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WATER

A Methodology for Managing Groundwater - Surface Water Interaction in Unregulated Streams

INCLUDING A CASE STUDY IN THE UPPER OVENS CATCHMENT, NORTH-EAST VICTORIA

- Final
- 29 June 2006

Water for Growth

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Executive Summary

E.1 Introduction

The fundamental requirement to maintain minimum stream flows during dry seasons in much of Australia has been recognised in many recent water sharing plans. Within Victoria, groundwater and surface water resources are strongly interactive within many catchments. The Victorian Government's White Paper (DSE, 2004) highlights the need for greater understanding of groundwater and surface water interaction and the need to move towards conjunctive management of the resource. This report is targeted at progressing the development of a sound technical basis for incorporation of groundwater management decisions associated with management of groundwater extraction to achieve environmental objectives within a stream.

Surface water groundwater interaction studies can be focussed on either catchment or basin scale water resource sustainability or on maintaining minimum stream flows at a local scale. Larger scale integrated management may address issues of salt discharge and total catchment yield. This report focuses on local scale issues to achieve environmental flow objectives for unregulated streams.

In unregulated streams, Streamflow Management Plans (SFMPs) have addressed minimum stream flow targets through the application of rosters and restrictions on surface water users. The impacts of groundwater abstraction upon streams have generally not been addressed in SFMPs because of a poor understanding of the time lag between groundwater abstraction and its impact upon the stream, particularly during critical low stream flow periods. This report explores the basis for regulating groundwater use to complement these direct diversion management measures, and explores methods available to achieve this. A methodology to integrate the management of groundwater with streamflow management objectives is presented.

The methodology is considered in the context of a case study in the Upper Ovens River in North East Victoria. In this catchment an integrated surface water/groundwater management plan is in the early stages of development.

E.2 Options for conjunctive management in unregulated catchments

Four options for conjunctive management in unregulated catchments to achieve streamflow management objectives have been considered, including permanent restrictions, short term restrictions, trading (groundwater to groundwater and groundwater to surface water) and substitution (surface water to groundwater). Conclusions regarding three of the four options are summarised below:

- Permanent (or semi-permanent) restrictions on entitlement are not sufficiently targeted to provide the types of streamflow objectives likely for an unregulated stream. The imposition of such measures are unlikely to be able to achieve stream protection without very large economic costs (and little environmental benefit) in most years, and would therefore be very difficult to sell to the community.
- Trading over the long term, could be important in reducing summer stream impacts but demand for trade over the short term will be small and therefore targeted rules will be ineffective in delivering short term benefits to the stream.
- Where the practical obstacles to substitution can be overcome, it may be a useful management tool. Its potential influence is increased in wide alluvial catchments where the time lag is of sufficient magnitude to move stream impacts from early season pumping into the winter period. In narrow catchments, careful design will be necessary so that conversion does not lead to unacceptable late season stream impacts arising from the timelag effect of early season pumping.

The most suitable method for addressing current groundwater user impacts on the stream is that of short term restriction, in conjunction with restrictions to surface water users. However, the potential exists to complement such reactive management measures with trading and substitution rules, which over a longer timeframe have potential for improving overall water access to all users, by reducing the severity and frequency of short term restrictions.

Of the options available for imposing restrictions, trigger based restrictions are considered the best primary method for managing groundwater user impacts on the stream because it is technically the most defensible option, as it can be targeted to deliver protection to the stream when required, yet minimise impacts on groundwater users at other times.

A trigger based on recent historical data, applied shortly before the start of the irrigation season is considered the best form of trigger to deal with the time lag issue. Rainfall records would seem to be the most appropriate parameter to use for this trigger, as it is a leading indicator of likely baseflow conditions. Further, the data is widely available and easily collected.

The potential for all methods, including short term restrictions, to be significantly undermined by sleeper / dozer licences needs to be recognised. In catchments where sleeper / dozer licences are a significant proportion of total allocation, actions to bring allocation and use into line or methods of restriction based on usage rather than allocation, are likely to be required in order for restrictions to be effective.

E.3 Numerical Groundwater Modelling in the Upper Ovens

A numerical groundwater model was developed for a section of the alluvial valley of the Upper Ovens catchment to test the impacts of groundwater abstraction on the stream and to help devise management rules. One of the primary aims of the modelling was to investigate the potential benefits of converting river water diversions to groundwater extractions. The principal findings of the modelling were that:

- Continuous pumping of groundwater from the relatively narrow alluvial aquifer gives rise to significant streamflow depletion. After 5 to 10 years of six month groundwater extraction and rest cycles the volumes of water extracted from bores is almost entirely sourced from streamflow depletion.
- Although long term pumping considerations indicate little streamflow benefit in replacing river diversions by groundwater pumping, there are small scale time lags that provide an opportunity for improving river flows through conversion of surface water diversions to groundwater extractions some distance from the river.
- Models aimed at investigating, in detail, the short time lags over particularly dry summer months were developed. The model results suggest that within the Upper Ovens Valley, substitution will provide a greater total summer flow, but risks greater stream depletion in the late summer period due to the cumulative impact of early season groundwater extraction. In designing substitution rules, it is therefore imperative to understand the particular environmental objectives and whether there are environmental tradeoffs in having greater early season river flows but the risk of late season lower flows. In other words, do early dry season benefits outweigh late season disbenefits which will only materialise in extended long dry seasons when very low flows would be expected anyway? If these late season environmental risks are considered too great, then the design of substitution rules may limit application to the late summer early autumn period.
- Due to the apparent late season impacts of the time lag in the Upper Ovens, it is clear that a substitution approach would have greater application in a wider alluvial valley where the time lag would be expected to be longer.

E.4 Using Analytical Models to Estimate Numerical Modelling Results

Undertaking numerical modelling for assessment of surface water – groundwater interaction in every instance is time consuming and costly. It is therefore preferable for simple analytical models to be available for assessing the impacts of groundwater pumping on streamflow due to their relatively low cost and ease of use. A comparison was therefore undertaken between analytical and numerical modelling of streamflow depletion in the Upper Ovens catchment to assess how accurately an analytical model could simulate the numerical model results.

In a bounded aquifer, such as that underlying the Upper Ovens River approximately 10 km upstream of Myrtleford, the Jenkins analytical model tends to slightly under-estimate the amount of stream flow depletion. A similar conclusion was obtained in a research paper prepared by Braaten and Gates (2004) on the effect of a bounded aquifer on surface water/groundwater interaction.

The degree of under-estimation is less than 10% for bores located within 300 m of the stream. At 600 m from the stream the impacts were under estimated by 20%, although this decreased to about 15% after 10 years pumping. An assessment of multiple bore pumping was similar to the single bore case. A correction factor could be developed to reduce the difference between the numerical and analytical model, which would significantly improve the applicability of the Jenkins model to the Upper Ovens River. It is likely that other analytical models which assume unconfined and infinite sized aquifers would also under-estimate the amount of streamflow depletion.

E.5 Proposed Conjunctive Management Approach in the Upper Ovens Catchment

Conjunctive management of groundwater and surface water in the Upper Ovens is critical given that numerical modelling suggests significant interaction between these two resources. The modelling results are consistent with the general acceptance of high levels of interaction, both within local agencies and the Ovens community. The modelling results therefore support the development of an integrated groundwater/surface water management plan for this sub-catchment, consistent with policy initiatives documented in Our Water Our Future (DSE, 2004).

Integrated management has the potential to ensure that pumping of existing licensed entitlements in the catchment are managed to assist in achieving agreed environmental objectives. Integrated management also has the potential to provide options for reducing the economic cost of achieving minimum environmental flows, by providing options for trading or conversion of surface water licences to groundwater licences.

Short term restrictions on groundwater users, commensurate with their impact upon the stream during critical times, must form the central plank of conjunctive management in the Upper Ovens Catchment. Depending upon environmental objectives and environmental tradeoffs, bores distant from the river are likely to require different management from bores closer to the river. Short term restrictions are best implemented in a zonal framework to allow for differing impacts of different groundwater users.

Subject to further investigations (particularly ground-truthing), two potential zones are proposed for consideration. Zone 1 is for bores up to 200m from the river, extending to the bedrock interface where the alluvial - bedrock boundary is 350m or less. Within this zone, similar management rules would be expected to that which applies to surface water users. Alluvial sediments outside this range would be classified as Zone 2. Ideally, further investigations are required to establish whether vertical zoning is warranted. This will depend upon the degree of confinement. A separate zone may also be required for bedrock aquifers.

Once management objectives have been developed for the area, additional technical work is warranted to 'road test' the above zoning proposals and design proposed management rules to achieve these objectives. These management rules may include restrictions and rules on trade and substitution. The development of restriction rules will also require additional technical work to assess whether rainfall indices can be used as a predictor for the likelihood of low summer streamflows.

As the Upper Ovens catchment is estimated to have a high proportion of sleeper / dozer licences, the potential for the proposed approach to be significantly undermined by these licences needs to be recognised. Actions to bring allocation and use into line or methods of restriction based on usage rather than allocation, are likely to be required in order for restrictions to be effective.

E.6 Recommendations

he recommendations arising from this investigation fall into two categories; those directly related to the Upper Ovens catchment, and those related to the general advancement of integrated groundwater and surface water management across Victoria. An overview of the key recommendations is provided below.

Upper Ovens Catchment

With respect to management of groundwater in the Upper Ovens catchment, the key recommendation of this report was that the proposed new Upper Ovens Streamflow Management Plan incorporate conjunctive surface and groundwater management. Other recommendations included:

- development of environmental management objectives to allow further refinement of local scale integrated management methodologies,
- conducting detailed investigations on the potential application of substitution and trading rules to encourage surface water and Zone 1 groundwater licences to be transferred to Zone 2.
- initiation of community engagement in the Upper Ovens on technical and equity issues associated with conjunctive water management.

Desktop investigations recommended included (in order of higher to lesser priority):

- assessment of an appropriate leading indicator of low stream flow
- a review of the monitoring bore network be undertaken to determine its suitability for assessment of groundwater surface water interaction,
- numerical modelling of the proposed groundwater restriction measures,

- the analytical modelling undertaken in this assessment be further developed into a more ‘user friendly’ process / tool to enable its use in other (including wider) alluvial catchments,
- an economic assessment of the implications of Zone 1 and Zone 2 restrictions be conducted; and,
- a broader desktop assessment of GDEs in the Upper Ovens be undertaken.

With respect to field investigations to advance understanding and management of groundwater in the Upper Ovens catchment, it is recommended that the zoning proposed in this report (two zones for groundwater management) be further investigated through site based investigations to prove the timelag predictions derived from modelling, and that the implementation of metering of groundwater bores in the Upper Ovens be accelerated to provide an understanding of groundwater use relative to entitlement in the Upper Ovens catchment.

General

To advance integrated management of groundwater and surface water across Victoria, it is recommended that:

- a baseflow/rainfall analysis be conducted for the Upper Ovens River to understand the reliability of seasonal and historic rainfall records (eg, in August/September) as an indicator of critically low summer flows,
- numerical modelling be undertaken of wider alluvial valleys to determine the approximate valley width (for different aquifer hydraulic properties) at which point the time lag is greater than about six months and,
- a methodology be developed for managing groundwater interaction in regulated catchments.
- two groundwater/stream monitoring sites (probably a bore transect) be established in a fractured rock aquifer and a semi-confined aquifer, in an unregulated catchment of relatively high groundwater use to assess the impact of stream interaction in these two environments.

1. Introduction

Groundwater and surface water resources are strongly interactive within many upper catchment environments within Victoria. The Victorian Government's White Paper (DSE, 2004) highlights the need for greater understanding of groundwater and surface water interaction and need to move towards conjunctive management of the resource. The White Paper also states that "in priority unregulated rivers and aquifers, the Environmental Water Reserve will be enhanced by requiring existing licences to be managed to provide an environmental water regime that will sustain ecological objectives within 10 years." Four of these priority regulated rivers, the Upper Ovens River, the Kiewa River, Yea River and King Parrot Creek are in areas where groundwater surface water interaction is known to be high. Each of these catchments have been targeted for the development of a Streamflow Management Plan, which at some level, will require consideration of groundwater impacts.

There has been little work done within Victoria to date in developing technically sound methodologies that can be incorporated into a Streamflow Management Plan to deal with groundwater stream interaction. Unless a very large number of monitoring bores and gauging stations are established (which will be at a very high cost), there will always be gaps in our ability to measure the impacts of pumping on streamflow. Even where such an approach is affordable, the complexity and variability of many systems such as fractured rock aquifers will still inhibit understanding and quantification of interaction.

This report is targeted at progressing the development of a sound technical basis for incorporation of groundwater management decisions associated with management of groundwater extraction to achieve environmental objectives within a stream. The report provides a summary of the technical understanding of issues associated with groundwater stream interaction and provides a general framework and practical applications for managing interaction. Policy issues within Victoria in managing interaction are identified. Results from a desktop study of testing the management framework to the Upper Ovens River is also presented.

2. Groundwater Stream Interaction - Definitions

2.1 Aquifer Types

Strong interactions between streams and the groundwater system are usually associated with shallow aquifers. The shallow aquifers are generally “unconfined”, but may sometimes be “semi-unconfined”. An “unconfined” aquifer is one where the surface of the groundwater body (also known as the water table) is contained within the aquifer. In this case the groundwater pressure in the aquifer and the water table level are effectively the same. In the “semi-unconfined” case the shallow aquifer is overlain by less permeable material (known as an aquitard), and the water table is contained within the aquitard. Water can be transmitted up or down through the aquitard, but lateral movement is very limited compared to lateral movement in the aquifer. The water table level in the aquitard at any point can be significantly different from the groundwater pressure in the underlying aquifer if there is any significant vertical transmission of water to or from the aquifer at that point.

2.2 Gaining and Losing Streams

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

A stream can be either “disconnected” from or “connected” with the groundwater body contained in the aquifer. The stream and the aquifer are considered to be “connected” if there is no zone of unsaturated material between the stream and the water table. A “connected” stream occurs when the watertable level intersects the surface water body. Under these conditions the surface water body can be affected by changes in the water table level and/or the groundwater level in the aquifer.

The stream and the aquifer are considered to be “disconnected”:

- if the water table level is below the base of the surface water body (ie the watertable level does not intersect the surface water body), and

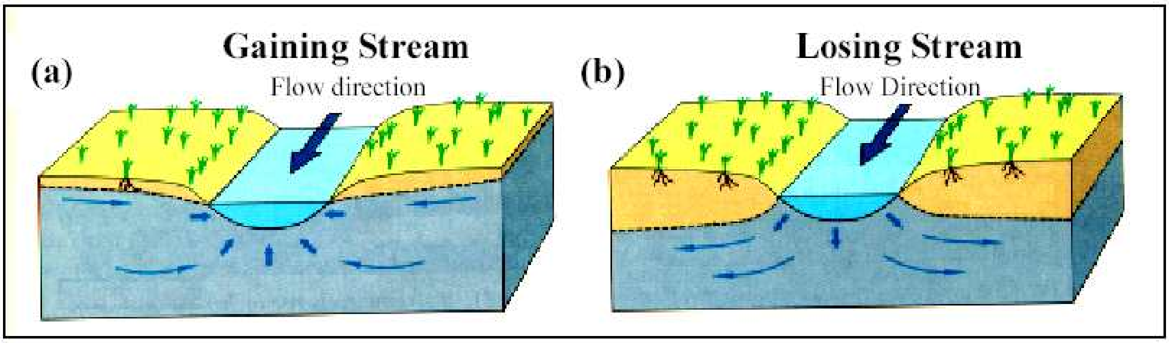
- a zone of unsaturated material exists between the surface water body and the water table.[1]

Any changes in the water table level and/or the groundwater level in the aquifer will have no effect on the surface water body where the water table and water body are disconnected.

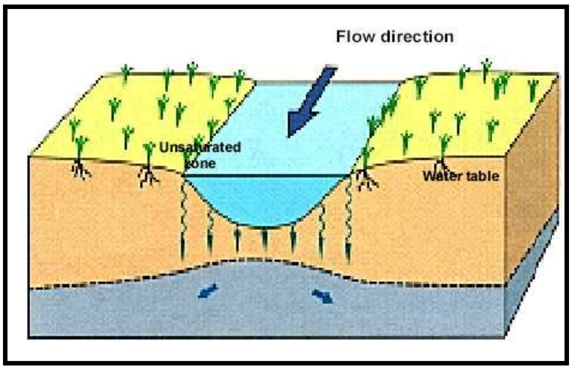
Figure 1 (a) and (b), and Figure 2 show examples for a shallow unconfined aquifer of:

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

- **Figure 1 Characterisation of Gaining (a) and Losing (b) Streams (after Winter et al, 1998, and MDBC, 2003)**



- **Figure 2 Disconnected losing stream**



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[1] Sophocleous (2002) notes that numerical simulations (eg, Peterson and Wilson, 1988) have demonstrated that even when the unsaturated condition is present, the stream and aquifer may in fact be connected, in the sense that further lowering of the regional watertable could increase stream losses. At some critical depth to the watertable, however, further lowering has no influence on channel losses (Bouwer and Maddock, 1997). At this depth, which depends mainly on soil properties and river head, the aquifer becomes hydraulically disconnected from the stream. For the purposes of this report however, the above definition of "disconnected" is considered suitable.

2.3 Recharge and Discharge Processes

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

2.3.1 Recharge Processes

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

- Recharge from rainfall and irrigation,
- Recharge from surface water bodies (stream leakage), and
- Recharge from underlying aquifers (upward leakage).

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

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

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

2.3.2 Discharge Processes

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

- Discharge through the unsaturated zone above the water table (ie evapotranspiration), or
- Groundwater flow to a surface water body (base flow), or
- Leakage to an underlying aquifer.

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

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

2.4 The Water Balance

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

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

2.5 Impacts of Groundwater Pumping on Streams

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

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

In the case of a losing stream, groundwater pumping will cause an increase in the rate of stream leakage (to offset the pumped discharge). The increased stream leakage is defined for this report as an "induced stream leakage". The induced stream leakage will increase progressively as the water table or groundwater level adjacent to the stream falls, even if the water table level falls to a point where the aquifer is disconnected from the stream[2].

If the stream is a gaining stream the effect of pumping can be twofold. The initial effect will be to reduce the base flow generated in that reach of the stream (eg after 100 days pumping in Figure 3). The base flow will decrease progressively as the water table or groundwater level adjacent to the stream falls. If pumping is at a high enough rate and/or continues for long enough the water table or groundwater level adjacent to the stream may fall to the same level as the running level in the stream. At that point, base flow will cease to be generated for that stream reach. If the water table or groundwater level continues to fall the stream becomes a losing stream with induced stream leakage (eg after 1000 days pumping in Figure 3). The transition from a gaining stream to a losing stream is illustrated in Figure 3.

