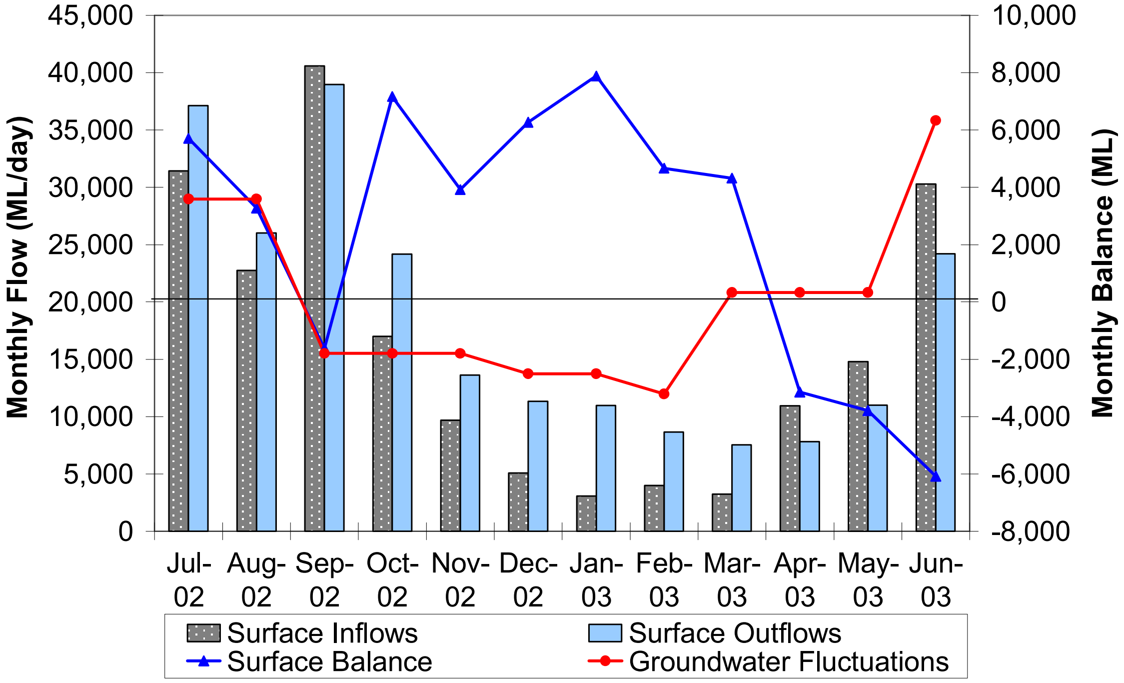

Figure 3-19: 2002/03 Monthly surface water system balance

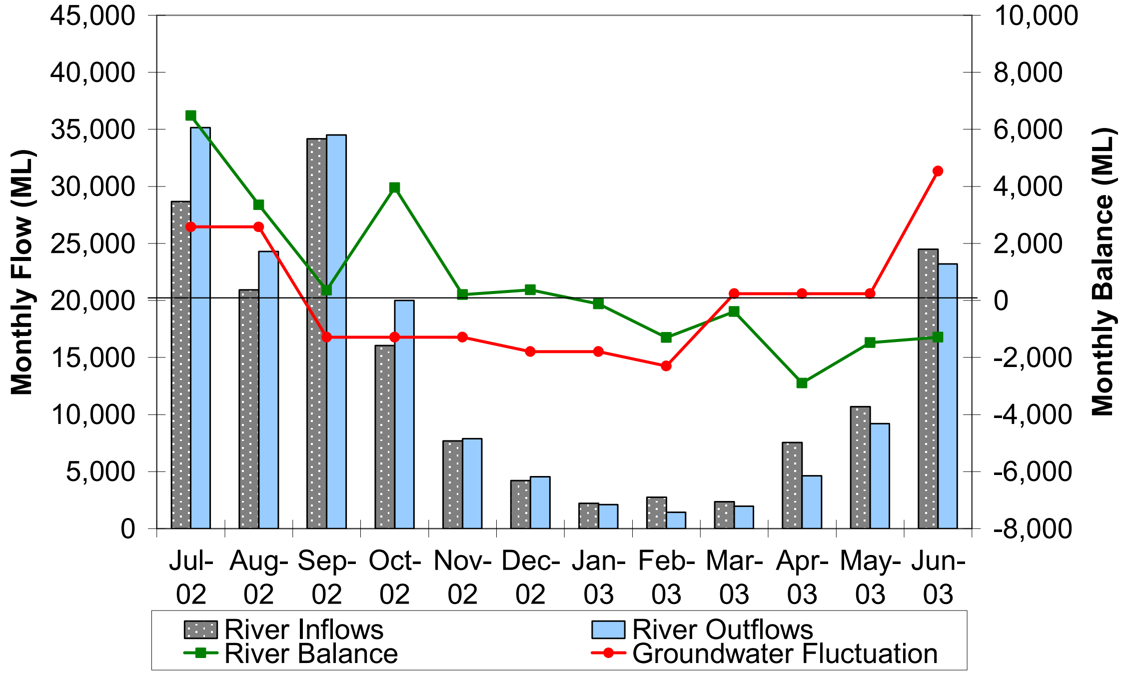

Figure 3-20: 2002/03 Monthly river reach balance

3.5.2 Runoff calculation investigation

The modelling of runoff using SIMHYD gives one averaged runoff coefficient value for the whole year (CSIRO 2008). The surface water balance has outflows exceeding inflows in high flow periods and inflows exceeding outflows in low flow periods. This indicates that the single runoff coefficient calculation may be underestimating runoff over high flow periods and overestimating in periods of low flow. When surface run-off and stream diversions were removed from the river reach balance, outflows were higher than inflows for all months, indicating an error in the runoff calculation. Further analysis investigated the influence of rainfall prior to an event and the wetting of the catchment. This relates to soil moisture and that in dry periods, more rain is needed to induce runoff, and in wet periods, a greater proportion of rainfall will turn into runoff. To allow for the soil moisture effect, runoff coefficients were varied for wet and dry periods. Wet periods were defined as when a variable x (mm) of rain has fallen in the 7 days prior to a rainfall event and dry when less than x (mm) had fallen.

Using trial and error, variations in x and the runoff coefficients found that with x = 30mm, runoff coefficients of 48% for wet periods and 5% for dry periods achieved a balance figure closest to zero in the low flow period. Changing runoff coefficients had no real impact on the water balance in high flow periods but had an impact in low flow periods. Best results for the low flow period were achieved when the dry period runoff coefficient was set to zero. However, the simplicity of the model meant that this increased errors in wet periods. Thus 5% was considered the optimal runoff coefficient for dry periods. The optimal 48% for wet periods coincided with the calculated runoff coefficient determined for adjoining catchments (CSIRO 2008).

Influences of changing runoff coefficients is highlighted when comparing the river reach balance with a 24% runoff coefficient (Figure 3-21) to the river reach balance with runoff coefficients of 5% for dry periods ($x < 30$mm) and 48% for wet periods ($x > 30$mm) (Figure 3-22). Changing the runoff coefficients for wet and dry periods reduced the error in the river reach balance between January and May (low inflows) and is important in these periods. Changing the runoff coefficients had minimal influence at other times, generally the higher flow periods. This suggests that the errors in the water balance during higher flow periods are driven by gauging errors.

Increasing the x value tended to cause an overall deficiency in the water balance and caused outflows to exceed inflows in all months. Decreasing the x value caused inflows to exceed outflows in all periods but most noticeably in low flow periods. Conceptually this fits with the expected results as decreasing x converts a greater proportion of rainfall to runoff and conversely increasing x reduces the proportion of rainfall converted to runoff.

The analysis indicated that the water balance is not sensitive to changes in the runoff component in high rainfall/flow periods but sensitive in low rainfall/flow periods. This is due to the relative proportion of the runoff component of catchment inflows increasing from 5% in August to 20% in March (Appendix 3).

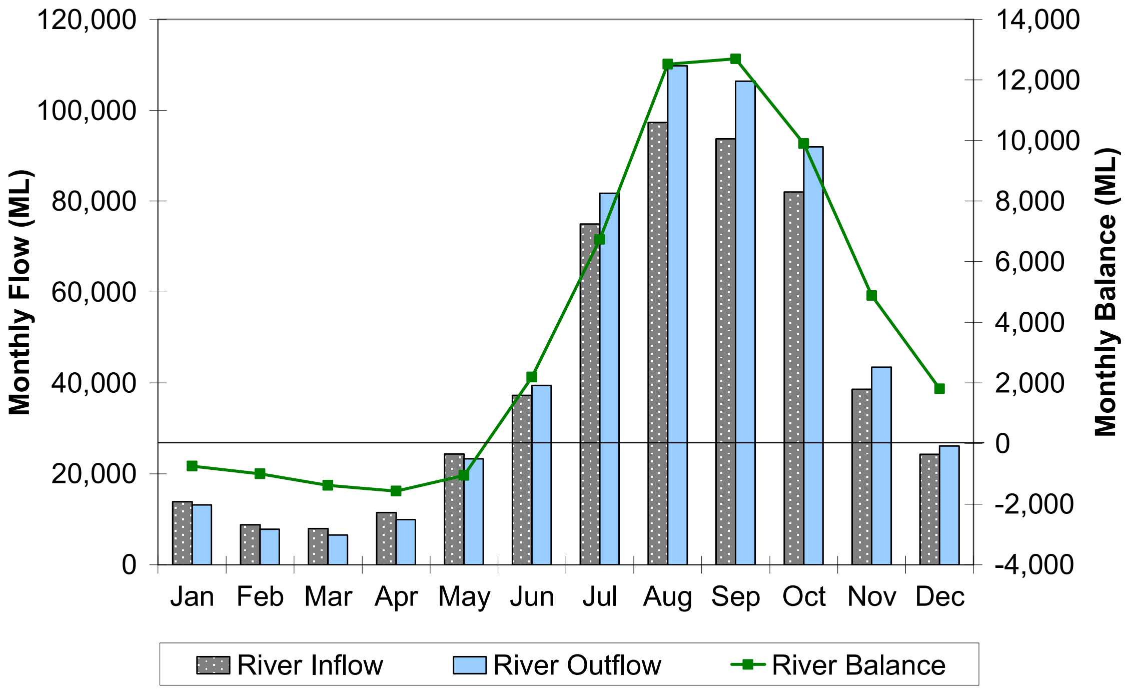

Figure 3-21: River balance with 24% runoff

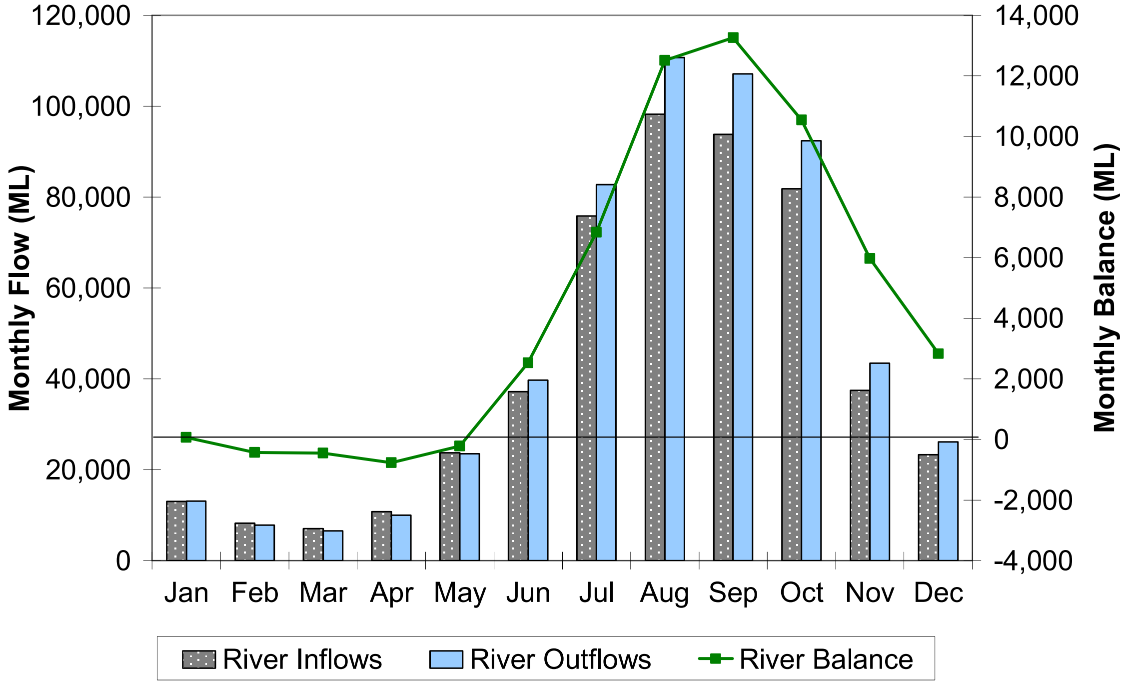

Figure 3-22: River balance using coefficients of 48% for wet periods (>30mm rain for prior 7 days) and 5% for dry periods

3.5.3 *ET* and groundwater investigation

The Penman Monteith equation can over estimate actual *ET* as it assumes unlimited soil moisture availability to supply *ET* at the potential rate, where, in reality there can be limitations on water availability that would reduce *ET* (Allen et al. 1998). This effect can be seen in Figure 3-19 where the *ET* was identified as the potential reason for outflows exceeding inflows (and potential groundwater system inputs) in the summer of 2002/2003. A lot of the study area is dryland farming and using the ET_o values would be overestimating *ET,* as there is likely to be a shortage of soil moisture in summer. There are also a lot of treed areas, both in the form of pine plantations and eucalypt trees, especially in the riparian zone. Larger trees can use above reference ET_o and access groundwater, thus using reference ET_o for these areas may offset areas where the actual *ET* may be less than ET_o.

The *ET* was varied to determine the sensitivity of the water balance to this component. Even when the runoff calculation is reduced from the original 24% in dry periods and set to the optimum level (48% for prior 7 days rainfall > 30mm and 5% for prior 30 days < 30mm), the water balance still has a greater excess of outflows in summer. As ET was identified as a possible reason for the excess outflows, ET_o was reduced for the non irrigation areas. Using trial and error it was found that reducing ET in the non-irrigated areas to 0.85 of ET_o has the water balance near to the average magnitudes set in the base case for the surface system balance and has the lowest excess of outflows in the low flow period.

However, when considering the whole of system water balance, adding in the groundwater fluctuations causes the inflows to exceed outflows over summer (Figure 3-23). As highlighted in section 3.3.1, the storativity value used to calculate the groundwater was initially set at the highest value and may cause an overestimation of actual fluctuation volumes. To determine the storage value's influence, it was varied in the whole of system water balance. By trial and error, the smallest balance error over summer was achieved when the aquifer storage value was set to 0.19 (Figure 3-24). This may be just one possible combination of parameter values that give the same result

A specific yield of 0.19 minimises the balance errors in summer. Optimising the water balance indicates a range for the specific yield of the groundwater system of between 0.19 and 0.26 depending on actual magnitudes of errors for surface system components.

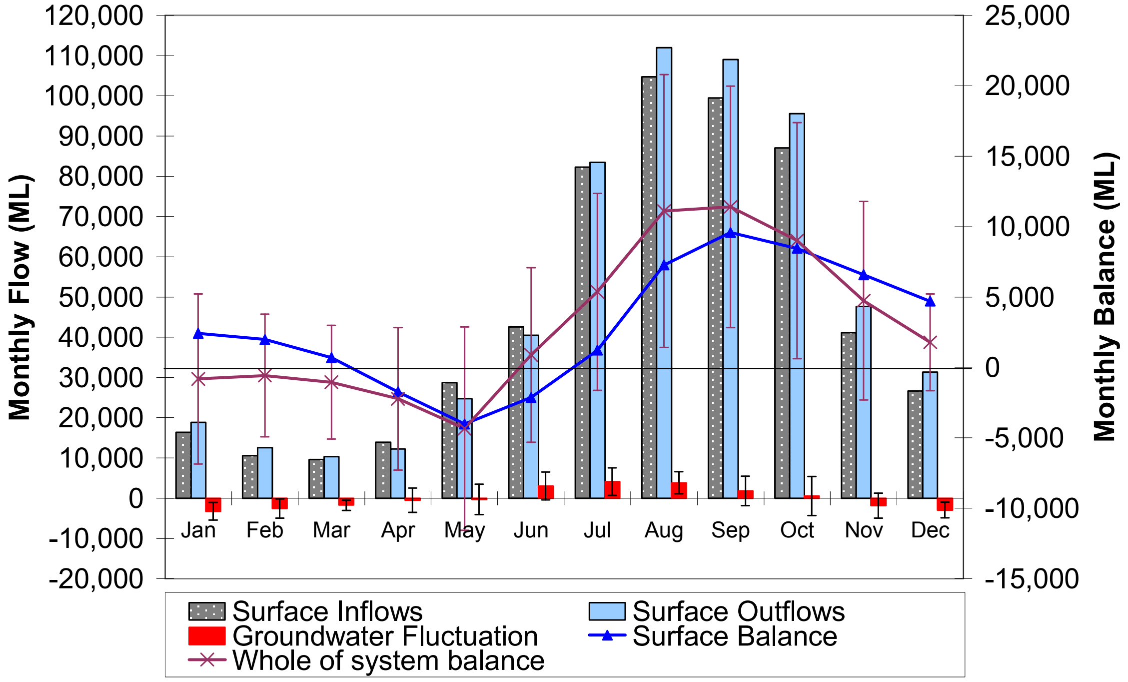

Figure 3-23: Whole of system balance with runoff and *ET* set to optimal levels (*ET*=0.85xET_o, Runoff = 5% and 48%) and groundwater storativity set to 0.26

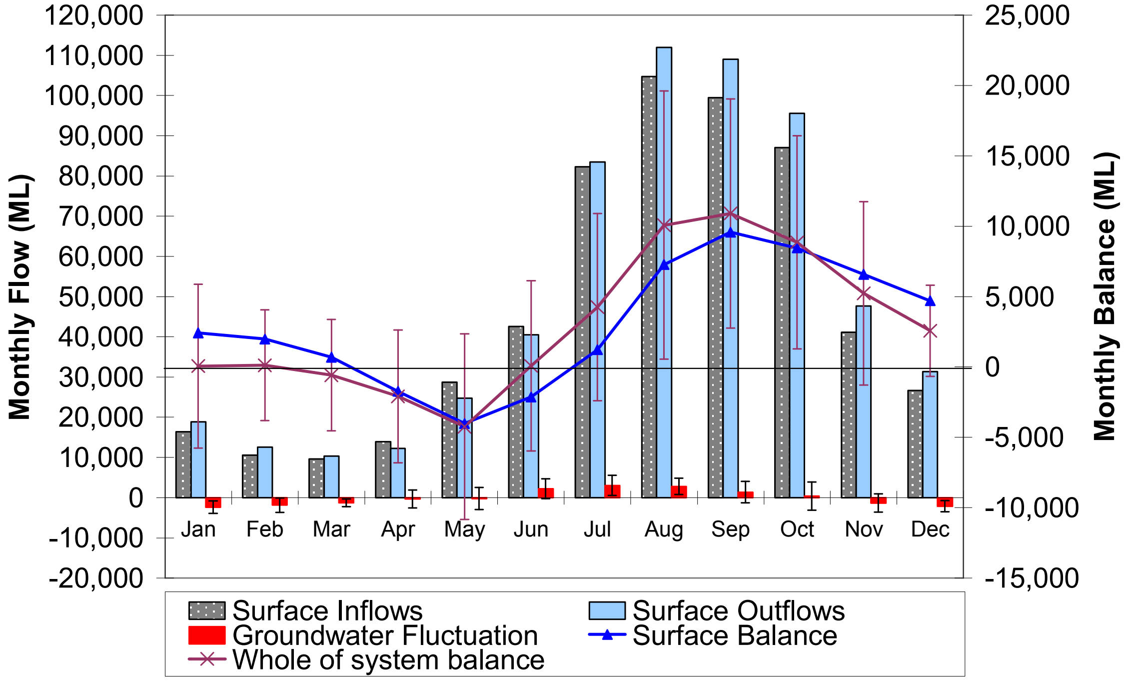

Figure 3-24: Whole of system water balance with runoff and *ET* set to optimal levels (*ET*=0.85xET_o, Runoff = 5% and 48%) and groundwater storativity set to 0.19

3.5.4 Gauge Errors

When other water balance components could not be altered to balance high flows, gauge errors were investigated to determine their influence on the water balance, in particular at high flow times. Initially a simplistic analysis was undertaken where all flows were increased/decreased by the same percentage. Ranges of gauge error were found to vary between +/- 5% and +/- 15% in a Gippsland study (Ozbey et al. 2008) and the gauge errors were trialled between this range. Only a small error allowance was needed to get the surface flows to balance in high flow months, however, this had negative influence on the April through to July periods with errors for the whole of system balance increasing in this time. With runoff set at 24%, *ET* set at ET_o and Sy of 0.26 (which are the figures of the base scenario), trial and error found that the best surface balance at high flows was achieved with an allowance for gauge errors of +5% at 403233, +5% at 403205, and -10% at 403210. With the allowance for gauge errors (Figure 3-25), errors in the surface water balance are greatly reduced from the base case (Figure 3-17) in high flow months. In these months, allowance for groundwater fluctuations reduces the errors in the whole of system water balance to almost zero, and for most months reduces the surface water balance errors.

Modification of other water balance components had helped to correct errors in the low flow periods and these were altered in addition to the gauge errors to determine the effect on the whole of system water balance. Alteration to the optimum values obtained for groundwater storativity (S=0.19), runoff coefficients (5% and 48%) and *ET* (0.85xET_o) increased the errors in the whole of system water balance in all months (Figure 3-26). The resulting errors shifted all balance values to be negative with inflows greater than outflows in comparison to Figure 3-25. This was attributed to the increase in runoff (inflow) in wet periods from 24% to 48% and the decrease in *ET* (outflow) in the dry months. Alteration of the runoff coefficient to the SIMHYD calculated value of 24% (CSIRO 2008) corrected this error in wet months. A slight increase in *ET* by increasing *ET* to be 0.9 x ET_o achieved the best water balance (when gauge errors are appropriated to all flows) as shown in Figure 3-27 (Optimal scenario 1).

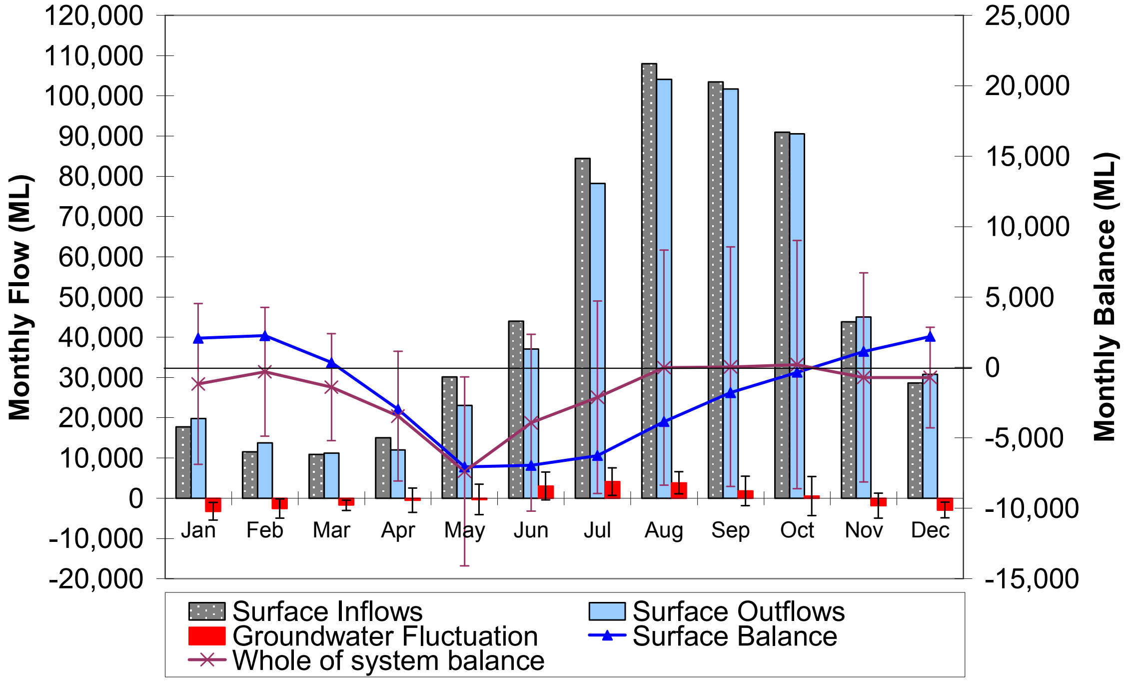

Figure 3-25: Monthly water balance with only modifications for gauge error (403205 and 403233 at +5%, 403210 = -10%) and S=0.26, *ET*=ET_o, Runoff = 24%

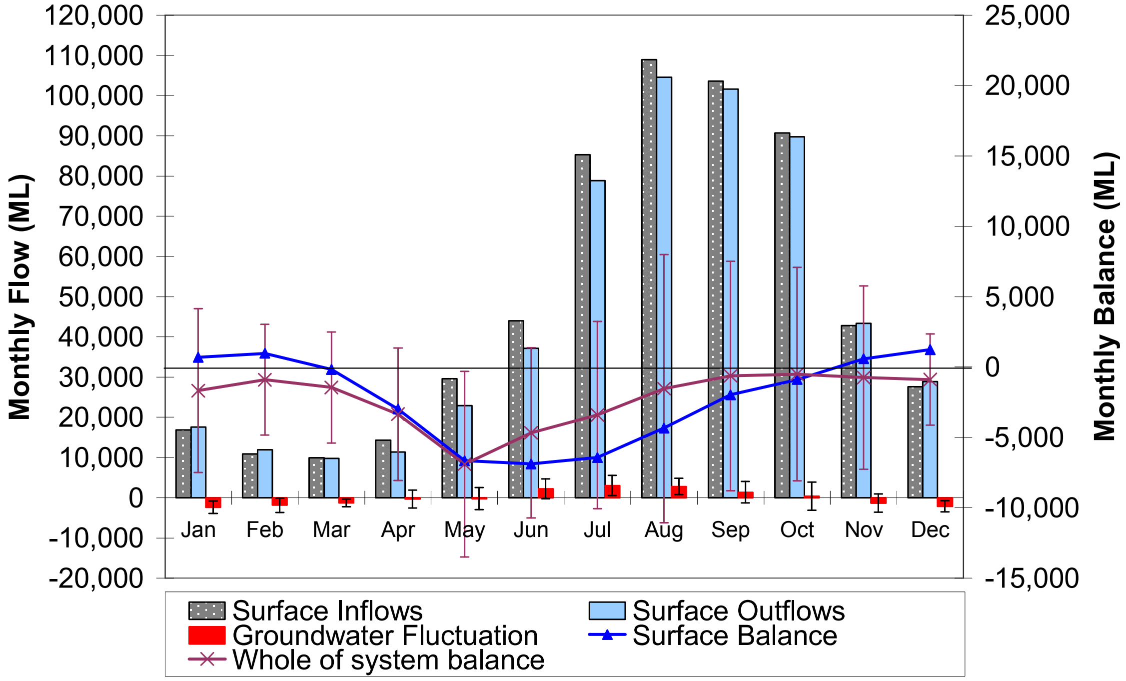

Figure 3-26: Monthly water balance with all flows modified for gauge error (403205 and 403233 at +5%, 403210 = -10%) and other components modified to optimum levels (S=0.19, *ET*=0.85xET_o, Runoff = 5% and 48%)

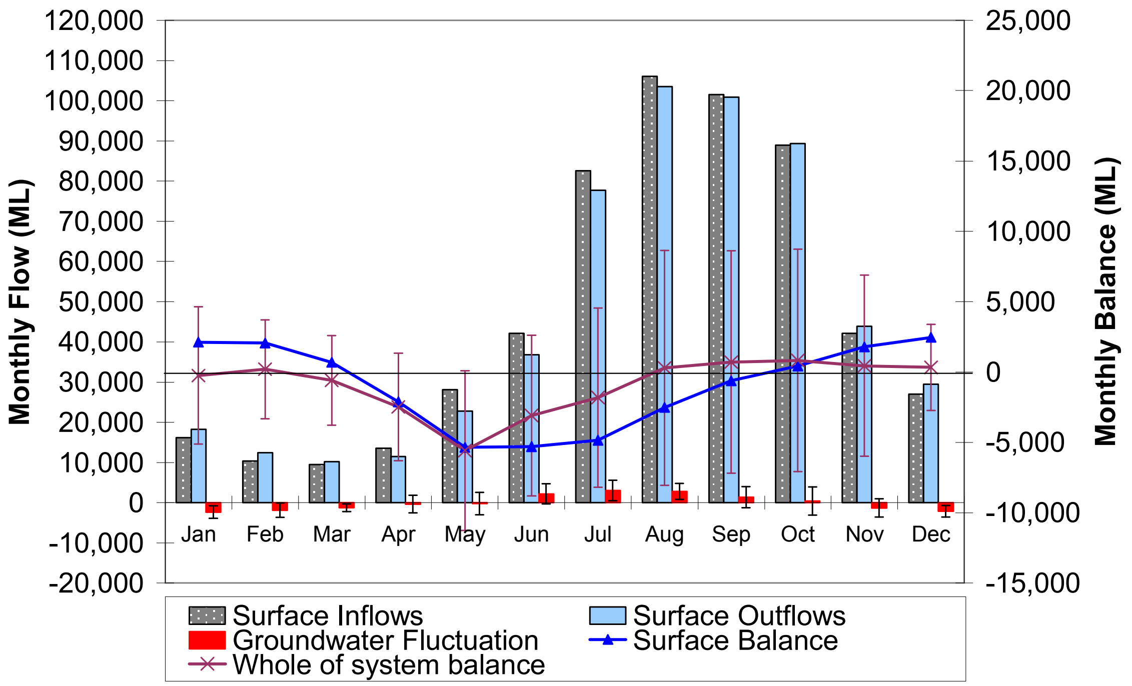

Figure 3-27: Optimal Scenario 1, Monthly water balance with all flows modified for gauge error (403205 and 403233 at +5%, 403210 = -10%) and other components modified to produce minimum errors (S=0.19, *ET*=0.9xET_o, Runoff = 5% and 24%)

The influence of gauge errors at high flows was investigated to see if the gauge error related only to high daily flows, rather than an error across all flows. A daily high flow value was chosen for each gauge and an allowance for errors of daily flows above this level was applied. Flows below this figure were assumed to have no gauge error. High flows were considered to be 1000 ML/day at the inflow gauges of Bright and Buckland, Flows of 2000 ML/day and above were considered to be high outflows at Myrtleford. Trial and error found that a gauge error at Myrtleford (403210) of -14% and gauge errors of +5% for Bright (403205) and the Buckland (403233) achieved the optimal water balance. Alteration of the other components to their optimum values resulted in increased errors. Trial and error found that the smallest errors were calculated when the runoff coefficient was 24% for wet periods and 5% for dry, *ET* set to be 0.85 x ET_o and S=0.26 (Optimum Scenario 2 in Figure 3-28).

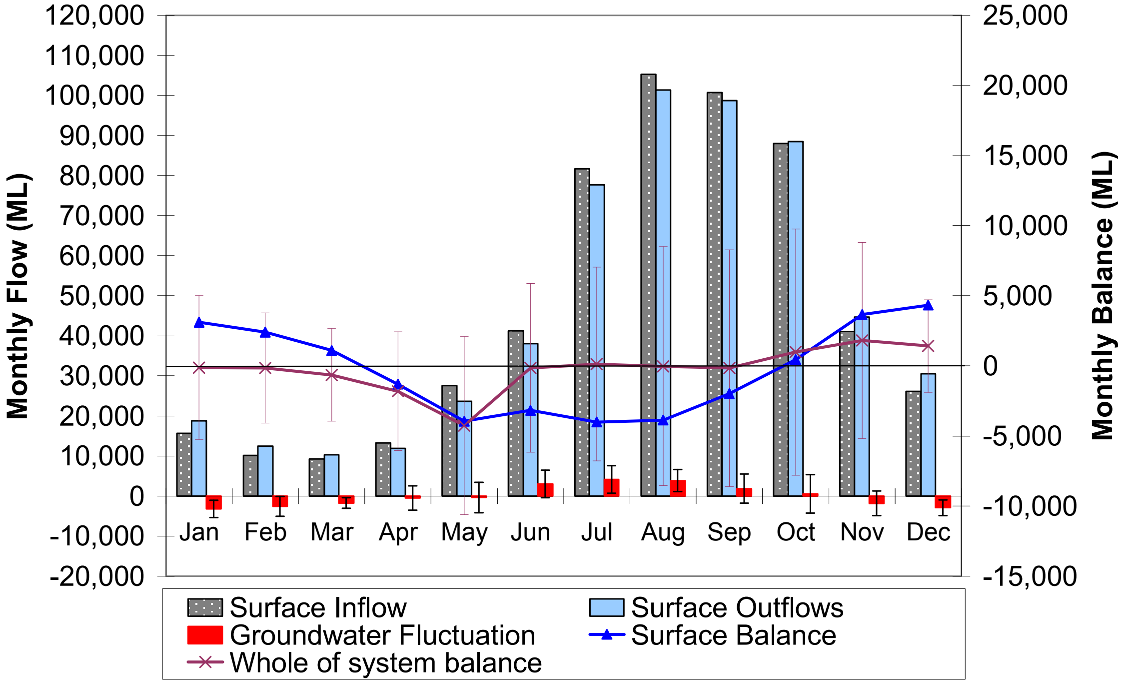

Figure 3-28: Optimal Scenario 2, Monthly water balance with high flows modified for gauge error (403205 and 403233 at +5%, 403210 = -15%) and other components modified to produce minimum errors (S=0.26, *ET*=0.85 xET_o, Runoff = 5% and 24%)

Only minor changes in magnitudes of the surface water balance in low and medium flow months were found by altering and optimising the constants used to calculate the individual components. The highest changes were for allowance of gauge errors in the high flow periods where the magnitudes of the surface water balance were reversed between July and September. This had the greatest effect on the whole of system balance, where for these months, the surface and groundwater balance were opposite and the whole of system balance was now near zero. This meant that the water balance now shows groundwater gaining from the surface system rather than both gaining (outflows in excess on inflows). The whole of system water balance error was also greatly reduced from 40,943 ML in the monthly average to -2,973 ML for Optimal Scenario 2 (Table 3-4). The highest balance errors are found in April and May. Alteration of the individual components did not influence the surface balance, in all sensitivity analyses, inflows always exceeded outflows, groundwater flux is always losing in these months which increases the error in the whole of system balance for all scenarios (Table 3-4). These two months have a large variation in rainfall and depending on the season and timing of rainfall, groundwater can be recharging or losing to the surface system. As a result the groundwater flux magnitudes are the lowest for these months as the average values indicate the variation and don't show a strong direction of flow. This is similar to October, which is when the system can change from gaining to losing and can go either direction depending on seasonal patterns of rainfall.

	Monthly Average Balance (Figure 3-17)			Optimal Scenario 1 (Figure 3-27)			Optimal Scenario 2 (Figure 3-28)		
Month	Surface	Ground-water	Whole of system	Surface	Ground-water	Whole of system	Surface Balance	Ground-water	Whole of system
Jan	3,807	-3,305	502	2,117	-2,369	-252	3,120	-3,242	-123
Feb	3,266	-2,610	655	2,064	-1,872	192	2,410	-2,561	-151
Mar	1,213	-1,779	-566	692	-1,276	-584	1,097	-1,746	-648
Apr	-1,707	-503	-2,211	-2,118	-361	-2,479	-1,315	-494	-1,809
May	-4,410	-327	-4,736	-5,354	-234	-5,588	-3,945	-320	-4,266
Jun	-2,197	3,082	884	-5,305	2,210	-3,096	-3,173	3,024	-149
Jul	1,399	4,220	5,619	-4,845	3,026	-1,819	-4,005	4,141	136
Aug	7,756	3,916	11,672	-2,514	2,807	294	-3,871	3,842	-29
Sep	9,754	1,862	11,616	-626	1,335	709	-1,981	1,826	-154
Oct	9,021	552	9,572	426	395	821	443	541	984
Nov	7,114	-1,874	5,240	1,784	-1,343	441	3,656	-1,838	1,818
Dec	5,665	-2,970	2,695	2,457	-2,129	328	4,333	-2,914	1,419
Annual Sum	**40,680**	**263**	**40,943**	**-11,222**	**188**	**-11,034**	**-3,231**	**258**	**-2,973**

Table 3-4: Comparison of the initial average monthly balance to the minimised balance errors allowing for variations of constants determined in the sensitivity analysis (ML).

Alteration of the parameters/variables used for calculating individual components of the water balance and allowing for errors in the data have minimised the errors in the whole of system water balance. The values obtained using the optimal scenario two (Table 3-5) of the sensitivity analysis increase the confidence in use of the numbers when identifying the magnitudes of the components of the water balance. This scenario may not be the only optimal combination of parameters/variables that minimises errors of the water balance.

Month	Ovens River Flow at Bright 403205	Buckland River Flows 403233	Buffalo Creek	Rainfall	Runoff	*Surface Inflow Total*	Ovens River Myrtle-ford 403210	Irriga-tion	D&S	Other Use	*ET*	*Surface Outflows*	Surface Balance	Ground -Water	Whole of System Balance
Jan	5,577	4,297	1,300	3,353	1,137	*15,664*	12,374	689	9	3	5,709	*18,784*	3,120	-3,242	**-123**
Feb	3,371	2,656	881	2,395	805	*10,107*	7,145	552	8	3	4,810	*12,517*	2,410	-2,561	**-151**
Mar	2,928	2,154	749	2,645	768	*9,243*	6,206	339	9	3	3,784	*10,340*	1,097	-1,746	**-648**
Apr	4,017	3,567	1,432	3,140	1,098	*13,254*	9,702	56	9	3	2,170	*11,939*	-1,315	-494	**-1,809**
May	8,598	8,639	3,419	4,960	1,961	*27,577*	22,456	3	9	3	1,160	*23,632*	-3,945	-320	**-4,266**
Jun	14,264	14,231	4,994	5,374	2,382	*41,243*	37,348	0	9	3	711	*38,070*	-3,173	3,024	**-149**
Jul	31,753	32,576	7,751	6,375	3,239	*81,694*	76,925	0	9	3	752	*77,690*	-4,005	4,141	**136**
Aug	43,889	43,073	8,513	6,472	3,301	*105,249*	100,134	0	9	3	1,232	*101,378*	-3,871	3,842	**-29**
Sep	43,378	41,690	7,372	5,659	2,587	*100,687*	96,730	0	9	3	1,965	*98,706*	-1,981	1,826	**-154**
Oct	38,765	35,717	6,011	5,243	2,243	*87,979*	85,252	2	9	3	3,156	*88,421*	443	541	**984**
Nov	17,680	15,852	2,720	3,650	1,147	*41,049*	40,380	64	9	3	4,250	*44,705*	3,656	-1,838	**1,818**
Dec	10,767	9,175	1,859	3,329	1,042	*26,171*	24,992	304	9	3	5,195	*30,503*	4,333	-2,914	**1,419**
Annual Sum	**224,987**	**213,627**	**47,001**	**52,592**	**21,710**	***559,917***	**519,644**	**2,007**	**104**	**38**	***34,893***	***556,686***	**-3,231**	**258**	**-2,973**

Table 3-5: Whole of system water balance values (ML) for optimal scenario 2: high flows modified for gauge error (403205 and 403233 at +5%, 403210 = -14%) and other components modified to produce minimum errors (S=0.26, ET=0.85 xET_o, Runoff = 5% and 24%)

3.6 Summary of the water balance results

Average monthly balances developed for the Upper Ovens River study area show a seasonal pattern of water movement in and through the study area and also between the groundwater and surface water systems. Results displayed on a monthly scale have a high variability, so monthly averages for the model period were used to give insight into the true nature of the water balance and smooth the variations shown in the monthly data. Fluxes between groundwater and surface water systems are small in comparison to the annual water budget. As such they are within the possible error bounds of other water balance components' data, and difficult to separate with a high level of confidence. Thus the flux volumes determined by the water balance can only be used to give insight into their magnitudes. Rather than give accurate flux volumes, the water balance show seasonal patterns for water movement through the study area and acts as a guide to the magnitudes of individual component contributions.

Sensitivity analysis was undertaken by varying the parameter values of the individual components within reasonable ranges or to allow for errors. Gauge errors were found to have the highest influence on the whole of system balance. In conjunction with small variations of other components the water balance error was reduced from 40,943 ML in the monthly average to -2,973 ML for Optimal Scenario 2 (Table 3-4). The sensitivity analysis increases the confidence in the magnitudes of fluxes in the water balance and also the possible model for water movement. It also narrows the possible ranges of some of the parameter values used in the calculation of individual components, such as the important storativity value used in the groundwater balance. However, the optimal parameter value combinations found may not be the only optimal set of values.

A possible model for seasonal water movement in the study area is inferred from the average monthly water balance results and conceptualisation. The model describes the relationship between the unconsolidated sediment aquifer bounded by the fractured rock aquifer with the Ovens River between Bright and Myrtleford. Seasonal patterns identified infer a strong relationship between the river and the aquifer system.

The surface-groundwater interaction relationship inferred from the water balance is as follows. Starting in winter, the aquifer recharges and is at its peak over the high rainfall winter and spring period, flows are also at their peak in this period. Reducing rainfall and increasing *ET* over late spring/early summer cause the river stage to drop, and high groundwater levels mean the water flux is from the groundwater system to surface water. Flux volumes (between groundwater and surface water systems) drop later in summer (possibly due to the groundwater level reducing as investigated in the next chapter) until groundwater losses are at the lowest in late summer. Once there is rain in autumn, the aquifer recharges through rainfall and river infiltration and the surface water system is in net loss. This continues until the aquifer levels are equal to, or higher than, the river stage and a rough equilibrium exists, usually in June. The equilibrium continues over winter and spring when low rainfall and flows cause the cycle to start over. At any stage over winter, if the river stage is higher than the water table, then the river will lose to the aquifer and vice versa.

Seasonal patterns do not change when magnitudes of the individual components are altered within the error bounds of the data identified in the sensitivity analysis. However the pattern does become more apparent once gauge errors are included (Section 3.5.4) The pattern is also the same in dry (low flow) seasons lending to the robustness of the seasonal pattern model and water balance method. Large errors in April and May are disproportionate to flows and this is probably due to the large variation in groundwater–surface fluxes at these times and the temporal variation of switching of the stream from gaining to losing in different years.

Quantities of individual components of the water balance show that river flow though the study area is the major water balance component. In low flow periods between December and April, study area runoff and rainfall nearly equal river inflows. For outflows, *ET* is nearly equal to river outflows. On a monthly basis, extraction for human uses is only a minor component of the water balance and for individual months it is never over 10% of average outflows (Table 3-5), even in the peak irrigation season and low flow times. As these are averaged results, the importance of extraction may be more important on a daily or weekly basis in drought times, such as the 1982/83 season.

Fluxes between groundwater and the surface water system are also small in magnitude with respect to river flows, although like human extraction, become a larger component of the water balance over low flow periods (Table 3-5). Groundwater contributions to the surface system become important in drought years such as 1982/83, where surface outflows are much larger than inflows and the groundwater contribution becomes significant. Due to the cyclic seasonal pattern of groundwater levels, averaging the fluctuations means that they have little impact in the annual water balance, as recharge generally equals discharge and as such the aquifer is in a state of equilibrium.

It is important to note that the fluxes between the groundwater and surface water systems shown in the water balances (Table 3-5) do not directly represent fluxes between the Ovens River and the alluvial aquifer. High groundwater levels mean that *ET* is a component of the groundwater flux when it is contributing to the surface system and fluxes from the surface system include rainfall recharge as well as river recharge. An exact breakdown to the contributions between groundwater and Ovens River is not possible to calculate due to the monthly scale, coarse data on groundwater levels and inaccuracy in recharge calculations. Indications of the direct flux quantities can be inferred from the river reach balance, which shows groundwater contributions to the river in the low flow period being a lot less than to the whole surface system.

Further investigation of groundwater to river fluxes is completed at a shorter time scale than the monthly water balance model in the following chapter. Relationships of aquifer levels to river levels at a shorter time frame are quantified to refine flux estimates and separate groundwater contributions to the river from contributions to *ET*.

Chapter 4: Groundwater Level – River Relationship

The water balance analysis has shown that water movement through the catchment, including the magnitude of fluxes between groundwater and surface water systems, has a defined seasonal pattern. Seasonal timing and magnitudes of the fluxes between groundwater and surface water systems were identified but evapotranspiration and direct rainfall recharge were not separated from the flux volumes. How the relationship and patterns of fluxes between groundwater and surface systems shown in the water balance relate to groundwater – river flux relationships will be investigated in this chapter. This investigation will also determine if the Ovens River switches from gaining to losing, and whether a groundwater – river level relationship can be found to show the flux relationship.

There are many methods available to investigate groundwater–surface water connectivity and fluxes (Sophocleous 2002; Brodie et al. 2007), however, for this project the chosen methodology has been based on conventionally used techniques suitable for data commonly available to water resource managers. Previous chapters have used hydrogeological mapping and water budgets to investigate the connectivity and fluxes between the groundwater and river systems. In this chapter, hydrometrics and hydraulic gradients based on Darcy's law, are used to investigate the direction and magnitude of these fluxes, and these are compared to the water balance results

Cross sections running across the valley and perpendicular to the Ovens River are used to examine relative groundwater and river levels in different periods and the associated hydraulic gradients. There are several locations with transects of bores across the valley and three sites have been chosen for investigation (Figure 4-1). Unfortunately, stream flow gauging locations are generally remote from these sites and groundwater levels are also measured infrequently. A combination of field studies to gather new data, and historical data have been utilised to investigate groundwater-river relationships at these cross section sites.

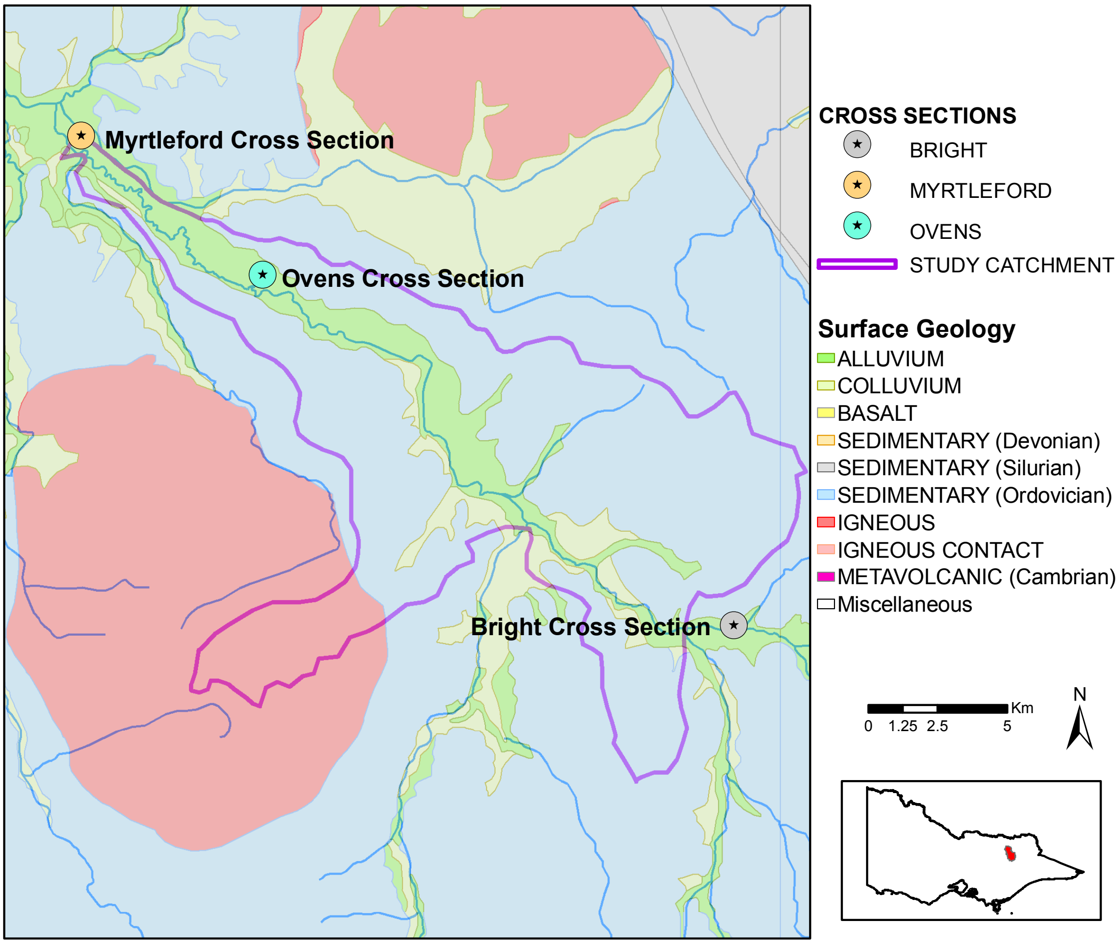

Figure 4-1: Bore transect locations

It has been established, from hydrographs in section 2.3.2, that river stage and groundwater levels follow the same trends. This chapter investigates how this relationship can be used to develop management trigger levels for groundwater. Historical water gradients between the river and groundwater are calculated and investigate relationships between groundwater and the stream levels. Fluxes of water are also estimated using the hydraulic gradients.

There are many complex ways to calculate the fluxes and groundwater movement, such as numerical computer models in three dimensions, Laplace transforms for two and three dimensional models, and simple one or two dimensional flow analysis based on Darcy's law and other equations (Barlow and Moench 1998; Barlow et al. 2000; Knight 2005). For the Upper Ovens River case, which is classified as a stream partially penetrating an unconfined homogeneous aquifer, several assumptions (described later in the chapter) are made in order to use the Dupuit equation to estimate the fluxes (Todd and Mays 2005).

In the Upper Ovens catchment, the water balance has shown that groundwater extraction is minimal and other human activities have limited impacts on the river flow regime. Thus the understanding of the system developed in this chapter relates to a near natural environment and can be used as a basis for the management recommendations. The catchment also has a lot of robust data that have not been fully investigated. These data are used to further refine the understanding of the groundwater-river interactions by examining historic groundwater levels, and the direction of the flux between groundwater and the Ovens River. Estimates of the flux volumes using simple analytical models are used to investigate the validity of the water balance results and attempt to isolate the volume of river-groundwater fluxes from the evapotranspiration and rainfall components identified in the water balance.

4.1 Water level measurement

Pressure loggers measuring depth of water and temperature were installed in several bores within the study area and also at one location in the Ovens River. The loggers were installed between November 2006 and March 2007 in the Ovens region (bores 48073, 48071 and 48070). Loggers were installed in the Myrtleford area (bores 83232 and 83229) in December 2007. These locations are shown in Figure 4-2. The loggers for the Ovens bores were installed for an experiment run by G-MW prior to the current project which was to investigate the impacts of pumping from a dragline on the river and groundwater levels. The location of the river logger was not ideal to relate river levels to groundwater levels, however, given the longer term data it was left at this location. The loggers at Myrtleford were installed specifically for the current project with the groundwater levels to be compared to gauged river levels at Myrtleford (403210).

The pressure loggers installed were LevelTROLL® 500 with a range of 21 metres and used vented cables to allow for atmospheric pressure changes. The accuracy of the logger is

0.05% of the range at 15°C which equates to +/- 10.5 mm. The loggers were set to record on a 0.5 hour interval for the river logger and bore 48073 and 1 hour for all other bores.

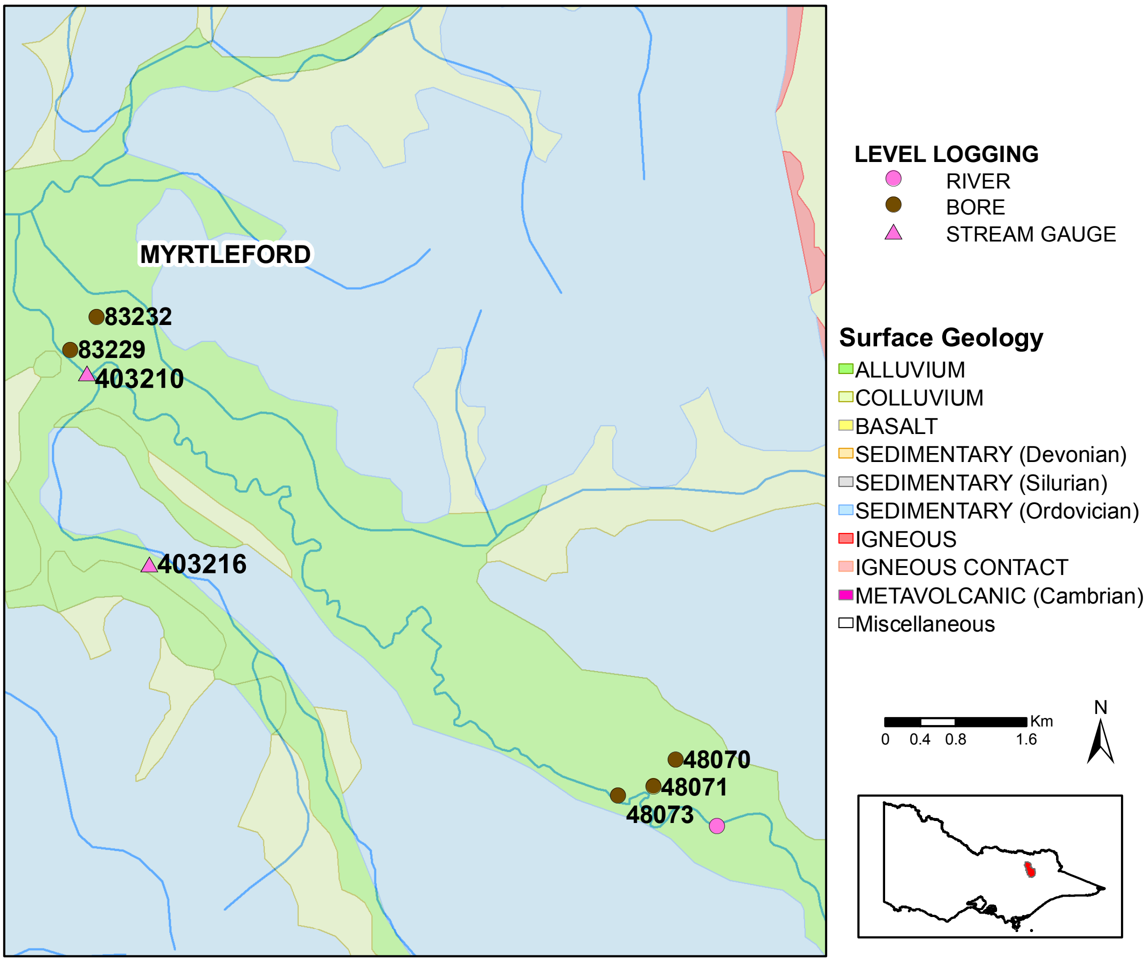

Figure 4-2: Location of level loggers in the Ovens Region of the study catchment.

One years results are available from the Ovens area loggers (to June 2008). Flows in the summer of 2008 did not reach very low levels, with minimum flows around 50 ML/day for one week in early March, other than that period, flows were generally over 100 ML/day. Two periods of interest within the data record were investigated, the first is the winter recharge period with definitive recharge events and the second is flow events over summer.

Figure 4-3 shows two definitive high flow events and related recharge in two bores. During this time the logger at groundwater bore 48073 was not working and the response of the groundwater levels near to the river is not known. The river level is the recorded depth of the river logging site transposed to be the depth of river above the lowest thalweg surveyed point of the river channel adjacent to bore 48073. As such it is an indication of the river level at this point of the cross section and not the absolute level, which is discussed in Section 4.2. At bores located further from the river, there is a delayed response in groundwater rise and at bore 48070 a lag of 6-8 days occurs between river rise and subsequent groundwater level rise. The groundwater level rise is considered to be the sharp increase in gradient of the groundwater hydrograph level after the river rise event. The relative timing of the groundwater rise events indicate that the primary recharge mechanism is from the stream flow. This can be seen from the relative vertical and horizontal distances of the recharge paths. Direct rainfall recharge is vertical and as the groundwater level is not deep (2-5m), the distance of travel is only a few metres. Recharge from the river is horizontal and the distance from river is much larger, hundreds of metres compared to several metres of groundwater below the surface. As can be seen in Figure 4-3, the river is recharging groundwater whilst river flows are high, and once they drop below the groundwater level, then groundwater starts draining to the river, indicating that direct rainfall recharge is only a minor component of the measured recharge event. There also may be a large difference between horizontal and vertical hydraulic conductivities which may be contributing to the patterns.

In Figure 4-3 groundwater levels reach a maximum height in response to river rising events. For bore 48070 this occurs 14 -20 days depending on the size of the river rising event. Bore 48052 reacts to river level changes in about 7 days, and bore 48073 within a day. In Figure 4-4, groundwater levels in Bore 48073 show a very fast response and similar pattern to changes in river levels. After groundwater levels reach a maximum height, following river recharge events, they start dropping in bores 48052 and 48073 both in winter (Figure 4-3) and summer (Figure 4-4). The reduction is probably a response to river levels falling and groundwater discharging to the river.

In bore 48070 groundwater levels don’t drop as rapidly as river levels. Levels remain steady or continue to rise in winter and a response to river level rises from individual freshes is not seen in summer. This indicates that there may be an influence of another flux in winter such as rainfall recharge. Another flux is the down valley groundwater flow, and as indicated by the flow direction modelled by SKM (2006a) and shown in Appendix 5, this may be the overlying cause. In bore 48070 overlying flow direction is down valley whereas at 48052 and 48703 flow is towards the river. This indicates that bore 48070 is primarily influenced by down valley flow and will show the regional groundwater seasonal trends of level increasing in winter and dropping in summer. Whereas, 48052 and 48073 are likely to be more influenced by the river and will rise and fall depending on the gradients between groundwater levels and the river stage.

The summer relationship shows that there is a more gradual reduction in groundwater levels as the system drains. The delayed recharge relationship in bore 48070 is shown but is much more subdued and some effects are masked by the impacts of pumping, which is the large dip in groundwater levels in December. Interestingly, the pumping impacts are not seen in bore 48052 which is only several hundreds of metres away, indicating that this is outside the cone of depression of the extraction bore.

The extraction bore is 250m from bore 48070 and 350m from 48052 and is a shallow dragline less than 5m deep used for domestic and stock purposes. The pumping event can be seen in Figure 4-4 over two days between the 19th and 20th December. A 0.4m drop was observed in bore 48070 but no response was observed in bore 48052. This may have been due to the short pumping period and the greater distance of bore 48052 meant that a response was not seen in the bore prior to the next fresh. Given the rapid response at bore 48052 to river flows, differences in the aquifer between the bores is more likely and possibly the extraction bore and 48070 are linked via an old stream, or on the same flow path as indicated in Appendix 5. Without additional bore logs this cannot be determined.

The logging information is further confirmation of the rapid response of groundwater levels to changes in river stage and the complexity of the flow cells.

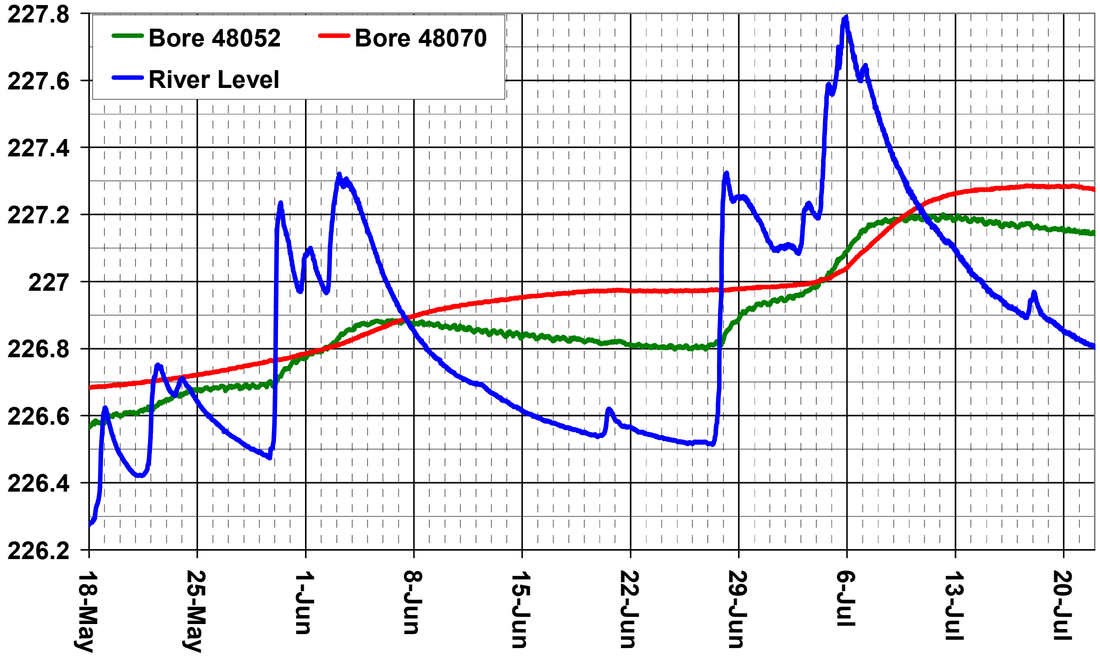

Figure 4-3: Groundwater response to river level rise – Rising GW levels in Autumn/Winter

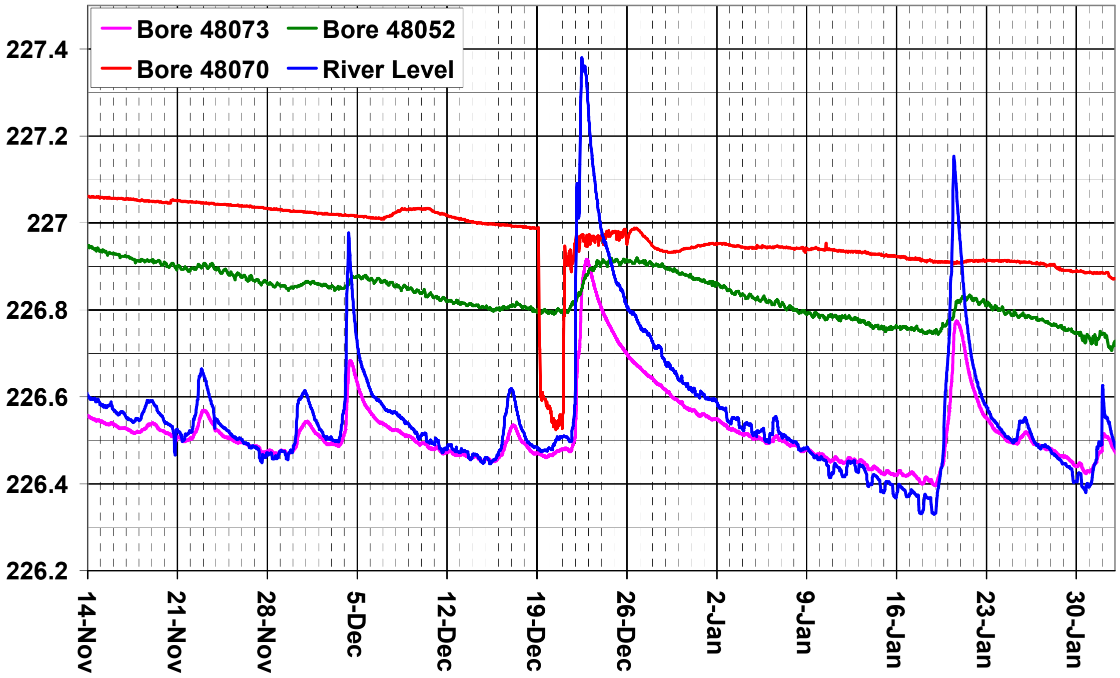

Figure 4-4: Groundwater response to river level rise events – Falling GW levels in summer

4.2 Hydraulic gradients at the valley cross sections

Surveys were undertaken at the cross sections highlighted in Figure 4-1 to get accurate representations of the surface levels at the bores, river channel elevation and channel features. Water levels for groundwater and the river are plotted to construct a hydraulic gradient line and show direction of water flow. Gradients are plotted for different periods depending on the timing of groundwater level readings, which are the limiting data. Recorded groundwater levels are compared to the river stage at the nearest river gauge site and plotted in the cross section. To calculate the depth of the river at the bore transect, the depth of water at the gauge is assumed to the same as at the transect and added to the lowest point on the river channel cross section. This assumption leads to the possibility of error in the calculated river level, as differences in the channel cross section, roughness of the channel, slope of the river bed, and any flow impediment structures will all affect depth of water between the gauge site and the bore transect. Locations of tributaries and flow inputs will also cause differences in river height. The method used to represent river levels are described in detail for each transect line. The Myrtleford cross section was investigated in much more detail as this is where environmental flow requirements were defined and where more information was available on stream flows.

Bores must be parallel to a flow line to accurately represent ground water flow and interactions with the river (Woessner 2000). A groundwater potentiometric surface has been developed by SKM (2007a), the scale of this map is coarse with equipotential lines shown at 50m intervals. A part of this map is shown in Figure 4-5. The potentiometric surface shows that the overall flow in the unconsolidated sediments is down valley however the contour shape shows some flow towards the river. With the position of observation bores perpendicular to the river at locations several kilometres apart, increasing the accuracy of equipotential lines is difficult. Detailed flow directions were modelled by SKM (2006a) for a small area near the Ovens cross section. These verify that closer to the river flow direction is towards the river, but as distance from the river increases, down valley flow influences increase (Appendix 5). This trend is greatest for areas where the river is at the valley edge, such as at the Ovens and Myrtleford cross sections. Use of bore transects perpendicular to the river is considered appropriate to verify the flow towards the river indicated by Figure 4-5. However, without further detail groundwater flow directions and the influence of down valley flow, this may be a source of error.

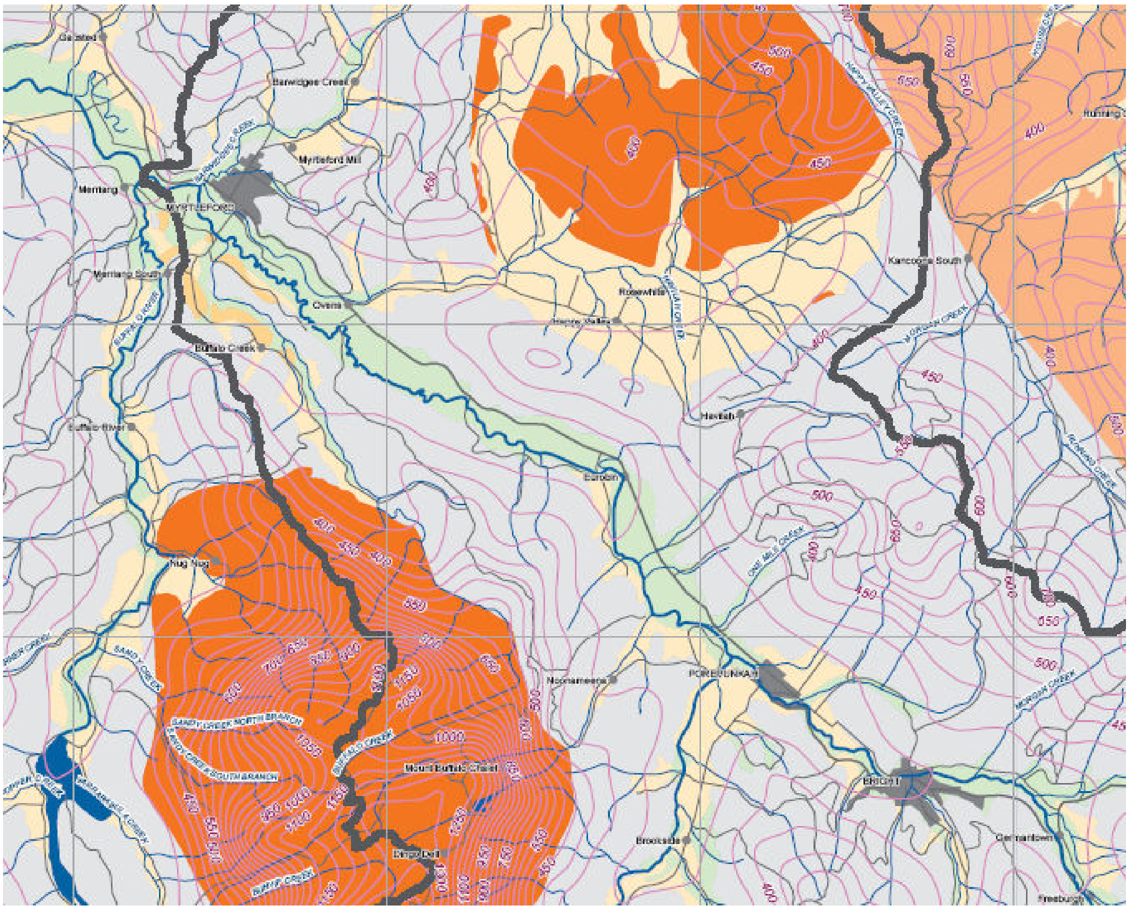

Figure 4-5: Groundwater Potentiometric surface with 50m intervals (Sinclair Knight Merz 2007a)

4.2.1 Myrtleford Cross section

The surveyed cross section represented in the data analysis is shown in Figure 4-6. The aquifer thickness (Figure 4-6) represents the thickness of the unconsolidated sediment aquifers from the surface to bedrock (Sinclair Knight Merz 2007a). At Myrtleford the cross section covers the majority of the unconsolidated aquifer. River stage for the day of the groundwater level recording was initially calculated by adding the recorded height of the river stage at the Myrtleford gauge 403210 to the lowest point of the surveyed cross section of the river channel. The initial assumption was that, due to the closeness of the Myrtleford gauge to the cross sections, recorded river gauge height would give an accurate enough representation of the river levels at the cross section, even though there are differences in channel morphology. Comparison of groundwater levels to river stage height using this assumption showed discrepancies at times of low flow and also at very high river flow.