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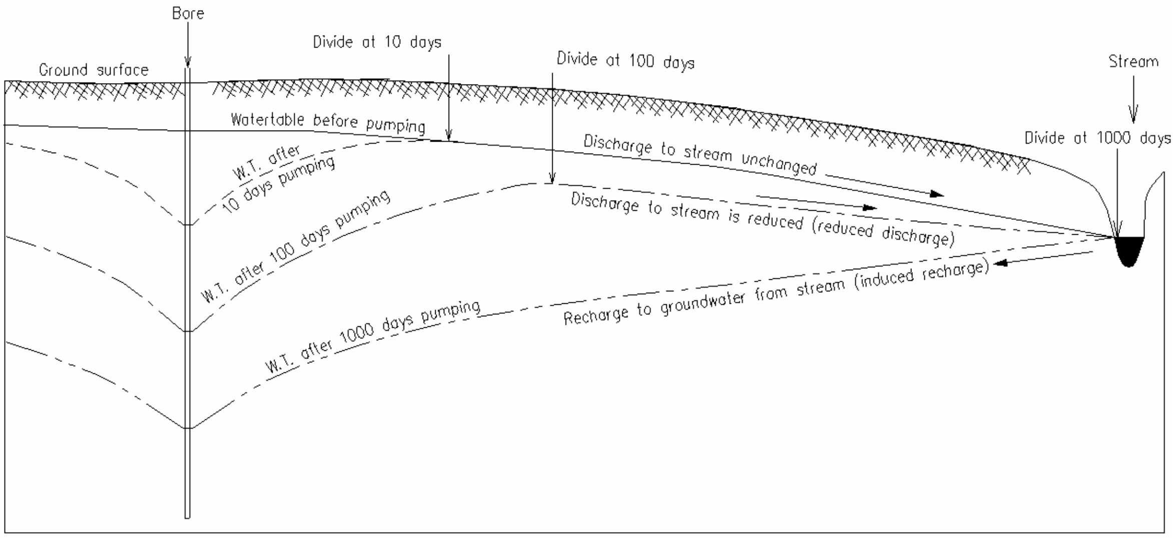
[2] If the water table or groundwater level continues to fall after the aquifer has become disconnected from the stream there will not be any further increase in induced stream leakage along the disconnected stream reach. However, in order to maintain the water balance additional water will need to be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

- **Figure 3 Effect of Groundwater Pumping on a Gaining Stream (note: induced stream leakage after 1000 days is labelled as "induced recharge")**



3. Calculation of Streamflow Impacts

Methods to calculate the impact of pumping on stream flow have been available since Theis developed the solution to transient groundwater flow. Following initial investigations by Theis (1940), Glover and Balmer (1954) developed an analytical solution for an idealised case where the stream fully penetrates the aquifer, the water table is flat (ie the stream is neither gaining or losing), and the streambed is not clogged with low permeability sediments. Using this model these investigators showed the proportion of the pumped groundwater derived from streamflow (as either reduced baseflow or induced stream leakage) to be a function of aquifer diffusivity (ie both aquifer transmissivity and storage co-efficient) and the square of the distance between the bore and the stream (ie a ten fold increase in distance causes a 100 fold time delay from the start of pumping till the commencement of reduced streamflow). From this simple model Jenkins (1968) and Glover (1974) developed an analytical solution for calculating stream flow depletion from a bore discharging at a constant rate at a fixed distance from a stream. The following discussion is included to illustrate the general principles of streamflow depletion due to groundwater pumping within the context of the idealised case.

The rate at which streamflow depletion increases is proportional to the change in the rate of drawdown (per log time) in the pumped bore and follows the shape of the curve shown in Figure 4 (in a dimensional form). The change in the rate of drawdown (ie the change in the slope of the drawdown curve) can be plotted in a dimensionless form that shows how the rate of streamflow depletion changes as bore pumping increases (Figure 5).

Figure 4: Effect of induced recharge on drawdown in the pumped bore

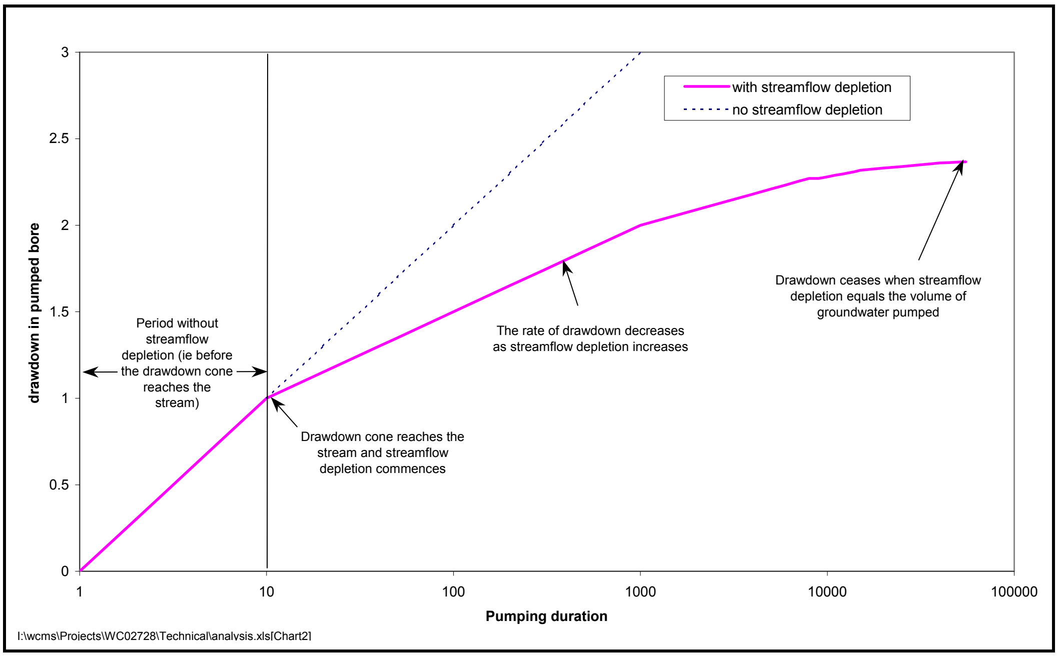
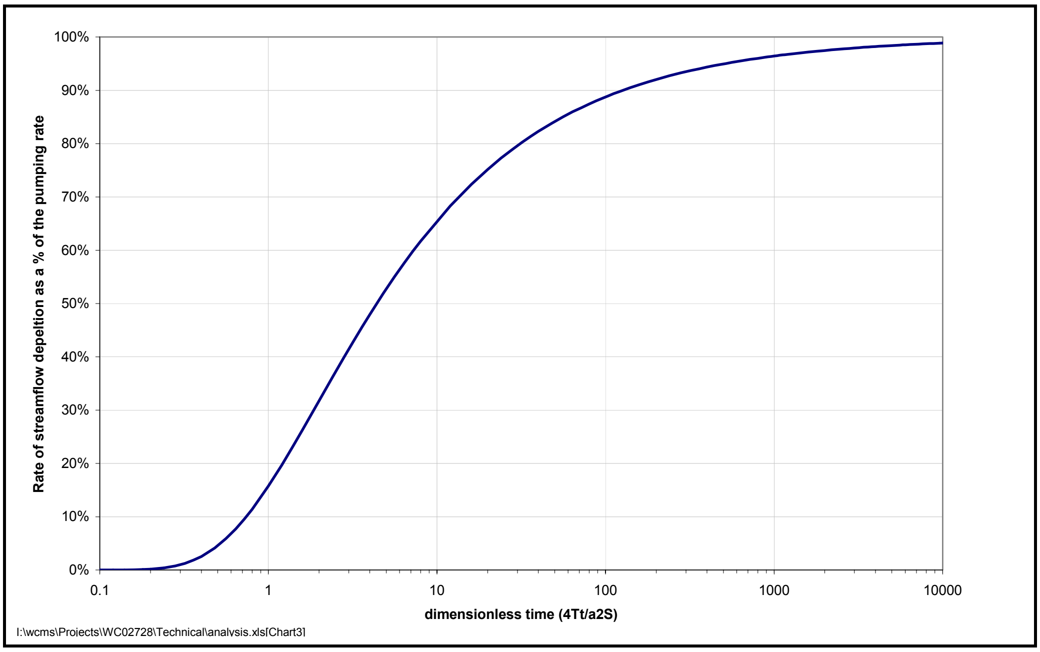
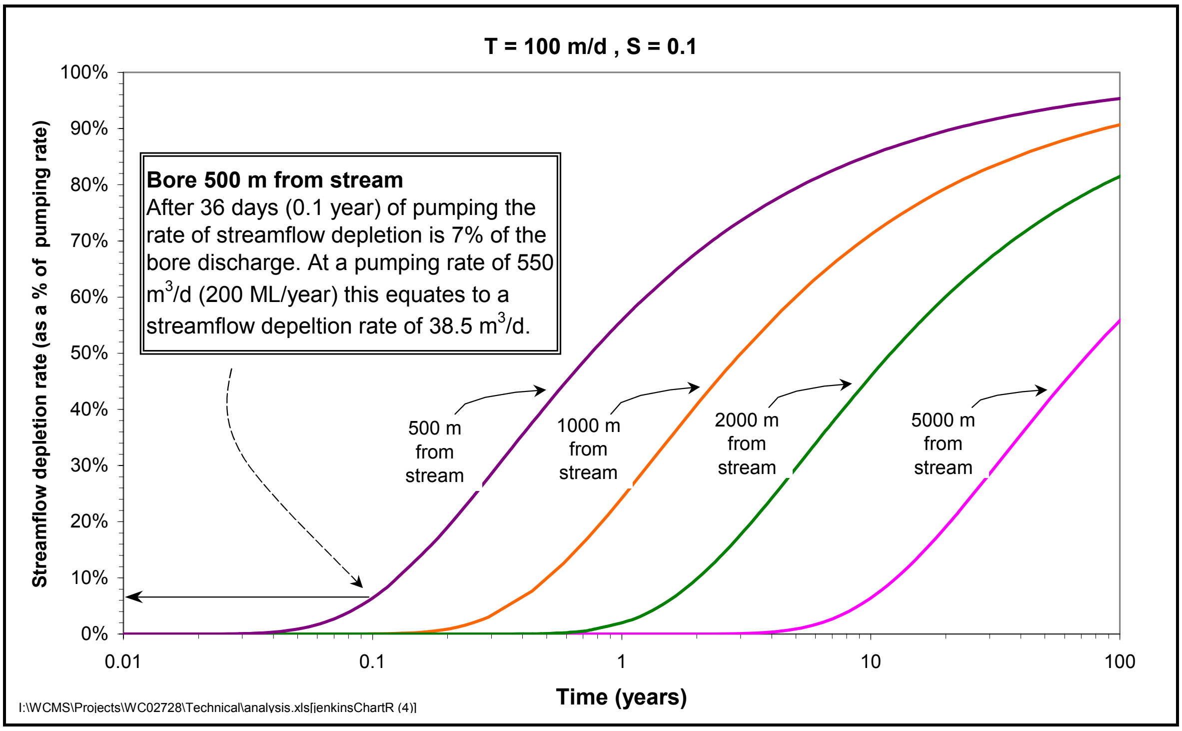


Figure 5: Rate of streamflow depletion as a percentage of the pumping rate, after Jenkins, (1968).



The duration of pumping required before streamflow depletion begins is dependent on the storage co-efficient, transmissivity, and the location of the bore. The pumping rate does not influence the rate at which the drawdown cone spreads and as such does not influence the timing at which streamflow depletion commences. By keeping the transmissivity and storage co-efficient constant the curve in Figure 5 can be split into a series of curves which show the effect of distance between the bore and the stream on the duration of pumping before streamflow depletion begins (Figure 6). These curves can also be used to calculate the rate of streamflow depletion. For example, a bore located 500 m from a stream that has been pumped for 36 days (0.1 year) from an aquifer with a transmissivity of 100 m^2/d and storage co-efficient of 0.1 will begin the deplete streamflow after 11 days pumping (0.03 years on Figure 6). The amount of streamflow depletion will increase as pumping continues, reaching 7% on day 36 (0.1 year). If the pumping rate is 550 m^3/d (200 ML/year) the streamflow depletion rate, on day 36, will be 38.5 m^3/d (Figure 6).

- **Figure 6: The delay before streamflow depletion commences at increasing distances between the bore and stream.**



Bore 500 m from stream
After 36 days (0.1 year) of pumping the rate of streamflow depletion is 7% of the bore discharge. At a pumping rate of 550 m^3/d (200 ML/year) this equates to a streamflow depeltion rate of 38.5 m^3/d.

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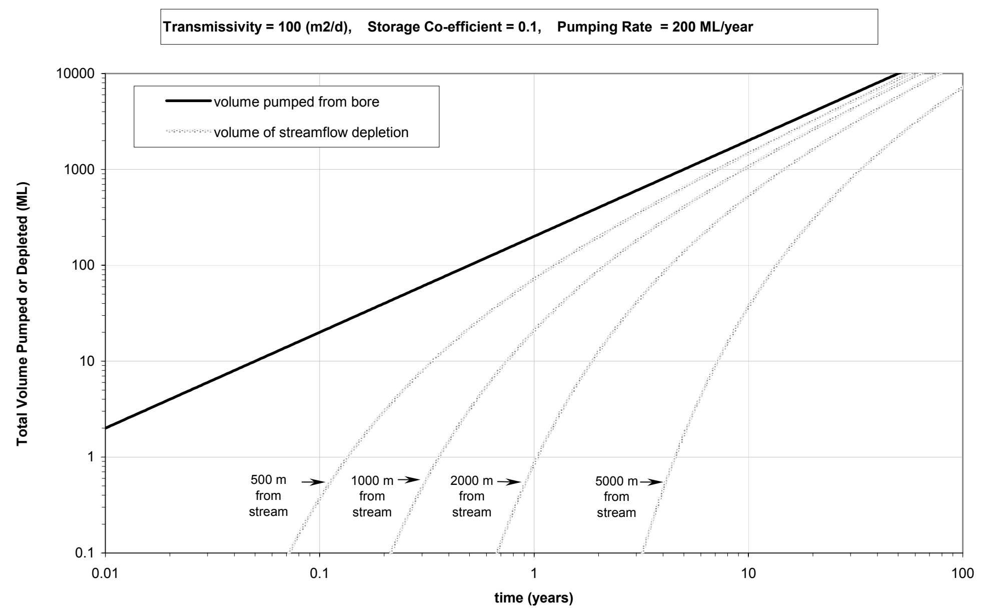
Curves showing the total volume depleted can also be calculated (Figure 7). After 36 days pumping the total volume depleted from streamflow is 0.386 ML or 1.9% of the total volume pumped (Figure 7).

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

- **Figure 7: The volume of streamflow depletion over time at increasing distances between the bore and stream.**



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Streams and aquifers are not typically configured in the manner described for the above idealised case. The idealised case rarely occurs and many researches have developed analytical and numerical techniques to more accurately described typical cases. For example, Cook and Lamontagne (2002) have incorporated recharge into the analysis, and Braaten and Gates (2004) have considered the cases of narrow alluvial valleys and semi-confined aquifers. An evaluation by Sophocleous *et al*. (1995) identified the range of discrepancy between the idealised case and simplified typical cases. The features that introduced the most significant error (>10% error in the predicted streamflow depletion) were streambed clogging, partial penetration of the aquifer, and aquifer heterogeneity. Nonetheless the general principles of stream aquifer interaction, and the resulting time lags, are well understood. Note: a more detailed description on calculating streamflow depletion is presented in Appendix A.

4. Methodology

4.1 Introduction

Minimum stream flow targets are currently achieved in unregulated catchments through the application of restrictions on surface water diversions. In catchments containing significant numbers of diverters and an established gauging station, a downward trend in the stream flow hydrograph provides an early warning of the likely need for restrictions. In smaller streams with no gauging station, the need for restrictions may be initiated based upon a visual assessment of stream flows and experience with respect to likely demand.

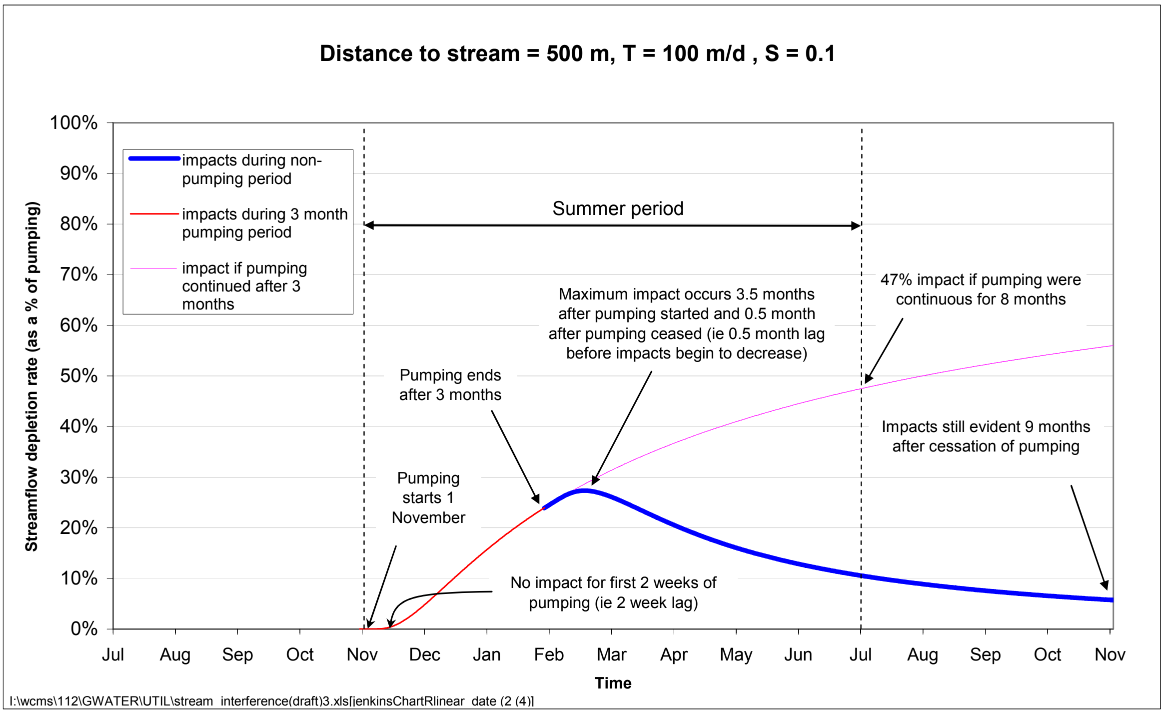
While the cause (pumping from the stream) and impact on streamflow are immediate, an administrative delay between observing and assessing trends and compiling and sending out letters advising licensees of rosters is inevitable. Ideally, the stream flow threshold triggering the need for rosters is anticipated prior to the event, and roster procedures are then initiated to coincide with the stream reaching the critical flow.

To date, the above roster restrictions have not been applied to groundwater users to achieve streamflow objectives, even though the impacts on many streams is clear as demonstrated in the preceding section. The exception is some catchments such as the Ovens where dragline holes close to the river are treated as surface water diversions (Sinclair Knight Merz, 1995). Exclusion of groundwater pumping from seasonal based management of streams in part reflects lack of adequate management tools and that the “tyranny of small decisions” was not well recognised in water resource management. While pumping from an individual bore may have an insignificant impact on a stream, even in the long term, it is clear that 100 or 1000 approved licences will cumulatively have an impact on the stream. An understanding of the cumulative impact of small decisions is now being recognised in other areas of water resource management within Victoria such as registration and licensing of farm dams, and managing salt disposal within salt disposal entitlements.

In order to incorporate groundwater pumping into the management of streamflows, consideration of the time lag between commencement of pumping and the impact on streamflow needs to be taken into account. As the distance between the pumping bore and stream increase so does the lag or delay between the commencement of pumping and the impact on streamflow (ie reduced discharge and/or induced recharge). When pumping ceases there is also a time lag between cessation of pumping and the reduction in streamflow impacts (Figure 8). The temporal lag between pumping groundwater and the impact on streamflow means that unlike unregulated surface water management described above, restrictions to achieve conjunctive management outcomes may be required to be determined well in advance of stream flow impacts arising from groundwater extraction.

In regulated streams there is a greater level of certainty on the volume of water that will be available during the year. Streamflow is managed using engineering structures and planned allocations. As a result, management decisions on streamflow are made several months before surface water diversions occur usually through the announcement of annual allocations that are periodically revised during the season. With improved conjunctive use management in regulated catchments, improved estimates of groundwater losses may be possible which could be built into planning models to improve seasonal allocations.

- **Figure 8 Lag between commencement of pumping and impacts on stream flow, and lag between cessation of pumping and the decline in impacts after pumping ceases.**



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4.2 General Framework

New groundwater licences are being assessed and approved on a day to day basis, groundwater trades are being considered and approved, and in some areas (eg Katunga Water Supply Protection Area, 2006) existing groundwater licences are being restricted as part of groundwater management plans. In parallel, Stream Flow Management Plans are being developed in Victoria for priority unregulated streams requiring improved flow regimes over the critical low flow period of summer/autumn. Sustainable Diversion Limits have also been developed for unregulated catchments that provide guidance on the likely resource available for winter diversion or capture, while having appropriate regard for the needs of the environment.

Given the need to integrate the above groundwater and stream management practices and planning in many catchments, it is proposed that a four zone classification be adopted when considering new groundwater licences / trades / restrictions, as follows:

Zone 1. This applies close to streams where there is major interference with stream flows. All existing groundwater licences in Zone 1 should be managed according to surface water extraction rules. The boundary of Zone 1 would be determined by hydrogeological factors. For an unconfined aquifer the boundary may be in the order of 100 m from a stream. This approach is consistent with the approach in New Zealand where the Canterbury Natural Resources Regional Plan (Environment Canterbury, 2004) deals with this matter as follows: "*any bore with a high hydraulic linkage, with a stream depletion effect that is greater than 90% of the average pump rate after 1 week continuous pumping, will be managed as a surface take for management purposes*".

Zone 2. This zone would deal with all groundwater usage which would impact on stream flow over the critical low flow period of the stream during the planning timeframe. In practice this applies to impacts which may be typically felt within 3 months of the commencement of pumping. Groundwater users would have restrictions equitable with those applied to surface water users over the critical period, where impacts are comparable. As with Zone 1, the width of Zone 2 would be based on hydrogeological factors.

Zone 3. This zone would deal with long term impacts of groundwater use on stream flow. Long term means in the order of 1-20^{+} years. This would often cover all groundwater users in a surface water catchments (except those in Zones 1 and 2). It is likely that other issues such as salinity will also occur in this zone (and perhaps also in Zone 2), some of which may take precedence over the protection of base flows. As a result zone 3 may ultimately comprise a number of different sub-zones that have different water management priorities.

It is expected that licensed bores in zone 3 would generally be managed by annual allocations or in accordance with a Permissible Consumptive Volume . In some circumstances annual allocations may be set to achieve minimum groundwater levels, with the impacts defined at the stream.

Zone 4. This zone is where there is no discernible impact of groundwater use on the stream. The zone would not necessarily be a certain distance from a stream, but would apply to certain hydrogeological situations, for example, deep confined aquifers or disconnected streams. Assuming the application of this methodology on a Victoria wide basis, Government would be required to decide at a policy level what "no discernible impact" means. Given the Murray Darling Basin Cap on surface water diversions, it would be highly desirable that all states within the Murray Darling Basin also reach agreement on this matter.

The zonal concept is shown in Figure 9 with a geographical example presented in Figure 10. From a technical perspective Zone 2 is likely to exist in most hydrogeological settings particularly for alluvial sediments. The most highly interactive groundwater surface water systems are likely to be the highly permeable alluvial systems such as in the Ovens or Kiewa Valleys but in some circumstances such as King Parrot Creek or Yea catchment, or in the basalt areas of the Upper Loddon, Zone 2 may also cover catchments where streams are incised into high yielding fractured rock aquifers.

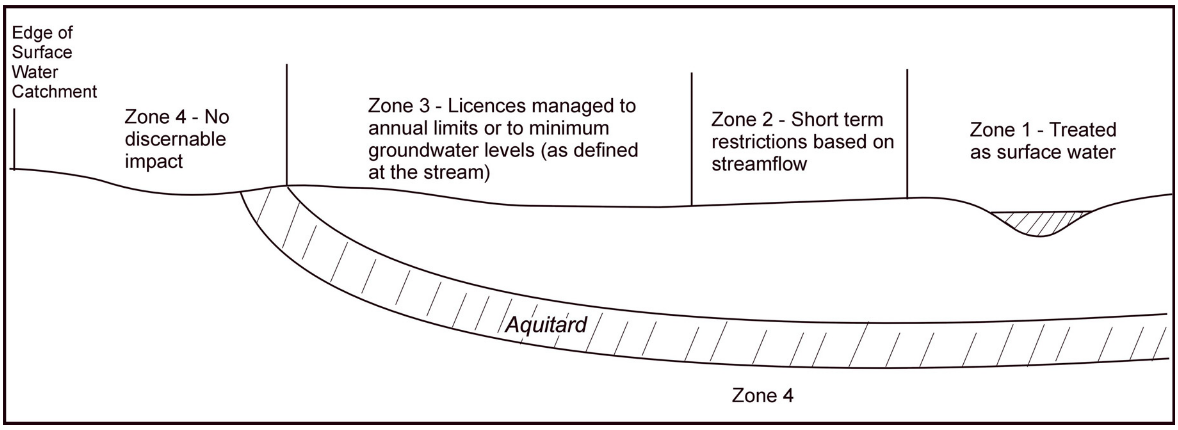
When the width of the alluvial aquifer becomes narrow the division of the aquifer into multiple-zones may not be practicable (ie Zones 2 would be very narrow and, hence, impractical to administer). Zone 3 may then exist within the bedrock adjacent to the alluvial aquifer as demonstrated in the example of Figure 10. This would apply particularly to areas where there is poor fracturing of the bedrock close to the stream.

When the alluvial aquifer widens to greater than say, 5 km, an alluvial Zone 3 may become a manageable size. Note that Zone 4 may also exist but a special case may need to be made for it to exist (ie where there is no impact on streamflow and most capture is derived from evapotranspiration or possibly discharge to the ocean).

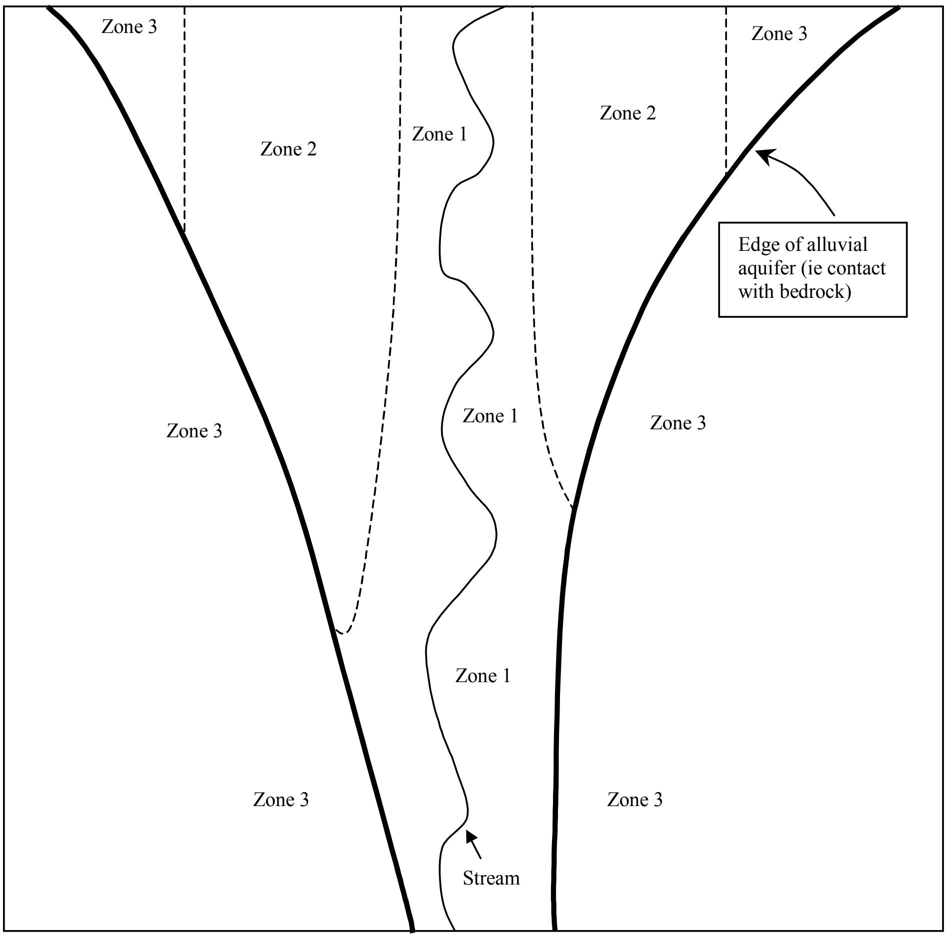
As implied above, in different hydrogeological situations, the boundaries of the zones would need to be determined and the distances given above could vary greatly. As the purpose of such boundaries is to apply rules which will impact on existing licences or licence applications, the technical justification for a particular zone boundary has the potential to become controversial. Therefore, in some cases, the boundary may be somewhat 'fuzzy', depending upon the management issues involved and the degree of technical certainty.

Not withstanding the above, most licences across Victoria would be expected to fall into Zones 1, 2 and 3 but not Zone 4. Even though the location of the zone boundaries are controlled by hydrogeological factors, the required policy (ie. how much interference is allowed to occur within a specified time frame) is fundamental to managing this issue. Note that the four zonal system described here is an example of a concept and could be simplified to a 3 or 2 zonal system as required.

- **Figure 9 Proposed zonal classification for managing groundwater licences**



- **Figure 10 Indicative location of Management Zones.**



4.3 Practical applications for managing exising licences

The following is a discussion on the criteria and practicality of operational rules (ie restrictions) that could be applied to groundwater users in zones 1, 2 and 3 to assist in achieving environmental flow objectives. Note that there are many possible types of restriction and triggers that could be implemented. While many of the issues are relevant to both regulated and unregulated streams, the emphasis for the remainder of this report is largely in considering groundwater management options for unregulated streams within the general framework discussed in section 4.2.

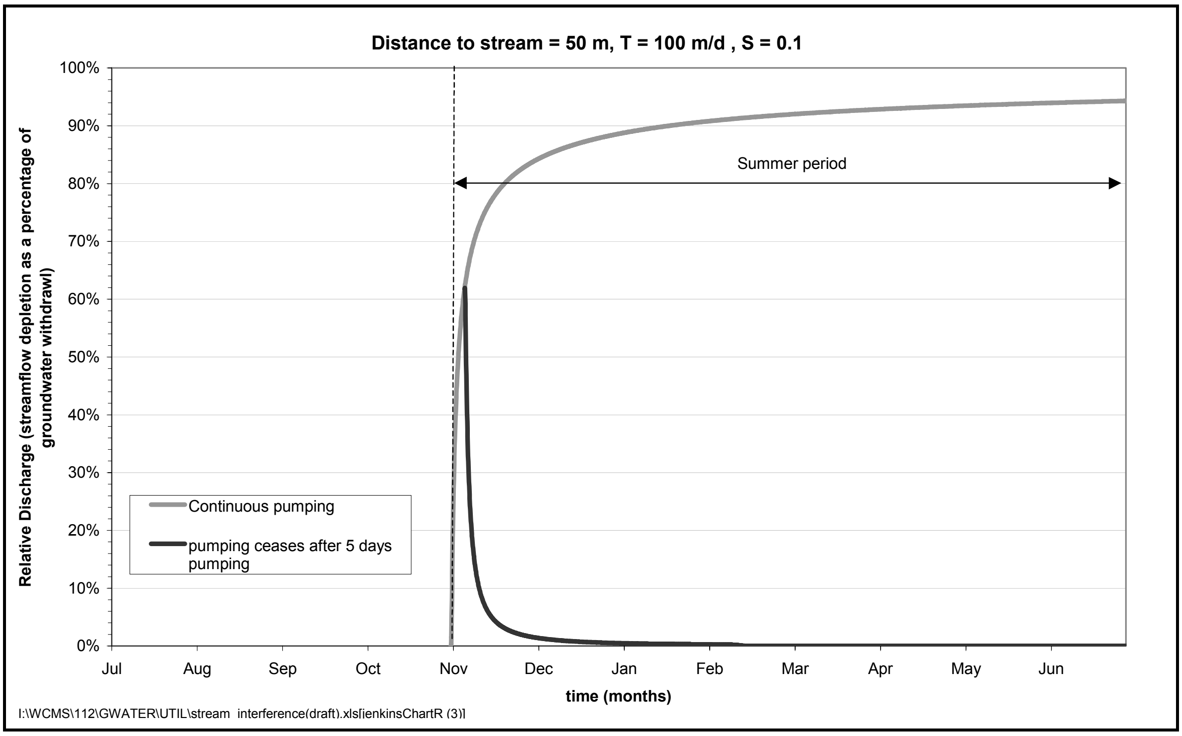
4.3.1 Short Term Lag ("Zone 1")

In areas where the lag is small, say less than 1 day, groundwater extraction could be managed in the same manner as surface water (ie restrictions on groundwater extraction would have an almost immediate effect on streamflow depletion, Figure 11). Groundwater restrictions could be implemented using two different approaches as used for surface water diversions:

1. Pre-determined period (eg operation of bores would only be permitted during the winter period July – November), or
2. roster during summer period (November – July).

The duration of pumping permitted during the pre-determined period will be dependent on the maximum allowable impact on streamflow. Restrictions could be implemented at short notice if low flow conditions trigger a management response. During the summer period rosters or bans could be used to achieve minimum flow requirements.

- **Figure 11 Summer operation of a bore located in Zone 1 (note the short lag between pumping and streamflow depletion, and short lag between cessation of pumping and reduction in streamflow depletion).**



4.3.2 Medium Term Lag ("Zone 2")

4.3.2.1 Type of Restriction

As the degree of hydraulic connection between the aquifer and stream declines or the distance between the bore and stream increases, conjunctive management to achieve minimum streamflow outcomes becomes more complex. As the lag in groundwater pumping impacting upon the stream increases, the potential for short term reactive management response is reduced (Figure 12).

As discussed previously, zone 1 groundwater users could be managed in conjunctive with streamflow triggers, however management options are less simple where there is a significant time lag between the start/end of pumping and the start/end of streamflow depletion.

Management methodologies that could be developed to deal with timelag includes restricting the period of pumping (ie a specific pumping season will need to be defined) or reducing the volume pumped or both. Currently most groundwater usage occurs during the irrigation season. It will require a significant cultural shift by irrigators for restriction on the duration of pumping to be understood and successfully implemented. The costs of compliance may also be significantly greater than for a volumetric restriction (ie meter reading may only be needed 3 to 4 times a year for a volumetric restriction, but may be needed monthly for a duration or combined duration and volumetric restriction).

A summary of the major issues associated with the two main categories of restriction are presented below. A wider discussion on the options associated with these restrictions are discussed in more detail later in this report.

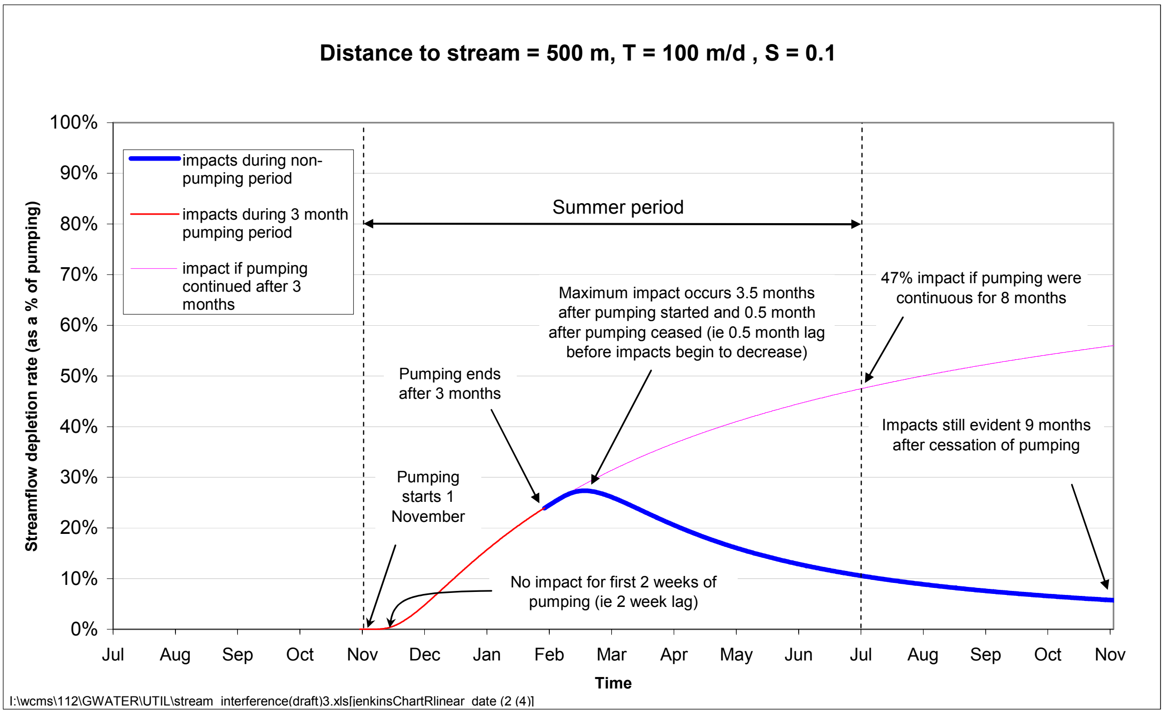
4.3.2.2 Entitlement restriction

A volumetric restriction would be most likely be applied as a percentage of the licensed entitlement.