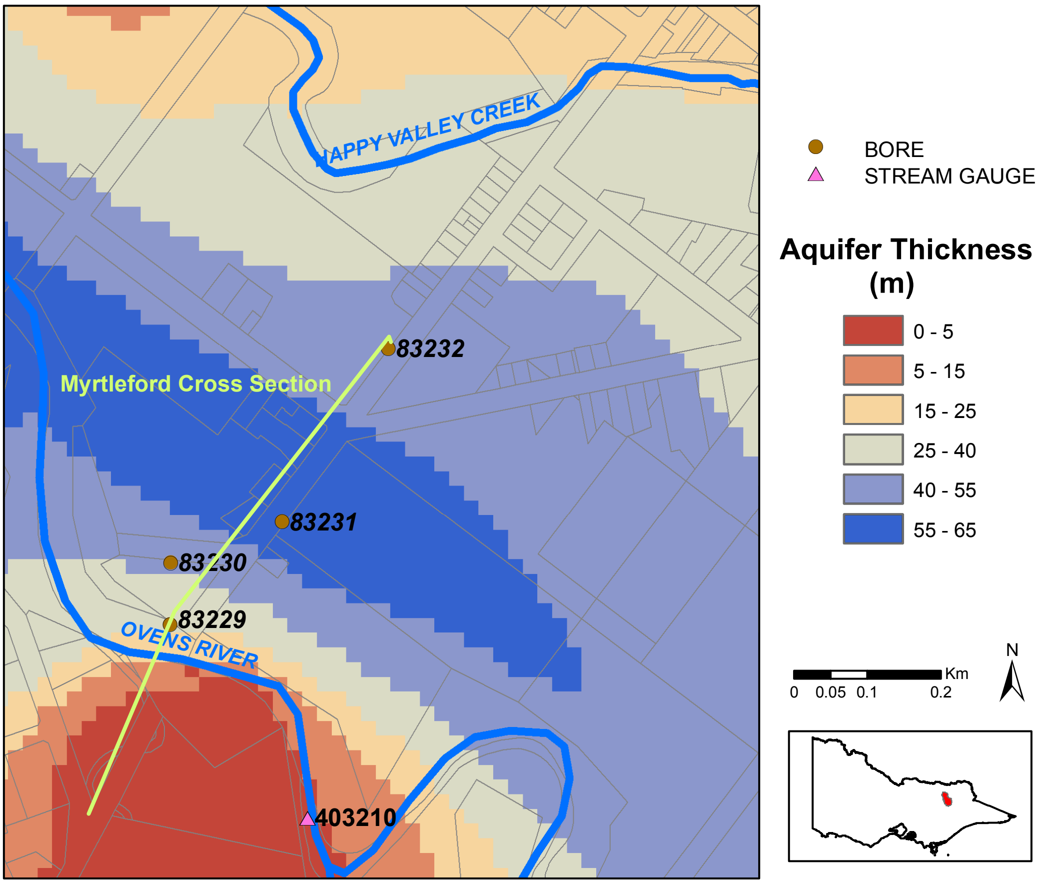

Figure 4-6: Myrtleford cross section and survey

The discrepancy was highlighted in October 2000 where a gradient away from the river was seen in all bores. Transposition of the gauged level resulted in a river level at the cross section lower than the groundwater level for the bores closest to the river (83229, 83230), indicating that either the river stage was wrong or that the river had subsided. To investigate the river stage trend, the 7 day average river height (at the gauge) was compared to groundwater levels and found to be even lower than the river stage on the day of the bore reading, indicating that the gauge height was wrong. There were several other days where the recorded groundwater gradient close to the river was away from the river (indicating a higher river stage than groundwater level) but the recorded river stage was shown to be lower. From the loggers (Section 4.1) it was shown that the lag relationship was much less than 7 days, indicating an error with the river stage transposition method.

Inspection of the river channel cross section identified that channel morphology at the gauge is very different to channel morphology at the bore transect. At the gauge the river channel cuts into fractured rock which forms a natural weir that affects river stage. This weir would impact on flow velocities and stage at the gauge, compounding differences in channel cross section morphology. To check possible effects, a hydraulic flow model, HEC-RAS, was used to create a flow rating curve for the river at the survey site. A model had been developed for the flows study (Sinclair Knight Merz 2006d) and the extra survey was added as an upstream survey point and flow curve created. Comparison of the rating curve for the gauge and the HEC-RAS model shows that gauge river stages are generally lower than modelled river stage at the cross section (Figure 4-7).

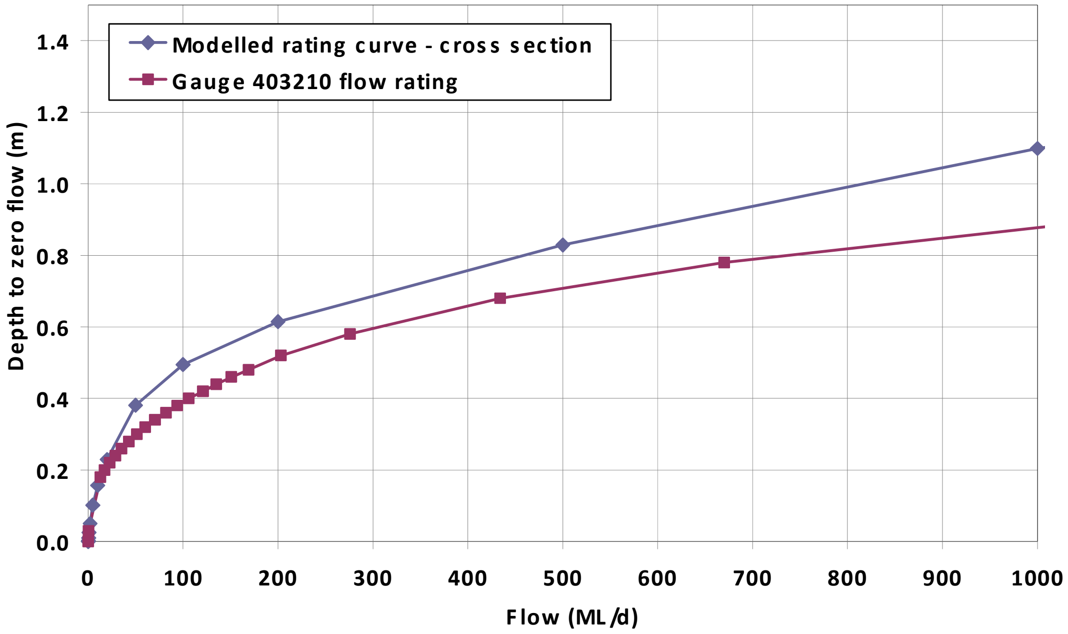

Figure 4-7: Comparison of modelled flow rating curve at cross section to gauge 403210 flow rating curve

Using the modelled flow curve, the recorded flows at the Myrtleford gauge were transposed to reflect the gauge height at the cross section. Using the new rating curve resulted in river levels being above groundwater levels in periods where the gradient was away from the river, thus giving a more accurate representation of the hydraulic gradient.

All groundwater bores in the cross section measure the shallow groundwater, are less than 15m deep and generally screened between 6 and 12m. The individual Bore details are outlined in Appendix 4. The river - groundwater relationships in cross section are shown in Figure 4-8 with the river levels represented by the flow rating curve modified from HEC-RAS. For the period of record, groundwater levels do not fall below the level of the bottom of the river bed at the cross section. As determined from the water balance, there are times when the river level rises above groundwater levels and the water flux is from the river as can be seen for October 2000 and September 2005 in Figure 4-8. However, for the majority of time the flux of water is from groundwater to the river as can be seen for the other months.

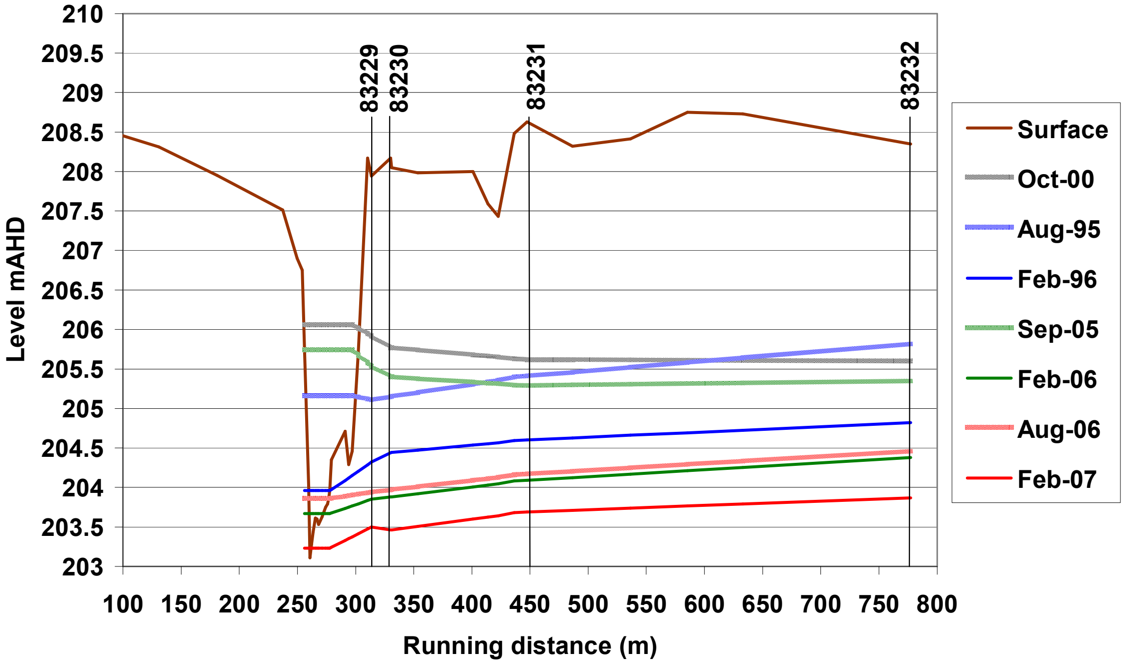

Figure 4-8: Myrtleford Selection of groundwater – river level relationships

The lowest groundwater levels recorded occurred in February 2007 and the highest recorded levels occurred in October 2000. The highest groundwater level recorded at bore 83232 occurred in August 1995, however, at the time of recording the gradient shows that the flux is towards the river.

4.2.2 Ovens Cross sections

At Ovens, the valley is approximately the same width as at the Myrtleford cross section. The survey line and bores monitored extend up to 1 km away from the Ovens River and cover over half of the unconsolidated sediment aquifer. At this point the Ovens River is on the very edge of the valley and results in the monitoring bores being located only on one side of the river. The area around the Ovens cross section has been modelled using MODFLOW (Sinclair Knight Merz 2006a)) and shows a large flow running parallel to the cross section in the direction towards the river from 48071 to 48073. Groundwater flow lines were down valley and perpendicular to the cross section between bores 48070 to 48071 but of a much smaller magnitude than those closer to the river (Sinclair Knight Merz 2006a). As can be seen in Figure 4-9, the cross section covers the majority of the valley with the thickness of the unconsolidated sediment aquifer not as great as at Myrtleford. All bores measure the shallow groundwater between 2 and 30 metres, depending on the bore depth. Further bore construction and screen details are outlined in Appendix 4.

The river level was represented by transposing the measured gauge height at the Myrtleford gauge to the Ovens cross section channel. The gauge at Myrtleford measures flows from Buffalo Creek which enters downstream of Ovens and as a result the represented river stage would be expected to be higher than actual stage heights. However, the river levels were found to be much lower than the groundwater levels as shown in Figure 4-10. As the river is deeply incised, there is a deep pool adjacent to bore 48073. Even in the February 2007 low flow event, there was a large pool of up to one metre in depth at this location (personal observation). This indicates that there may be a large volume of groundwater flux at this point, however without river stage measurement at this point the levels are an indication only. No HEC-RAS simulations were available for this location to more accurately represent river stage height.

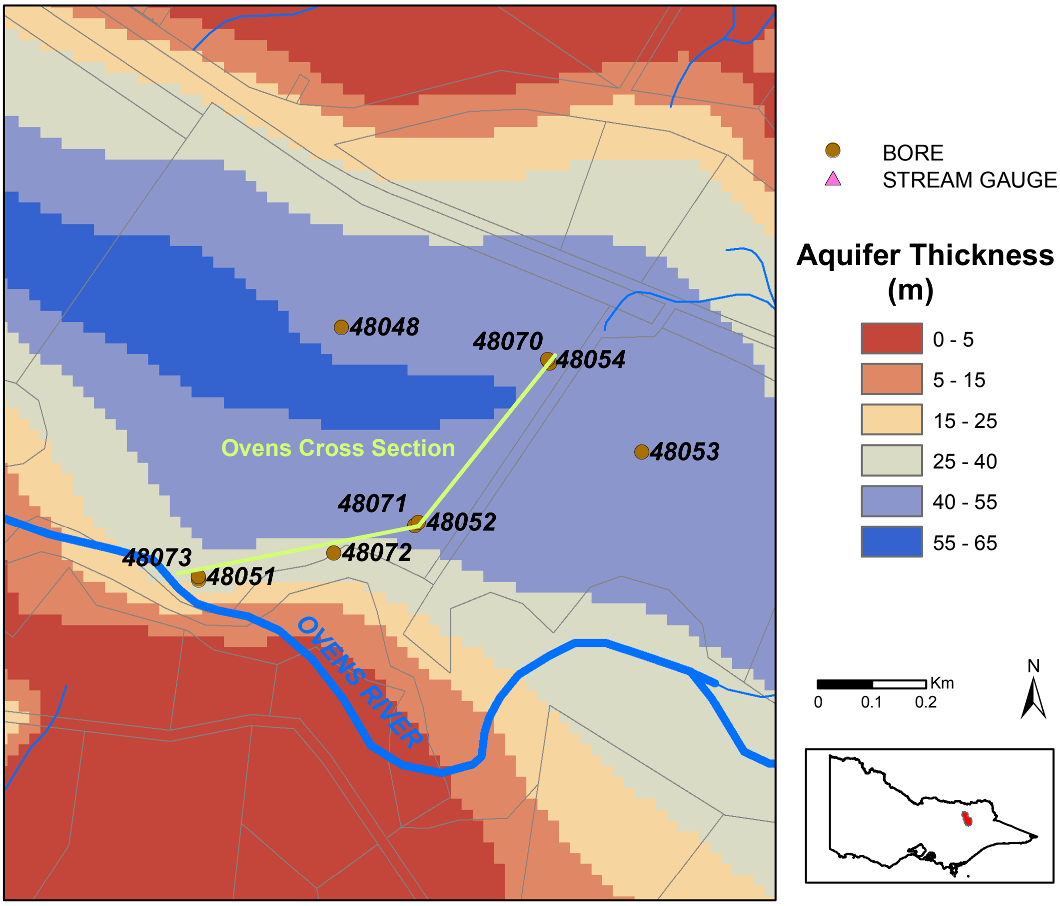

Figure 4-9: Survey cross section and bores at Ovens

Groundwater – river level relationships at the Ovens cross section followed the same trends as at the Myrtleford cross section, however the hydraulic gradient was towards the river for the period of record (Figure 4-10), indicating a flux from groundwater to the river at all times. The Ovens cross section is at a point where the river channel has deeply incised into the alluvial floodplain and this would explain the observed flux of water only being from groundwater to the river. The height of groundwater compared to river stage indicates that the groundwater is recharging from another source at this point, probably for the river further upstream. It is very interesting to note the hydraulic gradient and water level in August 2006. Groundwater levels dropped below the February 2006 level in May 2006 (not shown) but only recharged to the recorded low summer levels by August 2006. The following summer season had the lowest flows and groundwater levels for the period of record indicating that low winter groundwater recharge may be an indicator for low summer flows.

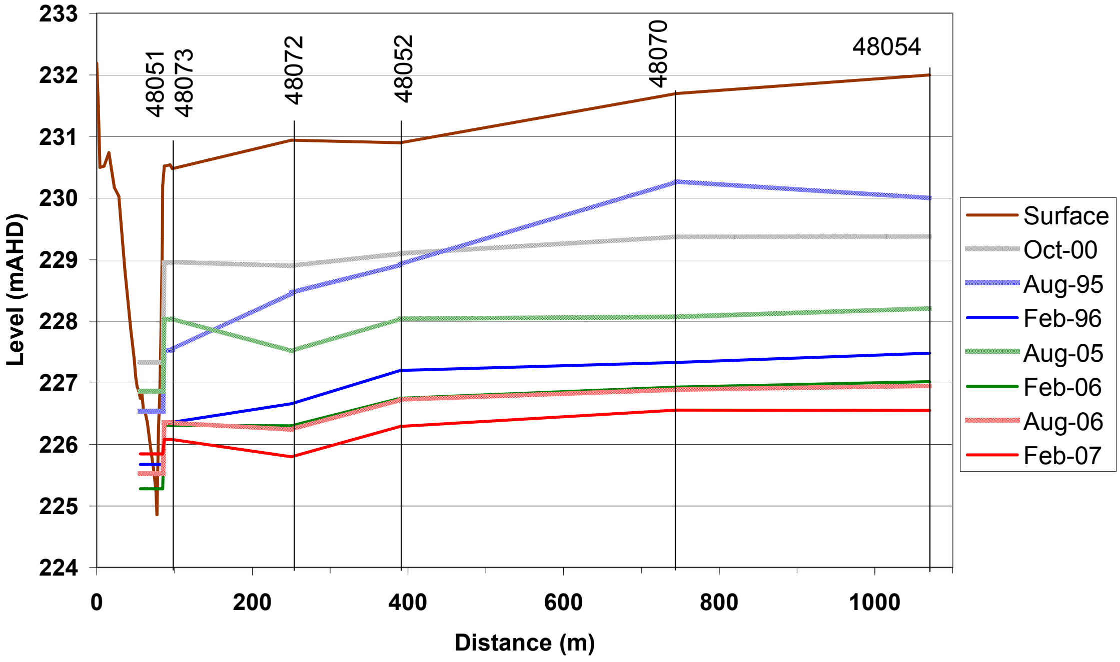

Figure 4-10: Ovens selection of groundwater- river relationships

4.2.3 Bright cross sections

At Bright, the river valley is considerably narrower than at the downstream cross sections. The Ovens River runs through the centre of the valley and there are bores on both sides of the river which give the gradient and direction of fluxes from both sides of the (Figure 4-11).

River levels are determined by transposing the recorded gauge height at the Bright gauge (403205) to the Bright survey cross section. As with the Ovens section, a major tributary, Morses Creek, comes in downstream of the cross section, but upstream of the gauge, resulting in recorded levels that would be expected to be higher than the river level at the bore cross section. Without HEC-RAS simulations, which are not available for this site, adjustment of stages to account for the differences in flows between the gauge and cross sections could not be achieved accurately. For the analysis it was assumed that the height of river flow at both sites was the same, with river stage just being a relative indication of the river flow at the cross section.

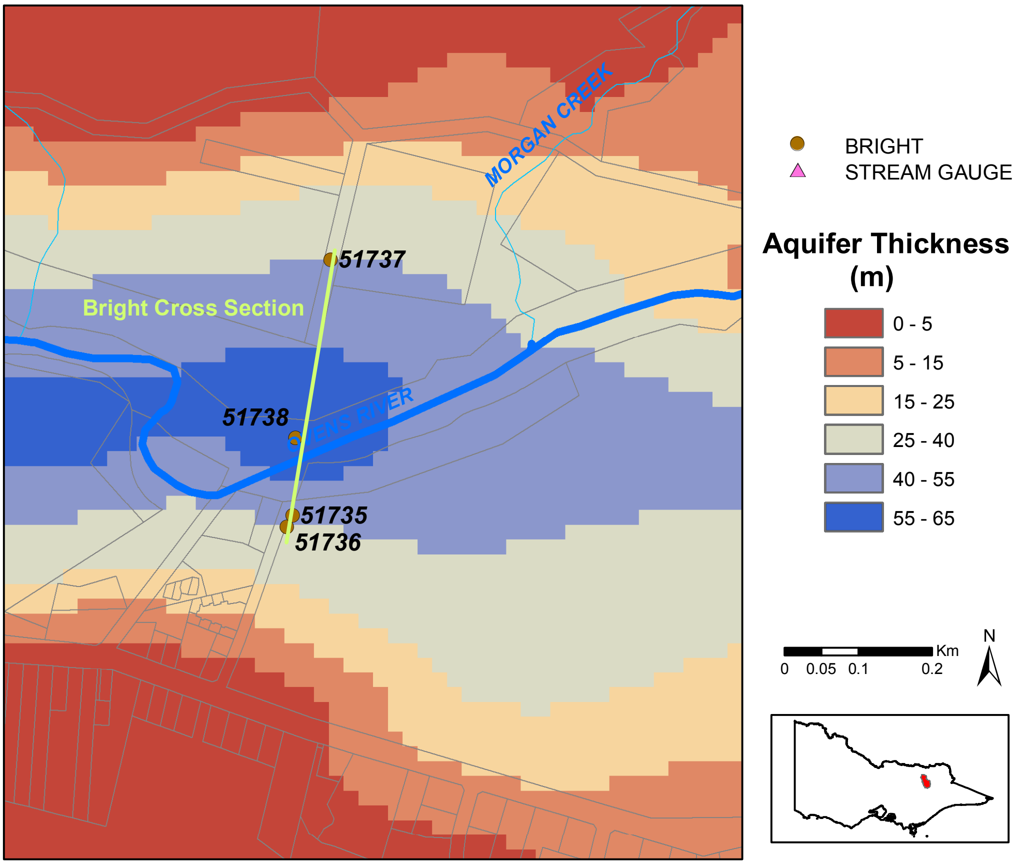

Figure 4-11: Bright survey and cross section.

Results of the groundwater and river level representations indicate that the river is losing to groundwater in some periods (Figure 4-12) and supports observations by Shugg (1987) who identified that the river upstream of Bright is the only section of river that loses to groundwater. The data in the extreme drought of February 2007 is interesting as it shows the lowest groundwater levels recorded and shows that the river is losing flow (Figure 4-12). The higher river levels could be a result of the higher flows recorded at the gauge allowing for Morses Creek, however, the recorded gradient between bores 51736 and 51735, compares well with the modelled gradient between bore 51735 and the river level. This is the same for August 2006, which indicates the river level would be a fairly good representation at this time. Morses Creek flows were negligible in February 07. Bore 51738 is close to the river bank and is subject to flooding as shown in Figure 4-12. At these times, bore recordings are not taken and the level has been represented to be the river level. This occurred in October 2000 and August 1995. The bore also becomes artesian during years of high rainfall and in winter. The bores at Bright are screened deeper in the unconsolidated sediments and also at varying depths and deposits in the aquifer. The bore cross section is represented in Appendix 6. There are confining layers between the river and the bore screen indicating that pressures from higher up the valley may be influencing levels at this point. It is also possible that due to the narrower valley, groundwater pressures from the fractured rock aquifer could be influencing the river levels.

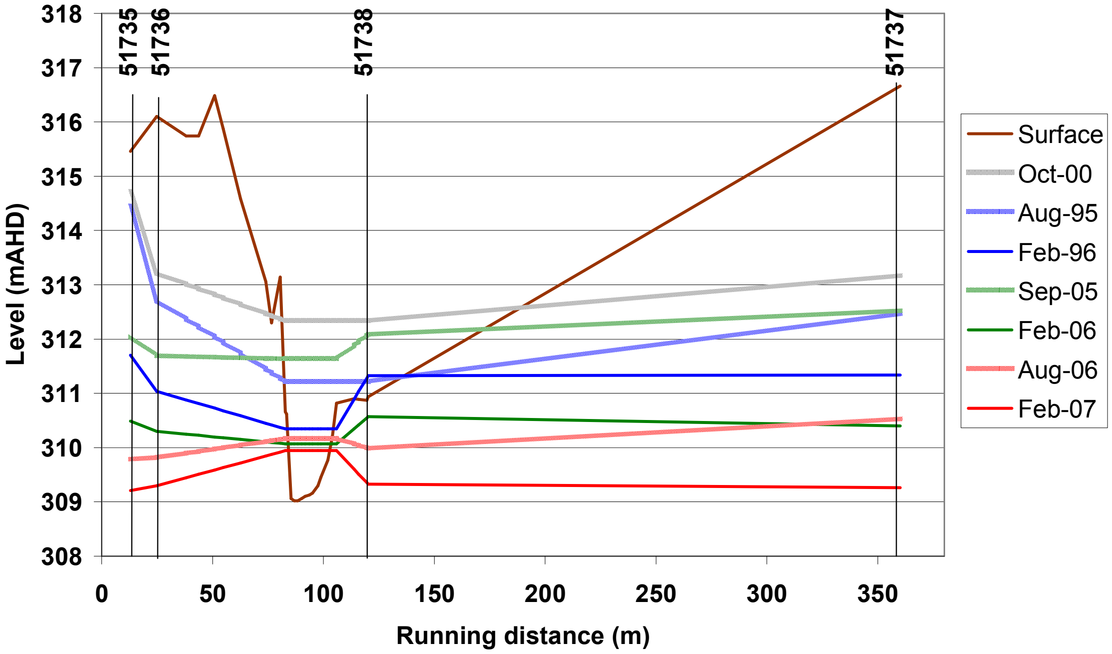

Figure 4-12: Bright selection of groundwater – surface water relationships

4.3 Regression Analysis

One of the key considerations for the development of conjunctive management options is the ability of managers to relate stream flow objectives to groundwater objectives. Stream flow objectives are centred around environmental flow objectives and can be related to a stream gauge at a point in the river. Groundwater levels have been used to set management objectives for groundwater in many Victorian aquifers (Thwaites 2003; Thwaites 2006). An equation to link river stage (measured at a gauge) to groundwater levels would be a valuable tool to enable managers to set groundwater level management objectives. This part of the research did not attempt to provide a set groundwater management heights but rather aimed to give a tool for resource managers to link a chosen stream flow management level to a groundwater level. The Myrtleford gauge has been proposed as the compliance point for stream flow measurement (Goulburn Murray Water 2003), so a method or equation to link groundwater levels to river levels at the gauge is required. This is the focus of the regression and statistical analysis in this section. The bore transect and cross sections at Myrtleford are compared to the river height at gauge 403210 as shown in Figure 4-6.

A common statistical method to show a relationship between two sets of variables is least squares regression analysis. Least squares can also be used to provide a prediction equation for a relationship using two data sets (Moore and McCabe 1993). Least squares analysis has been completed between the historical groundwater and river level data to investigate the relationship between the data and provide prediction equations. No published examples of other groundwater – surface water interaction studies using regression analysis to investigate the relationship have been found. The regression analysis gives a prediction equation and also defines the correlation (and strength) of the relationship between groundwater and river levels. Comparison of the relationship as the distance from the river increases may provide an indication of the groundwater aquifer characteristics.

Least squares analysis was completed using Microsoft Excel 2002. Results were cross referenced using Minitab and this program was also used to provide statistical analysis that was beyond the limitations of Excel. Statistical analysis in Excel has limitations relating to calculation of residuals, residual plots, graphing and will give wrong results if there are gaps in the data (McCullough and Wilson 2002; Miles 2008). For the analysis in this study, the data series were set up to take into account the limitations of Excel. Comparison of regression results from Excel to results from Minitab gave the same regression equations and correlations and verified the suitability of Excel for calculating these outputs. Differences were found in the residual plots as they were plotting different things, and Minitab had benefits in graphing the various tests for normality of data over Excel.

As discussed previously, groundwater levels have been measured at varying intervals over the past 30 years and surface water has been measured daily for the last 30 years. Sample size is limited by the number of groundwater level readings and river levels have been matched to the groundwater readings. The groundwater readings have been taken at varying intervals and at different times of the year. Samples have also been taken irrespective of river stage or groundwater height. Since 1998, the data has been sampled at a three monthly interval which could bring a bias into the result given that river levels and groundwater levels show a seasonal trend.

4.3.1 Myrtleford

The Myrtleford bores are represented in the cross section shown in Figure 4-6. This bore transect is only 250m from the Myrtleford gauge. Groundwater levels at each bore were initially compared to the river stage measured at gauge 403210 on the day of the bore groundwater level reading. Results from this analysis show a strong correlation and linear relationship for all bores (Figure 4-13, Figure 4-14, Figure 4-15 and Figure 4-16). Regression analysis of the relationships between groundwater and river level shows a reduction in correlation (R^2) of the data with increasing distance from the river. The highest correlation occurs at bore 83229 (19m from the river) and lowest correlation at bore 83232 (480m from the river). This trend indicates that the variance between groundwater and river levels increases as distance from the river increases. Visual inspection of outliers for bore 83232 identifies outliers that may have a strong influence on the regression equation and correlation. Generally the outliers are due to high river levels in comparison to groundwater levels. For bore 83229 the correlation is high and the spread of data is less with outliers having less of an influence on the results as shown in Figure 4-16. At bore 83231 (150m from the river) the data starts to have a larger spread and the outliers corresponding to high river levels have increased influence. The ANOVA outputs from the regression analysis show all relationships are statistically significant with a statistical significance (p) of less than 0.001.

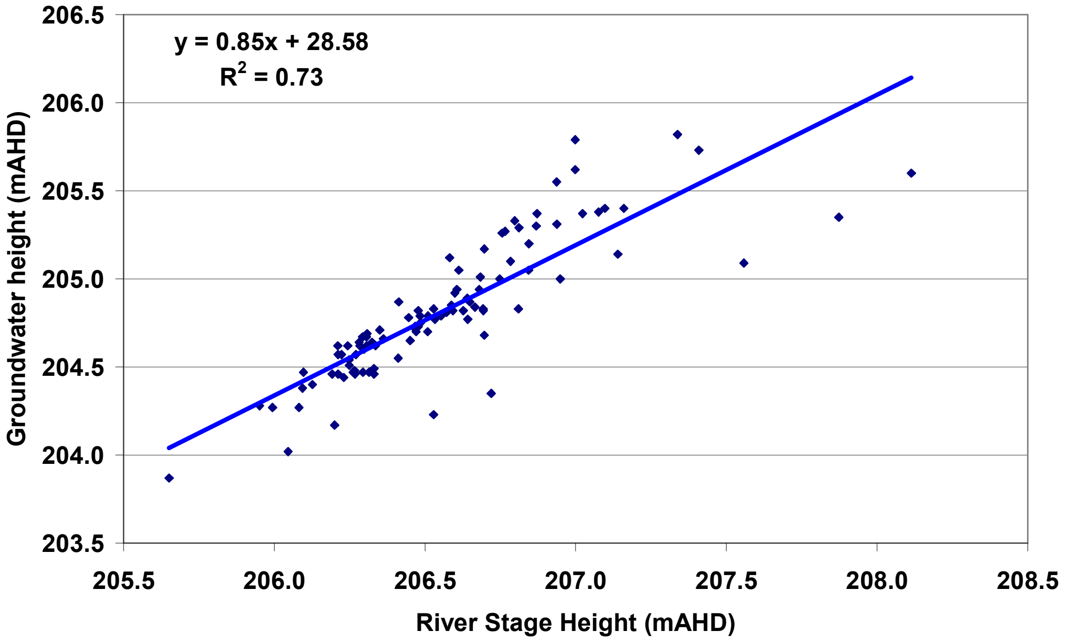

Figure 4-13: Bore 83232 (480m from river) groundwater level Vs river stage (on day of bore level read) - all groundwater observations (n=102, $p < 0.001$)

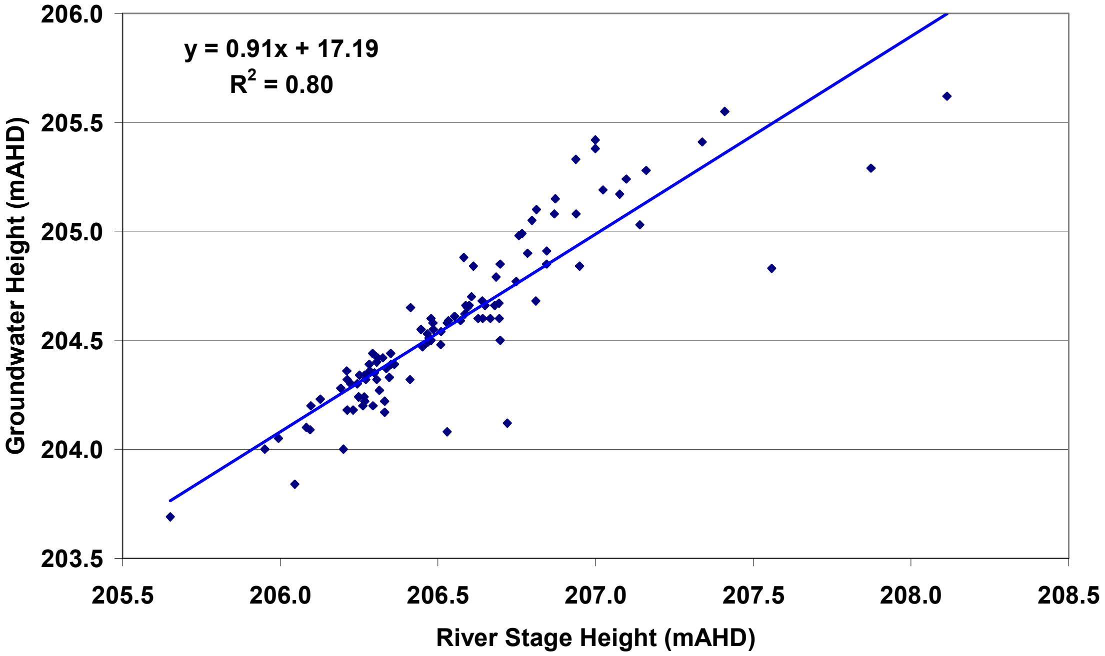

Figure 4-14: Bore 83231 (150m from river) groundwater level Vs river stage on day of bore read - all groundwater observations (n = 103, $p < 0.001$)

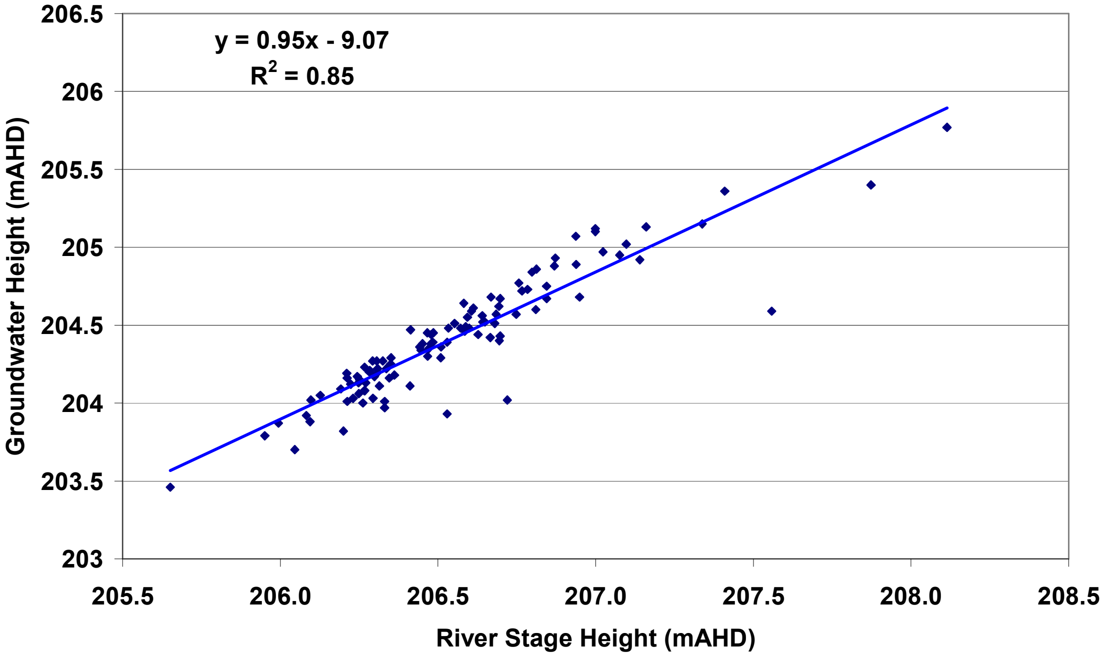

Figure 4-15: Bore 83230 (36m from river) groundwater level Vs river stage height on day of bore read - all groundwater observations (n=103, $p < 0.001$)

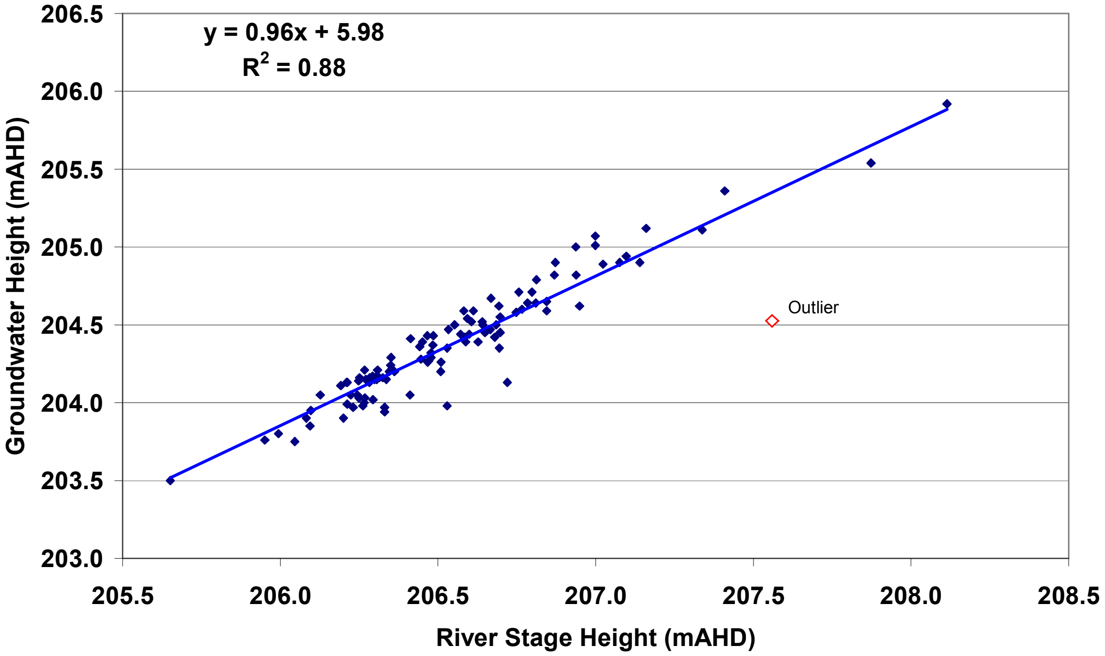

Figure 4-16: Bore 83229 (15m from river) groundwater level Vs river stage (on day of bore level read) - all groundwater observations (n=100, $p < 0.001$)

In the above graphs the river level on the day of the bore reading has been compared to the groundwater level. This does not take into account any lag period for groundwater levels to respond to river levels as distance increases, hence the observed trends in variance. River level rises in the Ovens River can be rapid. If the bore level reading is at, or close to, the start of a rising river event, the groundwater level may not have had time to show a response to the river rise. If the event is of a relatively short timeframe then a corresponding groundwater level rise may not occur in bores which are distant from the river. For the most accurate representation of the groundwater-river level relationship the effect of lag in response has to be considered.