As an example, a volumetric restriction could be applied in the following way. An irrigator with a bore 500 m from a stream is estimated to be withdrawing 47% of the volume pumped from the adjacent stream after 8 months pumping (Figure 12). If the allocation were reduced from say 500 ML/year (ie 2.7 ML/d) to 300 ML/y (ie 1.6 ML/d) the impact on the stream would theoretically decrease from 1.3 ML/d (ie 47% of 2.7 ML/d) to 0.75 ML/d (ie 47% of 1.6 ML/d).

Benefits to environmental flows using volumetric restriction would only be effective if the entitlement was not in excess of the annual volume pumped (ie sleeper licences would reduce the effectiveness of this approach).

- **Figure 12 Streamflow impacts with a "medium term" lag.**



4.3.2.3 Restrictions based on fixed pumping periods

The duration of pumping could be restricted through setting of predetermined periods during which pumping would be permitted. The setting of predetermined periods is a similar approach to the winter fill licences for surface water extraction being encouraged under many of the draft Stream Flow Management Plans. In the event that the restriction lead to complete bans during key irrigation months, similar adjustment packages as proposed in Stream Flow Management Plans may be required to allow groundwater users to adjust their management (which may include changing their existing irrigated enterprises).

Restrictions based upon the fixed pumping period would require robust justifications. Such justifications may include regular and/or repetitive stream flow behaviour whereby annual restrictions would provide a consistent outcome at the stream in a significant majority of years (eg restrictions in October/November maybe needed in most years to deliver streamflow outcomes in February/March).

4.3.2.4 Restrictions based upon triggers.

As the flow regime in unregulated streams are highly variable in response to climatic conditions, in many cases, restrictions based upon triggers will be easier to justify than restrictions based upon pre-determined pumping periods. However triggers must also withstand scrutiny and be clearly justifiable. Trigger options could include:

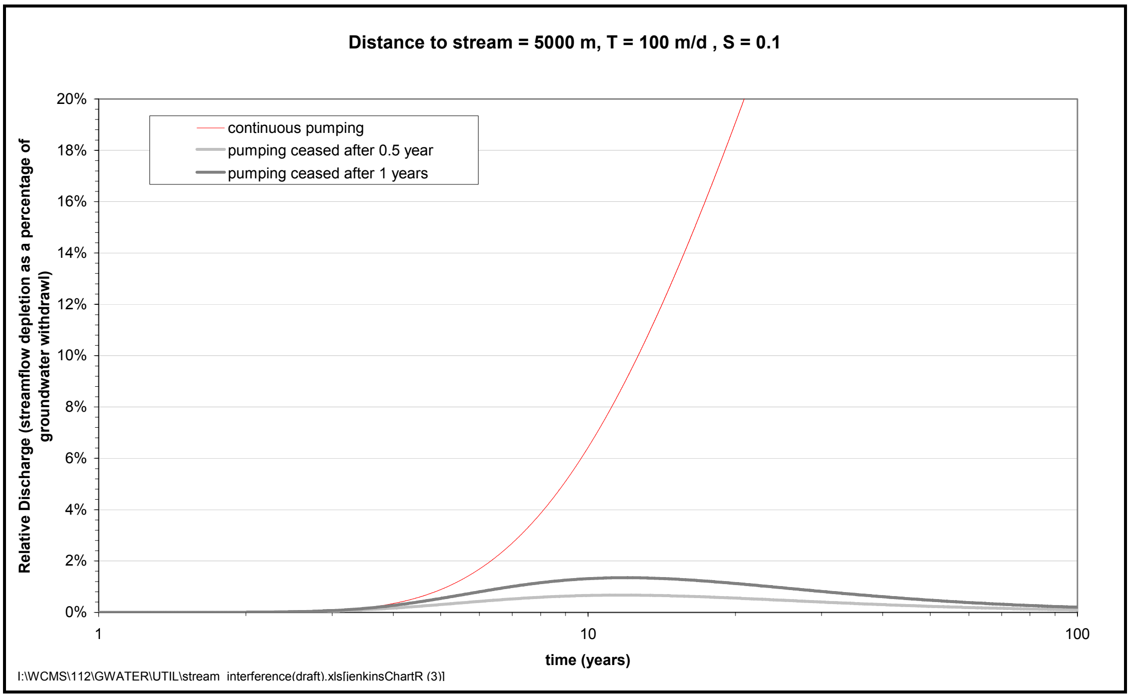
- An analysis of rainfall data leading to triggers established on the basis of likely upcoming risks to streams during critical time periods
- Minimum groundwater levels.
- Volume of groundwater pumped

Evaluation of options are summarised in Appendix B (Table 9, Table 10 and Table 11). Table 9 summarises options for applying restrictions. Table 10 summarises options for identifying the timing of restrictions and Table 11 proposes different types of restrictions.

4.4 Long term lag (Zone 3)

When the lag exceeds the length of the typical pumping season (Figure 13) the application of temporal based restrictions as a means of contributing to streamflow targets has the potential to become extremely complex and impractical to implement. The implications of Zone 3 to water managers may therefore be in ensuring that total usage within the zone does not exceed the sustainable yield, where a key element in the sustainable yield determination may be in maintaining or delivering throughflow contributions to surface water systems.

- **Figure 13 Example of a very long lag between commencement of pumping and impact on streamflow (note the long delay between cessation of pumping and the maximum impact)[1].**



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1. Note that the impacts after pumping has ceased are an over-estimate because the analysis assumes pumping was continuous during the 0.5 and 1year pumping periods (ie in reality pumping would be discontinuous and, hence, have a lesser impact).

5. Policy Issues

5.1 Introduction

Any evaluation of the significance of surface water groundwater interaction inherently involves, written or unwritten, assumptions concerning whether and when an effect is significant (or not). This invariably involves value judgements concerning the relative economic, social and environmental impact of various decisions. Unfortunately for too long our surface water and groundwater resources have been managed separately. Hence any reductions in water allocations have the potential to pit one group of water users (eg surface water users) against another group of water users (eg groundwater users). To minimise such conflicts, policy should aim to establish general principles of good practice. Such policy could be considered at two levels: national policy and operational policy. National policy aims to establish broad principles, while Operational policy can be considered to provide specific guidance of how various rules and operating procedures are to be applied. Operational policy can be at a State, catchment or local scale.

5.2 National Policy

In developing the general framework for the management of groundwater stream interaction, there are some major policy initiatives required to resolve the fundamental issues of social equity and sustainable groundwater resource management. Such policies would include the following:

- Both surface water and groundwater users sharing in an equitable manner the impacts of any reductions in total water allocations,
- Groundwater and surface water management plans should consider both short term (eg seasonal) and the long term (eg 50+ years) effects,
- Where groundwater and surface water systems share (or impact upon) a common water resource, management plans should have common objectives with respect to environmental, social, aesthetic and economic objectives,
- A holistic approach to the benefits of groundwater pumping (eg for salinity control) be recognised in groundwater and surface water management plans.

Under a National Heritage Trust initiative, a discussion paper on national policy principles has been developed (http://www.nht.gov.au/ncc/ground-surface-water.html). The above points are included in the paper. The discussion paper covers the following issues:

Policy Principle 1 – Define and apply consistent terminology relating to groundwater – surface water interaction

Policy Principle 2 – Assess or conceptualise the process of groundwater – surface water interaction

Policy Principle 3 – Define the potential impact of abstraction on groundwater and surface water interaction

Policy Principle 4 – Manage connected groundwater and surface water resources in an integrated manner

Policy Principle 5 – Consider the long term issues of groundwater and surface water interaction in water management plans

Policy Principle 6 – Ensure groundwater storage accessed during drought periods does not unacceptably impact groundwater and surface water systems

Policy Principle 7 – Consider all groundwater users in water management plans

Policy Principle 8 - Recognition cumulative groundwater use impacts in water management plans and the groundwater access entitlement application process

Policy Principle 9 – Consider enabling groundwater and surface water trading in areas with reasonable connectivity reaction times

Policy Principle 10 – Apply a precautionary approach to granting new water access entitlements

Many of these policy principles are already assumed at a fundamental level in the development of the methodology in this report. It is important to appreciate that the above broad policy principles apply to both existing and new groundwater licences, although some policies are more directly applicable to either new or existing licences. In most respects groundwater trades should be considered as if they are new licences.

Draft policy principle no. 3 is perhaps the most significant with respect to new licences in that it proposes that the volumetric impact on stream flow, as a consequence of groundwater extraction will be considered for all bores in a catchment to be a one to one hydraulic relationship, regardless of the distance of the bore from the stream, unless demonstrated otherwise to the satisfaction of the relevant government authority. This invariably points to the need for a catchment wide water balance and the identification of any double accounting. This policy principle should not be interpreted as saying that a one to one relationship should be assumed, but rather that the level of interaction should be assessed, and only if no assessment is undertaken then a one to one relationship be adopted.

5.3 Catchment Water Balance

This report is specifically focussed on the development of a methodology for managing the impact of existing groundwater licences on unregulated stream flow during critical low flow periods. Relevant rules are therefore operational (ie local) rather than national so broader issues of double accounting and possible double allocation in a catchment are not considered outside this chapter (assuming that the surface water catchment and groundwater regime are coincident). Nonetheless calculating the total catchment (hydrologic) water balance is a desirable precondition for adequately defining rules for managing the groundwater usage impacts of low flows in streams because acceptance of management rules for surface and groundwater users requires a level of understanding of future reliability of supply which will be compromised if major over allocation problems are unresolved. Hence the fundamental assumption in this project is that the catchment scale water balance has been considered and that significant double accounting does not occur.

At a policy level defining what is "significant" is considered to be an operational policy and may well vary between the States. For Victoria it would require that the Permissible Consumptive Volumes (PCVs) for areas requiring higher level management (eg. Water Supply Protection Areas) be reviewed and reassessed as to whether they adequately consider the total catchment water balance, ie. base flows or stream leakage should be adequately dealt with under the resource assessment. Alternatively, for areas that are subject to groundwater level response management, an assessment is required as to whether groundwater triggers and targets allow for stream flow requirements. Nonetheless, the approach in this report is that the methodology is aimed at managing the impacts of groundwater pumping in response to climatic stress, and not a stress caused by over allocation of the total (surface water and groundwater) water resource.

It is argued above that a catchment water balance is desirable prior to the application of local management rules (eg the Zonal system of applying restrictions, as in section 4), this is however not essential. Without a catchment water balance, the application of local management rules would still be feasible, it would just mean that where restrictions are entitlement based, progressively tighter restrictions may have to be applied to achieve the desired stream baseflow. In addition, the accuracy of most catchment water balances is such that double accounting is likely to be largely irrelevant when dealing with critical low flow in streams. This is especially the case where the summer low flow (that is aimed at being maintained) might only be about 1% of the total annual stream flow. In these cases the total volumetric component of the water balance is less important than, for example, the daily extraction rate, or the time period for which water is licensed to be diverted (eg winter fill). Hence, while a catchment water balance is always desirable, it is not essential to implement the management methodologies proposed in this report.

5.4 Operational Policies

5.4.1 Starting Condition

Any consideration of impacts needs to define the starting condition against which any impacts are assessed. Specifically, in the evaluation of an application for a new or transferred licence, will the impacts of previous decisions (ie current commitments) be considered, even if the effects have not yet been felt at the stream, due to time lags? In order to achieve long term sustainability, the answer is obviously – yes! Hence the "Base Case" must consider the cumulative impacts of previous decisions. This means that the starting condition (the base case) for new licences should be the current situation assuming that double counting has been resolved and that any time lag impacts have been considered.

5.4.2 General Approach

Within Victoria, an attempt has been made to address surface water groundwater interaction within the current groundwater resource management framework, by making an allowance for interaction to be included in the calculation of Permissible Consumptive Volume (PCV) limits for some GMAs. Outside GMAs/WSPAs a rule of thumb has generally been adopted to manage groundwater stream interaction through a 200m buffer zone from waterways, although in recent years, some cases have required more extensive technical work including test pumping requirements of a bore. Whilst widely used as a key element in determining whether to issue a licence, the statewide resource assessment process (PCV assessments which for some aquifers included simple volumetric groundwater stream interaction calculations) were not established as a stand alone basis for such a purpose. The initial purpose of PCV assessments was as a precautionary approach to establish a trigger for the commencement of higher level planning possibly including more detailed resource assessments.

Similarly, operational techniques such as test pumping do not fully address the inevitability of extended lag times discussed in this report. Given that this report has presented the argument that pumping from zones 2 and 3 will have medium to long term impacts upon surface water systems either by intercepting groundwater before it contributes to base flow or, by induced stream leakage, a policy issue in allowing for ongoing issue of licences in these zones is clearly apparent. In other words, zones 2 and 3 have significant relevance in terms of contributing to discussion on what is an acceptable impact of a new licence on surface water systems. As has been shown, the level of impact is dependent on time as well as the volume pumped. Thus prior to the application of the zonal approach to new licences, it is desirable that a Total Catchment Water Balance be undertaken so that double accounting is eliminated. An output of each water balance study would be a revised PCV.

5.4.3 Acceptable stream and time lag impacts.

The zonal approach to management, as defined in Section 4, has been developed primarily for existing licences. Such an application must be underpinned by policy decisions concerning what is the water management objective. The objective will then drive the operational policy for that catchment. Depending on the scale of the issue there can be very different management approaches. For example, if the objective is to achieve minimum stream flows at a local scale (so called micro-management) there would be one set of policies. However if the objective is the achieve acceptable groundwater impacts on stream flows at the Murray Darling Basin scale (so called macro-management) then there would be another set of policies. In addition, at the local scale different catchments may have different objectives and hence different policies. For this project, the methodology is largely focussed on minimising water use impacts on streams during critical (low flow) times of the year. It is within this context that the definition of the boundaries between each zone needs to be defined. It is proposed that the variables which need to be considered in the definition of the zonal boundaries are as follows:

- Time until impact
- Maximum stream flow impact

In defining a particular zone boundary, it is critical to understand the particular management objective. Even at a local scale, different catchments may well have different environmental/water sharing objectives. If groundwater pumping is a viable alternative to direct pumping from the stream (ie which has an immediate 100% impact), the plan may accept a relatively high level of groundwater pumping impact depending upon the sensitivity of the stream to the ultimate groundwater pumping impacts. The zone boundaries will therefore depend upon not just the hydrogeological aspects of the catchment, but also upon the needs and requirements of the stream. Not withstanding the need to understand the management objectives, arbitrary examples of the way in which boundaries may be defined are provided below.

Zone 1

Any bore where more than or equal to 10% of the bore discharge is derived from stream flow (ie the impact) if it were pumped continuously for 7 days could be considered to be in Zone 1. Impact is defined as the rate of stream flow depletion as a percentage of bore discharge. This means that the Zone1/Zone 2 boundary should be set such that the allowable depletion rate (ie the amount of water derived from stream flow) must be equal to 10% after 7 days continuous pumping. Note that the assumption of continuous pumping is a conservative approach, ie worst case.

Zone 2

Any bore where more than or equal to 10% of the bore discharge is derived from stream flow (ie the impact) if it were pumped continuously for 6 months is considered to be in Zone 2.

The choice of 7 days and 6 months is a somewhat pragmatic timeframe of what could be considered short term and medium term. The choice of 10% is equally pragmatic and is in effect a subjective decision of what might be considered “significant”. There is no doubt that in different hydrogeological environments and in different river systems that the “significance” level could be different.

Cumulative impacts (ie the effects of pumping in the past which have not yet resulted in reduced stream flow and /or have already impacted on stream flow) are not allowed for in the zonal system. The amount these cumulative impacts need to be recovered should be considered in the severity and type of the restriction to be applied (ie. the only way cumulative impacts can be recovered in the zonal system is with the use of restrictions).

5.5 Management Issues

Separate from operational policies are a broad range of other management issues, many of which require specific policy decisions. Specific issues and examples of possible management approaches include:

- Status of dragline holes (or shallow groundwater pumps) in close proximity to rivers (ie in Zone 1). Possible management approach: Treat as Zone 1 if very short time lag, ie surface water rules apply.
- Tradeability between groundwater and surface water. Possible management approach: Establish conversion rules where the water resource outcomes are consistent with management objectives. There may be cases (eg to achieve stream flow objectives) where one way trading from surface water to groundwater is to be encouraged to reduce short term extraction impacts on the stream, aligned with reduction in entitlement provisions to counter any impacts on increased reliability.
- Rights to substitute groundwater use for surface water use if surface water quality is poor. Possible management approach: As for tradability, establish conversion rules where the water resource outcomes are consistent with management objectives.
- Issue of groundwater licences near ephemeral streams where summer surface water flows are rare. Comment: This will have the effect of further reducing the frequency and duration of summer surface water flows and therefore potential impacts on surface water and groundwater dependent ecosystems requires consideration. Possible management approach: groundwater resource should be managed as per the agreed rules for Zone 2.

The application of management rules for groundwater extraction impacts on streams cannot be completely separated from surface water management rules. Clearly in order to gain general support for any management approach, issues of equity will be high on the agenda for those in the community reviewing management rules. While the next chapter provides discussion on application methods for managing groundwater stream interaction, adoption of any of these methods requires consideration of the wider water resource management approach required to achieve sustainable and equitable outcomes.

6. Methodology – Application

In many upland environments where there is limited area of shallow watertable (and therefore little potential for pumping to capture ET), pumping will ultimately be sourced via capture of stream leakage or interception of baseflow. There are essentially four primary tools available for achieving conjunctive management in these environments. These are as follows:

1) Permanent (or semi-permanent) restrictions on entitlements
2) Trading
3) Substitution
4) Short term (or interim) restrictions on timing or rate of extraction

These four tools deliver environmental benefits to a stream in two ways: either by reducing the volume of groundwater extraction (in turn reducing the volume of stream depletion), or by increasing the time lag to shift the timing of the pumping impact (or some of the impact) outside the critical low flow period. Seasonal or permanent restrictions on entitlements provide benefits primarily through reduced groundwater extraction, while trading and substitution tend to provide benefits by shifting the occurrence of the impact. Short term restrictions on the timing or rate of extraction has some potential to achieve both.

Application of these methods/tools requires that the management objectives be clearly understood. The various tools must also be applied in an integrated manner to ensure that the methods are compatible and deliver the intended objectives. All potential outcomes (including possible unintended outcomes) require investigation as new management rules and decisions have the potential to impact upon future investment (both private and public). Irrigators and other water users will, therefore, ultimately be looking for a consistent long term understanding of their reliability of supply and have an expectation that the rules will not continue to change over the short to medium term. Each of these methods is discussed below in the context of achieving environmental outcomes in an unregulated stream.

While these four tools may be introduced to deal with all groundwater licences within a catchment, practical implementation would require a framework in which to effectively set rules. The discussion of each method in this section is therefore largely built around the zonal framework outlined in section 4.

It is also worth noting that where systems are over-allocated (ie, allocations are above the sustainable yield of the aquifers and streams combined), there is potential that this over-allocation could influence the effectiveness of implementing one or more of the management tools discussed in this section. Restrictions on entitlements in order to achieve sustainable volumes should ideally occur prior to any additional management controls designed to protect low flow in streams.