Correlation is a measure of the proportion of variance between the two variables explained by the regression equation (Miles and Shevlin 2001). If correlation increases, the variance explained by the equation increases and hence the accuracy of predicted groundwater levels for a given stream flow also increases. To improve the correlation and give the most accurate regression equations, the influence of lag on the correlation, with groundwater as the dependant variable and river stage as the independent variable, was investigated.

Groundwater levels are not available as a continuous data series, rather as discrete points recorded in time. River level data are a continuous series and as the independent variable, it was varied to investigate lag. Two variables can be used to influence lag in groundwater level response when considering the fluctuating river levels. The first is that the groundwater level may be influenced by river levels at a certain time period before the measurement, or the groundwater may have a delay before rising/falling in response to river level changes (as seen in bore 48070 in Figure 4-3). This was represented as a delay in days before the bore level reading. The second is that a short rise in river levels may not be represented by an equal response in groundwater levels, or the groundwater level will correspond to an average river level for a certain period. This was represented by averaging river flows for varying intervals preceding the groundwater level reading. Averaging flows will have the effect of smoothing short term fluctuations in river level. For the analysis, each correlation was calculated separately, varying one variable at a time, and then both together to produce a correlation matrix. From the resulting matrix, the influences of altering these variables on the independent variable, river stage were determined. The highest correlation achieved by varying these two influences on the independent variable (river stage) was taken as the best representation of the relationship between groundwater levels and river levels.

4.3.1.1 Myrtleford bore 83232

Bore 83232 is 480m away from the nearest point of the river along the transect shown in Figure 4-6. It is 570m away from the Myrtleford Gauge. Analysis of the varying time parameters of lag before the bore reading and averaging river flows show that data fit and correlation improve by either increasing the delay or increasing the averaging period. When varying the delay, the highest correlation of data occurs when the delay is seven days and the highest correlation for varying the average period occurs when stream flows are averaged for fourteen days (Table 4-1). Interestingly, the correlation shows a normal type distribution with the correlation increasing to the peak value and then decreasing from this point. This occurs for both the lag and averaging levels. Correlations were calculated past the ranges shown in Table 4-1 and all correlations decreased.

	Days preceding bore read (Delay)						
		0	**1**	**2**	**3**	**5**	**7**
Average period (Days)	**0**	0.73	0.74	0.86	0.86	0.87	0.88
	2	0.74	0.82	0.87	0.88	0.89	
	4	0.84	0.88	0.89	0.83	0.90	
	7	0.89	*0.91*	*0.92*	*0.91*	0.90	0.85
	8	0.90	*0.92*	*0.92*	*0.91*	0.90	
	10	*0.91*	*0.92*	*0.91*	0.91	0.89	
	12	*0.91*	*0.92*	*0.91*	0.90	0.89	
	14	*0.92*	*0.91*	*0.91*	0.90	0.89	0.85
	16	*0.92*	*0.91*	0.91	0.90	0.88	
	21	*0.91*	0.90				0.84

Table 4-1: Correlation (R^2) for varying delay periods and averaging river stage preceding groundwater level readings of bore 83232

Varying both the delay and averaging period showed similar results to just varying one variable, in that when one parameter is fixed and the other is varied, the values will reach an maximum. This can be seen in the correlation matrix in Table 4-1 where the highlighted cells represent the maximum (peak value) for each of the delay intervals with the average stream flow varied. Comparison of the peak value for each average stream period and varied lag shows that the peak values are generally similar. The highest correlation was found with a lag period of one day and gauge heights averaged for eight to ten days.

Comparison of data plots show higher correlations relate to a better data fit with less data spread, as can be seen by comparing the seven day lag plot (Figure 4-17) to the highest value correlation graph (Figure 4-18). Varying delay removes outliers that correspond to rapid gauge height rises and averaging gauge height removes small fluctuations in stream height changes and indicates the time period required for groundwater to adjust to flow variations (lag). Results of this analysis indicate that the lag is 7 to 16 days for groundwater levels at groundwater bore 83232 to adjust to variations in stream height at gauge 403210.

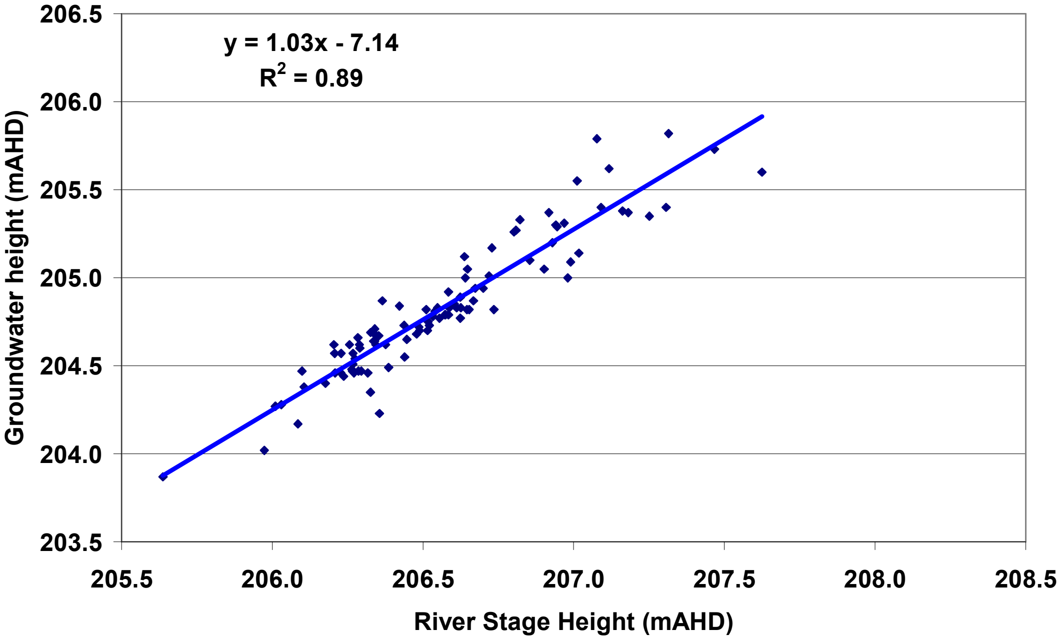

Figure 4-17: Bore 83232 groundwater level Vs river stage 7 days preceding bore read - all groundwater observations (n=100)

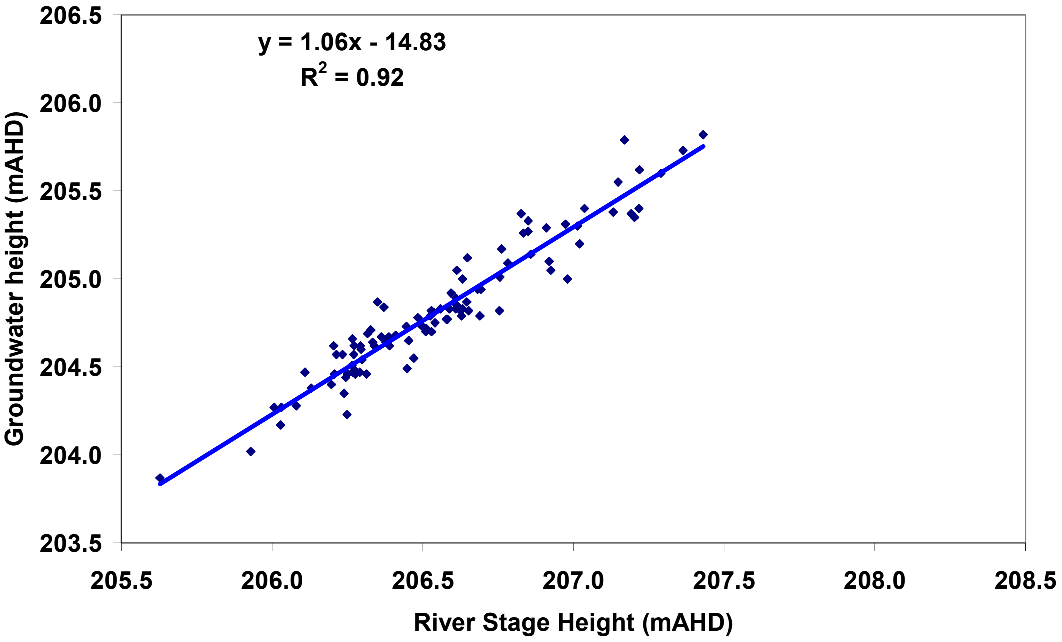

Figure 4-18: Bore 83232 groundwater level Vs 1 day delay and 10 day average river stage - all groundwater observations

A strong relationship is shown at bore 83232, in that varying the delay and averaging the gauge height can increase correlation for the regression equation. Highest correlation and best data fit occurs when the ten day average river level one day preceding the date of the bore level reading is compared to the groundwater level. It is considered that this equation gives the best prediction equation for determining groundwater height for a given stream height at gauge 403210. Although this optimal figure is used, it is acknowledged that there is unlikely to be any significant difference in the correlations shown in italics in Table 4-1. Thus groundwater level at bore 83232 (H_{83232}) can be predicted for a given stage height at gauge 403210 (H_{403210}) using Equation 11.

$$H_{83232} = 1.06 \times H_{403210} - 14.83 \qquad \textbf{(11)}$$

The range of data used to predict groundwater levels applies to prediction equations for all bores and is from a flow of 1 ML/day (205.6mAHD) to a flow of approximately 5400 ML/day (207.4mAHD), which are the 98th and 5th flow percentiles respectively.

4.3.1.2 Myrtleford Bore 83231

Bore 83231 is approximately 150 metres from the edge of the river. Analysis of the regression relationship and varying lag and average stream flows showed a similar pattern to bore 83232 with peak correlations and results shown in Table 4-2. The regression values indicate that it takes approximately between five and ten days for groundwater levels at bore 83231 to respond to river level changes at gauge 403210.

		Days Preceding bore Read (Delay)				
Average Period (Days)		**0**	**1**	**2**	**3**	**5**
	0	0.79	0.80	0.90	0.90	0.89
	2	0.80	0.87	0.91	0.91	0.91
	4	0.89	0.92	*0.92*	*0.92*	0.91
	7	*0.93*	*0.94*	*0.93*	*0.92*	0.89
	8	*0.94*	*0.94*	*0.93*	0.92	0.89
	10	*0.94*	*0.93*	*0.92*	0.91	0.87
	12	*0.93*	*0.92*	0.91	0.90	0.87
	14	*0.92*	0.91	0.90	0.89	0.87
	16	0.91	0.90	0.89	0.89	0.86

Table 4-2: Correlation (R^2) for varying delay periods and averaging river stage preceding groundwater level readings of bore 83231

Highest correlation and data fit occurs when the eight day average river levels ending one day preceding the bore level read date are compared to the bore level reads (Figure 4-19). Groundwater levels at bore 83231 (H_{83231}) can be predicted for a given stage height or flow at gauge 403210 (H_{403210}) using Equation 12.

$$H_{83231} = 1.09 \times H_{403210} - 20.29 \qquad (12)$$

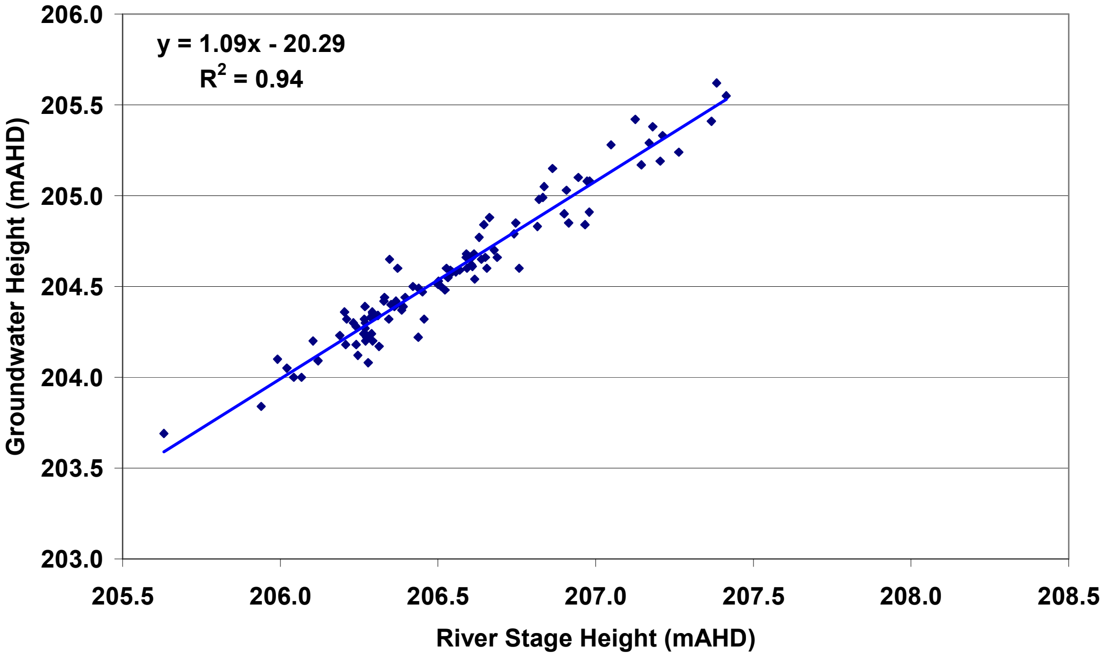

Figure 4-19: Bore 83231 groundwater level Vs 1 day delay and 8 day average river stage - all groundwater observations (n=103)

4.3.1.3 Myrtleford Bore 83230

Bore 83230 is 36 metres from the edge of the river channel but approximately 450m from the Myrtleford gauge. Analysis of the regression relationship and varying delay and average stream flows showed similar patterns to bores 83231 and 83232 with peak correlations and results shown in Table 4-3. The influence of an outlier identified for bore 83229 (Figure 4-16) was investigated but not found to have an influence on the delay/averaging period with the highest correlation. Removing the outlier increases correlations slightly but not the peak in lag variations, for example for a lag of zero days and seven days average flow the correlation is 0.94 compared to 0.93 but the latter is still the largest correlation for a lag of 0 days and varying averaging periods. As such the outlier value was included in the analysis. The regression values indicate that it takes a lag period of approximately between five and seven days for groundwater levels at bore 83230 to respond to river level changes at gauge 403210.

	Days Preceding bore Read (Delay)					
Average Period (Days)		0	1	2	3	5
	0	0.85	0.81	0.88	0.88	0.87
	2	0.84	0.87	0.90	0.90	0.89
	3	0.88	0.90	0.91	0.90	0.89
	4	0.90	0.91	0.91	0.91	0.87
	5	0.92	0.92	0.92	0.90	0.87
	6	*0.92*	*0.92*	0.91	0.90	0.86
	7	*0.93*	*0.92*	0.91	0.89	0.86
	8	*0.93*	0.92	0.90	0.89	0.85
	10	*0.92*	0.91	0.89	0.88	0.84

Table 4-3: Correlation (R^2) for varying delay periods and averaging river stage preceding groundwater level readings of bore 83230

Hhighest correlation occurs when river levels are averaged over 7 days and no delay is included (Figure 4-20). Groundwater level at bore 83230 (H_{83230}) can be predicted for a given river level at gauge 403210 (H_{403210}) using Equation 13.

$$H_{83230} = 1.08 \times H_{403210} - 18.25 \qquad (13)$$

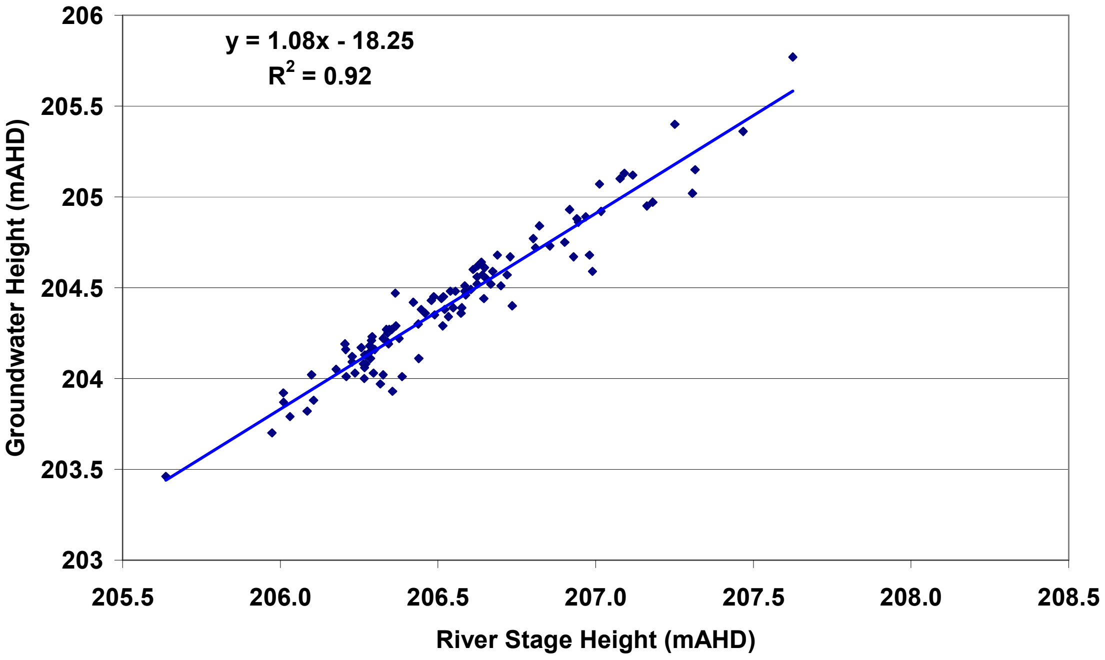

Figure 4-20: Bore 83230 groundwater level Vs 7 day average river stage - all groundwater observations (n = 101, p< 0.001)

4.3.1.4 Myrtleford Bore 83229

Comparison of groundwater levels to river stage at bore 83229 (Figure 4-16) shows an influential outlier occurring on the 8th June 1998. Regression analysis shows the standardised residual as -6.17 for the outlier and identifies it as a large residual value, with its measured river height giving it a high influence on the regression equation. Residual plots also highlight this outlier, as does the normal probability plot (shown in Appendix 7). The data associated with this outlier is from a rapid river rising event where the river rose 1.3m in the two days before the bore reading and went from 600 ML/day to over 10,000 ML/day and past the gauge's effective range. The bore reading was taken on the day after the peak flow. As a result groundwater levels had not responded fully to the rapid river rise and the point does not accurately reflect the relationship between groundwater and the river. The analysis was undertaken with and without the outlier.

Comparison of the regression equation with and without the outlier highlighted the influence of this outlier on the relationship. With the outlier removed correlation for the regression relationship between groundwater levels and river levels on the day of the bore read increases from 0.88 to 0.92 (Figure 4-16). With the outlier removed, highest correlation occurs when river levels are averaged for 2 days prior to the bore reading. The relationship is shown in Figure 4-21 and the equation is significant with a $p < 0.001$. With the outlier included the highest correlation occurs when the 7 days of river levels are compared to groundwater levels. Both models have a $p < 0.001$ and are significant. The difference between the correlations is probably not significant but the equation with the higher correlation (outlier removed) will be used for prediction analysis.

The regression relationship and data plot is represented in Figure 4-21 and groundwater levels at bore 83229 (H_{83229}) can be predicted for a given stage at gauge 403210 (H_{403210}) using Equation 14.

$$H_{83229} = 1.06 \times H_{403210} - 14.44 \qquad (14)$$

		Days Preceding bore Read (Lag)				
Average Period (Days)		**0**	**1**	**2**	**3**	**5**
	0	*0.92*	*0.92*	0.86	0.85	0.83
	2	*0.93*	*0.91*	0.86	0.86	0.85
	3	0.88	0.90	0.87	0.86	0.84
	4	0.89	0.89	0.87	0.86	0.82
	5	0.92	0.89	0.87	0.86	0.81
	6	0.91	0.89	0.87	0.85	0.81
	7	0.91	0.89	0.86	0.84	0.80
	8	0.90	0.88	0.85	0.83	0.80
	10	0.88	0.86	0.84	0.81	0.77

Table 4-4: Correlation (R^2) for varying delay periods and averaging river stage preceding groundwater level readings of bore 83229

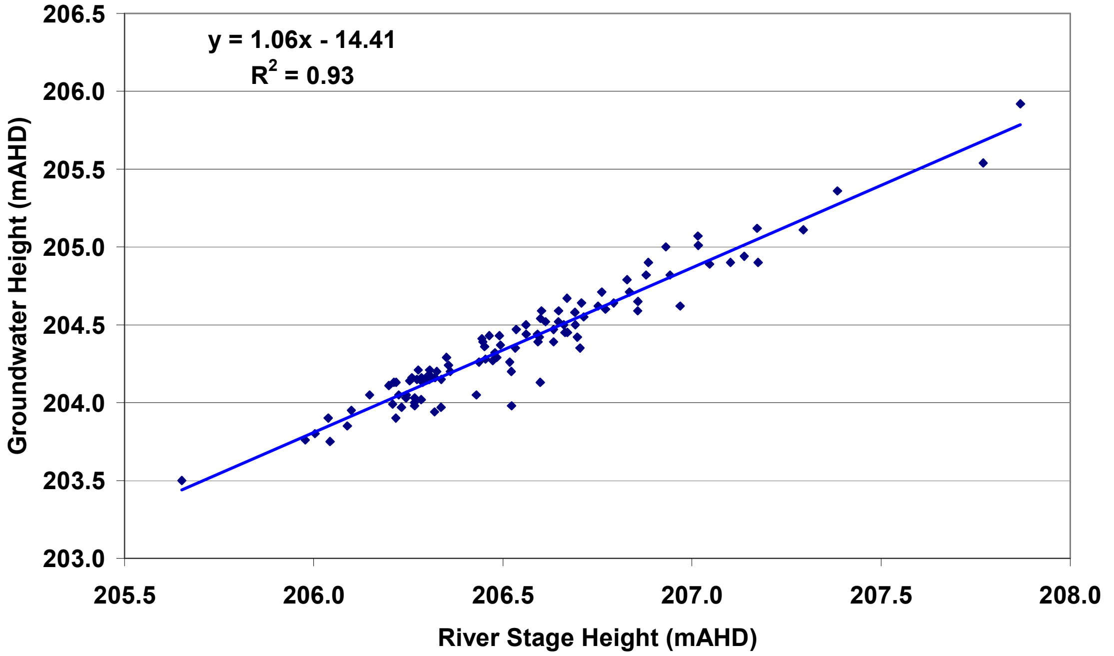

Figure 4-21: Bore 83229 groundwater level Vs 2 day average river stage – Outlier on 8 June 1998 removed

4.3.2 Investigation of low flow and rising and falling groundwater level periods

Periods of rising and falling groundwater levels were investigated individually to determine if the recharge/discharge relationships have different slopes or equations. Different slopes would mean that recharge or discharge relationships are quicker/slower at these times and may have implications for management. As management focus is for groundwater discharge in low flow periods, interaction relationships at these times were also investigated to see if they differed from the equations using all data. If relationships were different in these periods then use of the equations developed in Section 4.3.1 may set unrealistic groundwater management levels.

Bores closest (83229) and furthest from the river (83232) were used in the analysis. For comparison purposes and to allow for the time required for groundwater levels to equilibrate with river levels, data sets with the highest correlation, and chosen for the predictive equations, were used for the analysis (two days averaging and zero days lag for bore 83229 and ten days averaging and one day lag at bore 83232). Rising data were considered to be data where the recorded groundwater level was above the previous recorded level. Conversely, falling data were where the recorded groundwater level was below the previous reading. Low flow periods were considered to be when the river was at or below the environmental flow of 137 ML/day (206.2mAHD) and groundwater levels were at, or less than, the groundwater level predicted for this flow by the equations in Section 4.3.1 (204.0m for bore 83229 and 204.4m for bore 83232).

Regression analysis for e data separated into rising and falling periods found separate statistically significant equations at each bore. Similar slopes were found for rising and falling periods. Data for each period covered most of the data range, with high levels relating to rising groundwater periods, and extreme low relating to falling groundwater periods (Figure 4-22 for bore 83229 and Figure 4-23 for 83232). For low flow periods, regression analysis found that, even with less data, statistically significant equations were achieved. In the low flow analysis figures (Figure 4-24 and Figure 4-25), all data are represented by the blue lines and these are the same as the prediction equations in Section

4.3.1. The slopes and intercepts of low flow equations were slightly different from general equations however qualitatively the difference is minimal.

Due to the high correlations for all data, analysis of data subsets has resulted in regression equations very similar to the predictive equations. Quantitatively there is not a significant difference between subsets and prediction equations. For example, for the environmental flow of 137 ML/day (206.2mAHD) using regression equations at bore 83232 for low flow periods gave a predicted level of 204.40 metres, which is just less than the 204.44 metres calculated using Equation 11. For falling levels the predicted level is 204.44 meters which is the same as the predicted level using all data.

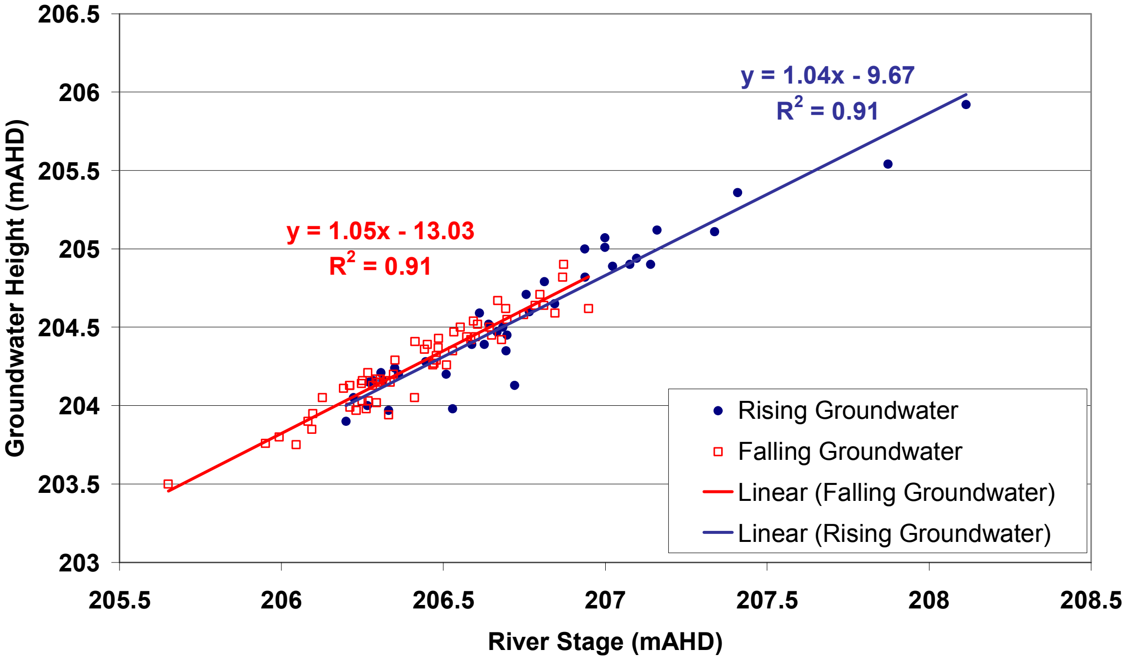

Figure 4-22: Regression comparison for periods of rising and falling groundwater levels at bore 83229 (Rising *n=38 p<0.001*, Falling *n=62 p<.001*)

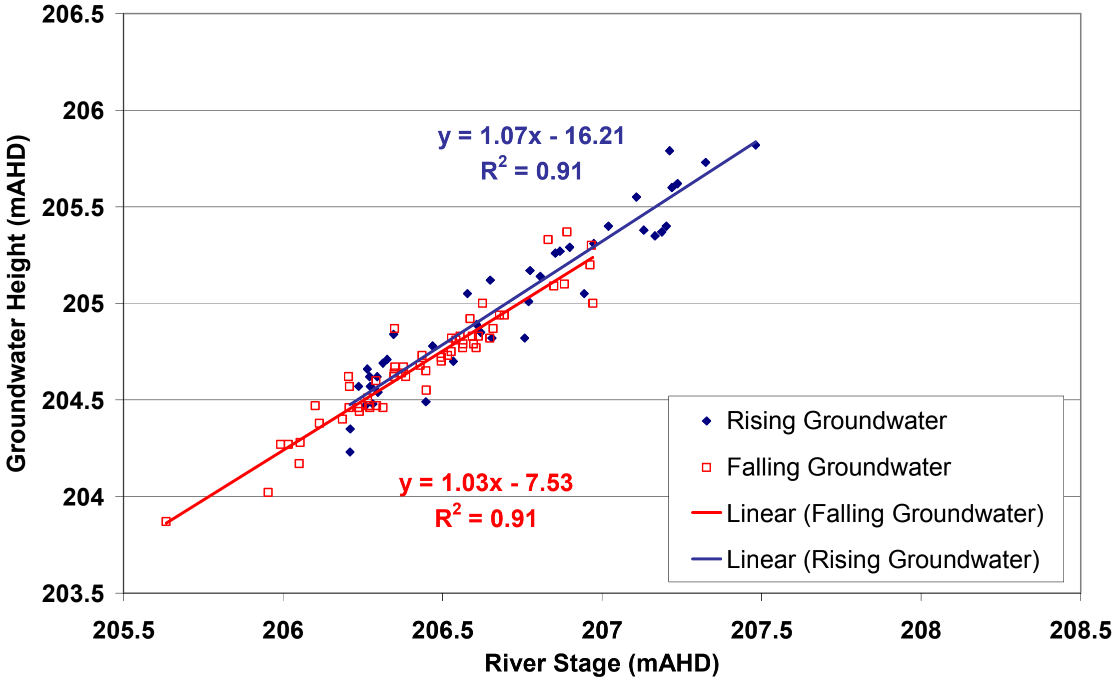

Figure 4-23: Regression comparison for periods of rising and falling groundwater levels at bore 83232 (Rising *n=40 p<0.001*, Falling *n=57 p<.001*)

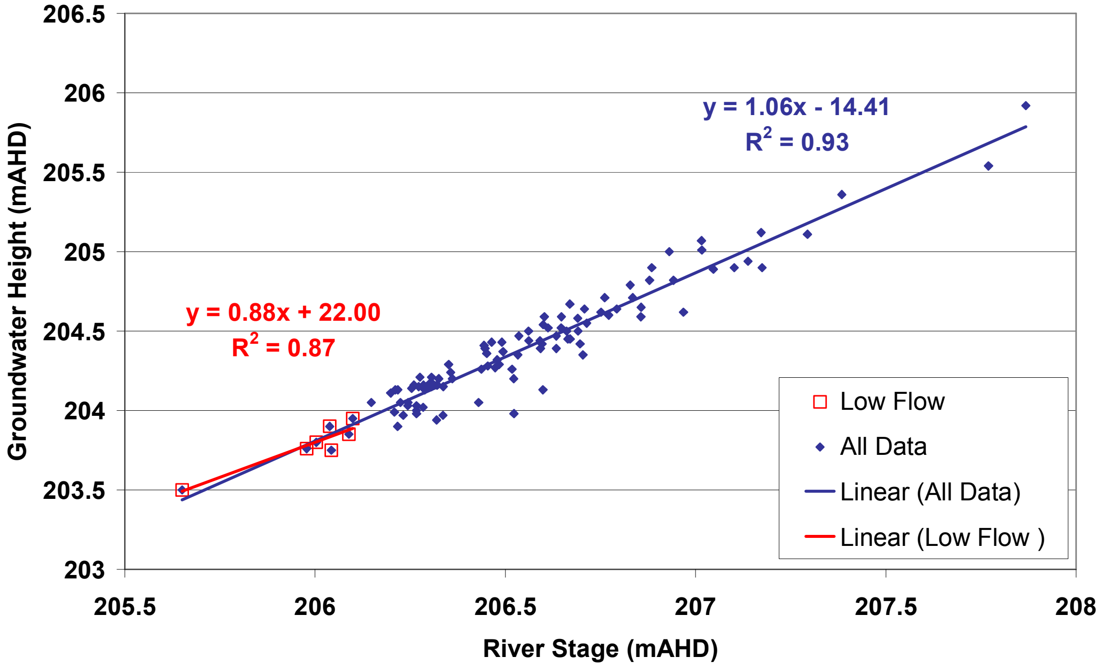

Figure 4-24: 83229 Low flow analysis with both flow criteria met (River ≤ 206.2, Groundwater ≤ 204.0) based on 2 day average flows (Low flow *n =8, p=0.001)*

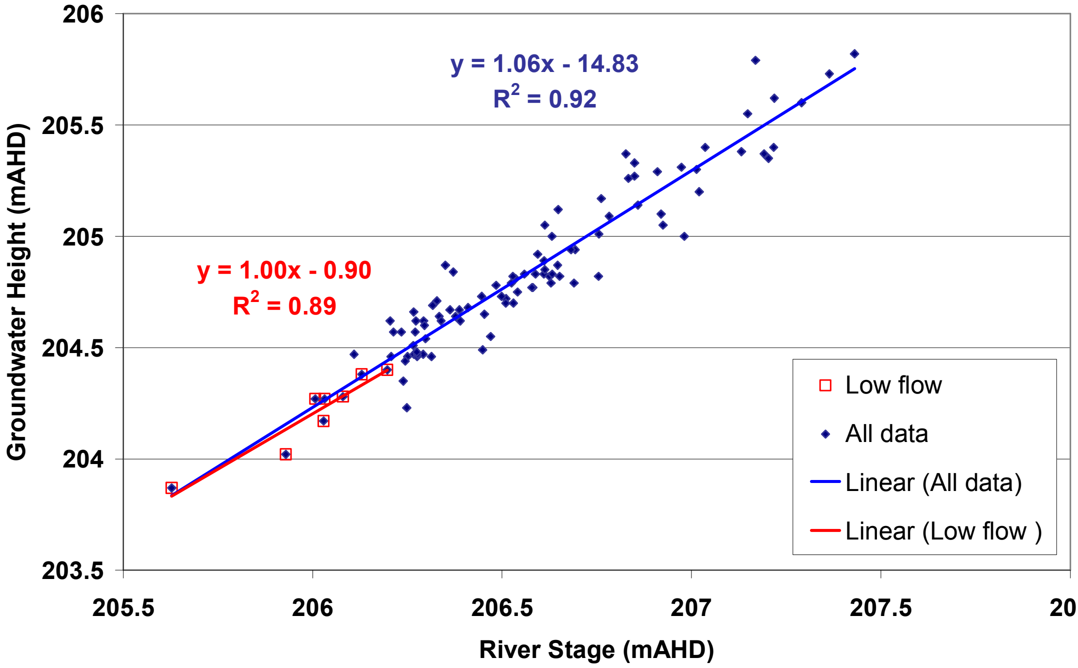

Figure 4-25: 83232 low flow analysis both flow criteria based on 10 day average flows (River ≤ 206.2, Groundwater ≤ 204.46) (Low flow *n =8, p=0.001*)

4.3.3 Predicting Groundwater levels from River stage height at Myrtleford

The regression analysis aimed to achieve the most representative and accurate prediction equation for groundwater levels based on river levels. Varying the averaging and lag period for representative river levels smooths out short term river level variations and improves statistical significance of the data.

Regression analysis prediction equations have been calculated to determine groundwater levels for a given stream level using the gauge height at Myrtleford (Gauge 403210). The equations are set out on an individual bore basis in section 4.3.1 for the Myrtleford cross section. Analysis of the groundwater-river relationships in low flow periods and when groundwater levels were rising or falling showed no real difference between them and regression relationships derived from all of the data. To obtain the highest level of accuracy and obtain an equation for the widest range, use of regression equations derived using all of the data are recommended. In these equations groundwater levels are calculated using the river stage. Use of the river stage and groundwater level overcomes any issues relating to future changes in channel morpholology as it is based on the relative heights of groundwater levels at the bore and the river at gauge 403210 rather than a flow.

Environmental flow objectives have been set using a flow in ML/day and these objectives can be converted into a river stage by using rating tables for the Myrtleford Gauge. For ease of use, the current rating table (Theiss 2007) created on the 18th January 2007 has been converted into a rating curve (Figure 4-26) that can be used to determine the river stage (mAHD) for a given flow. As the relationships are based on the river stage and not flow, this curve is only valid whilst the rating table it is based on is current.

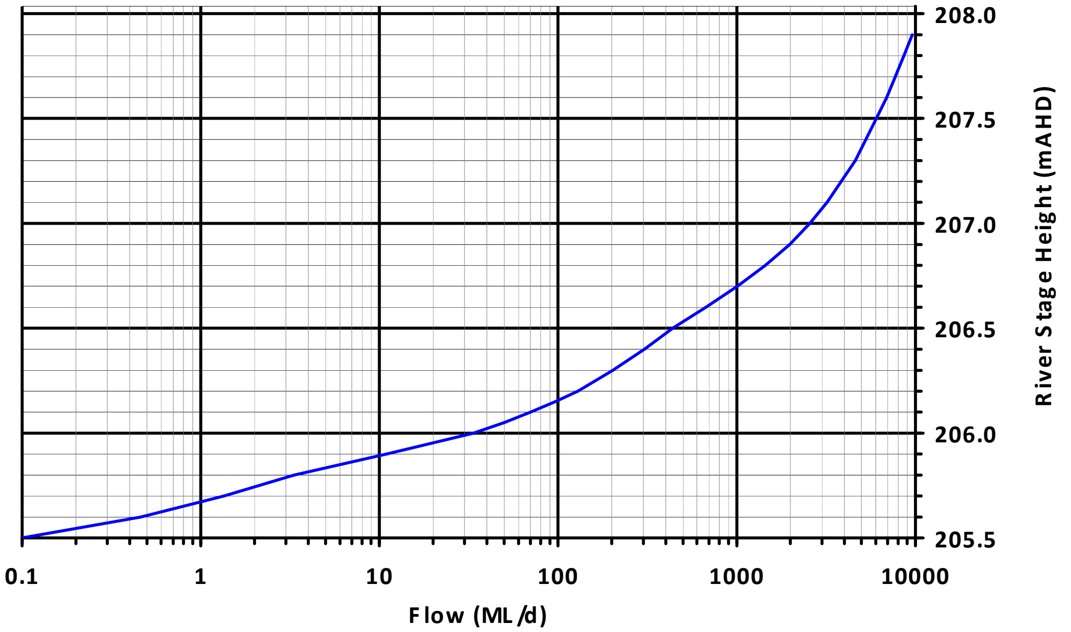

Figure 4-26: Rating curve for conversion of river flow into river stage at the Myrtleford Gauge (403210).

4.3.4 Other Sites

Application of the methodology to relate groundwater levels to river levels could be applied to any bore within the Upper Ovens Catchment. Issues arise when determining the river location to use in the analysis. At the Myrtleford site, continual river level monitoring has occurred just 250 metres from the transect of bores, however, no other river level monitoring sites are close (within 1km) to the other bore transects in the Upper Ovens.

Analysis of valley cross sections highlighted errors associated with transposing river stage recorded at the Myrtleford gauge to other points in the river. These errors may preclude accurate calculation of relationships at other bore sites that are some distance away from the river gauging site. As there are no other river gauging locations close to bore cross sections, the application of this methodology may be limited with current data.

To check how accurately the Myrtleford Gauge could be used for predicting groundwater levels at other sites, groundwater levels at the bores in the Ovens cross section (Figure 4-9) were considered for analysis. Using the same methodology as for the Myrtleford bores, regression analysis calculations, with groundwater as the dependent variable and river level as the independent variable, were carried out for each bore. The results from the analysis are summarised in Table 4-5, which show a correlation reduction as distance from the river increases, however, the reductions are much larger than at Myrtleford.

Lag analysis was applied to the Oven's bores using the same methodology as for the Myrtleford bores. Increases in correlation were identified as the lag/averaging period increased, however, unlike the Myrtleford bores, the correlation did not reach a maximum until flows were averaged for in excess of 60 days. Logging data show groundwater levels respond to changes in river stage within 20 days. This indicates that the average of 60 days may be smoothing results not represent actual lag. Errors associated with transposing river flows from one site to another mean that river levels measured at the Myrtleford gauge do not accurately represent levels at the Ovens bore transect. Also, the Myrtleford Gauge measures inflows from Buffalo Creek, which is a major tributary that enters the Ovens River downstream of the Ovens bore transect which would be a further source of error.

Although correlations are lower than at the Myrtleford bores, using traditional statistical analysis the regression relationships still have high correlations (R^2) using the assumption that a R^2 over 0.5 is taken as being high (Miles and Shevlin 2001). The ANOVA tests calculate that the significance (p) of the F value is less than 0.001 and the correlation is unlikely to be zero. From the ANOVA analysis it can be concluded that the correlation (R^2) (and thus the prediction equation) are statistically significant at the 99.9% level. For the equations in Table 4-5, H_{bore} is the groundwater level in the identified bore predicted by the river level at the Myrtleford gauge (H_{403210}). For hydrological investigations a $R^2 > 0.64$ is considered strong, and a $R^2 < 0.25$ is considered weak with other correlations between these values considered moderate (Gordon et al. 2004). Thus for the relationships at Ovens only the bores closest to the river (48073 and 48072) have a strong relationship with the others considered moderate.

As only half of the correlations for the relationship between the groundwater levels at the Ovens bores and the Myrtleford gauge are strong, there may be significant error using these equations to predict groundwater levels based on flows at the Myrtleford gauge 403210. Installation of a water level logger near the transect (adjacent to bore 48073) could be used to gather data to test the representativeness of the equations in Table 4-5 or produce new equations.

Bore	Distance from river (m)	Equation	R^2	p
48073	13	$H_{48073} = 1.22 \times H_{403210} - 24.50$	0.87	<0.001
48072	196	$H_{48072} = 1.44 \times H_{403210} - 70.94$	0.65	<0.001
48071	306	$H_{48071} = 1.13 \times H_{403210} - 6.42$	0.61	<0.001
48070	660	$H_{48070} = 1.47 \times H_{403210} - 75.52$	0.55	<0.001

Table 4-5: Regression analysis results for the comparison of bores in the Ovens transect to river levels recorded at the Myrtleford gauge.

4.4 Flux Volumes and Hydraulic Gradients

Flux between unconsolidated aquifers of the Upper Ovens Valley and the river will be calculated in this section to put boundary limits on this component of the water balance. In an unconfined aquifer, such as the Ovens, the water table is the upper boundary of the region of flow. Variation in the water table gradient increases possible directions of flow which complicates use of Darcy’s law to calculate the flux (Fetter 2001).

To calculate flux between groundwater and the stream, the Dupuit assumptions can be applied to calculate flow in the unconfined aquifer. These assumptions are (1) the hydraulic gradient is equal to slope of the water table and (2) for small water table gradients the streamlines are horizontal and equipotential lines are vertical. For unidirectional flow systems this is shown diagrammatically in Figure 4-27. The flow per unit width (*q'*) in m^2/day from the aquifer to the stream can be calculated using Equation 15 with the equation's components shown in Figure 4-27. The assumptions do not allow for a seepage face above the outflow side when flow is from the aquifer to a free surface (Fetter 2001). This is due to the parabolic form of Equation 15 not allowing for the true shape of the water table shown in Figure 4-27, however for flat slopes the equation closely predicts the water table position except near the outflow (Todd and Mays 2005). The hydraulic gradients at the cross sections developed in section 4.2 indicate this parabolic shape at Ovens and Myrtleford for most periods.

$$q' = \frac{1}{2} K \left(\frac{h_1^2 - h_2^2}{L} \right) \qquad (15)$$

where

q' is the unit flow per width in m^2/day

K is the Hydraulic Conductivity in m/day

h_1 is the head at the origin (or bore) in m

h_2 is the head at the river in m

X is the direction of flow (unit less)

L is the distance between the bore and river in m

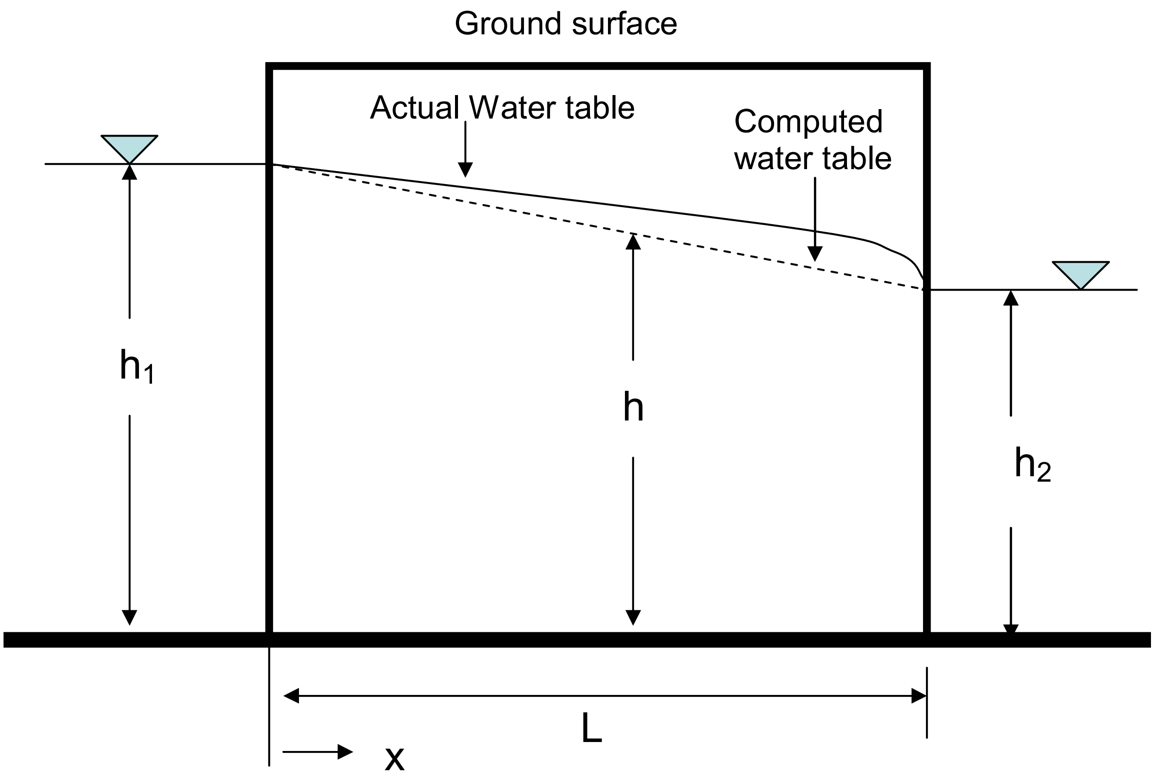

Figure 4-27: Steady flow in an unconfined aquifer between two water bodies with vertical boundaries (Todd and Mays 2005)

The Dupuit equation also assumes an impermeable base under the unconfined aquifer and that the stream fully penetrates the unconfined aquifer as seen in Figure 4-27. Cross sections in the Upper Ovens meet the first two assumptions but the stream does not fully penetrate to the relatively impermeable fractured rock aquifer. For the calculations it is assumed that the impermeable layer is at the base of the channel. With this assumption the calculations will only be capturing the fluxes between the side of the river channel and the aquifer and not capture flow to/from the river channel base. For the calculations, unidirectional flow is assumed, however, flow is unlikely to be unidirectional as the exact flow paths are not known. The numerical modelling by SKM showed multidirectional flow at the cross section at Ovens (Appendix 5) and changes in the hydraulic gradient could produce errors in the calculations. Using bores closer to the river are likely to overestimate average fluxes as there are stronger flux vectors. Using bores further from the river is likely to underestimate average fluxes as the predominant flow is down valley.

Calculations have assumed an aquifer of infinite width and that $h = h_l$ at $x=0$. Due to the equation not predicting water table gradients close to the outfall, bores closest to the river don't meet calculation assumptions. The flux has been calculated for different bores along each cross section. In each calculation $x=0$ has been assumed to be at the bore used for flux calculation. Thus L is the distance from bore to river channel edge. h_l was calculated as groundwater level minus the river channel's lowest point. h_2 was calculated as river stage minus the lowest point of the river channel. Flux between the aquifer and river was calculated for points in time when the bore reading was taken and these are considered to represent conditions for the given day. As such it is considered that there is no change with time and that the flow is assumed to be meeting steady state flow conditions required for the equation.

Parameters of Equation 15 were calculated using the surveyed information and historical groundwater and river level readings. Level readings for the river and the bore used to calculate the flux at each cross section were the levels used to produce the hydraulic gradient figures in section 4.2. As such a flow was produced for each day of a bore reading for each cross section. The unit width of the flow *(q')* was calculated for one kilometre of river to give a meaningful number for the fluxes. This assumes uniform flow along this length, however, the down valley gradient (4m in 1000m) and local variations in river channel morphology and topography limit accuracy of calculations for this distance. It was assumed that the water table gradient was equal for both sides of the river and the calculated flow was multiplied by two at Myrtleford and Ovens to give fluxes per km of stream. At Bright bores are on either side of the river so the flux was calculated for each side and added to give the flux per km.

One of the variables affecting magnitudes of calculated fluxes are the aquifer hydraulic conductivities (K). These have been calculated from various pump tests and studies conducted in the Upper Ovens Valley with results summarised in Appendix 2. There is a large variation in these parameters with an average of 17m/day, 90th percentile of 40m/day and 10th percentile of 5m/day. Values reflect the large variation in composition of the unconsolidated aquifer sediments due to the alluvial deposition process (as described in

Section 2.2.3). Without specific information on K values for aquifers near the cross sections the average value of 17m/day will be used for calculations. As K is a multiplier for the equation, depending on the aquifer at the cross section, in reality the actual flux could be up to approximately three times more or less (K = 5 - 40m/day) than the calculated value.

For comparison of fluxes to water balance values, the calculated fluxes were tabulated for each site and summarised on a monthly basis. Table 4-6 gives a summary of average fluxes for each cross section on a monthly basis, using the bores in the centre of the cross section for Myrtleford (83231) and Ovens (48072), and bores either side of the river at Bright (bores 51737 and 51735). For direct comparison to the water balance, the monthly fluxes at each cross section (representing 3km of river) have been summed and then multiplied by eight to represent the 24km of river in the study area. This is a simplistic calculation and compounds the errors associated with the assumption of consistent fluxes represented by the three cross sections. Hydraulic gradient variations, due to topography, aquifer parameters, or channel morphology, may actually change flux relationships over the distance.

The water balance monthly groundwater fluctuations (from Table 3-4) are shown in Table 4-6 for comparison (signs reversed). In general the calculated fluxes are smaller in magnitude and the fluxes do not show the seasonal variation of the water balance (Table 3-5). The calculated fluxes are shown for the low flow period in February 2007. This date is outside the water balance period but flows into the study area were 12 ML/day, with 4.98 ML from the Ovens River at Bright (403205) and 7.4 ML from the Buckland River (403233). Flows recorded at Myrtleford (403210) were only 1.2 ML/day so the calculated flux in Table 4-6 is a significant component of the water balance in this period.

Based on the seasonal pattern identified in the water balance (Table 3-4), it was expected that the flux analysis would have fluxes varying between negative values (river to groundwater) in winter/spring, and positive values in summer/autumn (groundwater to the river). However, on average the fluxes calculated at the cross sections show that the river is gaining from groundwater in all months. Two possible scenarios are raised as causes for this, the first is that the down valley flow is the major flow path and the cross sections represent parts of the aquifer where the gradient is predominantly to the river and the aquifer discharges water recharged from the river further upstream. The second is that the regional fractured rock aquifer is supplying water and pressure at valley margins resulting in the positive gradient towards the river. In the second case, the river –aquifer interactions would be occurring on top of the slower moving regional system.

	Number of readings			Flux volume (ML/month/km)				Study area Monthly Flux (ML)	Water Balance Groundwater fluctuations (ML)
Month	Myrtle-ford	Ovens	Bright	Myrtle-ford	Ovens	Bright	Sum		
Jan	1	1	2	2.8	4.3	-0.5	6.5	52.3	2,369
Feb	15	14	17	2.9	5.5	6.3	14.7	117.9	1,872
Mar	6	3	7	2.9	4.1	4.8	11.8	94.7	1,276
Apr	6	4	9	3.6	5.9	6.6	16.0	128.4	361
May	21	16	19	2.8	3.2	0.1	6.1	48.9	234
Jun	4	2	7	2.7	12.2	10.0	24.9	198.9	-2,210
Jul	2	1	6	4.9	22.7	19.1	46.7	373.3	-3,026
Aug	11	13	14	3.2	9.8	13.6	26.6	212.8	-2,807
Sep	2	1	5	-1.4	18.9	29.7	47.3	378.6	-1,335
Oct	3	4	7	0.8	18.9	33.5	53.2	426.0	-395
Nov	16	15	19	3.8	14.4	25.7	43.9	351.5	1,343
Dec	11	3	9	3.5	9.2	17.7	30.4	243.3	2,129
Annual	98	77	121	32.5	129.2	166.6	328.3	2626.6	-188
21 Feb 2007	1	1	1	0.01	0.6	-0.11	0.5	4	-

Table 4-6: Average monthly fluxes (ML/month) for the cross section sites (K = 15 ML/day).

To investigate if the small number of samples for each month is causing bias to the results, a daily flux series for the water balance period was developed. Groundwater levels were predicted using the equations developed in section 4.3.1 and based on the daily flows. The gauged river stage data were then altered to reflect the river stage at the bore cross section and the flux calculated. Results from the analysis (Table 4-7) show bores closer to the river have larger errors (difference) between flux volumes calculated using the predicted daily series and observed values. At bore 83232 there is little difference between the monthly fluxes apart from September and October; this is attributed to the small number of actual readings (Table 4-6). Fluxes calculated at bore 83231 have larger differences in most months and the differences at bore 83229 are large for all months. Magnitudes of calculated fluxes also increase when bores closer to the river are used. Errors in the flux calculated at bore 83229 are expected as it does not meet the assumptions of the flux calculations. However similar magnitudes of fluxes were expected at bore 83231 and 83232 as both bores were assumed to be on the same flow line and the fluxes are representative of the hydraulic gradient between the bore and the river. As this is not occurring there is evidence that the bores may not be on the same flow line. It could be that the cross section is being influenced by down valley flow, or other regional bedrock flow influences. Data logging at Ovens has shown the influence of the river is also less as distance from the river increases thus the fluxes at 83232 may be more indicative of regional seasonal influences of the unconfined aquifer. Local variations in hydraulic gradients due to aquifer composition or topography may also be a reason. Calculated fluxes for the bores in the Ovens cross section (Appendix 8) were of a higher volume than Myrtleford but showed the same trend with fluxes increasing as bores were closer to the river. As a comparison the fluxes were calculated using the bores in the cross section closest to the river. The calculated annual fluctuations were over 13,700 ML (Appendix 8) which are much larger than the water balance calculations (Table 3-5).

Although on average the flux at the cross sections is towards the river, there are periods where the flux is away from the river. Using the modelled series for the Myrtleford cross section, the percentage of time that the flux is away from the river was calculated for each bore (Appendix 8). As distance from the river decreases, the percentage of time that the hydraulic gradient is away from the river increases (7% at bore 83229, 1.4% at bore 83231 and only 0.2% at bore 83231). A possible reason for the highly gaining nature at the Myrtleford cross section is the influence of the bedrock high at gauge 403210. Comparison of the hydraulic gradient between the gauged river stages to groundwater levels at bore 83231 (Table 4-8) show that, on average, the gradient from this bore to the gauge is greater than that from the bore to the river. This indicates a local flow cell may be influencing flow directions.

Month	83232 (480m from river)			83231 (150m from river)			83229 (16m from river)		
	Series (ML)	Actual (ML)	Difference	Series (ML)	Actual (ML)	Difference	Series (ML)	Actual (ML)	Difference
Jan	1.75	1.55	-11%	3.41	2.75	-19%	18.60	6.80	-63%
Feb	1.68	1.57	-7%	3.29	2.92	-11%	18.60	7.67	-59%
Mar	1.65	1.53	-7%	3.22	2.91	-10%	18.36	8.95	-51%
Apr	1.78	1.80	1%	3.54	3.57	1%	21.21	11.46	-46%
May	2.01	1.57	-22%	4.11	2.79	-32%	26.81	7.26	-73%
Jun	2.16	1.83	-15%	4.41	2.73	-38%	28.22	-5.42	-119%
Jul	2.41	2.44	1%	5.04	4.92	-2%	36.98	18.85	-49%
Aug	2.45	1.81	-26%	5.04	3.17	-37%	35.17	4.69	-87%
Sep	2.36	-0.04	-102%	4.76	-1.36	-129%	30.52	-5.59	-118%
Oct	2.27	0.92	-60%	4.59	0.78	-83%	30.60	-0.25	-101%
Nov	1.93	2.12	10%	3.68	3.79	3%	19.38	8.33	-57%
Dec	1.87	1.76	-6%	3.64	3.50	-4%	20.21	12.72	-37%
Average	**2.03**	**1.57**	**-20%**	**4.06**	**2.71**	**-30%**	**25.39**	**6.29**	**-72%**

Table 4-7: Comparison between predicted and recorded values of average monthly fluxes at Myrtleford (K= 17m/day)

Down valley gradients are of similar magnitude to the gradients at cross sections of around five in a thousand (Table 4-8). Hydraulic gradients at the cross sections vary with time (high standard deviation) and with distance from the river, however, the down valley gradients are mostly constant in magnitude and have almost no variation. At the Myrtleford and Oven cross sections average hydraulic gradients towards the river increase as distance to the river decreases. In the bores further from the river (83232 and 48054) the gradients towards the river are less than the down valley gradients, indicating that flow in these areas are down valley. The steady state potentiometric surface and flow vectors (Appendix 5) developed by SKM (2006a) suggests this may be the case for the Ovens area where the predominant flow vector direction is down valley for the aquifer away from the river (bore 48054) but increases close to the river (bore 48072 and 48051). The flux results support this model as shown by flux gradients for different bores. Although no numerical modelling exists for Myrtleford, hydraulic gradients indicate a similar flux relationship. Further complicating the scenario is the Bright cross section, where flow was demonstrated to be away from the river in low flow periods (2007 in Figure 4-12), where it would be expected to be towards the river. Regional pressures should result in a positive gradient at all times, as observed at the Myrtleford and Ovens cross sections.

Whether variations in down valley flow is due to river recharge or part of regional aquifer flow cannot be differentiated by the simple two dimensional flux analysis undertaken in this study. Numerical modelling is required to separate the influences of river recharge and regional bedrock inputs into the unconsolidated aquifer. Chemical analysis of the water in the aquifer at different depths and in the river could help to determine the source of water and relative inputs.

Location	From	To	Distance (m)	Hydraulic Gradient				
				Average	SD	Max	Min	Count
Myrtleford Cross Section	83232	River	480	0.001	0.001	0.002	-0.001	98
	83231	River	150	0.003	0.001	0.005	-0.003	98
	83229	River	15	0.008	0.006	0.017	-0.025	98
Ovens Cross Section	48054	River	660	0.001	0.001	0.003	0.000	133
	48072	River	196	0.006	0.003	0.012	-0.003	77
	48051	River	16	0.072	0.020	0.139	-0.023	140
Bright Cross Section	51737	River	250	0.004	0.003	0.010	-0.003	121
Myrtleford	Gauge 403210	83231	250	0.007	0.000	0.007	0.000	5000
Down Valley gradients	Myrtleford	Bright	27,500	0.004	0.000	0.004	0.004	30
	Myrtleford	Ovens	7,500	0.003	0.000	0.003	0.003	30
	Ovens	Bright	20,000	0.004	0.000	0.004	0.004	30

Table 4-8: Average hydraulic gradients in the unconsolidated sediments

Cross sections only represent a minor part of the unconsolidated aquifer. The simplistic nature of the flux calculations, involving the Dupuit equation with its large number of assumptions, to relate the calculated fluxes to the whole river reach means the calculated fluxes have a large variation which precludes direct comparison to the water balance. Of higher importance is that the seasonal trend of fluctuations between the groundwater and surface water systems seen in the water balance has not been replicated in the calculated fluxes between the river and unconsolidated aquifers. Two possible reasons are given. The first is that the cross section analysis only investigated areas where local topography forces down-valley groundwater flow (recharging from upstream) towards the river. Another possible reason is that pressure from the regional bedrock aquifer provides flow at the valley margins, causing hydraulic gradients towards the river.

4.5 Groundwater Extraction and Groundwater levels

To investigate extraction scenarios properly and link these to relative impacts on stream flow and groundwater levels, a numerical model is required. From the water balance and other work, rapid recharge from the river (when there is flow) has been shown. Impacts of groundwater extraction on river levels are also minimal in terms of the mass balance. For broader scale management, an understanding of the risk of groundwater extraction on the river at low flows is required. In low flow periods, such as the summer of 2007, the river had basically stopped flowing and groundwater was providing water to keep the deeper pools full and provide a minimal base river flow. An identified risk to the river environment is groundwater extraction lowering the water table and removing base flow, or if sufficient extraction occurs, lowering water tables below the river channel bottom and drying out even the deeper pools. This is an event that has not been observed in the study period.

A rudimentary investigation has been undertaken to investigate potential drawdown levels in aquifers of the unconsolidated sediments within the study catchment area (Figure 3-2). A steady state model has been assumed with no inputs into the unconsolidated aquifer from the fractured rock aquifer, and through flow inputs equal to outputs in the unconsolidated aquifer. As such, the calculated aquifer draw-downs will be a worst case scenario, as in reality, increased throughflow and fractured rock aquifer contributions could provide a buffering to lowering water tables (Sophocleous 2002).

Aquifer drawdown has been calculated by rearranging Equation 16 which calculates the volume of water drained from the aquifer (V_w, in ML) of a certain horizontal area (A, in m^2) for a given storativity (S) and observed drawdown (Δh, in m). By considering the equation in terms of the drawdown (Δh), the drawdown for a given extraction volume can be calculated by Equation 17.

$$V_w = SA\Delta h \tag{16}$$

Re-arranging,

$$\Delta h = \frac{V_w}{SA} \tag{17}$$

Storage volumes were obtained by analysing all of the pump test data and literature for the area. The average storativity value for all aquifers was 0.03 and the 90th and 10th percentiles were 0.12 and 0.001 respectively, full details of pump test results can be found in Appendix 2. A storage value of 0.19 is the value determined to minimise the errors in the whole of system water balance in Section 3.5.4 and has been taken as the upper limit.

There is roughly 2000 ML of licenced groundwater entitlement in the study area (Section 2.6.1). Draw down in the aquifer was calculated for varying extraction volumes right up to the total licenced groundwater entitlement volume in the entire Upper Ovens River Catchment (3700 ML). Calculated draw downs (in m) are outlined in Table 4-9.

Extraction of the total entitlement in the sub catchment (2000ML) at the average storage value would result in a draw down of 1.46m. If this draw down were to occur in the summer of 2007 and assuming no inputs from other sources, then there is considerable risk that the water table could be drawn down past the river channel bottom at Myrtleford, Bright and possibly Ovens.

Use (ML)	Draw-Down (m)		
	S=0.19	S=0.03	S=0.001
300	0.03	0.22	6.57
500	0.06	0.36	10.94
1000	0.12	0.73	21.88
1500	0.17	1.09	32.83
2000	0.23	1.46	43.77
3000	0.35	2.19	65.65
3700	0.43	2.7	80.97

Table 4-9: Unconsolidated aquifer draw down predictions (m) for varying volumes and Aquifer storage values.

At Myrtleford, even a draw down of 0.73 metres (relating to current estimates of extraction of 1000 ML) could lower groundwater levels below the base of the river and dry the river up. The gradients and fluxes towards the river, and buffering of bores away from the river shown in the flux analysis indicate that there is a source of water either from the unconsolidated aquifer down valley flow or regional inflows from the fractured rock. If additional water is being provided from the fractured rock aquifer, then there may be potential for sustainable extraction.

4.6 Summary.

Following on from the seasonal pattern of fluxes shown from the water balance in Chapter 3, this chapter explored further the groundwater–river level relationship and the key research question of whether a hinge point or groundwater-river level relationship could be defined to show when the river switches from gaining to losing.

At the valley cross sections, groundwater levels were shown not to have fallen below the river channels base for the period of record (Section 4.2). For lowest recorded water levels in February 2007, groundwater levels were above the lowest point of the river channel and the flux was from groundwater to the river at Myrtleford and Ovens. At Bright the flux of groundwater was from the river to groundwater, however, this may have been due to errors in transposing river levels. Differences in flux direction may also be due to stream channel morphology and surface topography. Bright is a riffle zone with the river close to the surrounding surface topography, whereas Ovens is deeply incised and has a deep pool. Myrtleford is a riffle zone just downstream of a deep pool but the river channel is incised so the level is still much lower than the surrounding surface level. Results indicate that in any periods of low river flow and low groundwater levels, the river is dependant on groundwater to supply the deep pools and provide minimal baseflow. During these periods the river will develop into a series of pools fed by groundwater with flow only in sections where the river channel has incised lower than the saturated groundwater water table. This observation is supported by the hydraulic gradients and numerical modelling completed by SKM (2006a) and shown in Appendix 5. Whether the source of groundwater at these periods is due to down valley flow from river recharge or from regional flows from the fractured rock aquifer to the unconsolidated aquifer is uncertain.

Investigation of cross sections comparing river levels to groundwater levels supported the water balance results, with fluxes of water between groundwater and the river being shown to vary seasonally. Analyses of water levels have shown that the Ovens River only loses water to groundwater at each cross section during river rising events when the river level is above groundwater levels. Due to the low frequency of groundwater level monitoring, the length and frequency of these events is not certain, however, the logging information shows that groundwater levels rise in response to the river rising and reach a maximum level in response to river levels after a period of days. The length of time taken to reach the maximum level is dependent on distance from the river but for the logged data this was after a maximum of 14 days for bore 48070 (660m from the river) during a river rising event in June 2008.

Regression analyses showed that the relationships between groundwater and river levels at the Myrtleford gauge have linear trends which were statistically significant. Predictive equations were developed using the linear trend and can be used to predict the groundwater level for a given river level or flow. The strong correlations mean that these can confidently be used to determine a groundwater level for a stream level which can be in the form of a flow (ML/day) or a gauge height. Investigation of data subsets found that the regression relationship did not vary significantly between periods of rising and falling groundwater levels or in periods of low flow. The high correlation between river level and groundwater level for all bores indicate a high hydraulic connectivity between the aquifer and the river.