6.1 Permanent (or semi permanent) restrictions on entitlement

Permanent restrictions on entitlement refer to a prescribed permanent (or semi-permanent) volumetric reduction in access to the annual volume listed on groundwater licences. This could involve a permanent reduction in the licence volume (under a declared permanent water shortage) or a semi-permanent restriction prescribed in a Water Management Plan. There are two main variables to be considered in the suitability of this management tool:

1) Determining the level of entitlement restriction applied; and,
2) The spatial distribution of the restriction, ie, is it uniform for all groundwater users in the catchment, or based upon the zones (as proposed in section 4 - established on criteria such as distance from the river)

The level of entitlement restriction will depend on the particular streamflow objectives, and the extent to which it is likely that the restrictions will achieve these objectives.

If the desired environmental outcome in the stream is focussed on maintaining minimum flows at critically low flow periods of the year (which is likely to be the key objective for most unregulated streams), then this tool could be designed through a zonal approach. Bores closer to the river would be subject to greater restrictions than those further away from the river, because the impact of bores further away is delayed and likely to be spread out over a longer period, reducing the impact over a given short timeframe.

Key advantages of this approach are that:

- if agreed environmental/economic tradeoffs are established, leading to prescribed 'permanent' restrictions, management and administrative costs would be negligible.
- if relatively permanent/consistent restrictions can be agreed, then this approach offers greater certainty albeit that irrigators will still be subject to the normal range of climatic factors.
- there is potential down basin advantages to the catchment as a whole through reduced use of entitlement.

Disadvantages associated with this approach are that:

- it is a relatively blanket approach in that it is poorly targeted towards the individual licences responsible for most impacts on the stream, and the periods when streamflow outcomes are most under threat (ie, does not target low flow periods).

- if the restrictions were determined as permanent reductions in entitlement, the restrictions would need to be very large if there were large volumes of sleeper licences, as low level restrictions would have little effect on the high users who would be having the predominant impact on the stream. This means therefore that this tool is likely to provide a low benefit/cost outcome because it potentially imposes high economic costs before beginning to achieve significant environmental outcomes.
- if trading markets were permitted to allow users to adjust to entitlement restrictions, increasingly tighter restrictions may be necessary to achieve streamflow outcomes due to activation of sleeper licences.

Not-with-standing the above limitations, progress towards achieving environmental objectives for the stream could be achieved through this approach (subject to the restrictions being sufficiently large). The method is commonly employed in other countries (eg, the US) as a management tool in catchments highly affected by groundwater stream interaction, eg Republican River catchment, (Evans, 2006). However to be effective, it is likely that it would need to be incorporated into a suite of measures better targeted to achieving streamflow objectives.

6.2 Trading

6.2.1 Groundwater to groundwater trading

Groundwater trading refers to one groundwater user selling their groundwater entitlement to another groundwater user for economic reasons and is provided for under Victorian legislation (Section 62 of the Water Act 1989). Financial incentives for the seller would be the liquidation of a capital asset. Financial incentives for the buyer could include access to increased water resources to expand development, or increased reliability of supply to maintain current developments.

While there are clearly benefits to trade for those directly involved in the market, institutionally, transfer rules have the potential to be developed with sustainability outcomes in mind, including reducing the impact of groundwater pumping on streamflow. If transfer rules are appropriately designed, groundwater pumping impacts on a stream could be reduced volumetrically (largely through integration with restrictions on entitlements discussed in section 6.1) or via reducing short term impacts on streamflow, most practically achieved by shifting the extraction point further away from the river. At its simplest level, groundwater – groundwater trading would only be allowed if trade was from an inner zone to an outer zone. Similarly, rules could prevent a transfer from shifting extraction closer to the river, or banning extraction within a certain distance to the river to reduce short term impacts on stream flow.

Permanent and Temporary Trading

Groundwater to groundwater trading may be either temporary or permanent. A permanent trade refers to the permanent sale of all, or part, of one's entitlement, whereas temporary trading is the once off annual sale of all, or part, of one's entitlement. Permanent trading (assuming it occurs away from the river) has greater potential for reducing groundwater pumping impacts on stream flow, simply because the exchange and associated benefits are for the long term. Temporary groundwater trading will not have a long term benefit, however it could play an important role in managing water demand during trigger based groundwater restrictions imposed to meet stream flow targets.

Summary

Appropriately designed groundwater to groundwater trading rules may provide some benefit to the long term stream management objectives but will not be effective to achieve short term outcomes. The implications for the introduction of transfers for long term water use also needs to be thoroughly considered, as transfers in some cases may in fact increase stream impacts if the transferor's licence was associated with a poor yielding site, and hence results in an overall increase in the volume of groundwater being pumped. In such cases the financial advantage to the seller would be the financial return from a portion of entitlement that could not be utilised.

6.2.2 Surface water to groundwater trading

Surface water to groundwater trading is a potentially more effective tool than groundwater to groundwater trading for managing low flow periods in unregulated streams because it offers the potential to reduce the instantaneous impact of surface water diversion from the stream during periods of critically low flow. While not currently permitted in Victoria, the State Government's policy direction (Action 2.7 - Our Water Our Future, 2004) states that '*The government will.….where there is a high degree of connectivity between groundwater and surface water, develop trading rules between surface and groundwater systems*'. Development of this policy into relevant rules is beyond the scope of this report as they depend upon local management objectives, along with an understanding of the local stream hydrology and hydrogeological environment. However the basic technical premise justifying more detailed investigation at a local level is that such rules could realise stream flow benefits by using the time lag in groundwater to delay (or at least dampen) the impact on the stream during the critical period, compared to direct extraction from the stream.

As for groundwater-groundwater transfers, adoption of surface water to groundwater trading is likely to be slow and may require bans on surface water-surface water transfers to encourage new developers to consider groundwater pumping. As with groundwater-groundwater transfers, there may be some circumstances where the new development will increase reliability of supply to the purchaser, ultimately leading to increased impacts on the stream. It is therefore likely that regulations would need to be designed at a local scale to ensure that unexpected and undesirable outcomes do not arise as a consequence of some outcomes being poorly understood. Such regulations may include restrictions discussed in section 6.4.

A further issue is that of property rights. Surface and groundwater licences in northern Victoria have different attributes and the compatibility of these attributes (or appropriate conversion to common attributes) requires resolution prior to transferability being considered a realistic option.

These aspects are not yet clearly understood even in relation to surface water licences alone, where historic reliability of supply may be undermined by new environmental objectives under a streamflow management plan. Clearly, transferring such a surface water licence to a groundwater licence adds layers of additional complexity, under current licensing arrangements. At the very least, it is imperative that buyers fully understand the attributes associated with the purchased licence and that the suite of management rules designed for environmental benefit, also provide a level of certainty for the buyer over a reasonable timeframe

In summary therefore, while appropriately designed trading rules have the potential to contribute to achieving environmental objectives, the potential for negative outcomes for the environment and those involved in the transaction must be first explored and understood for the target catchment.

6.3 Substitution

Substitution refers to conversion of surface water diversion to groundwater abstraction by the same user. It is distinguished from trading in this report because it relates to the conversion of an existing licence held before and after (the conversion) by a single person. This differs from a transfer of a licence which involves a transfer from one person to another.

As for the other tools discussed in this report, the effectiveness of achieving desired streamflow outcomes is dependent to some extent on the design of the substitution rules as well as some of the issues raised within section 6.2. Matters to be considered in the design include:

- Percentage conversion – A full range of conversion to groundwater is possible, from a few percent to one hundred percent of the surface water licence. The greatest reduction in short term stream impacts of pumping would come from full conversion to a groundwater licence.
- Temporal – The conversion could be temporary or permanent, ie the diverter could switch to groundwater use only when critical stream flow levels are reached, or alternately a permanent proportion of the surface water licence could be converted to a groundwater licence. Given that the time lag impact of groundwater pumping has the potential to push the impacts of groundwater extraction beyond the critical streamflow period, substitution may be best managed by use of surface water when streamflows are well above critical low flow periods, and substitution initiated wherever possible as flows decline towards critical levels.

- Spatial – Conversion to groundwater extraction is only a useful tool to meet streamflow objectives if the substituted groundwater extraction occurs a reasonable distance from the river. For instance, there would be little benefit achieved by substitution to zone 1. The streamflow benefits would only be secured if conversion to Zone 2 or 3 took place.

Holland et al. (2005) discuss some of the advantages and disadvantages of substitution to achieve streamflow management outcomes. These form the basis of the following discussion. The main disadvantages of this tool include:

- The surface water diverter may not have access to land at a sufficient distance from the stream;
- The surface water diverter may not have access to a sufficiently productive aquifer within available land to achieve desired extraction rates;
- There may be significant costs associated with installing the bore and the infrastructure required to connect to the existing irrigation system;
- Groundwater quality may not be suitable for substitution;
- There is a risk of increased total catchment water use as a consequence of improved reliability of supply (also discussed in section 6.2 with respect to trading). This may not necessarily comprise local streamflow management objectives, provided the time lag shifts impacts outside critical low flow periods, and streamflow depletion outside these periods is considered acceptable. At a basin scale however, it may mean that in the longer term there is greater use of water resources that may have external impacts such as reduced reliability for downstream regulated users.

Where the above practical obstacles can be overcome, this technique offers the significant attraction of reducing the frequency or length of time for which demand for water impacts on streamflow during critically low flow periods, whilst also providing greater reliability of supply for surface diverters during these low streamflow periods.

Notwithstanding the above benefits, the practical difficulties will be a significant reality in many catchments such that as a management tool, this approach is not by itself likely to deliver the desired environmental outcomes. Nevertheless, it is potentially a very useful proactive management option which could reduce the need and frequency of more reactive applications such as restrictions on the timing or rate of direct stream diversion.

6.4 Short-term restrictions on timing or rate of extraction

Section 4.3 has already discussed a number of the aspects associated with restrictions on timing or rate of extraction. These are discussed here in more detail.

Restrictions on the timing or rate of extraction imposes limits on groundwater pumping for a certain portion of the year. The restricted period is either a predetermined interval or is based upon a trigger. There is a further division that can be made within the predetermined interval option, such that two different options for applying restrictions have been identified:

1) *Trigger based restriction* – A natural trigger based on real time or recent historical data is used to identify the period when restrictions to pumping are to be applied (and possibly also to define when lifted), and the magnitude of those restrictions.
2) *Pre-determined restriction period* – A pre-determined restriction for a fixed period of the year is implemented (eg pumping duration restricted by 75% in February, or full summer period).

It is also possible to have a combination of options 1 and 2, eg where there is a pre-determined restriction period but the size of the restriction is based upon a trigger or natural variable. The following sections discuss these options further.

6.4.1 Trigger based restriction

As described above, there are two broad types of triggers that can be applied to define the restriction period (and potentially also the magnitude of those restrictions):

- *Real time data* – This refers to a trigger based on data recorded during the pumping season. This means that the trigger and associated restriction can occur at any time during the irrigation / pumping season.
- *Recent historical data* – This is a trigger based on the immediate period leading up to the pumping season. Under this method the trigger would occur before, or at the start of, the irrigation season. This difference is very important in consideration of the relative merits of the two approaches.

Each of these options is further discussed below.

Real Time Data

For real time data, four different options on which the trigger could be based have been identified:

i. Stream flow during irrigation / pumping season – This trigger could be based upon actual stream flow within the pumping season. For example, if stream flow drops below a certain figure then restrictions would be enforced. The option could provide for progressive tightening of restrictions in response to continued decline in stream flow.

   This approach has the advantage of being consistent with the current approach for managing unregulated surface water diversions in northern Victoria. On the other hand, while such consistency is useful, it is not necessarily technically robust, as a timelag of one to two months in groundwater pumping impacts on the stream, may mean that in some years, the restrictions on groundwater extraction may be applied too late to have a beneficial impact on stream flow. The approach would therefore be appropriate for Zone 1, but not for bores more distant from the river.

ii. Rainfall during the irrigation / pumping season – This trigger could be based upon a minimum cumulative rainfall threshold for a certain period within the pumping season. For example, restrictions may be implemented if rainfall is less than 75% of average for the first month of the pumping season. The option would exist to progressively tighten (or ease) restrictions, if required, based on rainfall in subsequent months.

Groundwater restrictions based on rainfall during the irrigation season are likely to be approximately in phase with surface water restrictions. Hence the pros and cons discussed in (i) are equally valid. It does however potentially provide for greater opportunities to incorporate rules that accommodate an allowance for the time lag. Yet it may not be able to fully address the issue because rainfall during the irrigation season will contribute relatively little to baseflow. Hence, the delay between rainfall and stream flow is only likely to be in the order of days, and not the weeks to months that is required for predicting stream flow. Therefore restrictions based on this approach will be largely ineffectual for managing critical low flow periods.

iii. Groundwater levels during irrigation / pumping season – The trigger could be based on average groundwater levels during the irrigation / pumping season. For example, when groundwater levels drop below a certain level (deemed significant for maintaining baseflow) then restrictions are enforced. The trigger groundwater level could be based on data from one observation bore, or averaged from multiple bores. The selected bore/s would need to be located sufficiently close to the river, that they reflect the local driving groundwater gradient to the river, but not so close as to be impacted by local river level fluctuations.

The main advantage of this approach is that it reflects the process which actually sustains baseflow to (or limits losses from) the river during critical periods. It therefore deals directly with the parameter that ultimately must be managed in order to achieve the objectives of the restriction. By selecting bores at an appropriate distance from the river, this parameter could potentially apply restrictions to groundwater users prior to severe impacts of extraction impacting upon the stream, and thereby directly addressing the time lag issue. If practical, such an approach may be effective at protecting critical low flow periods.

The main disadvantages of this approach are that:

a. it is not directly based on stream flow, and hence occasions may arise where restrictions are unnecessarily enforced. For example, groundwater levels may be below the threshold level where baseflow is normally unacceptably impacted (and restrictions enforced), but higher than average rainfall during the irrigation season means that streams do not reach critically low flow.

b. it may be difficult to identify sites where the groundwater levels will be representative of the "average" groundwater status. This problem will apply particularly to fractured rock systems, but may also pose a problem in unconfined aquifers in narrow alluvial valleys where it may be difficult to site appropriate observation bores that identify regional watertable trends particularly beyond the start of the pumping season.

c. the sensitivity of baseflow to groundwater levels. A very small change in water level may represent a very large change in baseflow, and these small changes may not be easily measured.

d. an increased observation bore network is likely to be required for most catchments in order to use this method, resulting in higher costs associated with monitoring and data analysis.

iv. <u>Groundwater pumping volume during irrigation season</u> - The trigger could apply after a certain cumulative groundwater volume is extracted by all pumpers however there are multiple problems with this approach:

- the trigger is not linked at all to actual stream flows and hence restrictions will not be properly targeted; and
- there will be a high cost of obtaining real time series pumping data; and
- in some circumstances, it may encourage higher use early in the season before restrictions are introduced, thereby potentially worsening late season problems when the timelag impacts begin to capture streamflows.

Recent Historical Data

Triggers derived from recent historical data could be based on either rainfall prior to the irrigation season or groundwater levels prior to the season, as discussed further below:

i. Rainfall prior to the irrigation/pumping season

The trigger would be based on rainfall patterns prior to the irrigation/pumping season, eg a minimum cumulative rainfall trend, in the order of one to six months prior to the normal pumping season or a negative residual mass rainfall trend for a period of 'x' months prior to the start of the pumping season. Historical analysis of the relationship between winter/spring rainfall and stream flow in the critical period of the year (ie late summer/autumn) would be required in order to determine an appropriate trigger. In practice a weighted approach that combines trends in recent rainfall (eg, 1-2 months), winter-spring rainfall (eg, previous 6 months) and longer term rainfall (eg, 2-5 years) would possibly give the most accurate prediction on periods of critical baseflow. For most catchments / groundwater systems, it is likely that recent rainfall would be given the heaviest weighting, followed by total winter-spring rainfall, with a lower weighting given to long term rainfall.

By definition, the trigger that is used in this method is one that is applied before the start of the irrigation season, either immediately prior to commencement of the season, or several months beforehand. An early warning of restrictions would obviously be favoured by irrigators who need to plan for the season ahead (ie, what crops and how much to sow etc). However an assessment and trigger at the start of the irrigation season is more favourable for achieving outcomes for the river, as predictions on the risk of critically low flows would improve as the season progresses. The timing of predictions and any resulting restrictions may therefore require a trade-off between providing certainty for irrigators, and achieving a reasonably robust forecast of the need for restrictions.

A significant advantage of this method is that it is based upon a parameter which is a leading indicator of baseflow, and hence addresses the issue of groundwater pumping time lag. The basis for establishing the critical rainfall trend (that would trigger a restriction) would require deriving a relationship between short term rainfall trends and the subsequent season of low flow, that would in today's environment, trigger restrictions.

Limitations to this approach include:

- Potential for a lack of historical data to enable assessment of the relationship between rainfall trends and baseflow. In most catchments this would not be a problem, although in some catchments, new rainfall gauging station may be required within the upper catchment to ensure that the data is derived from a weather station that accurately reflects the local climatic conditions that ultimately drive baseflow.
- Occasions may arise where restrictions are unnecessarily enforced, such as when above average summer rainfall occurs and hence streams do not reach critically low flow. This could possibly be overcome by allowing restrictions to be eased or lifted mid-season, if

real time rainfall data indicated sufficiently high summer rainfall (ie, a combination of recent historical and 'real time' rainfall), however the time lag (between pumping and its impact on the stream) means that in terms of impacts, hindsight would dictate whether the restrictions could have been eased off earlier in the season.

ii. Groundwater levels prior to the irrigation season

This is similar to the rainfall option but the trigger would be based on representative groundwater levels prior to the irrigation season. A variation may also be to combine an assessment of trends in groundwater level and the actual groundwater level but is likely to be overly complicated.

While such early season groundwater levels and trends may be a basis for initiating restrictions early in the season, they would not reflect water level trends during the season which may be required to adjust restrictions later in the season.

6.4.2 Predetermined restriction period

A predetermined restriction is a limit applied on pumping for a fixed period of the year (eg pumping duration restricted by 75% in February, or full summer period). The main advantage of this approach is that it is technically simple to implement once the critical stream flow 'risk periods' for baseflow protection have been identified and if an assessment can be made of the average time lag between pumping and its impact on the stream. The restriction period could be based on at risk months, determined using historical rainfall, historical stream flow or historical groundwater level data. Identifying the appropriate level of restriction however, is not straightforward. The problem faced is one of setting a restriction that is either: a) overly conservative in order to ensure that the restriction protects the stream in extreme stress periods, with the consequence that restrictions in many years will be unnecessary tight, or b) inadequate to protect the stream in extreme stress periods because the restriction is only designed to cover the "typical" case.

While this option offers long term benefits in terms of reliability of supply for groundwater users (albeit lower than current levels of access), the fact that it is not specifically targeted to an actual event means that it may be challenged and hence will probably not be easy to sell to the community.

A subset of this option is where the restriction period covers the entire year, which is the same as a restriction on entitlements discussed in Section 6.1.