An equation, to define the relationship describing when the river switches from gaining to losing, was to be focused around setting a groundwater level for the whole valley to determine the hinge point (or groundwater level) when the whole river switches to losing (when the groundwater level drops below the base of the stream channel). As the groundwater levels have not dropped below the stream channel base, calculations have been defined to predict the groundwater level for a given stream flow based on the historic relationships. The river mainly loses to groundwater during river flow events following rainfall when river levels are above groundwater levels. Prediction of these events has not been attempted in this research.

Volumes of fluxes between groundwater and the river were calculated on a monthly basis using the Dupuit assumptions for the Darcy equation. Cross section and flux analysis complicated the study results as the seasonal trend of fluctuations between the groundwater and surface water systems shown by the water balance were not replicated. Rather, the cross sections and flux analysis showed that at cross sections, fluxes have been from river to aquifer for only a small proportion of the study period and possibly for only small events. This proportion also reduces as distance from the river increases. Two possible reasons were identified for this trend; the first was that the cross section analysis only investiged areas where the local topography forces down-valley groundwater flow (recharging from upstream) towards the river. The second possible cause is that pressure from down valley flow or the regional bedrock aquifer is providing flow at the valley margins and causing the hydraulic gradients towards the river.

Estimates of draw down due to pumping of the unconsolidated aquifer in the study area were calculated assuming a steady state with no fractured rock aquifer inputs and with through flow inputs equal to outputs. This assumption would be appropriate for periods such as the 2006/2007 summer where low recharge occurred over winter and no rainfall meant that groundwater levels and river flows were low. Current pumping estimates of one third of entitlement relate to approximately 700 ML of usage and possible draw downs of 0.2 to 0.7m (based on a storativity of 0.06). These draw downs were not sufficient to drop the groundwater level below that of the river, however, the actual extent that groundwater pumping is impacting on groundwater levels is not certain due to the uncertainties around groundwater extraction levels and storativity values. An increase level of pumping on top of the 2006/07 conditions has the risk of lowering groundwater levels further and could drop water levels below the river channel bottom. This is a big management risk especially in extended dry periods over summer following dry winters with low recharge and low groundwater levels. Potential buffering of groundwater level responses to river stage fluctuations at the margins of the unconsolidated aquifer has been shown in the flux analysis. If this is due to inputs from the fractured rock aquifer then there is potential that a slower moving regional groundwater flow influence and fluctuations of the unconsolidated aquifer with the river are occurring seasonally over this system. In this case there may be potential for extraction of a sustainable yield from the unconsolidated aquifer without influencing river levels.

The next chapter will explore the implications of the results of the hydrogeological understanding of the area, water balance and investigations of groundwater-river level relationships on the conjunctive management plan.

Chapter 5: Conjunctive Management

Using the understanding of the timing and magnitude of the interactions between groundwater and surface water gained from the water balance and water level analysis, methods for conjunctive management are investigated in this chapter. Rather than set definitive management rules, a broad outline of objectives and principles with possible options for different methods of management are discussed. Implications of water extraction on environmental flow requirements and considerations for management are based around objectives set out in the SKM (2006) environmental flows assessment.

The final key research question, seeking to answer whether groundwater extraction can be managed to provide increased security of supply to irrigators without compromising environmental flows, is also discussed.

In the Upper Ovens the focus for conjunctive management should be the interactions between the groundwater and the Ovens River, in particular, management of any potential impacts of groundwater extraction on river flows. The main risk period for the environment in terms of river flow has been identified as the low flow periods over summer where impacts of water extraction on river flows are the greatest (Sinclair Knight Merz 2006d). The water balance in Chapter three, analysis of groundwater–river interactions and potential impacts of groundwater extraction in chapter four, have also shown that the low flow period over summer is critical in terms of water resource availability and the magnitude of extraction in terms of total flow.

In addition to the water balance (Chapter 3), investigation of the hydraulic gradients at points in the valley in Section 4.2 has shown groundwater to be important for maintaining water in the river in low river flow periods. Groundwater extraction from the unconsolidated sediments has the potential to reduce groundwater levels during these times and reduce river flows. During summer periods with average river flows of around 500 ML/day, groundwater extraction at current levels (1200 ML/yr), or even at full entitlement

(3700 ML/yr) would not have a large influence on river flows. However in extreme drought years such as 2006/07 river flows drop to below 5 ML/day; at these times the flux of water from groundwater is critical for provision of water in the river (Section 4.2). Groundwater extraction from the unconsolidated aquifer has the potential to intercept these contributions or reduce ground water level below the river (Section 4.5). For conjunctive management, the focus will be on maintaining flow in the river during low flow periods where demand and risks of extraction are greatest.

5.1 Idealised conjunctive management option

The objective of the idealised management case is to protect low flows in the Upper Ovens River. Under the idealised management option, groundwater users in the unconsolidated aquifer are managed in line with surface water users. Surface water users are managed according to flow triggers based on minimum river flow requirements (Goulburn Murray Water 2003). Access to water is reduced as flow in the river drops until all extraction is banned as explained in Section 2.6.3. In addition, triggers for restriction of groundwater extraction will follow river flow triggers as explained in management principle number two (Section 5.1.2). It is also proposed that an additional requirement placing extraction restrictions based on groundwater levels is included. Under management principle number three, groundwater users will be restricted if groundwater levels of the unconsolidated aquifer fall to a set trigger level. The groundwater level will be set as a level that represents an environmental flow trigger level and be calculated using the regression relationships defined in Section 4.3.1.

Under Victorian water management legislation (Section 2.6.4), the flow trigger levels for restrictions will be determined in the future water management planning process. They will be a compromise between environmental flow levels and the security of supply for irrigators. Knowing the exact environmental flow figure and restriction level is not necessary for the idealised option, the principles and method outlined below can be adapted to any trigger flow level.

For the idealised case it is proposed that conjunctive management of groundwater be based on the following four principles:

1) Groundwater and surface water are hydraulically connected, manage as one;
2) Restrict groundwater extraction in line with surface water restrictions;
3) Manage groundwater according to minimum groundwater levels; and
4) Manage groundwater in the unconsolidated sediments as one aquifer.

Managing groundwater in line with surface water is not a new concept for the Upper Ovens; SKM (2006a) suggested a zone (river zone) for a set distance from the Ovens River where groundwater users were managed in line with surface water users. Only two zones were suggested for the aquifers of the unconsolidated sediments of the Upper Ovens. For groundwater users in the second zone outside the river zone, management rules were proposed to be set based on the degree and timing of impacts of the groundwater extraction on the river. SKM (2007a) proposed the river zone be the unconsolidated aquifer 200m from any mapped surface water feature. This study supports these recommendations for the idealised management scenario, but recommends that the river zone should be extended to cover all of the unconsolidated sediment aquifer. This recommendation is explained in detail by principle three in Section 5.1.4. and is based on the behaviour and composition of the aquifers of the unconsolidated sediments (Chapter 2), the strong hydraulic connection shown in the regression analysis (Section 4.3) and the short response times (less than 20 days) of groundwater rises to river rises seen in the field water level measurement (Section 4.1).

Each of the four principles could be converted to management rules. The justification and explanation of the principles are described in detail in the following sections.

5.1.1 Principle No 1: Groundwater and surface water are hydraulically linked – manage as one.

The water balance (Chapter 3) has shown that for the monthly average of a 30 year modelling period, movement of water between the groundwater and surface water systems shows a seasonal pattern. In the seasonal pattern, surface water recharges groundwater in the wet periods of winter and spring, and then groundwater discharges to the surface water system (and ET) in summer and autumn.

High transmissivity of the shallow aquifer leads to a rapid exchange between groundwater and the river. Any rise in river levels above groundwater levels sees a rapid response in groundwater recharge to reach a maximum level in around 14-20 days at 750m from the river (Figure 4-3 and Figure 4-4). The groundwater recharge level is dependant on the gradient between the river stage and the groundwater level, however, the time to reach the level remains relatively constant for the recorded recharge events. Lag periods of regression relationships indicate a similar time period and indicate that lag increases as distance from the river increases. Without monitoring bores at valley margins, lag cannot be determined with certainty for aquifer areas further from the river than the monitoring bores. However, with the width of the valley flats and unconsolidated aquifer generally less than 2km, there is a reasonable expectation that interactions for the whole aquifer width would occur well within one irrigation season (90-100 days). As it is only the top few metres of the unconsolidated aquifer that are interacting with the river, it is winter recharge that is acting as annual storage for summer discharge. In years with low winter recharge there may not be enough groundwater storage in the unconsolidated aquifer to allow extractio without dropping groundwater levels below the river channel base (Figure 5-1). The volume of water held in the top few metres is dynamic and changes seasonally.

Investigation of hydraulic gradients at cross sections (Section 4.4) showed the predominant hydraulic gradient as towards the river, with the gradient (and calculated flux contributions to the river) decreasing as distance from the river increased. Also, as the distance from the river increased the amount of time river levels were above groundwater levels decreased. For example at Myrtleford bore 83232 (500m from the river), the hydraulic gradient was from the river for less than 1% of the time between 1973 and 2000. This indicated that either the cross sections were all in areas where the topography forced the hydraulic gradient towards the river or the groundwater levels were being buffered from either down valley groundwater flow or regional bedrock inputs. If regional bedrock inputs are causing the buffering then potentially parts of the aquifer are not strongly influenced by river level fluctuations. However, responses to rapid river level rises were recorded in bores furthest from the river at Ovens and Myrtleford (Section 4.1), indicating that there is still a strong hydraulic connection with the river and down valley flow is the probable source of the fluctuation. The regression relationships also showed a strong correlation between groundwater levels and river levels for all bores further supporting the strong hydraulic connection. It is reasonable to expect that the whole of the unconsolidated aquifers are connected and that they can be managed together.

The seasonal pattern of water movement and high rate of transfer between groundwater and the Ovens River show that water will exist in either storage depending on the hydraulic gradients. The strong relationship between groundwater levels and river levels and the rapid transfer of water between the unconsolidated aquifer and river mean that any groundwater unconfined aquifer extraction will result in lowering water tables and recharge from the river to cover extraction. Thus groundwater and surface water have to be managed as one resource knowing that alteration of the water balance through extraction of groundwater in the unconsolidated aquifer will result in altered flows in the Ovens River.

Under this management principle consideration could be given to having one licence type which allows for extraction from the river or groundwater in aquifers of the unconsolidated sediments. Under this ‘one extraction licence’ scenario, licences converted into this new licence type would be river extraction licences, groundwater licences, and bulk entitlements. The total volume of this new licence type would be 15,404 ML (Table 2-3). These licences would be restricted based on restriction rules set out in principle two. The addition of the total volume of groundwater licence (3,700 ML) to river extraction would have minimal influence on river flows in terms of the average water balance, but may impact in low flow years. River flows in low flow periods would be protected under principle number two, so the impact of increasing the volume of extraction from the river would be to the security of supply for irrigators. With increased extraction, irrigator access to water over summer will be reduced and they will be on restrictions more often and for longer (Section 2.6.). The risks of negatively impacting low flows from river extraction are low as the impacts can be turned off when flows reach a set level. However, for groundwater extraction, the potential lag of less than 90 days between groundwater extraction and impacts on the river gives the potential for groundwater extraction to reduce stream flow even once it has been banned (Section 5.1.3). In low flow years this has the potential to significantly reduce contributions from groundwater to river flow.

The water balance has shown that the average long term groundwater balance is in equilibrium, with average annual recharge of 9,773 ML nearly equal to average annual discharge of 9,584 ML (Optimum scenario 2, Table 3-4). This shows that groundwater recharge over the wet period is discharging from the aquifer as base flow or evaporation in the dry season. In years where groundwater levels are not in equilibrium, such as 2002 where discharge was 10,000 ML greater than recharge, the balance in the following year often is in reverse (recharge 10,000 ML greater than discharge in 2003) as shown in Figure 3-16. This means that in years with low winter recharge and low summer river flows the groundwater system borrows from the next season's winter river flow. Generally this volume is insignificant in terms of the winter/spring total flow, e.g. 10,000 ML of recharge compared to several hundred thousand megalitres of flow. For the period of record there have not been two consecutive years with low winter river flows and subsequent low groundwater recharge. Groundwater levels have not dropped below the river channel bottom in the cross section sites in Section 4.2, as following the years with low groundwater levels there has been significant winter recharge to provide for the next season's baseflows. Groundwater extraction volumes are currently low; an increase in extraction volumes could change this equilibrium in years of low flow. A further risk to this equilibrium (and the chance of further reducing groundwater levels below the stream level) is if under the new one extraction licence scenario more water is taken from groundwater. The current groundwater licence volume limits extraction to 4,010 ML, however, under the one extraction licence, up to 15,404 ML could be potentially extracted. This is greater than the average annual recharge/discharge volumes, and risks intercepting all of the summer groundwater contributions to the river and comprising critical low summer flows.

The SKM (2006a) report also suggested substitution of surface water licences to groundwater to produce short term benefits in stream flow early in the season. This modelling did not consider a lager catchment water balance. Based on the steady state draw-down results (Section 4.5), it is considered that substitution carries too much risk, as depending on the season this could result in the groundwater table dropping below river level and reducing environmental flows. Based on the improved knowledge of groundwater – river interaction it is considered that groundwater cannot be used to increase the security of supply to irrigators. This is because to increase the security of supply, groundwater extraction would have to occur in the years with the lowest river flows. In these years, generally winter recharge and groundwater levels are lower and the risk of lowering groundwater levels below the river level is highest. Using the proposed principles for conjunctive management, the security of supply (for irrigators) for groundwater users is less than that for surface water users (Section 5.1.3).

Under the one water extraction licence scenario, there is the risk that increasing amounts of water taken from groundwater may significantly reduce stream flows. In low flow years a potential lag means impacts of groundwater extraction on stream flow may occur after extraction has ceased. As explained later in principal three, groundwater may be required to be managed to a minimum level. In this case, resource managers may manage licences extracting water from groundwater separately to those extracting water from the river as restrictions on groundwater extraction may occur before surface water restrictions. As such, the potential benefits of one licence are reduced as management effort is the same as separate licences. Combined with the potential risk of increased groundwater extraction to stream flow in low flow periods, resource managers can minimise the above potential risks to environmental flows by managing groundwater and surface water with separate licences and at their current volumes.

5.1.2 Principle No 2: Restrict groundwater extraction in line with surface water restrictions

Exchange of water between groundwater and the river generally follows a seasonal pattern and for the majority of time, it is the river levels and flow into and out of the study area that control the water balance and the groundwater-river relationship. It is only in years where flow into the catchment is very low that groundwater is critical for provision of base flow.

The flux analysis in Section 4.4 shows that, on average only a small volume of groundwater (between 1.5 ML/day and 15 ML/day) flows into the river. In low flow periods such as 21 February 2007 where recorded flows were 1.2 ML/day at Myrtleford, groundwater contributions (4 ML/day in Table 4-6) have a significant influence on river flows. In particular the fact that groundwater levels have not dropped below the level of the stream at Ovens and Myrtleford means that groundwater is providing water for the deep pools which is habitat for in stream biota. Groundwater also provides significant volumes for ET and this is critical for deep rooted plants on the valley floor and also riparian vegetation.

Field measurement of groundwater levels and river levels show a rapid groundwater recharge response to increased river levels. Due to minimal groundwater extraction, the response of river levels to a drop in groundwater levels was not captured in the data recording period. Rather it can be seen that groundwater levels decrease in response to lowering river levels after flow events. Data indicates that groundwater acts as a balancing storage and will remain steady if river flows are steady. Over summer, dropping river levels see the groundwater table lower and provide base flow. Given the rapid response of groundwater to rises in river flows, it is conceptualised that the reverse would hold and that rapid extraction of groundwater and drops in groundwater levels would result in losses from the river. In the limited numerical modelling and pump testing, extraction close to the river was shown to result in almost immediate losses from the river and give evidence of the predicted response to groundwater levels (Sinclair Knight Merz 2006a; Sinclair Knight Merz 2007b).

The unconfined nature of the aquifer means any extraction will lower water tables and induce river leakage. With sufficient flow in the river this is not an issue as river leakage will not be sufficient to impact significantly on flow. For example if the full 3700 ML were extracted from the aquifer over 100 days and all water was recharged from the river in this period then the loss from river leakage would be 37 ML/day. In times of average summer flows of 500 ML/day, the impact would be minimal. However, in low flow periods, the lowering of water tables could significantly reduce flows. Hence it is the flows in the river that dominate the relationship and importance of groundwater to stream flow and groundwater management aims should be set around river flow objectives.

An increase in usage may cause groundwater levels to drop below the stream bed bottom. The simple steady state analysis (no flow) in Section 4.5 shows that even an extraction of 1000 ML over the summer period can drop the groundwater levels 0.73 m (S=0.03) in the study area. In periods of extreme low flow, such as summer 2006/2007, the steady state assumptions would be fairly accurate as stream flow into the sub catchment was less than 2 ML/day for two months. The potential impacts of groundwater extraction for the 2006/2007 low flow period are shown for the Myrtleford cross section in Figure 5-1 and at Ovens in Figure 5-2. Groundwater extraction of 1000 ML could result in groundwater levels dropping below the base of the river at Myrtleford and close to the base of the river at Ovens. If this were to happen, the small but critical flux from the unconsolidated aquifer to the river would be lost and more importantly, the deeper pools could be drained of water removing any habitat for in-stream biota.

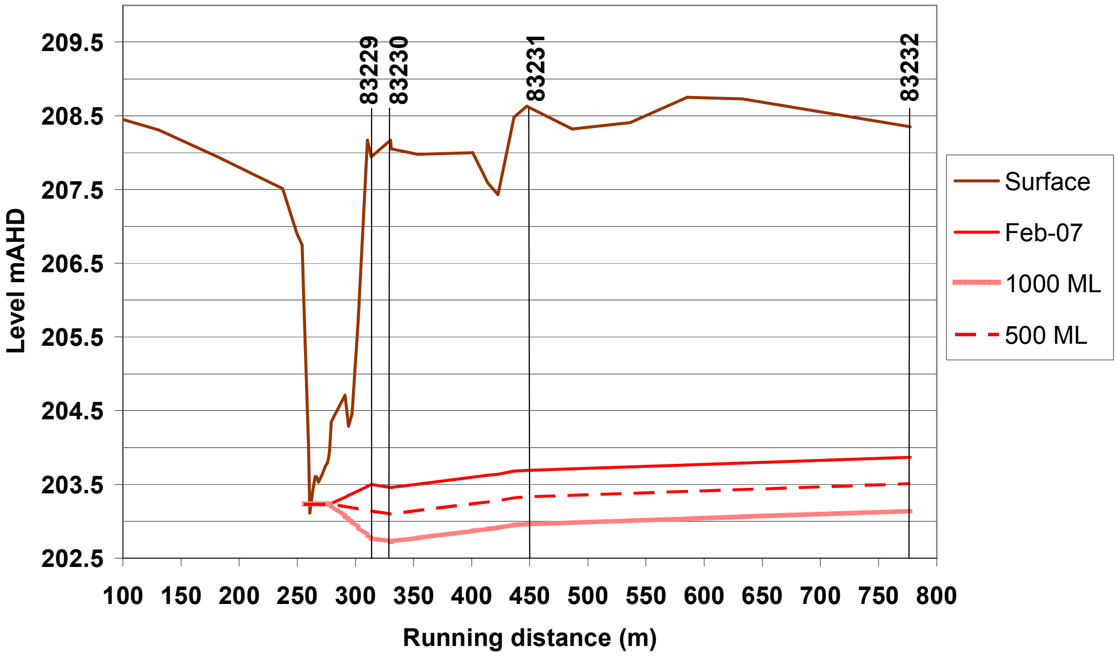

Figure 5-1: Myrtleford predicted groundwater level responses to extraction (S=0.03) below historic low groundwater levels reached in February 2007

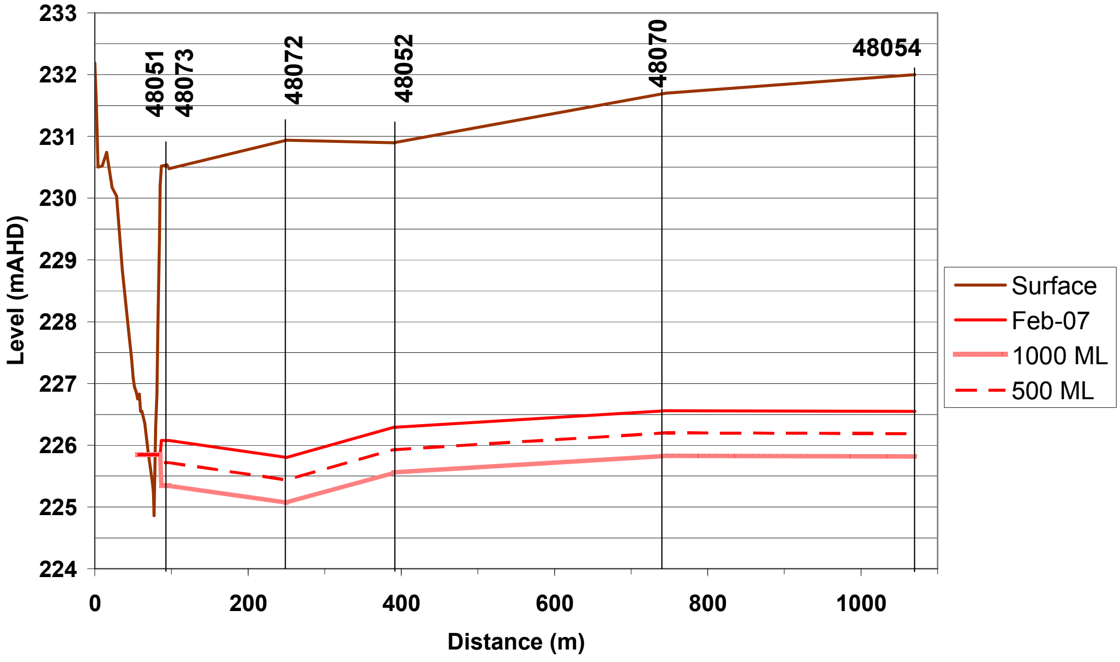

Figure 5-2: Ovens predicted groundwater level responses to extraction (S=0.03) below historic low groundwater levels reached in February 2007

Groundwater extraction should be managed to provide for maximum base flow to the river in low flow periods with highest priority given to preventing groundwater extraction lowering groundwater levels below the stream base.

The strong relationship between groundwater and river levels, the relatively short lag period between groundwater extraction and resulting losses from the river, river flows controlling the water balance and the small influence of groundwater extraction on the water balance, mean that groundwater extraction could be restricted in line with river flow restriction triggers. In this case groundwater extraction would be on the same level of restriction as surface water users. The river restriction trigger levels would be determined in the stream flow management plan process. This would be the simplest method and be equitable for all water users. It means that if stream flows drop and groundwater levels are high, the maximum flux from groundwater to the river is achieved which protects baseflows and groundwater inflows to the river.

5.1.3 Principle No.3: Manage groundwater to minimum groundwater levels

Restricting groundwater extraction based on stream flow levels assumes that the robust historic groundwater-river level relationships will hold true and ignores actual groundwater levels. Although the lag period is short between river level changes and groundwater level changes, there is the risk that if groundwater extraction increases then groundwater levels could be lower than the level indicated by the historic prediction equation. This scenario could occur if groundwater extraction is at a much greater rate than river recharge from. Also, due to lag times between impacts on river flow from groundwater extraction, extraction at the valley margins could delay impacts to river flows for up to 90 days. If river flows reduced suddenly, such as occurred in the 2006/2007 summer, groundwater levels may remain low and baseflow would be reduced. Also, as indicated by SKM (2006a) the lag between extraction and impacts could move the impacts to later in the season where it would be more critical to flows. In an extreme case, groundwater levels may drop below the base of the river and losses from the river could cause the stream to dry.

To prevent this scenario, groundwater restrictions could be based on set groundwater level triggers as well as river flow triggers. Target groundwater levels could be based on the plan-negotiated surface water flow trigger levels or a higher flow level. A higher flow level could provide greater security of fluxes from groundwater to the river and allow for lag times from groundwater extraction to impact on river flows. The greatest justification for setting a groundwater target level above the flow triggers is if the plan negotiates lower flow triggers for restrictions than the recommended environmental flow at Myrtleford of 137 ML/day (Sinclair Knight Merz 2006d). In this case, setting the groundwater target level to the recommended environmental flow means that groundwater levels can’t drop below a level where the environmental flows may be impacted by groundwater extraction. Groundwater users may also argue for a reduced groundwater level target in line with the negotiated stream flow trigger levels, as a higher level would reduce their security of supply.

Basing the target groundwater level on a flow target allows direct comparison for conjunctive management and reduces the probability of groundwater levels dropping below a level that compromises environmental flow objectives, such as in the 2006/07 example explained below. The regression relationships can be used to relate stream flow to a groundwater level in individual bores and by calculating average groundwater levels based on a set flow at the Myrtleford gauge, hypothetical management levels can be set as in Figure 5-3. These levels would be the easiest to conceptualise and explain to water users as the groundwater level trigger would have a relevance to a tangible level related to a visual flow. It also fits the objectives of maximising stream flows in low flow periods. Groundwater extraction would be restricted if either the groundwater level or river flow level drop to the trigger levels. To develop the groundwater management levels for a set flow level, the following steps can be taken based on the currently available information;

1) Convert the desired flow trigger level in ML/day into a river stage in mAHD using Figure 4-26.
2) Calculate the predicted groundwater level relating to the flow level by inserting the river stage from 1) into the prediction equations for each individual bore (for Myrtleford use equations 11 to 14, and for Ovens the equations in Table 4-5).
3) Develop management levels, either on an individual bore basis, or by averaging bore levels to give one management level for the aquifer.

Relating groundwater levels to flows at the Myrtleford gauge is limited by the moderate correlation of the regression equations which may create a source of error. The environmental flow at Myrtleford only relates to the Ovens River reach between Bright and Myrtleford (Sinclair Knight Merz 2006d). Groundwater management levels would only be applicable for this reach also. To create groundwater levels for upper reaches of the Ovens River and its tributaries river and groundwater level monitoring would be required to create regression relationships.

In the Campaspe management plan, the groundwater levels for the area are averaged using representative bores. For the Upper Ovens it is proposed that the bores in the Myrtleford and Ovens cross sections shown in Figure 4-6 and Figure 4-10 are used. These bores have been shown not to be influenced by pumping and represent groundwater level fluctuation trends for the unconsolidated aquifer. Using multiple bores has the benefit of representing average aquifer levels and reduces the likelihood of local effects (e.g., pumping) resulting in restrictions where the overall aquifer levels are not affected.

Another scenario where restrictions based on groundwater levels would protect stream flows, is for years with low groundwater recharge over winter. In these years groundwater levels may not reach the level expected for the environmental flow trigger based on the prediction equations. This occurred in 2006/07 where the winter groundwater recharge level was lower than the expected groundwater level for the recommended environmental flow at Myrtleford of 137 ML/day (Figure 5-3). In this year groundwater extraction could significantly reduce groundwater levels and compromise base flow from groundwater to the river. Having a groundwater extraction restriction trigger based on minimum groundwater levels will overcome this issue.

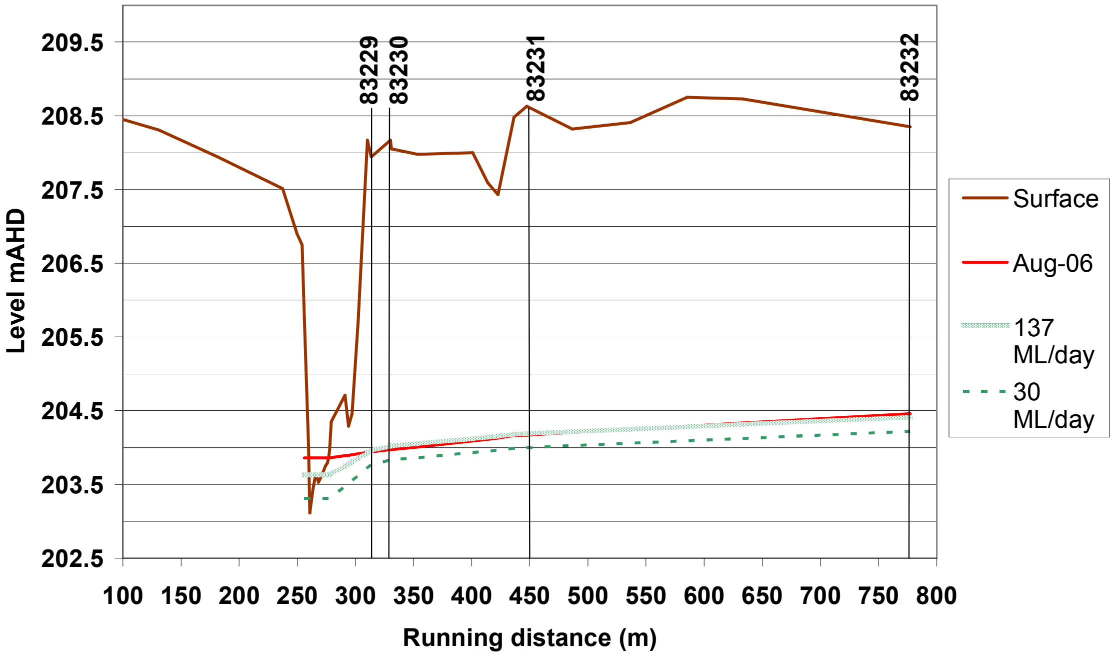

Figure 5-3: Winter recovery for 2006/07 compared to predicted groundwater levels for different environmental flow levels

The water management plan process will determine the acceptable risk of water extraction on the environment and set environmental flow trigger levels based on acceptable flow levels. This is the same for minimum groundwater levels. Regression relationships and equations can be used to determine groundwater levels to match the flow trigger levels at Myrtleford. However, with the current available information this can only be done with a high level of confidence for groundwater levels at Myrtleford.

5.1.4 Principle No 4: Manage Unconsolidated Sediments as one aquifer

As explained in the stratigraphy section (Section 2.2.3), descriptions of the alluvial aquifer by Heislers (1993), Shugg (1987) and SKM (2006) contradict that described by Vandeberg (2004). The former split the alluvial aquifer into three sections; the Calivil Formation overlain by the Shepparton Formation overlain by the Coonambidgal Formation. However, bore logs and described geological process (VandenBerg et al. 2004), indicate that this description is not correct. The Pliocene era was a period of erosion where the deeper Shepparton and Calivil sediments were eroded to an unknown extent. Evidence from bore logs shows the whole valley may be in-filled with recent alluvium with only patches of Calivil Formation sediments possibly left in areas such as Bright. Bore logs at Ovens show no presence of the Calivil formation, only what would be expected of recent alluvial sediments in an anastomosing system with discrete heterogenous shoestring layers of stream deposition. Differentiation of colluvium from bore logs is also difficult and some show similar composition to alluvial sediments. For management it would be better to consider the whole of the unconsolidated sediments in the valleys as one unit.

The Ovens River floodplain below Myrtleford is described as an anastomosing system (Schumm et al. 1996). Bore logs and current understanding of the stratigraphy of the Upper Ovens floodplain support alluvial sediment deposition following the same process with variations in aquifer parameters and stratigraphy occurring both horizontally and vertically. As such it will be very hard to map, describe and model the alluvial aquifer and aquifer parameters. Connectivity between the stream bed and groundwater will vary spatially. The stream may cut through old meanders or deposit fines in floods which can act as impermeable layers. Determining connectivity between individual extraction bores and the river will be very difficult due to aquifer variations. Treating all unconsolidated aquifer areas the same in terms of their potential interactions with the river will be the equitable and most efficient management method. Setting a zone to be managed as surface water based on a distance from a water feature or depth of aquifer is not possible with the current level of data. This is due to the high variability of aquifer features (eg ancestral channels, shoestring sands), both horizontally and vertically and their potential connection and relationships with the river. Bores a similar distance from the river may be screened in different features and assuming they have the same interaction timeframes may not be correct. For example, a bore 500 metres from the river in a gravel paleochannel with a direct connection to the river may have a much greater interaction with the river than a bore close to the river but separated from the river by a leaky aquitard. Although based on limited data, bore monitoring undertaken in this study indicates that regardless of individual bore locations, extraction from the unconsolidated aquifer will have potential interactions with the river within one season.

The large range of values from pump tests and estimated aquifer properties support the variability of the unconsolidated sediments. Pump tests at Bright classified bore 51738 as being screened in a deeper semi confined aquifer (Sinclair Knight Merz 2007b), however, this contradicts hydrographs which show levels and fluctuations the same as a near by shallow bore 51735. The short term nature of the pump test is probably the reason for the results. Long term hydrographs show the true nature of the aquifer, and that in time, the water taken from deeper in the aquifer would be supplied from increased river leakage. Aquifer parameters for the confining layers of the valley identified in bore logs and pump tests are closer to a leaky aquitard than a confining layer (Sinclair Knight Merz 2007a) and thus there is probably limited potential for any identified aquitards to limit leakage from the river. Hydrographs (Section 2.3.2) show high transmissivity with similar annual responses at all depths. The limited lateral and down valley extent of the identified aquitards also limits their confining ability. Confined valleys, narrow distances to valley walls and limited leaky aquitard extents, increase the probability that any partially confined aquifers will have significant connection to the river. The high identified K values, averaging 12 m/day

(Appendix 2), also indicate that there is the potential that any pumping will have an influence on groundwater levels over the whole aquifer within one season. Although this is suggested by the current evidence, longer term pump testing in the deeper aquifer is required to investigate the validity of the above hypothesis and more accurately determine lag times between extraction from the deeper aquifer and leakage from the river. Chemical analysis of groundwater spatially and at different depths of the aquifer could also be utilised to compare components of water in the aquifer and determine if all the water is hydraulically connected.

SKM (2007) has proposed two zones for the management of the unconsolidated aquifer, the first (Zone 1) is 200 m from major water courses. The second zone (Zone 2), accounting for the narrow valley width and where the stream is less than 350 m from the outcropping fractured rock, has the boundary increased to 350 m. Zone 1 is set up on the results from the numerical modelling (Sinclair Knight Merz 2006a), where a bore 10 m from the river will source 100% of its water from the river within one season and a bore 300 m from the river will source 65% of its water from the river within one irrigation season. The maps showing the extent of Zone 1 show a very complex layer that would be very hard to manage due to the meandering of the river and variable nature of surface water features. The Zone 2 boundary shown on the maps basically covers the rest of the unconsolidated aquifer. There may be exceptions on the valley sides with some bores in confined aquifers disconnected from the river or with lag times greater than one season, but these would be managed individually and an option for a possible method of dealing with these is set out later in the chapter.

From management experience in Campaspe and other areas, zones not covering the whole aquifer lead to a proliferation of bores just outside the zone boundary and lead to numerous management issues (G-MW personal communication). Any zones set in the unconsolidated sediment area of the Upper Ovens would still be in the same aquifer. Since the valley is narrow and lag times short, there is little potential for the differentiation of zones with enough width sufficiently to differentiate impacts from pumping. This was recognised in the SKM (2006a, 2007a) reports where it was suggested that the zones represent the degree and timing of impacts to surface water and the proposed zones were preliminary only and based on the limited numerical modelling.