6.4.3 Implementing short term (interim) restrictions

There are essentially two ways of implementing short term restrictions:

1. Time restriction – This refers to rostering periods where pumping is allowed / not allowed. The roster may be based on geographic location (eg, zones or certain lengths along the river) or on a random system (eg, odd / even number extraction licence).
2. Volume restriction – This method could impose either:
    a. Annual volumetric restriction - a restriction on the proportion of entitlement that could be pumped within the irrigation season (commonly implemented as a seasonal allocation), eg upon start of restriction (either fixed period or trigger based), the licensee would not be allowed to pump more than a certain percentage of their total entitlement within the restricted period. In contrast to the 'time restriction', the individual groundwater user would decide when to administer this restriction; or
    b. Short term extraction rate (ie the volume that may be extracted over an irrigation cycle)

Within all of the above, there are options for secondary control measures including a complete ban. These two types of implementation are discussed below.

Time and extraction rate restriction (roster)

When a roster is triggered, increasing levels of restriction are applied on how much water each user can take. Under some rosters (such as are applied for surface water users), a total ban may be triggered if the stream reaches critically low rates of flow.

In practice, rosters combine the timing of extraction (1 above) and limits on short term extraction rate (2b above) and may be applied to licensed groundwater users as follows:

- An estimate would be made of the total water requirements (TWR) over a 10 day roster cycle to meet the types of licensed water use in the aquifer zone.
- Each entitlement holder's share during the 10 day roster cycle would be:

$$\text{Entitlement share} = \frac{\text{Individual entitlement X TWR}}{\text{Total zone entitlement}}$$

In applying such a roster to surface water users, a schedule determines the time and short term extracted volume that can be taken by each water user. If flows continue to fall, rosters are further imposed by reducing the pumping time allowed, and thus the volume that can be taken. Rates of diversion may also be limited by excluding pumps over a certain capacity from a roster.

The approach (for surface water rosters) is designed to even out the impacts of diversion on the streamflow. A roster for groundwater extraction may not be required to be as detailed. The impacts of groundwater users on the stream are more likely to be evened out (at least during the early part of the season) by the time lag rather than by controlling short term extraction rates

Annual volumetric restriction
A seasonal volumetric restriction applied that allows an irrigator to determine when pumping occurred would be simple to administer, and would therefore have major benefits if it could achieve the same outcome as rostering However the disadvantages are largely identical to those raised in section 6.1 and successful application would therefore be likely to require complementary measures to achieve streamflow objectives.

While annual allocations (compared with permanent or semi-permanent volumetric restrictions) could be designed with some flexibility in response to triggers, allowance for a progressive decline in allocation if streamflow outcomes during a year were worse than anticipated and reduced pumping was required is unlikely to be acceptable because of the economic impacts. Therefore flexibility is only likely to be practical in terms of easing off restrictions if conditions improved.

6.4.4 Conclusions

This chapter has considered four options for managing groundwater pumping impacts on streams to achieve streamflow management objectives. Some of the methods (substitution and trading) are opportunistic, and hence by themselves may not be able to deliver the desired outcome in the short term. However in the long run they can assist in achieving streamflow outcomes. Conclusions regarding three of the four options are summarised below:

- Permanent or semi-permanent restrictions on entitlement are not sufficiently targeted to provide proper protection to the stream. The imposition of severe cuts may achieve stream protection but such an approach would be very difficult to sell to the community due to unnecessarily harsh cuts in the majority of years. This method is also particularly vulnerable to being undermined by sleeper licences.
- Participation in trading markets that require extraction at greater distances from the stream are unlikely to be significant in the short to medium term and will therefore will not effectively contribute to short term outcomes for the stream. The development of such rules are however warranted to ensure that wherever possible, new developments have minimal impact upon the stream.

- Substitution is potentially a very useful management tool where practical obstacles can be overcome. Its potential influence is increased in catchments where there are only a limited number of large surface water diverters (as opposed to numerous small diverters) who could switch their extractions to groundwater. Such substitution may be partial in some cases. For example, a mid-season substitution would reduce the total pumping impact by removing the instantaneous affect of extraction on streamflow while delaying the onset of groundwater extraction impacts for some time, possibly until after the critical streamflow period has passed.

Proposed method

In summary, current groundwater user impacts on the stream are likely to be best managed through the application of interim (short term) restrictions in conjunction with appropriate management of surface water extraction. The potential exists to complement this approach with trading and substitution, which over a longer timeframe can be designed to reduce impacts of surface water users on the stream, and possibly reduce the frequency and severity of restrictions.

Of the options available for imposing restrictions, trigger based restrictions are likely to be the most appropriate mechanism for managing streamflow impacts within zone 2, because it is technically the most defensible option. It can be targeted to deliver protection to the stream when required, yet minimise impacts on groundwater users at other times. It is also likely to be the most socially acceptable option, as the community can see the link between stream condition and the trigger, and hence the need for restrictions.[3] A predetermined restriction period and permanent restrictions on entitlement are unlikely to be suitable approaches for managing short term impacts of groundwater extraction on the stream.

While the real time trigger has some important advantages, this method cannot properly deal with the key issue of the time lag associated with groundwater pumping. Further, it seriously reduces the reliability of supply for groundwater users who previously based their development with relative confidence in their reliability of supply, only to find that such confidence was unfounded in the longer term . Notwithstanding the above, increased uncertainty is also facing surface water irrigators in many catchments as the bar is progressively lifted on passing flow requirements to achieve improved environmental flow outcomes.

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[3] This may not always be the case however, particularly if the trigger is applied a long time before the critical stream period arrives. However, over time, if the trigger is shown to accurately predict critically important flow periods, and mechanisms are in place to ease off restrictions if appropriate, then it is expected that community acceptance of this method would increase over time.

A real time trigger would therefore tend to encourage groundwater users to investigate options for coping with declining reliability of supply. Such farm scale options have been explored elsewhere (Sinclair Knight Merz, 2005).

In summary therefore, despite some attractive advantages, a real time trigger is unlikely to be practical for imposing groundwater restrictions in Zone 2 and 3. A trigger based on recent historical data, applied shortly before the start of the irrigation season is therefore the preferred trigger based option. Cumulative or residual mass rainfall may be the most appropriate parameter to use for this trigger, as it is leading indicator of likely groundwater conditions and the data is widely available and easily collected.

Not withstanding the above, ultimately the most appropriate tool will depend upon management objectives and local issues for a particular stream. The tool or suite of tools to deliver these objectives can then be designed accordingly.

Finally, the potential for all methods, including short term restrictions, to be significantly undermined by sleeper / dozer licences needs to be recognised. In catchments where sleeper / dozer licences are a significant proportion of total allocation, actions to bring allocation and use into line or methods of restriction based on usage rather than allocation, are likely to be required in order for restrictions to be effective.

7. Upper Ovens Valley Case Study

7.1 Introduction

Surface water groundwater interaction studies can be focussed at catchment or basin scale water resource management. Larger scale integrated management may address issues of salt discharge and total catchment yield. For smaller catchments and sub-catchments, water sharing arrangements, economic development and environmental objectives at a local scale are likely to be the focus of conjunctive management plans. Elements of the general management framework (discussed in section 4.2) could potentially be adopted to address both basin and local issues.

As this report is largely focused towards addressing environmental flow objectives for unregulated streams at a local scale, a case study was considered useful to gain a preliminary understanding of whether some of the management tools proposed in previous chapters could assist in achieving improved streamflow outcomes in low flow seasons.

The Upper Ovens catchment was selected as an appropriate catchment because an integrated surface water/groundwater management plan is proposed to be developed over the next few years and an existing draft plan has identified the need to manage periods of low streamflow. The Catchment Management Authority and general community also generally acknowledge the extent of interaction and appear to support an integrated management approach.

To test the implications for streamflow from groundwater pumping, a numerical groundwater model was developed to assess groundwater river interactions in a six kilometre stretch of the Upper Ovens River. The model is based on the actual aquifer geometry and hydraulic parameters prevailing within the region of interest. While the model has been developed using measured groundwater responses and observed features of a particular river reach it is considered to be representative of the Upper Ovens River in general where the river valley is relatively steep and narrow and the hydrogeology is dominated by relatively high permeability alluvial sediments to depths of about 50 m.

Previous investigations of the Upper Ovens hydrogeology have included test pumping (Cox, 1989) and numerical modelling (Cox 1990). An Aquifem-N finite element model of the Upper Ovens aquifers near the town of Bright was developed by Cox (1990). The model was used to investigate the influence of aquifer transmissivity, groundwater extraction rate and aquifer storage parameters on the magnitude of the fluxes out of the river that are induced by groundwater extraction. The investigation concluded that river flows were impacted by groundwater pumping and that the degree of interaction is dependent on the pumping rate.

The current investigation has used a rudimentary calibration of a three dimensional finite difference model (McDonald and Harbaugh, 1984) to help constrain aquifer properties and climatic stresses.

The model was used to assess the interaction between groundwater extraction and surface water depletion for various configurations of groundwater extraction. It has included the assessment of likely impacts of converting surface water diversions to groundwater abstractions some distance from the river.

7.2 Hydrogeological Conceptualisation

The Ovens River is located in north eastern Victoria, extending from the Barry Mountains in the Great Dividing Range to the Murray River. The interactions between groundwater and surface water in the Ovens Valley are being assessed in this study using the river reach between Myrtleford and Porepunkah, which is located in the Upper Ovens System.

The water resources in the Upper Ovens and its tributaries are utilised for both urban and rural development. The townships of Bright, Myrtleford, Harrietville and Porepunkah draw their water from the Upper Ovens River and tributaries, and large volumes of water are also diverted for irrigation, domestic and stock purposes (Rural Water Corporation, 1988). Groundwater resources are also used, particularly during drought years, to supplement stream diversions.

A REALM model was developed in 1995 by SKM to provide information relevant to both a dam safety review and bulk entitlements conversions within the catchment (Sinclair Knight Merz, 1995). This REALM model has been updated twice since then, in 2000 (Sinclair Knight Merz, 2001) and more recently in 2005 (Sinclair Knight Merz, 2005). Where possible, inputs to the groundwater model described in this report are the same as or are consistent with the REALM model inputs and outputs.

7.2.1 Geology and Hydrogeology

The geology of the Ovens Valley can be loosely categorised as consolidated and unconsolidated sediments. The basement rocks include the Devonian Granite which forms Mount Buffalo and the surrounding ranges are comprised of Ordovician rocks. These Ordovician rocks have been deeply incised by alluvial processes, which have formed steep, narrow sided valleys. Upstream of the town of Myrtleford the unconsolidated deposits comprise alluvial deposits of the Coonambidgal Formation which consist of clay, sand and sandy clays.

The shallow aquifer is present along the Ovens River and tributaries between Mytrleford and Harrietville and is typically less than 15 m thick. Government and private exploration bores drilled into the deeper aquifers (15 to 70 m depth) generally have low yields, due to lateral and vertical confinement (RWC, 1988). There are two exceptions to this, a town bore at Myrtleford and an investigation bore at Porepunkah (RWC, 1988).

Several pumping tests and slug tests have been undertaken in both aquifers to determine aquifer parameters (RWC, 1988). The hydraulic conductivity of the shallow aquifer has been found to generally range between 1 and 8 m/d, but several bores reported higher conductivities ranging between 21 and 65 m/d. The hydraulic conductivity of the deeper aquifer was found to be less than 7 m/d. Storativity values for the deeper aquifer ranged between 4 x 10^{-7} and 1 x 10^{-3}, while the specific yield of the shallow aquifer ranged between 0.15 and 0.25 (RWC, 1988).

Groundwater flow in the shallow unconfined aquifer is to the north west, consistent with the topographic decline. The Ovens River is predominantly a gaining stream in this reach, where groundwater provides baseflow to the river. Only during very high flow events, and possibly during drought conditions when groundwater levels fall, does the river recharge the groundwater system. Recharge to the shallow unconfined aquifer is via direct infiltration of rainfall and more recently from irrigation recharge.

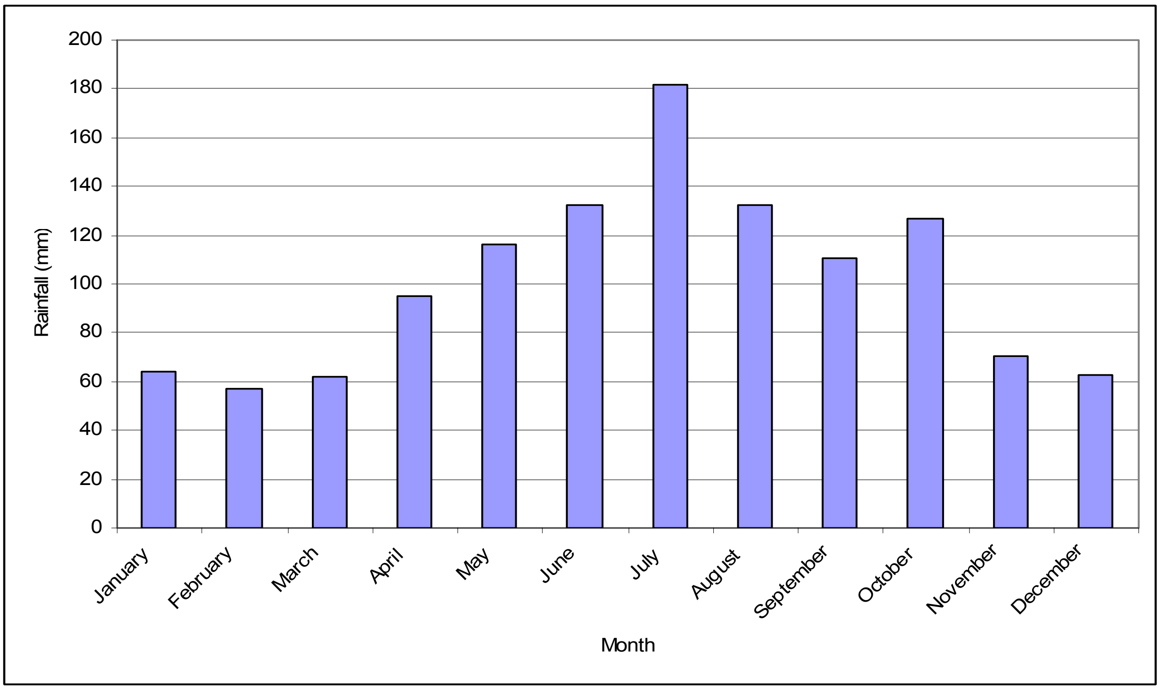
The Murmungee Groundwater Management Area (GMA) includes the valley of the Upper Ovens River and major tributaries (Sinclair Knight Merz 1998). When originally defined, the GMA was assigned a depth of 25 m. Approximately 88% of the available resource (assessed at that time) has been allocated to date. There is some uncertainty associated with the degree of confinement between the alluvial aquifer and the deeper aquifers. Therefore as a precautionary measure, Goulburn-Murray Water (G-MW) have established a moratorium on the allocation of any additional groundwater extraction licences within the geographic boundary of the GMA, which includes all depths (pers comm. Greg Holland, G-MW, April 2004).

7.2.2 Rainfall and Evaporation

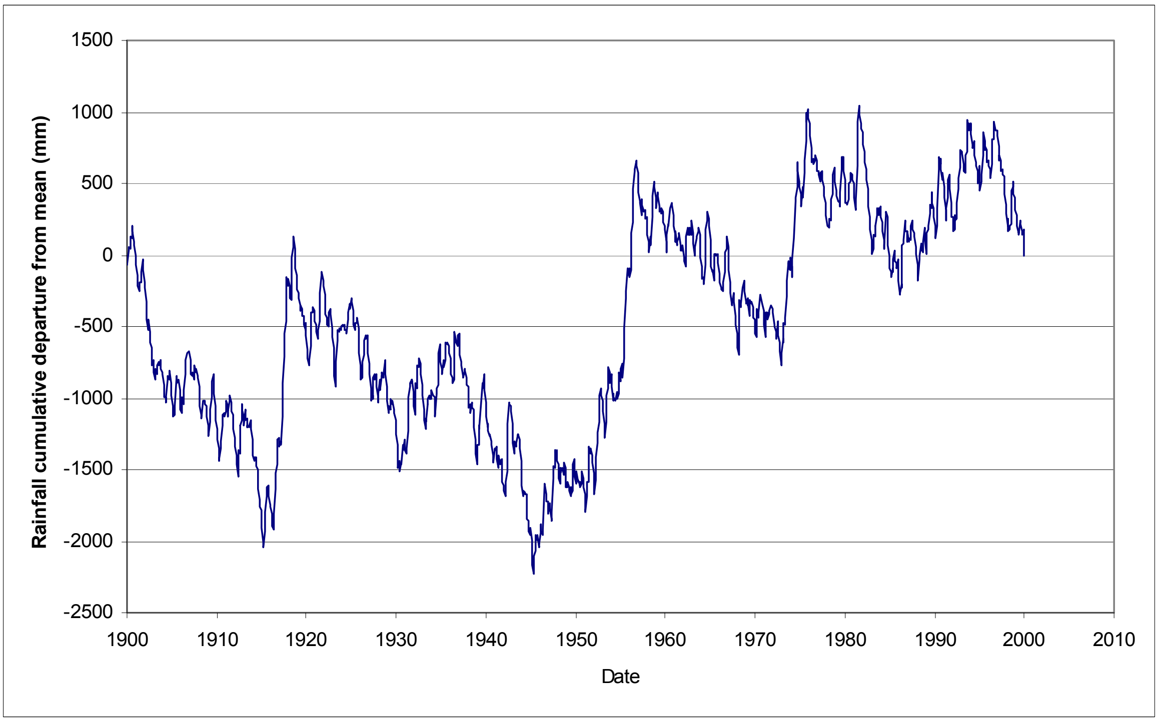
The Ovens Valley upstream of Myrtleford receives on average 1200 mm of rainfall annually, with average monthly rainfall fluctuating between 57 mm in February and 181 mm in July. The mean monthly rainfall is shown in Figure 14. The rainfall residual mass curve for the period 1900 to 2000 is presented in Figure 15. The falling trends in Figure 15 between 1920 and 1945, 1958 and 1975 and the late 1970s into the early 1980s highlights that the region experienced below average rainfall during these periods. Short periods of rising rainfall residual prior to 1920, during the mid 1950s and the early 1970s indicate sequences of very wet years.

The mean monthly evaporation is shown in Figure 16. The average annual evaporation is 1170 mm, with average monthly evaporation ranging between 22 mm in June and 228 mm in January.

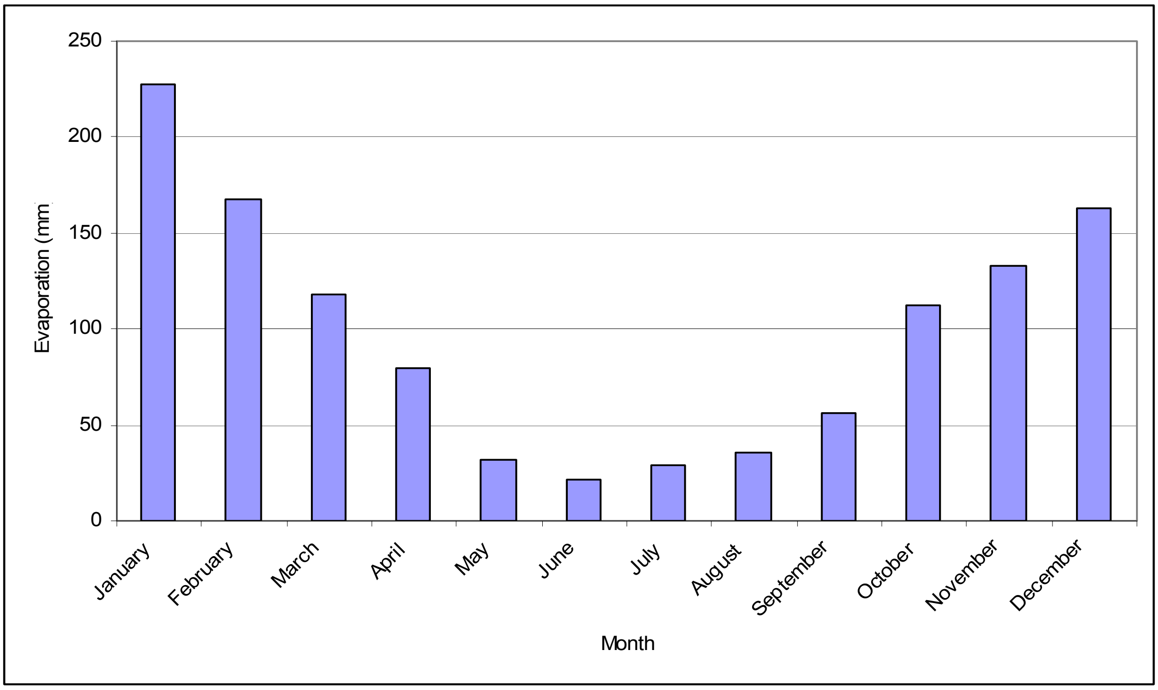
- **Figure 14 Mean monthly rainfall from REALM model (Lake Buffalo and Lake William Hovell)**



- **Figure 15 Rainfall residual mass from REALM model (Lake Buffalo and Lake William Hovell)**



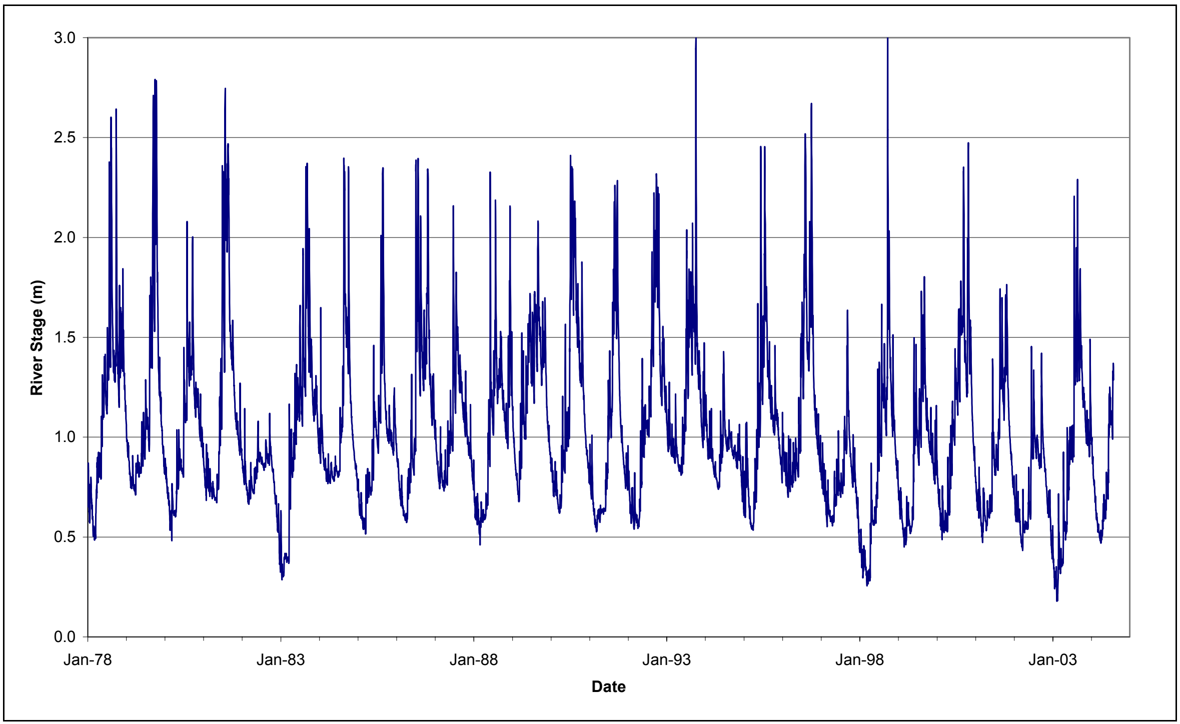
- **Figure 16 Mean monthly evaporation from REALM model (Lake Buffalo and Lake William Hovell)**



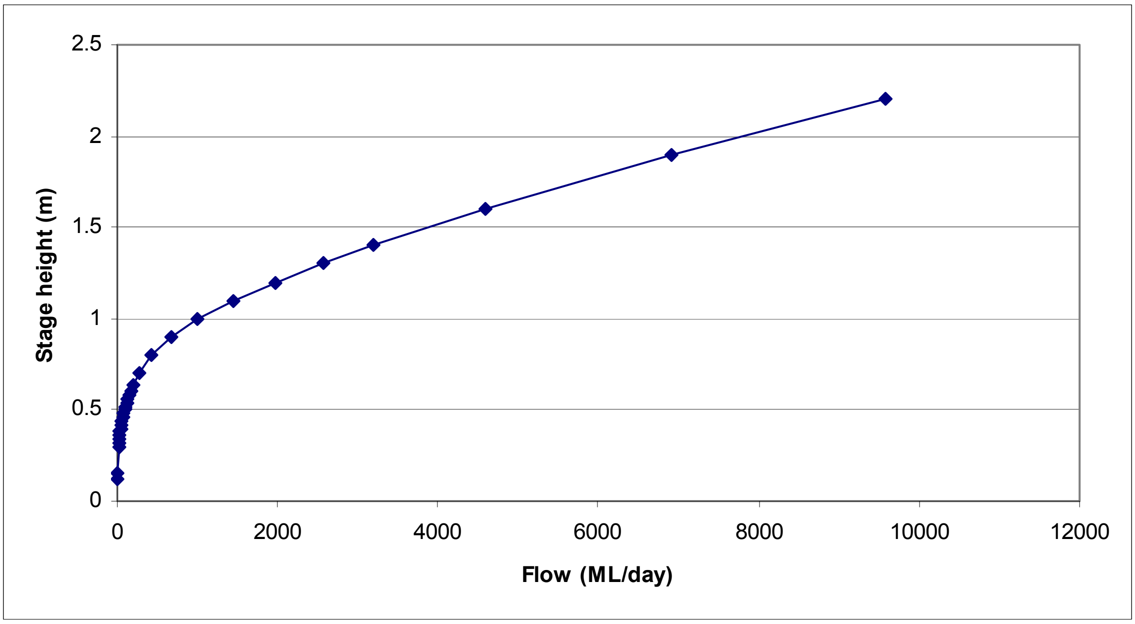
7.2.3 River Flow

The closest stream gauge to the river reach of concern is Gauge No. 403214, which is located on the Ovens River downstream of the confluence with Buffalo Creek. The average daily river stage height is shown in Figure 17. However, given this gauge is downstream of the confluence with Buffalo Creek estimates of stream levels upstream of the confluence, were derived consistent with REALM flow estimates (see Figure 18). While it is recognised that the rating curve for the river will differ upstream and downstream of the confluence, this is the best available means of estimating the river level within the model domain. The derived stage height of the Ovens River upstream of Buffalo Creek using the rating curve from the downstream stream gauge is shown in Figure 19.

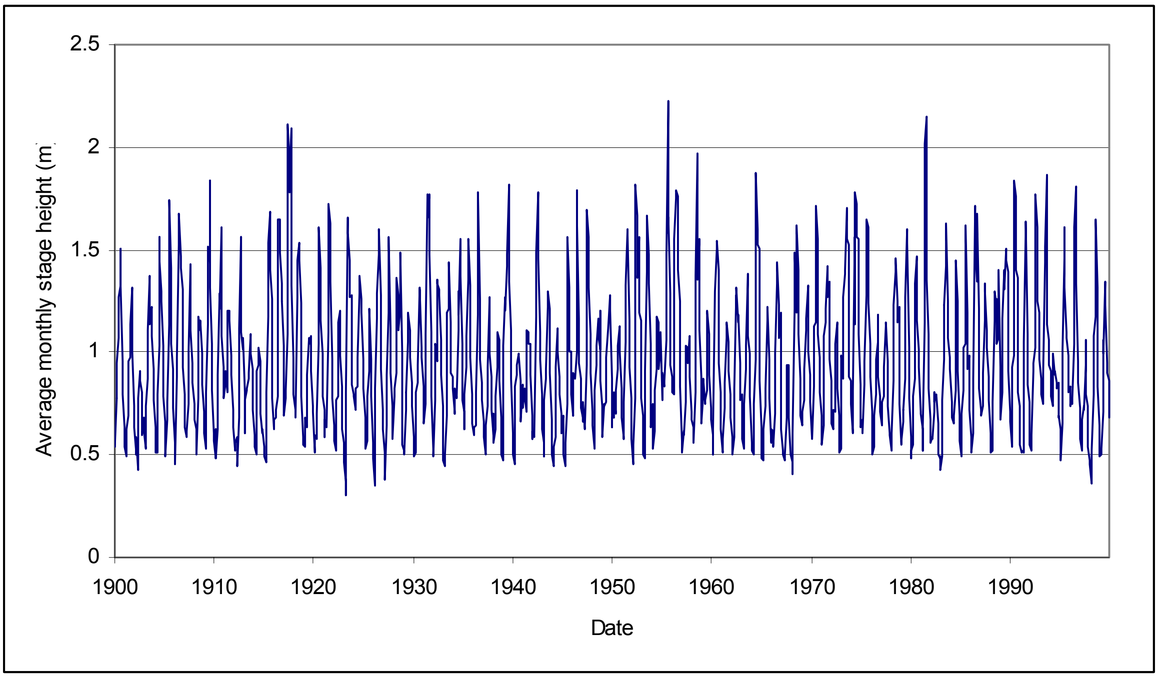
- **Figure 17 Average daily stage height Ovens River downstream of Buffalo Creek (403214)**



- **Figure 18 Rating Curve for stream gauge downstream of Buffalo Creek (403214)**



- **Figure 19 Estimated stage height of Ovens River upstream of Buffalo Creek using REALM flow data and rating curve for stream gauge 403210**



7.2.4 Irrigation

The irrigation areas were approximated using an infrared satellite image of the region. The image was derived from an aerial photograph taken in the year 2000 (available from the Department of Primary Industries). Approximately 540 ha of irrigated land is indicated within the study area. This is slightly higher than the irrigation areas assumed in the REALM model (460 ha) (SKM, 2001). The information obtained in the current study is considered to be more accurate than the estimates used to formulate the REALM model and consequently these areas were applied to the model.

7.3 Model Description

The objectives of the modelling is to investigate the impacts of groundwater pumping on streamflow. In particular the model is designed to investigate the relative merits of a number of groundwater extraction scenarios in relation to streamflow depletion during critical low flow periods when restrictions may be required on both direct stream diversion and groundwater pumping to achieve minimum environmental flow requirements.

The model covers a 6 km reach of the Upper Ovens River Valley with the downstream model boundary being approximately 6 km to the southeast (upstream) of Myrtleford. Figure 20 shows the location size and orientation of the model domain.

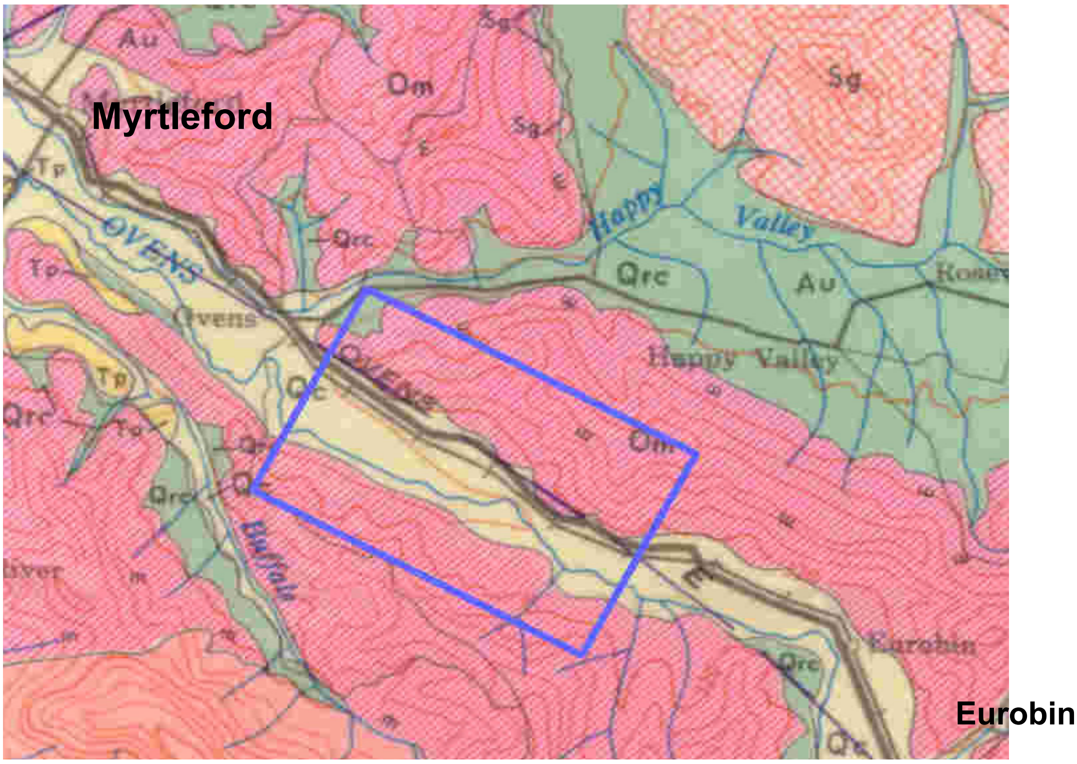
The model is subdivided into a finite difference grid of square elements of 50 m sides and in the vertical plane is divided into four layers corresponding to nominal stratigraphic units as:

- Layer 1 - shallow unconfined unit corresponding to Coonambidgal Formation
- Layer 2 - shallow semi-confined alluvial sediments of the Shepparton Formation
- Layer 3 - deeper semi-confined alluvials (of lower conductivity) also of the Shepparton Formation
- Layer 4 - deep lead or Calivil Formation.

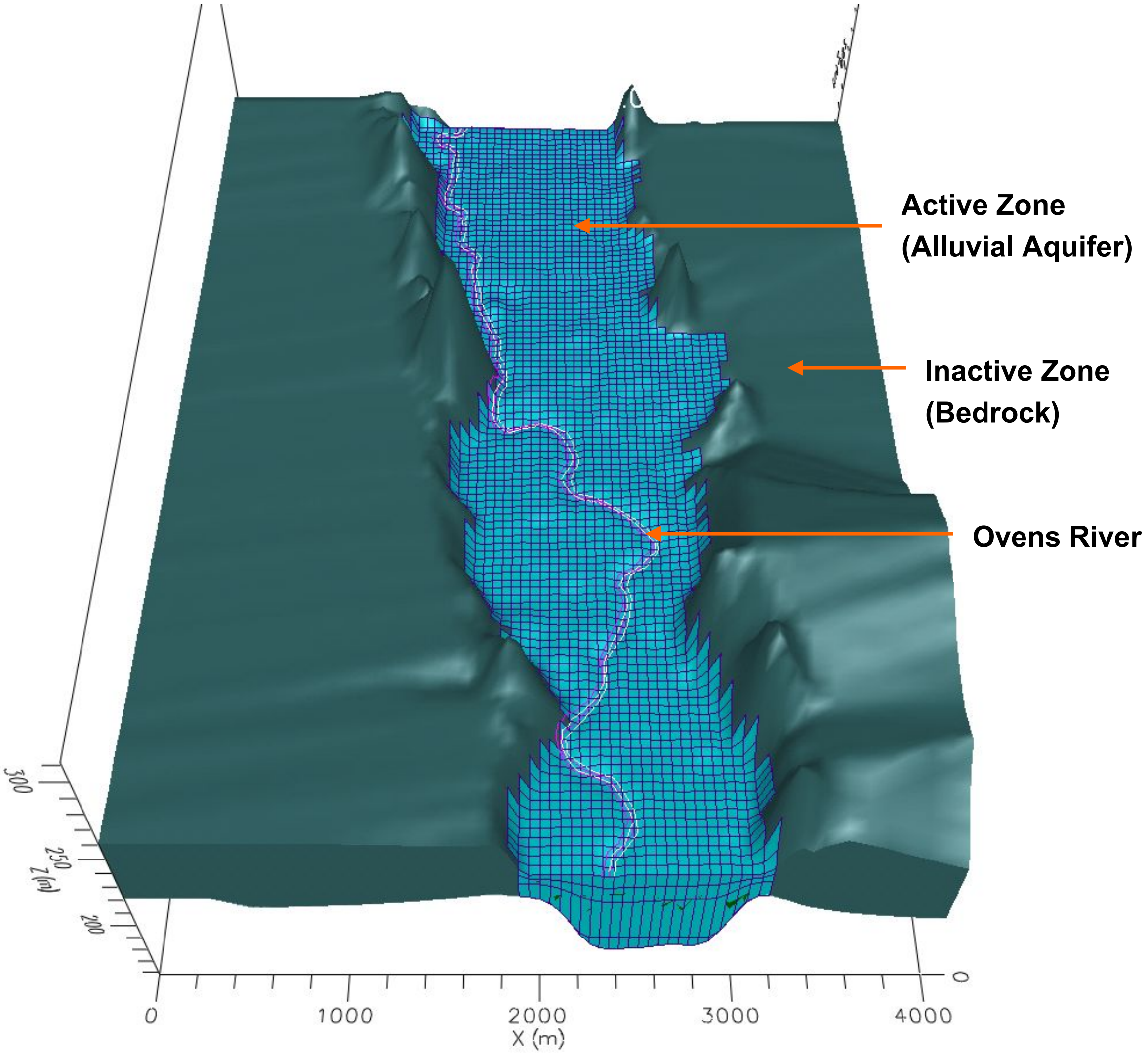
This nominal stratigraphy is typical of the Upper Ovens River Valley in general. The local stratigraphy is relatively poorly defined due to a lack of deep borelogs available from within the model area. In fact borelogs obtained from the area suggest that the sediments of the Calivil and Shepparton Formations are indistinguishable in terms of their hydraulic parameters. Also worth noting is the fact that much of the river bed and valley has been dredged in the search for gold. The dredging process involved substantial disturbance of the shallow sediments by successive excavation, mixing, reconstitution and re-deposition (Shugg, 1987).