Overall the basic analysis of potential level draw downs in the unconsolidated aquifer, and the fact that it is only the top few metres of the aquifer interacting with the river in low flow periods, mean that the whole aquifer should be managed as one unit. This is the simplest scenario for management with minimum rules and minimum room for interpretation. Implementation of the management principle would mean any bores screened within the unconsolidated aquifer would be managed in line with river flow targets based on flow restriction triggers.

5.2 Management Zones

Extending research results from the study area to encompass the rest of the Upper Ovens catchment depends on uniformity of the geology and groundwater – river interactions. Management issues will vary depending on the geology and aquifers. Zones may be required to be set on a broad scale using geology and on a smaller (aquifer) scale using interaction relationships.

Based on the interactions between groundwater and the rivers of the Upper Ovens Catchment, it is proposed that there should be two broad management zones. Each zone is set based on the risk of groundwater extraction in each zone reducing flows in the Ovens River during low flow periods.

Proposed areas for zoning are based on the two clear hydrogeological units of the Upper Ovens Catchment and follow surface geology features (Figure 2-1). The first zone is defined by the extent of the alluvium and colluvium shown in Figure 2-1, and represents aquifers of these unconsolidated sediments, which make up the intermediate and local groundwater flow cells of the catchment. The second zone is the fractured rock aquifer that covers the rest of the catchment area in Figure 2-1. This zone is made up primarily of Ordovician sandstone and forms the regional groundwater flow system of the area. The separation is based on aquifer parameters and potential for interaction with the rivers and streams.

The fractured rock aquifer's interactions with the Ovens River have not been investigated and little is known about this aquifer in general. However, given the low transmissivity, large storage volume and unpredictable nature of fractured rock aquifer responses to extraction, there is less potential that extraction of the current licensed volume could significantly reduce stream flow. Potential timeframes for interactions would be long and the potential for interactions within the short periods of low flow are less. This aquifer should be managed separately until further information is known. Management of the fractured rock aquifer is not a priority in terms of groundwater-surface water interaction and objectives should be set once more monitoring leads to greater understanding of the aquifer.

The hydraulic gradient and flux analysis in Section 4.4 showed that potentially the regional fractured rock aquifer is buffering the interactions of the unconsolidated aquifer with the river at the valley margins. Evidence to date from this study and the limited numerical modelling (Sinclair Knight Merz 2006a), indicate that the buffering is probably due to down valley flows. However, the lack of data on the fractured rock aquifer means that buffering from the fractured rock aquifer cannot be ruled out. If it is found that the fractured rock aquifer is providing critical water for the unconsolidated aquifer, then management will be required to protect the potential fractured rock aquifer inputs to the unconsolidated aquifer and river.

All of the unconsolidated aquifer should be managed as one unit with all bores screened in the aquifer managed the same way as described by principle number four.

5.3 Implications for users

Under current management, groundwater extraction is limited to extraction of licenced volumes (3700 ML) but is not restricted at any time. If groundwater extraction is restricted in line with surface water restrictions there will be a large shift in usage patterns. Changes to water use practices and irrigation methods would be required to cope with periods of restricted, or no water supply source. Groundwater users would experience an additional impact (over surface water users) as in the years where winter recharge is not sufficient and groundwater levels don't reach possible minimum trigger level they will not be able to access water.

For irrigators with both groundwater and surface water licences, generally groundwater is used as a backup source of water to supplement irrigation in times when there are restrictions on extraction from the river. Using the idealised management scenario would mean that groundwater could no longer be used in this manner and remove the benefit of groundwater. Water users relying on groundwater only would also be impacted by periods of restriction or no access to groundwater. These users will be most impacted as they do not have access to an alternative water supply and have not had to deal with restrictions in the past. An alternative supply of water such as storage would be required by these irrigators for times when supply from the river is banned. Generally users with a groundwater only licence extract at a low rate and use water directly from the bore. Installation of a storage may not be cost effective. If groundwater users change to an open storage there will be evaporation losses and possible leakage that would not be encountered when using groundwater, resulting in sub-optimal water use efficiency.

The frequency and duration of any restrictions will depend on flow levels decided during planning process. A higher trigger flow level means a higher frequency of years with restrictions and also increased lengths of time on restrictions or bans. At an extraction ban of the summer environmental flow recommendation of 137 ML/day (Sinclair Knight Merz 2006d) users will experience a ban on extraction 70 years in every 100 for an average duration of 6 weeks (Goulburn Murray Water 2003). As this timing will occur in the peak irrigation season for many of the crops in the Ovens catchment, this will result in altered irrigation methods or reduced yields.

5.4 Alternative options for conjunctive management

To mitigate the impacts to users of the idealised management scenario suggested by this report, resource managers may wish to consider other management options to provide a security of supply and certainty in groundwater availability for irrigators.

For other Victorian aquifers, restrictions on groundwater extraction have only occurred where large volumes of extraction have caused large aquifer level draw down, resulting in access problems for users (Thwaites 2003; Thwaites 2006). Further indicating the need for management in these areas were the observed reductions in the annual recovery level, indicating that groundwater extraction is above sustainable levels (Spring Hill Groundwater Supply Protection Area Consultative Committee 2001; Campaspe Deed Lead Water Supply Protection Area Consultative Committee 2003; Thwaites 2003). In the Ovens, the proposed restrictions are based on possible rather than observed responses to pumping. Predicting draw down in response to pumping is difficult in a non closed system such as the Ovens catchment. This is due to aquifers generally gaining increased recharge from adjoining aquifers or other sources (Devlin and Sophocleous 2005), in this case the Ovens River and fractured rock aquifer.

In the Katunga WSPA, which borders the Murray River in North Central Victoria, the relationship between extraction volumes and observed draw-down and recovery levels has been used to determine the sustainable level of pumping (Thwaites 2006). Based on the pumping level for the preceding five years, a percentage of the entitlement is allocated for the following season. This gives a level of certainty and allows the irrigators to plan for a given volume of water. Due to the lack of groundwater extraction data for the Upper Ovens catchment, this method cannot be applied. However, the allocation method for the Campaspe WSPA, located in the Campaspe river catchment between Elmore and Echuca in Victoria’s North West, could be applied to the Ovens catchment. In the Campaspe WSPA, a minimum average annual groundwater level target has been set. Water allocations for the following season are based on the spring recovery level and the predicted volume of extraction that will prevent the average groundwater level for the year dropping below the target level (Thwaites 2003).

The Katunga management plan is for a confined deep lead aquifer, and although there is a link with surface water systems for recharge, groundwater extraction does not directly impact on surface features (Thwaites 2006). Due to recharge occurring over time scales of tens to hundreds of years, long term management planning where extraction is balanced with recharge, can be utilised. Water recharging from the Campaspe River and highland area to the south of the Campaspe WSPA provides primary recharge for the water extracted in the WSPA and there is a level of connection with the Campaspe River. This was recognised in the plan and an annual allocation approach to prevent groundwater levels dropping below a set minimum target level was taken to protect the connection (Thwaites 2003). The unconfined nature of the unconsolidated aquifer in the study area, its connectivity with the Ovens River, and the need to protect groundwater fluxes to the stream means that a longer term planning approach cannot be taken. Rapid management responses to adjust for the rapid changes in the groundwater – river relationship, which can occur on a monthly basis, are required, as outlined by the idealised case. However, current groundwater extraction of approximately 1200 ML/yr has not had a significant impact on the flow regime and there may be potential that a volume of water may be allocated for each season with minimal risk to river flow requirements. An annual allocation would give some certainty to groundwater users. As the allocation is annual, a risk of potential impacts in consecutive years of low winter rainfall and recharge exists, and is discussed in each of the options outlined below.

Several options for determining an allocation are discussed with the pros and cons of each option outlined. The purpose of each option is to give a groundwater allocation for the whole of the irrigation season whilst minimising the risk that the extraction of the allocated volume will lower groundwater levels below the river base.

Further analysis may be needed for each option to determine possible implications on river flows under several use and climate scenarios. The difficulty of predicting draw-down responses to pumping and the non-predictive nature of this study mean that accurate comparison of options cannot be produced. Instead a qualitative assessment, using existing data and assuming steady state conditions, with expected responses from the existing knowledge and data gained from this experiment, has been used. A numerical model is needed to run scenarios of different extraction volumes and different climate scenarios. The complexity of the interactions and the simple analysis based on historic data conducted by this study means that the results, and in particular the regression relationships, cannot be used for prediction beyond the bounds of the current data without risking large errors (Moore and McCabe 1993).

5.4.1 Annual recharge based groundwater allocation

The seasonal pattern of fluxes between groundwater and the river shows groundwater being recharged by the surface water system in the winter and discharging to the surface water system over summer. This pattern is similar to the pattern of groundwater level fluctuations seen in the Campaspe deep lead aquifers due to summer pumping (Thwaites 2003).

A similar allocation system to that used in the Campaspe system could be utilised for the unconsolidated aquifer in the Upper Ovens. In the Upper Ovens, the height of the seasonal groundwater recharge would be used rather than the annual recovery level of the aquifer used in the Campaspe WSPA. In the Campaspe the annual recovery level is the aquifer pressures rising due to inflows from recharge and other aquifers after summer extraction ceases. If extraction from the aquifer is greater than flows into the aquifer then the recovery level reduces. In the Upper Ovens, due to the rapid recharge response of the unconsolidated aquifer from the river and the low levels of extraction, aquifer fluctuations in the Upper Ovens are more of a response to the level of surface water (rainfall and flow) over winter and are not related to pumping. The seasonal allocation would be proportional to the recharge over winter.

As discussed in management principle three, the minimum groundwater target level could be based on a chosen river level relating to an environmental flow requirement and would be a level where groundwater is above the stream channel bottom as in Figure 5-4. An allocation would be made for the following season by calculating the winter/spring recharge above the target groundwater level. For years with high winter rainfall and recharge there would be a higher allocation. In years with low winter recharge the allocation would be less.

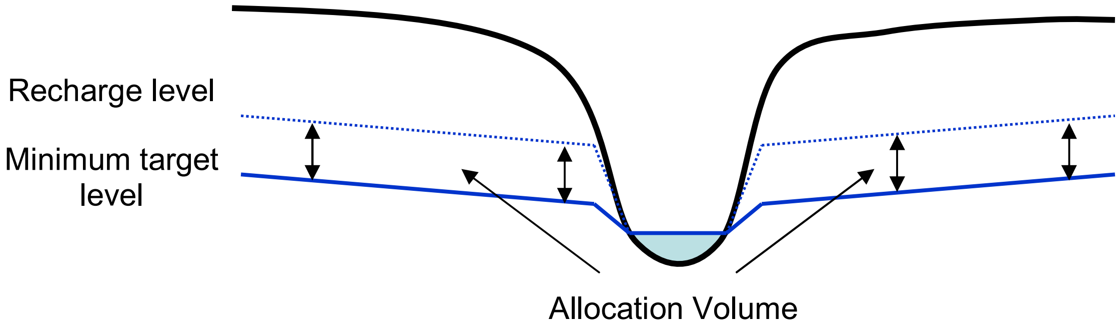

Figure 5-4: Cross sectional representation of groundwater allocation volumes

The benefit of this allocation policy is that it would be conservative as it would not consider recharge from the river in response to pumping. Risks of this approach are the uncertainties around the storage value of the aquifer (high variation of recorded values in Appendix 2) and the actual volume of water held in the aquifer. If a storage value used for allocations is higher than the actual value, there is the risk that groundwater levels would drop below the desired level and could impact on stream flow. If the value used is lower than actual, the allocation would be lower and water users would be affected. The usage patterns of irrigators are also a risk, as the majority of groundwater use is as a backup to surface supply. Thus, they would only turn to groundwater once they are put on surface water restrictions and as a result, groundwater extraction and lowering of groundwater levels would the highest when the risks of groundwater extraction to the low river flows are the greatest.

Use of the allocation volume would intercept flow contributions from groundwater to the river and result in lower flows than without extraction. This may affect other parts of the flow regime, however, as discussed in the introduction to this chapter, apart from in low flow years, the potential interception (37 ML/day) is usually small in comparison to average flows (summer of 500 ML/day).

Depending on the minimum target level, there may be some years where winter recharge is not sufficient to reach the minimum target level, such as the 2006/07 season as explained in Section 5.1.3. In these years an allocation would not be possible and thus this method would not guarantee an allocation every year. This allocation method would also reduce the risk that extraction in one season would effect groundwater contributions for the following season in the event of poor winter recharge. This is because allocations are set to prevent groundwater levels dropping below a set target level.

5.4.2 Allocate groundwater as a percentage of entitlement

An alternative to a recharge based allocation is to use a bulk sustainable extraction volume that can be extracted every year without compromising environmental flow objectives. The allocation percentage would be the proportion of the bulk extraction volume of the total entitlement.

Extraction of groundwater at current levels has been shown not to have a large influence on the water balance, even in low flow periods (Chapter 3). In the 2007 season, groundwater levels did not drop below critical levels when there were no restrictions on groundwater extraction. The simple steady state analysis in this model shows possible impacts of further extraction on groundwater levels in the lowest measured level in Figure 5-1. As discussed previously, this analysis does not allow for potential inflows from the fractured rock aquifer or through flows in the unconsolidated aquifer. It also does not allow for recharge from the river, however, in low flow periods this would not be desirable. The potential for regional fractured rock system inflows to be buffering the fluctuations between the unconsolidated aquifer and the river was identified in Section 4.4. If this is the case the annual fluxes with the river may be occurring on top of the regional flow system and if it can be determined there may be the potential for an annual sustainable allocation of these inflows.

A bulk sustainable extraction volume has not been identified or suggested in this study. The uncertainties around groundwater level equilibriums and inflows from the fractured rock aquifer cannot be calculated with confidence with the analysis used in this study. If a sustainable volume is identified from future studies, it is likely that rules for restrictions on extraction would be required in summer to prevent river flows or groundwater levels to drop below minimum levels. As such there may be no significant benefit of having an allocation as the likelihood of irrigators having restricted access to water may be similar to that if the whole entitlement were available.

5.4.3 Zonal approach based on proven exceptions

Although indicated (Chapter 4), it has not been shown with confidence that the whole of the unconsolidated aquifer has the same relationship with the river as the study area and bores used in analysis. There may be some bores that are disconnected from the river by aquitards where their vertical or spatial distance from the river means that the lag time for the impacts of extraction on the river are much longer than those observed in this study. There may also be areas on the valley margins where inflows from the fractured rock aquifer may buffer extractions from the unconsolidated aquifer and limit impacts of extraction on river flows. Resource managers may wish to have an option for different management of these licences.

Under this option the unconsolidated aquifer would be managed as two zones as proposed by SKM (2007a), where the first zone is managed to the idealised case. The second zone takes into consideration the aquifer variability and recognises bores that may have a longer lag period for impacts than the summer period. It could also consider areas where extraction is intercepting inflows from the fractured rock aquifer that are not influencing river flows. For Zone 2, the bores would not be managed as surface water but as groundwater and would be subject to another set of rules. The water balance indicates that if these bores have a lag time of greater than 4 months, then the possible impacts during the critical low flow period would be minimal and recharge would occur in the winter period. Bores in Zone 2 could be allowed to extract without restrictions, however, the resource manager should recognise that there may still be an impact and should groundwater levels drop significantly, restrictions may be necessary. A groundwater level trigger should be set for these restrictions as a fail safe and appropriate monitoring conducted by the licence holder or resource manager.

As discussed in management principle 3, it is not feasible with the current level of knowledge to define a second zone using distance from the river or aquifer depth. The onus would be on the groundwater users to show that their extraction bore in the unconsolidated aquifer is disconnected from the river or lag times for interactions are greater than one season. Due to the complexity of the aquifer, the costs and difficulty to prove through pump tests and analysis will be high. This is due to the variability of the aquifer with old meanders and shoestring aquifers. Many observation bores would be required. An example was highlighted with the data capture and analysis at Ovens where a response to pumping from a nearby bore was seen in bore 48070 but not 48052 (Section 4.1). The results highlight the difficulty in using short term pumping tests to investigate longer term interactions. Also, the bore locations used for monitoring relative to aquifer features of the extraction bore will also have an influence on the results especially for the shorter term pump tests.

A risk for the resource manager in this option is the perceived equity between users and creation of the “haves and have nots”.

Chapter 6: Conclusions

The Upper Ovens River Catchment has a wet winter/spring and dry summers. River flow follows these climate patterns with peak median monthly flows of 2,730 ML/day (Table 2-2) after the wet period and with spring snow melt, and low median monthly flows (133 ML/day) over the dry summer. Two major aquifer systems exist in the Upper Ovens catchment. A larger regional fractured rock aquifer exists in the Ordivican marine sediments, with water containing less than 300 mg/L TDS and yields less than 0.1 ML/day, it is used generally for domestic and stock use. The second aquifer system occurs in the unconsolidated sediments that have in-filled the valleys by alluvial processes. The TDS of this groundwater is less than 200 mg/L and its higher bore yields (up to 1 ML/day) lead to its use for irrigation. It is hard to differentiate the sediments into aquifer units from bore logs, different formations exist as heterogeneous shoestring layers and discrete units rather than layers extending across the valley (Section 2.2.3). The aquifer systems of the unconsolidated aquifer are unconfined, connected to the Ovens River and show seasonal responses to river and climate fluctuations (Figure 2-5).

On average, water extraction from the Ovens River and groundwater is only a small amount (less than 6,000 ML) of the mean annual flow (584,000 ML) and for the majority of time does not have a large influence on the flow regime. However, the low flow periods over summer have been identified as being the part of the flow regime that are stressed and an environmental flow recommendation of 137 ML/day has been recommended for these times (Sinclair Knight Merz 2006c; Sinclair Knight Merz 2006d). Currently, extraction is banned when flows drop below 4 ML/day (Section 2.6.3). As daily demand (from the river) can peak at 35 ML/day (Figure 2-13), this can have an influence on the riverine environment at low flow periods and a Water Management Plan is proposed to protect environmental flows for the Upper Ovens River (Victorian Government 2004). Due to the high connectivity between groundwater and surface water, and for effective protection of stream flow, especially in times of low flow, groundwater extraction has to be managed conjunctively with stream flows. Environmental stream flow objectives have been identified, but no method exists to link these to groundwater objectives. Without this link, water resource managers cannot develop management methods and plans for groundwater to achieve surface flow objectives.

Analysis of existing data commonly available to water resource managers was utilised to investigate the groundwater-surface water relationship and water cycle in the Upper Ovens catchment. In the study area (Figure 3-2) the average of water balance values (between 1975 and 2005) show a clear seasonal pattern for movement of water between surface water and groundwater and infer the strong relationship between the river and the aquifer system. Groundwater levels have remained in equilibrium, with average annual groundwater recharge from rainfall and the river of 9,773 ML nearly equal to average annual discharge of 9,584 ML from the aquifer as baseflow or evaporation in the dry season. Generally extraction of groundwater and surface water (3,200 ML/yr) are only minor components of the water balance (560,000 ML/yr) and do not affect the flow patterns in the Ovens River. However, in years with very low flows over the Summer/Autumn period, extraction from the river can potentially significantly reduce flow in the river. Management of river flow at this time should be the focus for water resource managers.

A possible model for the seasonal water movement in the study area is inferred from the average monthly water balance results and conceptualisation. The model describes the relationship between the unconsolidated sediment aquifer bounded by the relatively impermeable (compared to alluvial) fractured rock aquifer and the Ovens River between Bright and Myrtleford. The surface-groundwater interaction relationship inferred from the water balance is as follows. Starting in winter, the aquifer recharges and the water table is at its peak over the high rainfall winter and spring period. River flows are also at their peak in this period. Reducing rainfall and increasing ET over late spring/early summer cause the river stage to drop, and high groundwater levels mean the water flux is from the groundwater system to surface water. Flux volumes drop later in summer (possibly due to the groundwater gradient (head) reducing) until groundwater losses are at the lowest in late summer. Once there is rain in autumn, the aquifer recharges through rainfall and river infiltration and the surface water system is in net loss. This continues until the aquifer levels are level to, or higher than, the river stage and a rough equilibrium exists, usually in

June. The equilibrium continues over winter and spring when low rainfall and flows cause the cycle to start over. At any stage over winter, if the river stage is higher than the water table, then the river will lose to the aquifer and vice versa.

Construction of hydraulic gradients at selected valley cross sections showed that groundwater levels have not fallen below the base of the stream channels for the period of record. The results indicate that in any periods of low river flow and groundwater levels, the river is dependant on groundwater to supply the deep pools and provide minimal baseflow in some areas (Section 4.2). During these periods, the river will develop into a series of pools fed by groundwater with flow only in sections where the river channel has incised lower than the water table. High transmissivity of the shallow aquifer leads to a rapid exchange between groundwater and the river. It can be seen from Figure 4-3 and Figure 4-4 that any rise in river levels above groundwater levels sees a rapid response in groundwater recharge to reach an equilibrium point in around 14-20 days at 750m from the river. With the valley flats and unconsolidated aquifer generally less than 2km wide, there is a reasonable expectation that interactions for the whole aquifer width would occur well within one irrigation season (90-100 days).

At the cross sections, the Ovens River was shown to only lose water to groundwater during river rising events when the river level is above groundwater levels. As the distance from the river increased, the amount of time that river levels were above groundwater levels decreased. For example at Myrtleford bore 83232 (500m from the river), the hydraulic gradient was from the river for less than 1% of the time between 1973 and 2007. This indicated that either the cross sections were all in areas where the topography forced the hydraulic gradient towards the river, or the groundwater levels were being buffered from either down valley groundwater flow or regional bedrock inputs. Responses to rapid river level rises were seen in the monitoring of bores furthest from the river at Ovens and Myrtleford (Section 4.1), indicating that there is still a strong hydraulic connection with the river, and down valley flow is the probable source of the fluctuation. The regression relationships also showed a strong correlation between groundwater levels and river levels for all bores, further supporting the strong hydraulic connection from the predominant down valley flow, identified by SKM (2006a) when flow vectors were modelled for a small section of the study area (Appendix 5). It is reasonable to expect that the whole of the unconsolidated aquifers are connected.

Regression analysis produced equations relating Ovens River levels to groundwater levels with a high correlation. These equations can relate stream flow objectives to corresponding groundwater management that can be used by resource managers with a high level of confidence (currently only at Myrtleford). Investigation of data subsets found that the regression relationship did not vary significantly between periods of rising and falling groundwater levels or in periods of low flow. The high correlation between river level and groundwater level for all bores indicate a high hydraulic connectivity between the aquifer and the river.

Groundwater and surface water in the form of river flows are intrinsically linked and to protect flows in the Ovens River during times of low flow, an idealised management option has been identified where groundwater users in the unconsolidated aquifer are managed in line with surface water users. Four principles have been identified for idealised conjunctive management option in the Upper Ovens; resource managers should set management rules based on the following principles:

1) Groundwater and surface water are hydraulically connected, manage as one;
2) Restrict groundwater extraction in line with surface water restrictions;
3) Manage groundwater to minimum groundwater levels; and
4) Manage groundwater in the unconsolidated sediments as one aquifer.

6.1 Limitations and further research

This thesis has established the rapid rate of interactions between groundwater and the Ovens River, and that they can be managed as one. Some uncertainty exists around the calculated volumes of groundwater in the unconsolidated aquifer due to limited numbers of pump tests and high variability in the measured aquifer parameters. Aquifer parameters also have a large influence on the calculated value of fluxes between the groundwater and surface water and, more importantly, the volume of water in the aquifer and related draw down for a given extraction volume. Increased certainty in these values through further analysis such as pump testing will help to verify results of this research and increase confidence for future conjunctive management.

Different methods used in this study identified variations in calculated down valley flow and river-groundwater fluxes (Section 4.4). Whether this variation is recharge from the river or part of the regional aquifer system is uncertain, and flow cannot be differentiated by the two dimensional flux analysis undertaken in this study. Draw-down calculations in Section 4.5 use simple equations that don't allow for increased recharge or input from other sources to influence the groundwater equilibrium level after extraction. Volumes calculated are a guide only and not a robust sustainable yield estimate. There is the potential that the down valley flow or inflows from the fractured rock could buffer extraction from the unconsolidated aquifers. With sufficient buffering extraction may not reduce groundwater levels to a level where they won't reduce river flow in low flow periods.

Additionally there is the possibility of there being a significant groundwater resource in the fractured rock aquifer and there may be a potential to shift licences to this aquifer. Very little is known about the aquifer and its interactions with the unconsolidated aquifers of the valley and with surface water. Investigations on the resource potential, interaction with surface features and lag times, or impacts on base flow in low flow times, would enable consideration of the potential use of this resource without impacting on Ovens River flow.

A resource investigation using a numerical model of the whole catchment including the fractured rock system could be developed. This could investigate if it is possible for fractured rock inflows to buffer extraction from the unconsolidated aquifer. Sustainable yield volumes could also be calculated for the fractured rock aquifer. Monitoring bores are required in the fractured rock aquifer so the resource can be investigated and managed as an alternate water supply.

Limited information is available on the deeper unconsolidated aquifer and its connectivity to the shallower aquifer and the river or surface water features. The logging and lag times calculated in this study were for the shallower aquifer and interactions. Assumptions, and limited pump testing at Bright, have been used to evaluate the connectivity. The assumption of connectivity is based on the unconfined nature of the aquifer with confining layers being limited in extent and acting as leaky aquifers rather than aquitards. Further evidence showing the actual connectivity of the deeper unconsolidated aquifer to the shallow aquifer and river, and that extraction from anywhere in the unconsolidated aquifer will impact on stream flow within one irrigation season, is required. Research could include chemical analysis to investigate if water in all parts of the aquifer has similar chemical composition (well mixed) and are similar in age. Another technique to improve certainty in lag times for impacts of extraction on river levels is pump testing. These would be beneficial for a resource manager wishing to give further confidence to the results of this study showing that all groundwater can be managed under the same rules as surface water.

The cross sections and regression equations are only representative of the aquifer at these points or in close proximity. Only the cross section at Myrtleford has regression relationships with a high level of confidence. Developing regression relationships at the other cross sections and tributaries within the Ovens Catchment outside the study area will enable prediction of groundwater level for the whole aquifer. To develop regression relationships requires river level monitoring and development of HEC-RAS models at the existing cross sections at Ovens and Bright. Development of new bore cross sections and river monitoring would be required for the major tributaries if predictive equations are needed in these areas. The new sites could also confirm the assumption of this study that the groundwater-stream relationships are the same for the tributaries as the study area. Installation close to existing river gauges would reduce costs and enable historic relationships to be investigated.

6.2 Further research recommendations

To investigate the potential use of groundwater in the future and to increase confidence in some conclusions of this research the following recommendations for further studies are:

1) Pump testing to increase confidence in aquifer parameters and confirm connectivity between shallow and deep aquifers.
2) Numerical modelling of the whole catchment including the fractured rock aquifer to investigate the potential for groundwater extraction without impacting on low flows in the Ovens River.
3) Installation of monitoring bores in the fractured rock aquifer.
4) Chemical analysis to investigate if water in all parts of the aquifer has similar chemical composition (well mixed) and are similar in age.
5) Pump testing to confirm lag times for impacts of pumping on stream losses are of similar magnitude to those outlined in this thesis.
6) River level monitoring and development of HEC-RAS models at the bore transects at Ovens and Bright to allow the development of statistically significant regression relationships at these sites.
7) Installation of new observation bores near existing river gauges in the Ovens River tributaries confirm that relationships between groundwater and the streams are the same as the main stem. Possible sites include the Buckland River, Barwidgee and Happy Valley creeks.

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Appendix 1: Evapotranspiration Calculations

Evapotranspiration (ET) is a complex and detailed factor to calculate. This appendix details the assumptions and calculations used to develop the ET series used in the study area water balance in Section 3.2.2. Evapotranspiration and Rainfall are the 2 major components of the water balance and required accurate estimates to make the water balance, balance. There are many methods for calculating Evapotranspiration however the FAO Penman-Monteith is considered the international standard for calculating reference crop evapotranspiration (Chiew et al. 1995).

The Australian Bureau of Meteorology (BOM) has produced potential aerial evapotranspiration maps for Australia. These maps are based on Morton's (1983) complementary relationship which is based on the Priestly-Taylor equation (Australian Bureau of Meteorology 2001). They have been based on 30 years of data between 1961 and 1990. Interpreting these maps gives the average potential Evapotranspiration which can be approximated to the Penman-Monteith ET_o. From these maps the average ET_o for the area is 1100mm per year.

For the study the FAO Penman-Monteith methodology will be used to determine evapotranspiration as it allows for the potential to alter ET estimates for different crop types. The definition of reference crop Evapotranspiration is as defined by the FAO and is the rate of evapotranspiration from a hypothetical grass reference crop with specific characteristics that is not short of water (Allen et al. 1998).

Evapotranspiration rates vary between plant species and also vary for different times of the year and different stages of plant growth. To account for these variations the reference evapotranspiration (ET_o) is multiplied by a crop factor (k_c) to give a particular crop evapotranspiration (ET_c) as shown in Equation 18.

$$ET_c = k_c \times ET_o \tag{18}$$

Calculation of Reference Evapotranspiration - FAO Penman-Monteith method

The FAO Penman-Monteith method for calculating the reference crop evapotranspiration (ET_0)is the adopted standard for this calculation (Allen et al. 1998). The method requires climate data that may not be readily available for the study catchment and there are several variations provided that can be used depending on the availability of the climate data (Grayson et al. 1996; Allen et al. 1998).

The Penman-Monteith method for determining Evapotranspiration is shown in Equation 19. It uses an energy balance to determine the potential Evapotranspiration on a given time step for the reference crop. For the water balance ET_0 has been calculated on a daily interval.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad \textbf{(19)}$$

The components that make up the equation are defined as

ET_0	Reference crop Evapotranspiration [mm d^{-1}]
R_n	net radiation at crop surface [MJ m^{-2} d^{-1}]
G	soil heat flux [MJ m^{-2} d^{-1}]
T	average temperature [˚C]
U_2	windspeed measured at 2m height [m s^{-1}]
(e_s-e_a)	vapour pressure deficit [kPa]
Δ	slope of vapour pressure (see Equation 29)
γ	psychometric constant [kPa °C^{-1}].

Components of the Penman-Monteith equation require several other backing equations for determining them. The following sections outline equations used and how each component was calculated from the climate data available.

Average Temperature

Average temperature has been calculated by averaging the daily recorded maximum and minimum temperatures at the climate site as shown in Equation 20. This has been recommended for use in saturation equations due to the non-linear nature of saturation vapour pressure with temperature (Allen et al. 1998).

$$T = \frac{T_{\max} + T_{\min}}{2} \qquad (20)$$

Climate data has been recorded by the Australian Bureau of Meteorology (BOM) at several local climate stations. There was one site in the study area at Myrtleford (site 082034) however this site was closed in 1968 with temperature data recorded between 1965 and 1969. There are several climate sites in the surrounding area and these were used to develop the temperature series. The sites used are Wangaratta Aero (site 082138) with data from 1987 to present, Wangaratta (site 082053) with data from 1868 to 1987 and Buffalo Chalet (site 083073) with data from 1910 to present.

Wangaratta is approximately 50km north east of Myrtleford It also has an elevation of 150m which is a similar elevation to Myrtleford at 220m. The Buffalo Chalet site has an elevation of 1500m and thus was not considered appropriate for estimating temperatures in the study area. The Wangaratta data was used as the basis to develop a temperature time series for the water balance. A series called the Wangaratta composite was developed by adding Wangaratta Aero to the Wangaratta data as the Aero site is the replacement for the Wangaratta site.

The Wangaratta Composite had several periods with no data. These periods were infilled using recorded temperatures at the Buffalo chalet site converted to represent Wangaratta temperatures. Regression relationships between recorded temperatures at the Buffalo and Wangaratta sites were utilized to modify the Buffalo Data to reflect expected temperatures at Wangaratta. Maximum and Minimum temperatures were analysed separately between the period of 1965 -1980. Only days with a recorded temperature at both sites were included. Maximum temperature relationships had 4807 days of data comparison and had a R^2 of 0.9221 with the regression relationship shown in Equation 21. Minimum temperatures had 4867 days for comparison. Due to the large elevation difference, minimum temperature relationship correlations were lower with a R^2 of 0.6604 The relationship equation is defined by Equation 22. Remaining data gaps in the Wangaratta Composite temperatures series were infilled using a linear relationship between the temperatures recorded before and after the data gap.

$$WangarattaComposite = 1.0403 \times BuffaloChalet + 8.8463 \qquad (21)$$

$$WangarattaComposite = 0.8146 \times BuffaloChalet + 4.211 \qquad (22)$$

A temperature series representing study area was developed to represent the climate station at Myrtleford. To develop the series the complete Wangaratta Composite series was converted to represent Myrtleford temperatures using a regression analysis between the sites. The regression method was as for the Buffalo – Wangaratta regression analysis. The period of analysis was between 1965 and 1969 and 720 days of data were used in the analysis. Both data sets had a high regression correlation with Maximum temperatures represented by Equation 23 and (R^2 of 0.9561) and Minimum temperatures represented by Equation 24 (R^2 of 0.8614).

$$Myrtleford = 0.9859\ x\ Wangaratta + 0.2325 \qquad (23)$$

$$Myrtleford = 0.8926 * Wangaratta - 0.6497 \qquad (24)$$

Soil Heat Flux

If there is a lack of data this component can be set to zero as ET_o is only sensitive to the soil heat flux (*G*) if there is a large difference in temperature between two days (Grayson et al. 1996). Equation 25 has been used for calculating *G* (Allen et al. 1998). Good temperature data is available for the whole period and the average temperature as calculated in section 0 was used. The volumetric heat capacity of the soil (c_s) has been set at 2.1 which is the calculated value for moist soil (Grayson et al. 1996). The effective soil depth (d_s) has been set at 0.2m which is considered the depth of soil affected by daily temperature fluxes (Allen et al. 1998).

$$G = c_s d_s \left(\frac{T_n - T_{n-1}}{\Delta t} \right) \qquad (25)$$

where

c_s volumetric heat capacity of soil [MJ m^{-3} $°C^{-1}$] ≈ 2.1 for moist soil

d_s estimated effective soil depth [m] – taken as 0.2 m due to daily time step

T_n average temperature on day

T_{n-1} average temperature on preceding day

Δt Length of period

Vapour pressure deficit

Generally the two parts of the vapour pressure deficit calculation, saturation vapour pressure (e_s) and actual vapour pressure (e_a) are calculated from Equation 26 and Equation 27 respectively (Grayson et al. 1996; Allen et al. 1998). However Equation 27 requires relative humidity data (RH) and Relative humidity data for the area is very incomplete and only covers a small period of the water balance period.

$$e_s = 0.611 \exp\left(\frac{17.27T}{T + 237.3} \right) \qquad (26)$$

$$e_a = RHe_s \qquad (27)$$

An alternative, Equation 28 is provided using dewpoint temperature (T_{dew}) to calculate the actual saturation vapour pressure (Allen et al. 1998). A good record of dewpoint temperature data is available at the Wangaratta BOM stations (082138 and 082053). Data from both sites has been combined to create a data series that was used in analysis. Temperature data was the average temperature series as described in section 0.

$$e_a = 0.6108 \exp\left(\frac{17.27 T_{dew}}{T_{dew} + 237.3} \right) \quad (28)$$

6.2.1.1 Slope of vapour pressure curve

The slope of vapour pressure (Δ) is calculated by Equation 29 (Allen et al. 1998) and uses the average temperature and saturation vapour pressures calculated in earlier sections.

$$\Delta = \frac{4098 e_s}{(T + 237.3)^2} \quad (29)$$

Windspeed Calculations

Only a limited amount of data was available between 1965 and 1969 for the Myrtleford site. A data series has been created for the modelling period using the Wangaratta BOM stations (082138 and 082053) and used in the Evapotranspiration calculations. Days with no record were infilled using the default value of 2m/s (Allen et al. 1998).

Available recorded windspeed data for Myrtleford only had a low correlation ($R^2 = 0.14$) with recorded wind speeds at Wangaratta. Low windspeed correlations ($R^2 = 0.21$-0.28) were also shown between three sites in central Australia (Justin F. Costello et al. 2007) which indicates that windspeed is highly variable between sites. This high variability has the risk of incorporating an error into the ET_0 calculation if the Wangaratta data is used.

Evapotranspiration calculations using the FAO penman Monteith method have been shown to not be overly sensitive to windspeed (Allen et al. 1998). To confirm that the high variability in windspeed did not incorporate a high error for the ET_0 calculations, a comparison of the ET_0 calculated for the Wangaratta windspeed series was compared to ET_0 calculated for a representative Myrtleford wind speed series. Comparison of the calculated ET_0 showed less than 1% difference between using the different windspeed series for the 30 year modelling period confirming the applicability of using the Wangaratta data.

6.2.1.2 Net Radiation Calculations

Net Radiation (R_n) was calculated based on the FAO expert panel methodology (Allen et al. 1998) which has been considered a standard in other studies (Grayson et al. 1996; Justin F. Costello et al. 2007). R_n is calculated by subtracting the net incoming short-wave radiation (R_{ns}) from the net outgoing longwave radiation (R_{nl}) as summarised in Equation 30.

$$\begin{aligned} R_n &= (1-\alpha)\times\left(a_s + b_s\frac{n}{N}\right)R_a - \left(0.1 + 0.9\left(\frac{n}{N}\right)\right) \\ &\times 2.45\times10^{-9}\left[0.34 - 0.14\sqrt{e_a}\right]\times\left[T_{\max}^4 - T_{\min}^4\right] \end{aligned} \qquad (30)$$

where α is albedo (0.023 for grass), a_s is the fraction of extraterrestrial radiation on overcast days (set at 0.25), b_s is a constant at 0.5 for average climate, n is the sunshine hours per day, N is the total day length in hours, R_a is the solar radiation, e_a is the saturation vapour pressure, T_{max} is the maximum daily temperature and T_{min} is the minimum daily temperature. The solar radiation term (R_a) is calculated from Equation 31.

$$R_a = 37.6(1 + 0.033\cos(0.0172J))\times(\omega_s\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega_s) \qquad (31)$$

where J is the Julian Day, ω_s is the sunset hour angle (rad), φ is the latitude (rad), δ is the solar declination (rad).

Sunshine hours are not recorded at any of the local BOM climate sites. Regionally data is collected at Lake Eildon (site 88023). This site is 100 km west of Mytleford. Regional data has been used in other Australian studies on Evapotranspiration (Costello et al. 2007) and shown to provide acceptable results in an North American study (Winter 1999).

Psychometric constant

Elevation of the Myrtleford BOM station is 220 mAHD. The psychometric constant (γ) at 200m elevation is 0.066, Table 2.2 (Allen et al. 1998). This γ value has been used in all calculations.

Appendix 2: Recorded unconsolidated sediment aquifer parameters

Location	Aquifer	Bore ID	Screen interval from (m)	Screen interval to (m)	Literature Storativity (S)	Storativity Value for analysis	Hydraulic conductivity (K) (m/d)	K Value for analysis	Pump test type	Source
Bright	Shallow	51740	44.5	49.5	0.00024	0.00024	1 to 15	7		(Shugg and Slater 1987)
Barwidgee	Shallow				0.0001	0.0001	60	60		(Thompson 1972)
Porepunkah	Shallow				0.0001	0.0001	5 to 10m	7.5		(Shugg 1987b)
Myrtleford	Shallow				0.0009	0.0009	0.5 to 8	4		(Rural Water Commission of Victoria 1986)
Myrtleford	Shallow				0.0009	0.0009	7	7		(Shugg and Slater 1987)
Myrtleford	Shallow				0.1 to 0.25	0.125	21 to 65	30		(Rural Water Commission of Victoria 1986)
Ovens	Shallow				0.26	0.26			Analysis value	(Sinclair Knight Merz 2007a)
Bright	Shallow				0.2	0.2			Analysis value	(Shugg 1987a)
Millewa	Shallow		7	9	0.1	0.1	10	10		(URS 2007)
Wangaratta	Deep	G8021177/01			0.0004 to 0.0013				step drawdown and constant rate	(Sinclair Knight Merz 2007c)
Ovens	Shallow	Coonambidgal	0	15	0.0501	0.0501	9	9	MODFLOW	(Sinclair Knight Merz 2006a)
Ovens	Shallow	Shepparton	15	30	0.0501	0.0501	9	9	MODFLOW	
Ovens	Deep	Shepparton	30	70	0.0011	0.0011	4	4	MODFLOW	
Ovens	Deep	Calivil	70	85	0.0501	0.0501	9	9	MODFLOW	
Bright	Shallow	51747	3	20	0.02	0.02	15	15		(Cox. F 1989)
Bright	Deep	51738	58	63	0.001	0.001	0.985915493	1	Constant Rate	(Sinclair Knight Merz 2007b)
Bright	Deep	51737	36	42	0.0009	0.0009	4.730769231	5	Constant Rate	
Bright	Deep	51735	26.4	32.6	0.00012	0.00012	4.704545455	5	Constant Rate	
Bright	Shallow	51745	5	11	0.01	0.01	16.75	17	Constant Rate	
Bright	Shallow	51743	5	11	0.00135	0.00135	42	42	Constant Rate	
Bright	Shallow	51747	3	20	0.01	0.01	7.65	8	Constant Rate	
Boorhaman	Deep	62863	109	122	0.001	0.001	3.387096774	3	Constant Rate	(GHD 2008)
Boorhaman	Deep	62864	111	121	0.001	0.001	2.928571429	3	Constant Rate	
All Results	Average					0.03		12.2		
	median					0.001		7.5		
	10th percentile					0.00013		3		
	90th percentile					0.12		30		
Shallow Aquifer	Average					0.059		16.9		
	10th percentile					0.00034		4.6		
	90th percentile					0.18		39.6		

Appendix 3: Surface Water System Balance

Month	Ovens River Flow at Bright 403205	Buckland Flows 403233	Buffalo Creek Flows	Volume Rainfall	Study Area runoff (24% fixed)	*Surface Inflow Total*	Myrtleford Flows 403210 (Infill 1)	Irrigation	D&S	Other	ETo	*Surface Outflows*	**Surface Balance**	Ground water Fluctuation (S=0.265)
	1	2	3	4	5	7	8	9	10	11	13	15	17	18
						= 1+2+3+4 +5						*=8+9+10 +11+13*	**=15 - 7**	
Jan	5,577	4,294	1,300	3,353	2,683	*17,206*	12,412	689	9	3	7,901	*21,014*	**3,807**	-3,305
Feb	3,367	2,642	881	2,395	1,916	*11,201*	7,247	552	8	3	6,657	*14,467*	**3,266**	-2,610
Mar	2,928	2,154	749	2,645	2,116	*10,592*	6,217	339	9	3	5,237	*11,805*	**1,213**	-1,779
Apr	3,993	3,536	1,432	3,140	2,512	*14,613*	9,835	56	9	3	3,004	*12,906*	**-1,707**	-503
May	8,463	8,475	3,419	4,960	3,969	*29,286*	23,256	3	9	3	1,605	*24,876*	**-4,410**	-327
Jun	14,001	13,950	4,994	5,374	4,300	*42,618*	39,425	0	9	3	984	*40,421*	**-2,197**	3,082
Jul	30,669	31,440	7,751	6,375	5,101	*81,336*	81,683	0	9	3	1,041	*82,736*	**1,399**	4,220
Aug	42,187	41,421	8,513	6,472	5,179	*103,772*	109,811	0	9	3	1,705	*111,528*	**7,756**	3,916
Sep	41,688	40,101	7,372	5,659	4,529	*99,349*	106,373	0	9	3	2,719	*109,104*	**9,754**	1,862
Oct	37,368	34,479	6,011	5,243	4,195	*87,295*	91,934	2	9	3	4,368	*96,316*	**9,021**	552
Nov	17,382	15,559	2,720	3,650	2,921	*42,232*	43,388	64	9	3	5,882	*49,346*	**7,114**	-1,874
Dec	10,686	9,094	1,859	3,329	2,664	*27,631*	25,790	304	9	3	7,190	*33,296*	**5,665**	-2,970
Annual Sum	218,310	207,145	47,001	52,592	42,085	*567,133*	557,369	2,007	104	38	48,294	*607,813*	**40,680**	263

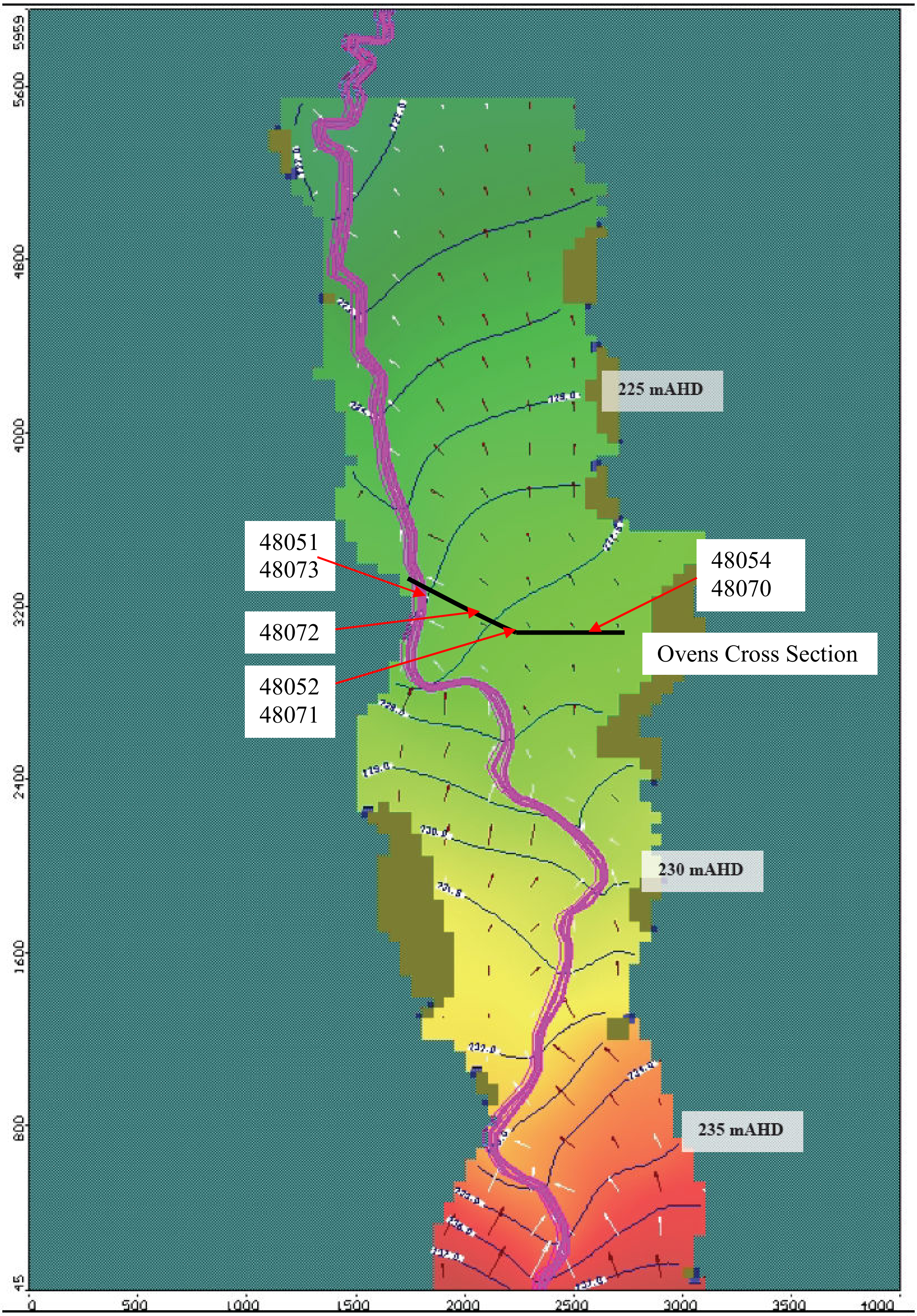
All values shown are in ML

Appendix 4: Upper Ovens State Observation Bore Details

Bore	Construction Date	Depth (m)	Screen Top (m)	Screen Bottom (m)	Registered Screened Lithology	Natural Surface Level (mAHD)	Zone 55 Easting	Zone 55 Northing
109653	21.05.1979	60	39	42	CALIVIL FORMATION	283.99	493271.4	5938081
109652	21.05.1979	60	11	15	SHEPPARTON FORMATION	283.99	493271.4	5938081
109462	28.08.1978	51	45	51	BEDROCK	310.02	497817.4	5935265
109461	28.08.1978	51	5	51	SHEPPARTON FORMATION	310.02	497817.4	5935265
88274	21.08.1987	90.5	33	53	CALIVIL FORMATION	266.4	491113.4	5939534
88273	20.06.1979	15	9	15	SHEPPARTON FORMATION	283.7	493217.4	5938027
88272	13.06.1979	15	10	15	SHEPPARTON FORMATION	284.21	493256.4	5938066
88271	07.06.1979	15	10	15	SHEPPARTON FORMATION	283.88	493295.4	5938060
83232	08.10.1987	13	6	12	SHEPPARTON FORMATION	208.27	474813.4	5953234
83231	07.10.1987	14.5	8	14	SHEPPARTON FORMATION	208.6	474913.4	5952984
83230	23.09.1987	15	8	14	SHEPPARTON FORMATION	208.17	474663.4	5952984
83229	21.09.1987	15	8	14	SHEPPARTON FORMATION	207.91	474663.4	5952984
51747	05.03.1989	20	2	20	SHEPPARTON FORMATION	316.79	499213.4	5935414
51745	28.10.1987	12	5	11	SHEPPARTON FORMATION	322.33	499063.4	5935134
51744	27.10.1987	13	6	12	SHEPPARTON FORMATION	322.15	499063.4	5934984
51743	22.10.1987	12	5	11	SHEPPARTON FORMATION	315.56	499163.4	5935384
51741	15.07.1980	58	44	50	SHEPPARTON FORMATION	311.95	497163.4	5934734
51740	15.05.1980	58	44.5	49.5	CALIVIL FORMATION	311.95	497163.4	5934734
51738	19.10.1979	71	58	63	CALIVIL FORMATION	311.17	498395.4	5935418
51737	16.08.1979	52	36	42	SHEPPARTON FORMATION	316.78	498443.4	5935660
51736	05.06.1979	29	20	26	SHEPPARTON FORMATION	315.63	498383.4	5935297
51735	23.05.1979	44	26.4	32.6	SHEPPARTON FORMATION	316.3	498391.4	5935313
48073	21.10.1987	11	4	10	SHEPPARTON FORMATION	230.5	480813.4	5947884
48072	20.10.1987	12	5	11	SHEPPARTON FORMATION	230.6	481063.4	5947934
48071	14.10.1987	12	5	11	SHEPPARTON FORMATION	230.97	481213.4	5947984
48070	13.10.1987	12	5	11	SHEPPARTON FORMATION	231.69	481463.4	5948284
48069	01.10.1987	9	5	8	SHEPPARTON FORMATION	250.8	487813.4	5944634
48068	09.09.1987	15	7	13	SHEPPARTON FORMATION	251.41	487763.4	5944634
48067	04.09.1987	15	-9999	-9999	SHEPPARTON FORMATION	250.47	487613.4	5944584
48066	28.08.1987	16	9	15	SHEPPARTON FORMATION	251.62	487563.4	5944534
48054	05.12.1971	57.6	2.4	55.4	SHEPPARTON FORMATION	231.57	481709.4	5948171
48053	21.11.1971	61.26	3.66	51.51	SHEPPARTON FORMATION	231.95	481633.4	5948120
48052	29.10.1971	45.11	4.3	43.8	SHEPPARTON FORMATION	230.86	481468.4	5947893
48051	17.10.1971	37.18	2.7	11.5	SHEPPARTON FORMATION	230.55	481126.4	5947831
48048	31.08.1971	53.03	17	50	SHEPPARTON FORMATION	228.71	481077.4	5948350

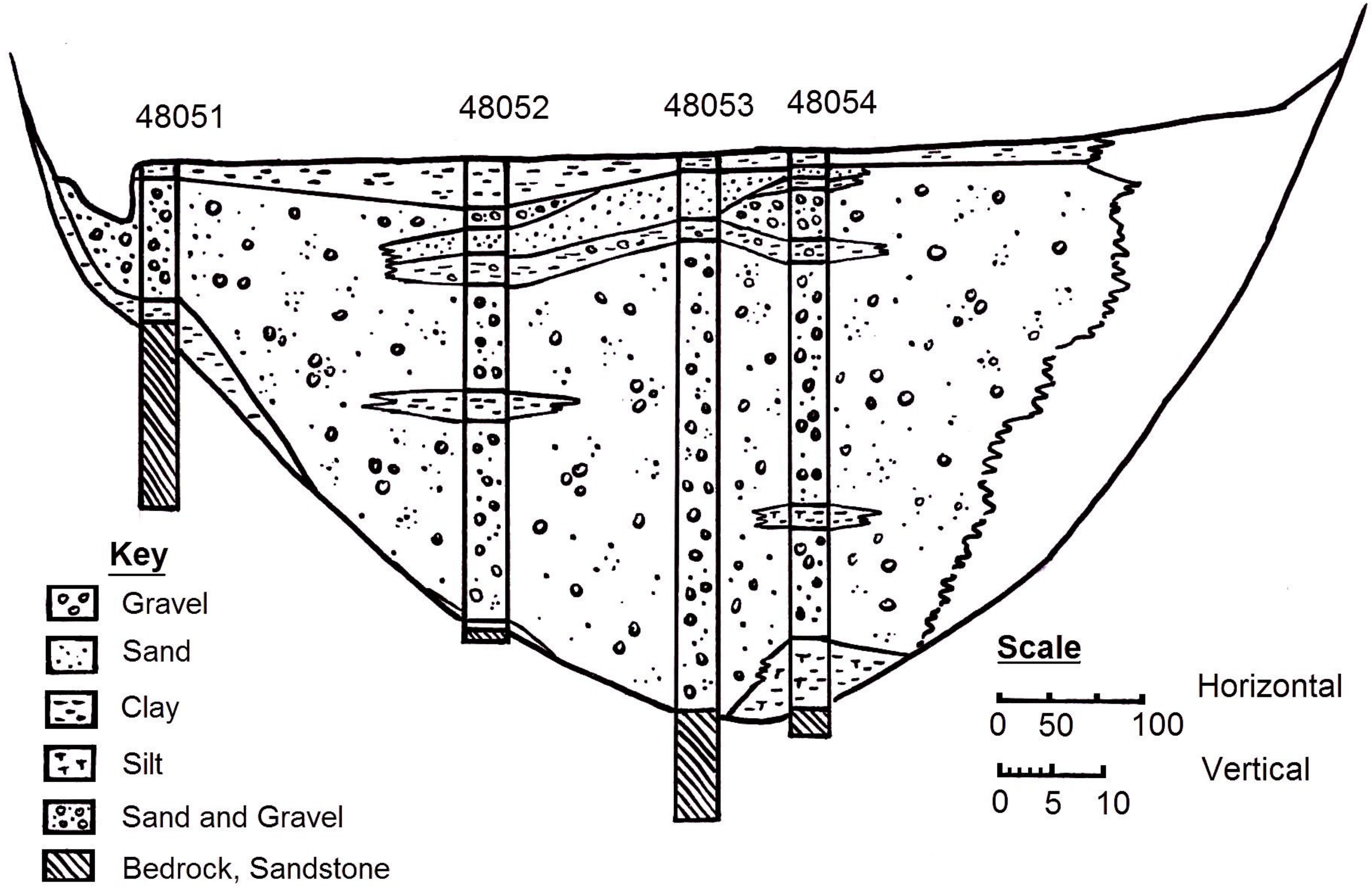
🟩 Myrtleford cross section
🟨 Ovens cross section
🟦 Bright cross section

Appendix 5: Steady state potentiometric surface and flow vectors (SKM 2006a)



Appendix 6: Cross sections and bore logs

Ovens Cross Section



Appendix 6: Cross sections and bore logs

Ovens Drillers Logs

SITE NO	DEPTH FROM (m)	DEPTH TO (m)	MATERIAL
48051	0	0.3	Brown Topsoil
48051	0.3	0.91	Light Brown Sandy Clay
48051	0.91	1.83	Dark Brown Sandy Clay
48051	1.83	11.58	Coarse Gravel And Sand
48051	11.58	13.11	Red Mottled Clay
48051	13.11	14.33	Red Mottled Clay And Lge Gravel (Embedded)
48051	14.33	24.08	Soft Red & Yellow Sandstone
48051	24.08	30.18	Hd & Soft Bds Red Sandstone
48051	30.18	32.31	Soft, Dark Brown Sandstone
48051	32.31	37.19	Soft Yellow Sandstone

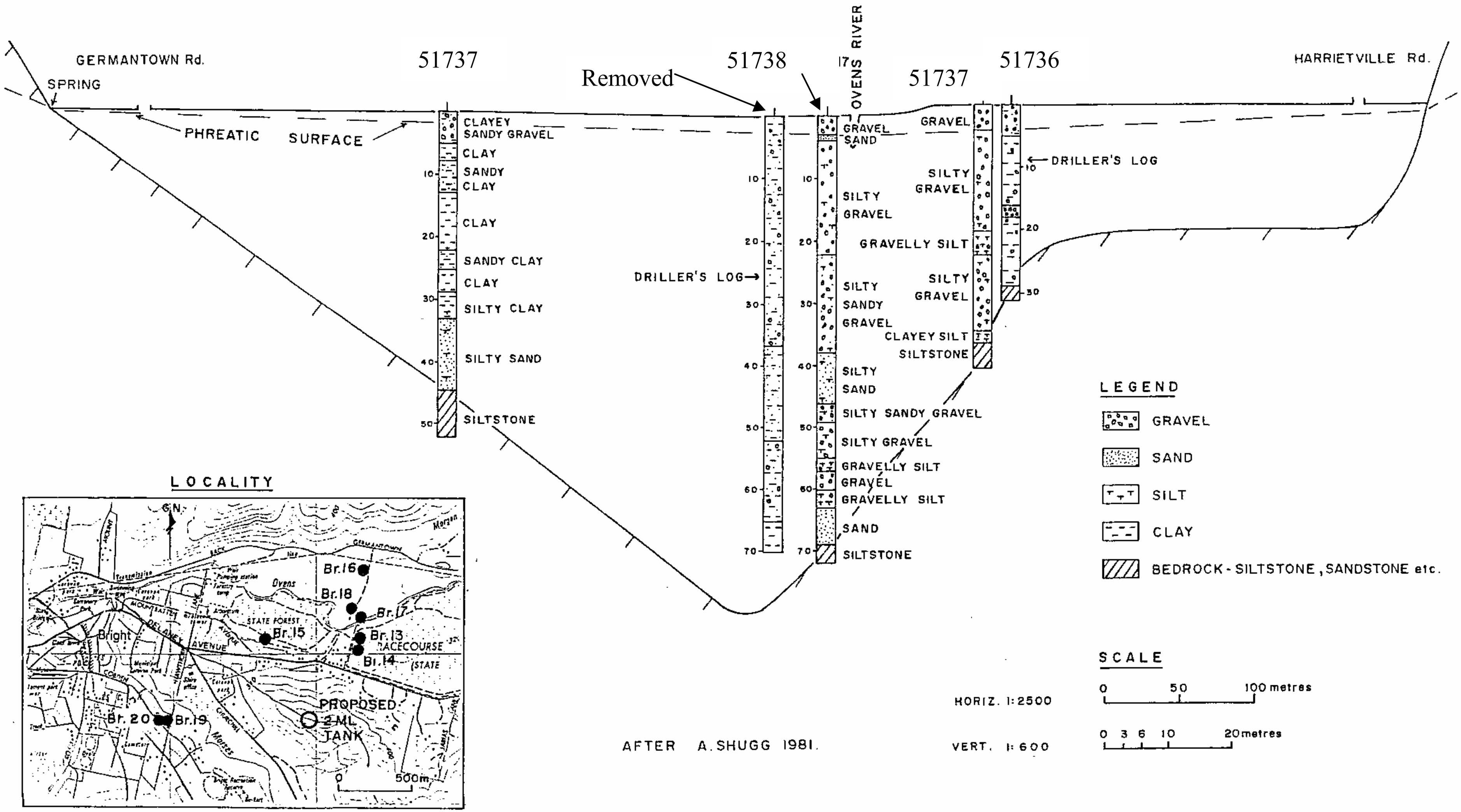
SITE NO	DEPTH FROM (m)	DEPTH TO (m)	MATERIAL
48052	0	0.305	Brown Topsoil
48052	0.305	1.524	Light Brown Sandy Clay
48052	1.524	3.048	Soft Mottled Brown And Yellow Clay
48052	3.048	4.267	Black Silts
48052	4.267	6.096	Dark Grey Coarse Gravels
48052	6.096	8.839	Coarse Yellow Sands
48052	8.839	11.887	Yellow Mottled Clay And Embedded (Gravel)
48052	11.887	21.641	Coarse Sands And Gravels
48052	21.641	22.86	Mottled Grey Clay And Embedded Gravel
48052	22.86	24.689	Brown Silty Clay
48052	24.689	43.891	Coarse Sand And Fatty Gravel
48052	43.891	44.501	Yellow Sandy Clay
48052	44.501	45.11	Hard Grey Slate

SITE NO	DEPTH FROM (m)	DEPTH TO (m)	MATERIAL
48053	0	0.91	Reddish Brown Sdy Topsoil
48053	0.91	1.52	Fine Yellow Sand
48053	1.52	3.66	Fine Grey Sand
48053	3.66	4.27	Coarse Fatty Sands
48053	4.27	6.1	Fine Sandy Mottled Clay
48053	6.1	17.68	Coarse Fatty Sand & Gravel
48053	17.68	19.2	Mottled Yellow Silty Sands
48053	19.2	45.42	Cse Fatty Sand And Gravel
48053	45.42	51.51	Grey Fatty Sand And Gravel
48053	51.51	61.26	Bluey Grey Slatey Clay

SITE NO	DEPTH FROM (m)	DEPTH TO (m)	MATERIAL
48054	0	0.3	Brown Topsoil
48054	0.3	0.6	Reddish Brown Clay
48054	0.6	1.22	Yellow Sandy Clay
48054	1.22	2.44	Fine Yellow Sand (Moist)
48054	2.44	3.05	Mottled Brown Gravelly Clay
48054	3.05	4.27	Coarse Gravel & Sand
48054	4.27	8.23	Fatty Sand & Gravel
48054	8.23	10.06	Mottled Sandy Clay And Embedded Gravel
48054	10.06	13.11	Coarse Fatty Sand
48054	13.11	33.53	Cse Fatty Sand & Gravel
48054	33.53	35.05	Mottled Brown & Grey Silty Clay
48054	35.05	46.02	Cse Fatty Sand & Gravel
48054	46.02	49.68	Brown Silty Clay
48054	49.68	52.73	Slatey Brown Clay
48054	52.73	53.34	Brown Silty Clay
48054	53.34	54.86	Soft Reddish Brown Sandstone
48054	54.86	57.61	Reddish Brown Sandstone

Appendix 6: Cross sections and bore logs

Bright Cross Section



Example of the complexity of distinguishing layers and formations from bore logs as described in Sections 2.2.3 and 5.1.4, after Cox (1989)

Appendix 7: Bore 83229 Minitab Regression Analysis Output: 0 days Lag and 0 Days Averaging Period

Predictor	Coef	SE Coef	T	P
Constant	5.982	7.35	0.81	0.418
Gauge He	0.96054	0.03558	27	0
S = 0.1382 R-Sq = 87.5% R-Sq(adj) = 87.4%				

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	13.91	13.91	728.74	0
Residual Error	104	1.985	0.019		
Total	105	15.896			

Unusual Observations

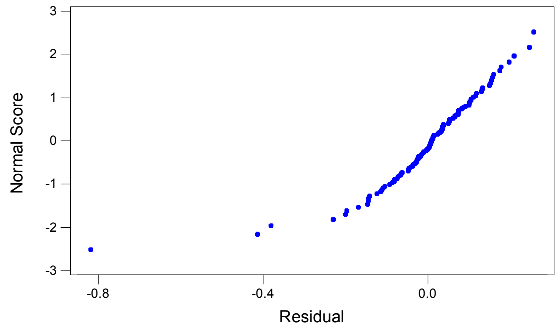
Obs	Gauge Height	83229	Fit	SE Fit	Residual	St Resid
26	208	204.53	205.349	0.038	-0.819	-6.17RX
56	207	205.36	205.206	0.033	0.154	1.15 X
78	208	205.92	205.883	0.057	0.037	0.29 X
88	207	204.13	204.544	0.015	-0.414	-3.02R
97	208	205.54	205.652	0.049	-0.112	-0.86 X
103	206	203.5	203.517	0.035	-0.017	-0.13 X
104	207	203.98	204.361	0.013	-0.381	-2.77R

R denotes an observation with a large standardized residual

X denotes an observation whose X value gives it large influence.

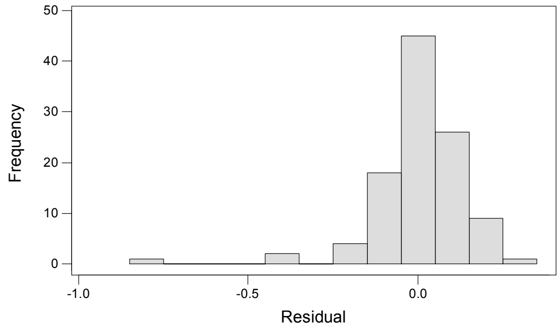
Normal Probability Plot of the Residuals

(response is 83229)



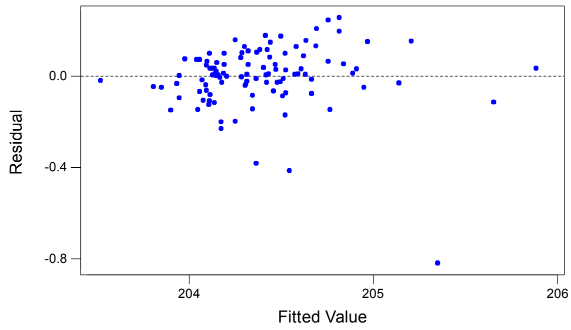
Histogram of the Residuals

(response is 83229)



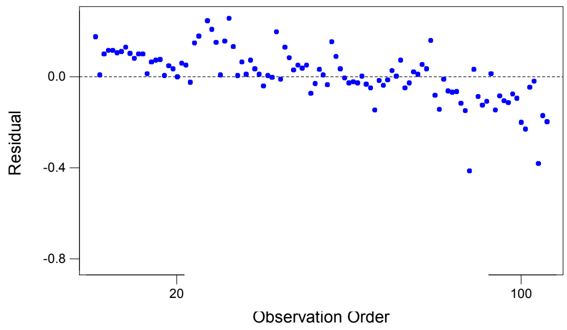
Residuals Versus the Fitted Values

(response is 83229)



Residuals Versus the Order of the Data

(response is 83229)



Appendix 8: Flux analysis results

	Number of Readings			Monthly Flux Volume (ML)				Study Area Monthly Flux (ML)
Month	Myrtleford 83229	Ovens 48073	Bright 51735, 51738	Myrtleford 83229	Ovens 48073	Bright 51735, 51738	Sum	
Jan	1	1	2	6.80	57.77	1.48	66.05	528.41
Feb	15	14	17	6.92	55.27	34.78	96.98	775.84
Mar	6	3	7	8.95	49.79	31.61	90.35	722.81
Apr	6	4	9	11.09	56.58	34.28	101.96	815.68
May	21	16	19	7.26	54.95	8.38	70.58	564.66
Jun	4	2	7	-5.24	79.15	35.24	109.15	873.18
Jul	2	1	6	18.85	124.65	55.14	198.64	1589.10
Aug	11	13	14	4.69	110.67	33.82	149.18	1193.46
Sep	2	1	5	-5.41	160.85	64.87	220.31	1762.48
Oct	3	4	7	-0.25	146.55	93.94	240.24	1921.92
Nov	16	15	19	8.06	97.52	98.61	204.19	1633.54
Dec	11	3	9	12.72	73.22	84.31	170.25	1362.02
Annual	98	77	121	74.45	1067.00	576.44	1717.89	13743.11

Monthly flux volumes in ML/day for bores closest to the river, per km of river K=17, based on recorded bore levels. For comparison to Table 4-6 with calculated fluxes for bores in the centre of the valley

Appendix 8: Flux analysis results

Month	**Flux at Ovens (ML/day)**		
	48051	**48072**	**48054**
Jan	57.7739	4.27815	1.73054
Feb	55.2731	5.53835	1.30413
Mar	49.7886	4.08883	1.17469
Apr	56.5842	5.86869	1.05676
May	54.9476	3.23406	0.8236
Jun	79.152	12.181	1.43538
Jul	124.654	22.681	2.67768
Aug	110.673	9.81424	2.77834
Sep	160.854	18.9338	4.25839
Oct	146.55	18.9445	4.82608
Nov	97.5215	14.4488	3.48281
Dec	73.2228	9.211	2.12184
Average	1067	129.222	27.6702

Monthly flux volumes in ML/day for Ovens bores per km of river K=17, based on recorded bore levels

Month	83232			83231			83229		
	Groundwater to River	River to Groundwater	Time River Groundwater	Groundwater to River	River to Groundwater	Time River Groundwater	Groundwater to River	River to Groundwater	Time River Groundwater
Jan	1084	0	0.0%	1083	0	0.0%	1083	1	0.1%
Feb	988	0	0.0%	988	0	0.0%	985	3	0.3%
Mar	1085	0	0.0%	1085	0	0.0%	1085	0	0.0%
Apr	1050	0	0.0%	1050	0	0.0%	1049	1	0.1%
May	1081	0	0.0%	1081	0	0.0%	1074	7	0.6%
Jun	1016	4	0.4%	1012	8	0.8%	981	39	3.8%
Jul	1052	2	0.2%	1031	23	2.2%	953	101	9.6%
Aug	1052	2	0.2%	1021	33	3.1%	847	207	19.6%
Sep	1013	7	0.7%	964	56	5.5%	773	247	24.2%
Oct	1049	5	0.5%	1017	37	3.5%	882	172	16.3%
Nov	1017	3	0.3%	1007	13	1.3%	942	78	7.6%
Dec	1054	0	0.0%	1050	4	0.4%	1034	20	1.9%
Average	12541	23	0.2%	12389	174	1.4%	11688	876	7.0%

Periods (days) and percentage of time where the hydraulic gradient is from the river to the aquifer using the predicted series calculations at individual bores in the Myrtleford Cross section