The model grid layout and orientation are shown schematically in Figure 21. The lateral model boundaries coincide with the edges of the alluvial sediments and all cells located outside the lateral extent of the alluvial deposits are inactivated.

- **Figure 20 Location of Numerical Model Domain**

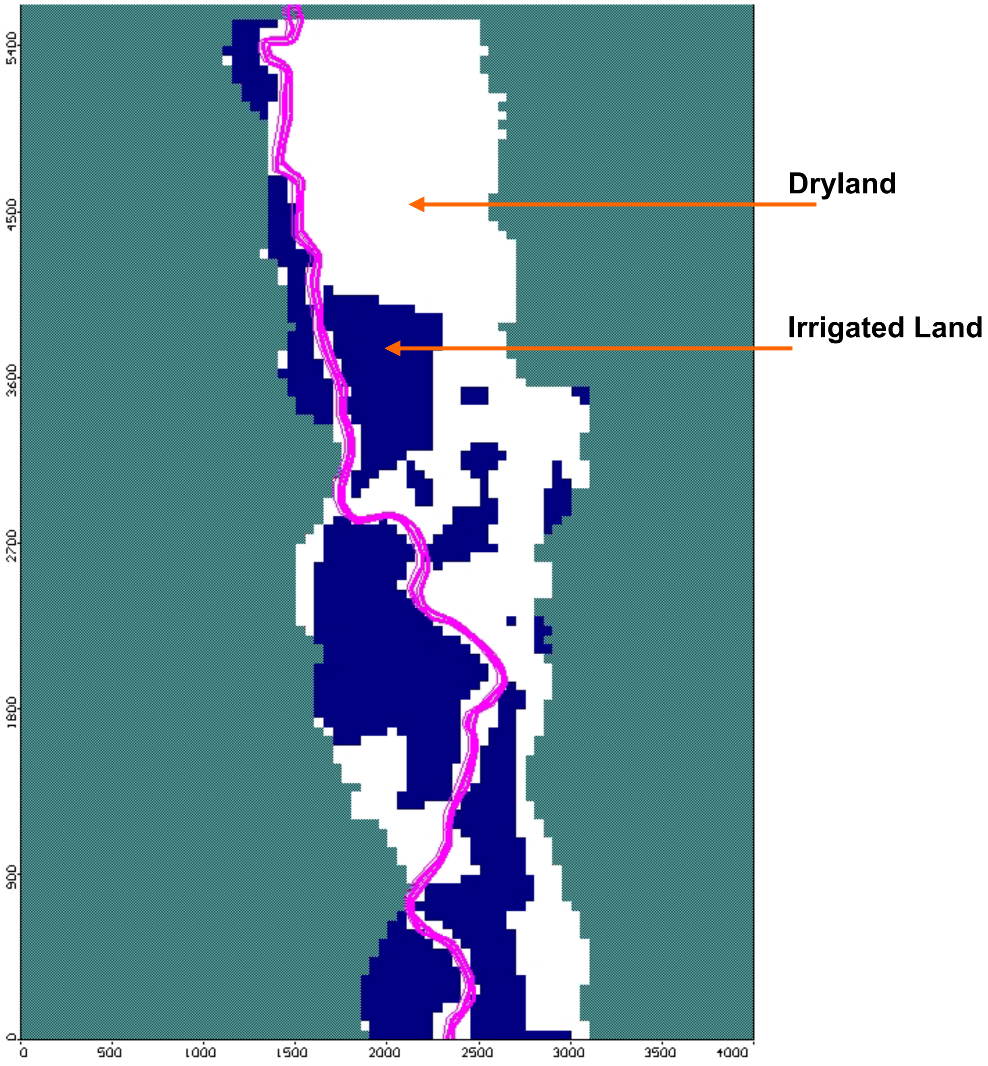


- **Figure 21 Model Structure**



The model includes the river represented as a time varying “Third Type” boundary condition in which the river stage elevation and a pre-defined flow resistance term control the groundwater heads at relevant locations. River stage data included in the model has been extrapolated from measurements of stage height and flow at Myrtleford. Rainfall recharge is defined as being equivalent to 5% of the measured rainfall over the entire model domain. Additional groundwater recharge is allocated to 540 Ha of irrigated land identified on the basis of satellite image analysis. In this region an additional amounting to 550 mm/year of recharge is applied between November and April each year. The pattern of irrigated land included in the model is shown in Figure 22. Evapotranspiration has been defined as measured evaporation when the water table is at the surface, linearly reducing to an extinction depth of 2m below the surface.

- **Figure 22 Distribution of Irrigation**



7.3.1 GMS data

In the 10 km reach upstream of Myrtleford, there are 96 groundwater bores in the Ovens Valley. In the model area there are 6 bores with a groundwater extraction licence and 11 bores with water level monitoring data. The details of these bores are outlined in Table 1.

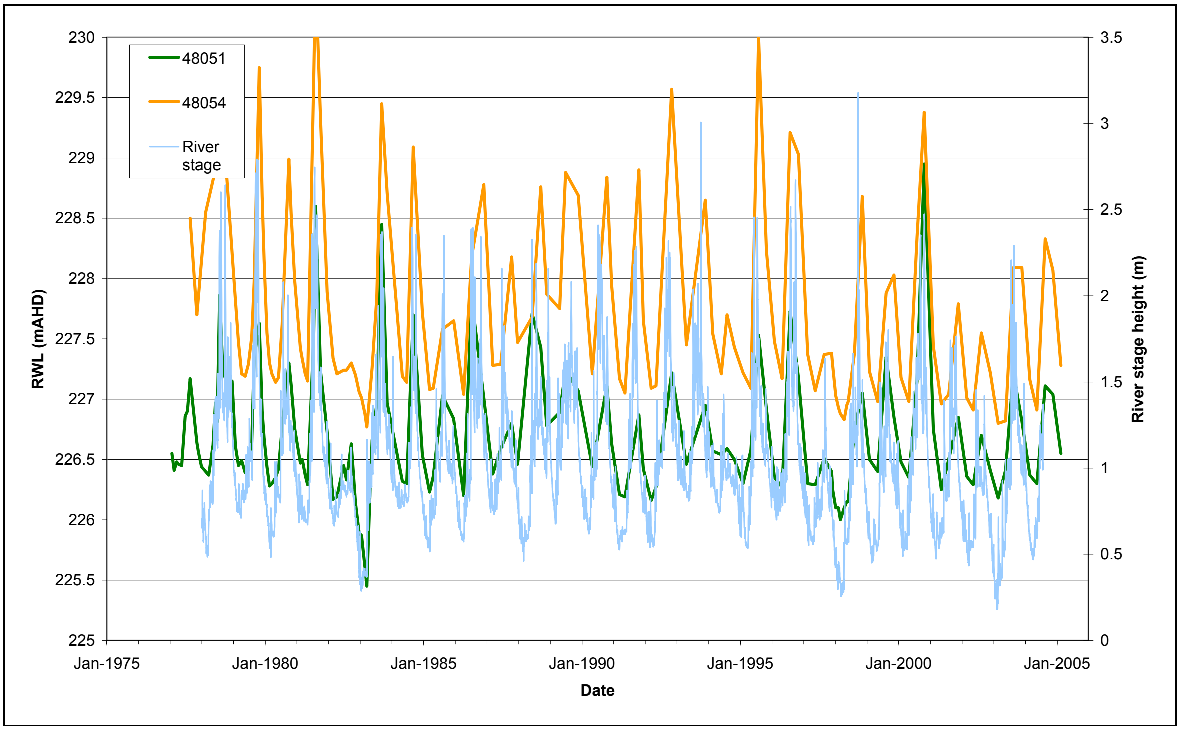
- **Table 1 Summary of extraction and observation bores in the study area**

Bore ID	Easting	Northing	Date drilled	Depth (m)	Bore Use
48084	482175	5947725	31\12\1967	6.4	Domestic stock irrigation
48180	481875	5946750	11\02\1991	7	Domestic stock irrigation
138550	479025	5949375	01\01\1800	3	Irrigation
48081	485462	5946262	31\12\1968	4.57	Irrigation

Bore ID	Easting	Northing	Date drilled	Depth (m)	Bore Use
83250	478676	5950109	31\12\1970	4.8	Irrigation
131755	481850	5948325	02\04\1997	60	Irrigation
48066	487450	5944350	28\08\1987	16	Observation
48051	481013	5947647	17\10\1971	37.18	Observation
48048	480964	5948166	31\08\1971	53.03	Observation
48073	480700	5947700	21\10\1987	11	Observation
48067	487500	5944400	04\09\1987	15	Observation
48068	487650	5944450	09\09\1987	15	Observation
48069	487700	5944450	01\10\1987	9	Observation
48070	481350	5948100	13\10\1987	12	Observation
48071	481100	5947800	14\10\1987	12	Observation
48072	480950	5947750	20\10\1987	12	Observation
48054	481596	5947987	05\12\1971	57.6	Observation

Two observation bores (Bores 48051 and 48054) were selected for the model calibration on the basis of their location and length of record. . The hydrographs of these bores and the river stage height (from gauge no 403214) are provided in Figure 23.

- **Figure 23 Hydrographs of observation bores and river stage height**



7.4 Model Calibration

The model was initially run to steady state in order to verify that the model is capable of adequately representing some of the principal features of the hydrogeological conceptualisation. The steady state potentiometric surface predicted by the model is shown in Figure 24. The figure indicates that groundwater is flowing towards the river from both sides and as such demonstrates that groundwater is discharging to the river in this reach. Groundwater gradients are consistent with the river grade over the reach.

Three groundwater extraction licence supply points are registered within the model area. Extraction bores are included in the model at the location and with assigned discharge rates that correspond to these licences. It was assumed that the current annual licensed volume is extracted over the summer months (November to April) of each year. Details of the licences are shown in Table 2.

- **Table 2 Groundwater Extraction Licences in Model Area**

ID	AREA	AMG ZONE	AMG NORTHING	AMG EASTING	ANNUAL VOLUME [ML]	COMMENT
48180	149.00	55	5946750	481875	448.00	2 dragline holes used to irrigate hops and tobacco
48084	4.20	55	5947725	482175	28.00	dragline hole used to irrigate pasture
131755	4.00	55	5948325	481850	12.00	drilled bore used to irrigate grape vines

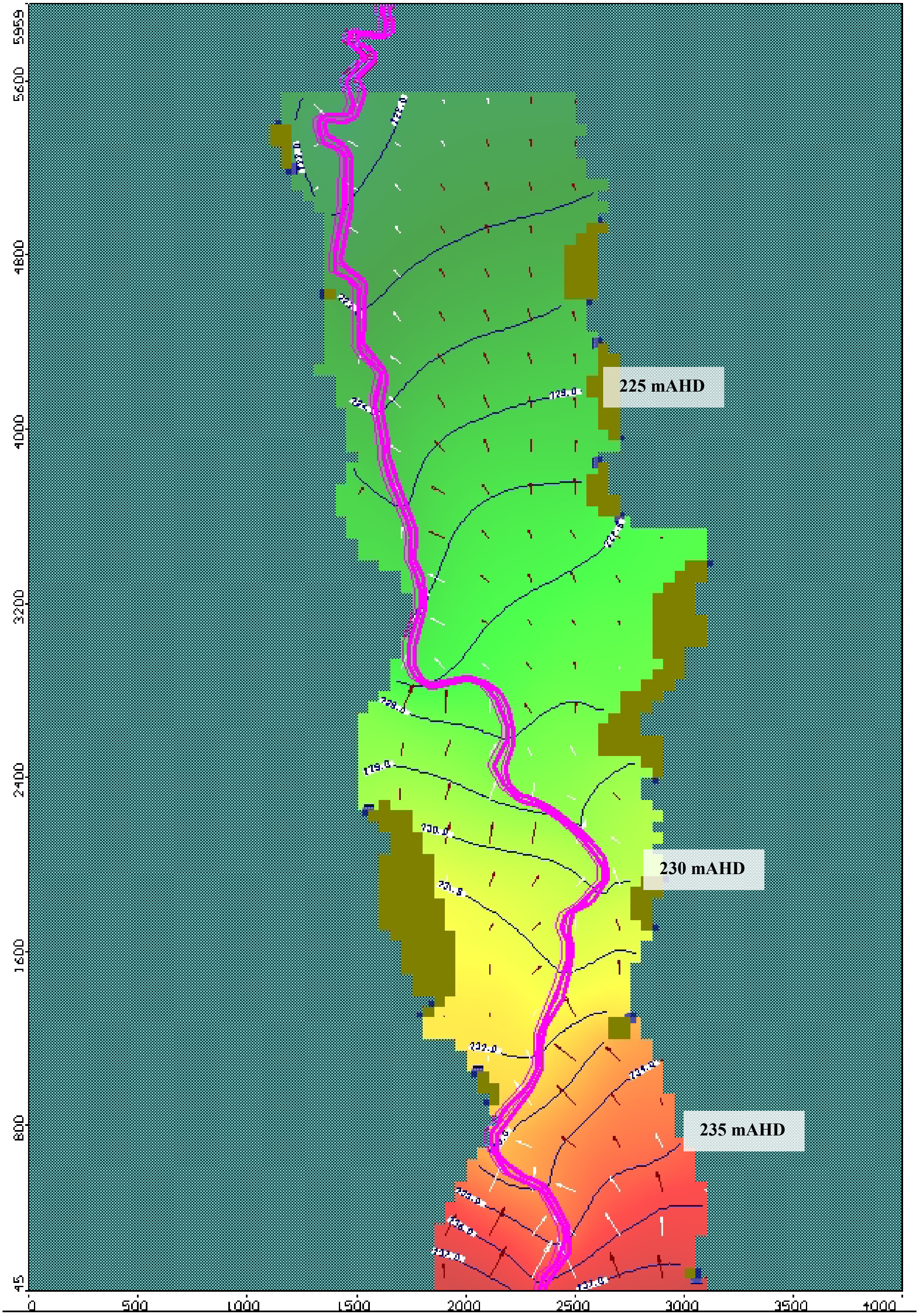
Modelling results suggest that the aquifer is unable to support an extraction rate equivalent to 448 ML/year at the location of licence #48180. When the model is run with this pumping rate all cells at the location of the extraction bore dry out and the pumping rate is automatically reset to zero. It is assumed that either;

- the full licensed volume is never extracted
- the licensed volume is obtained from a number of bores or drag lines on the property or,
- the licensed volume is obtained from a combination of extractions on this and other properties.

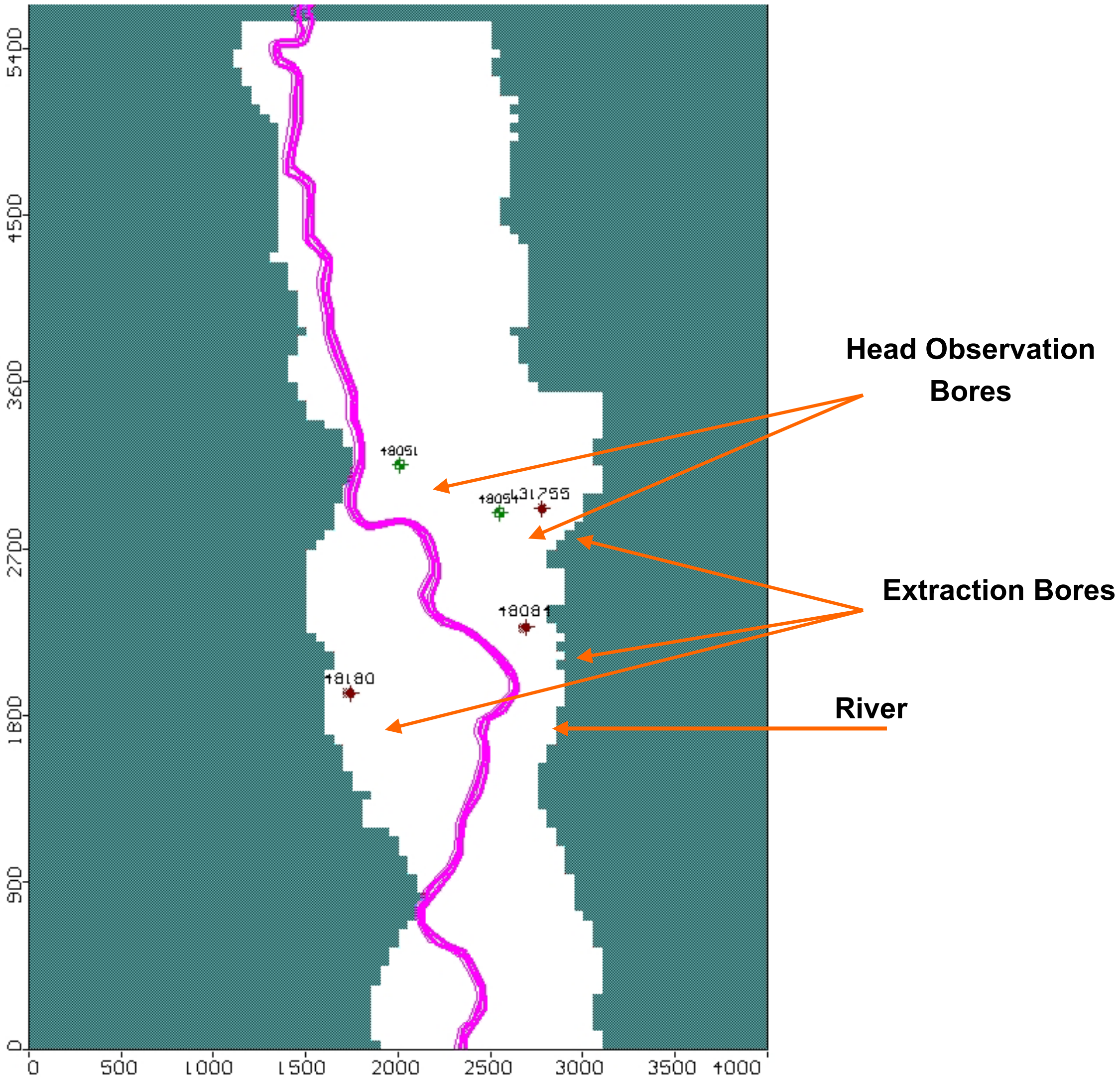
While the licence conditions specify approved access to groundwater via two dragline holes, the model was still unable to support the full extraction rate when run with two pumping locations. Trial and error simulations resulted in a maximum pumping rate of approximately 84 ML/year at this location. All subsequent models were run with this extraction rate for Licence #48180.

Records from two groundwater monitoring bores within the model domain were available and allowed a limited transient mode calibration. The location of the extraction and water level observation bores are shown in Figure 25. Both bores are monitoring water levels in the Shepparton Formation and correspond to Model Layer 3.

- **Figure 24 Steady State Potentiometric Surface and Flow Vectors**

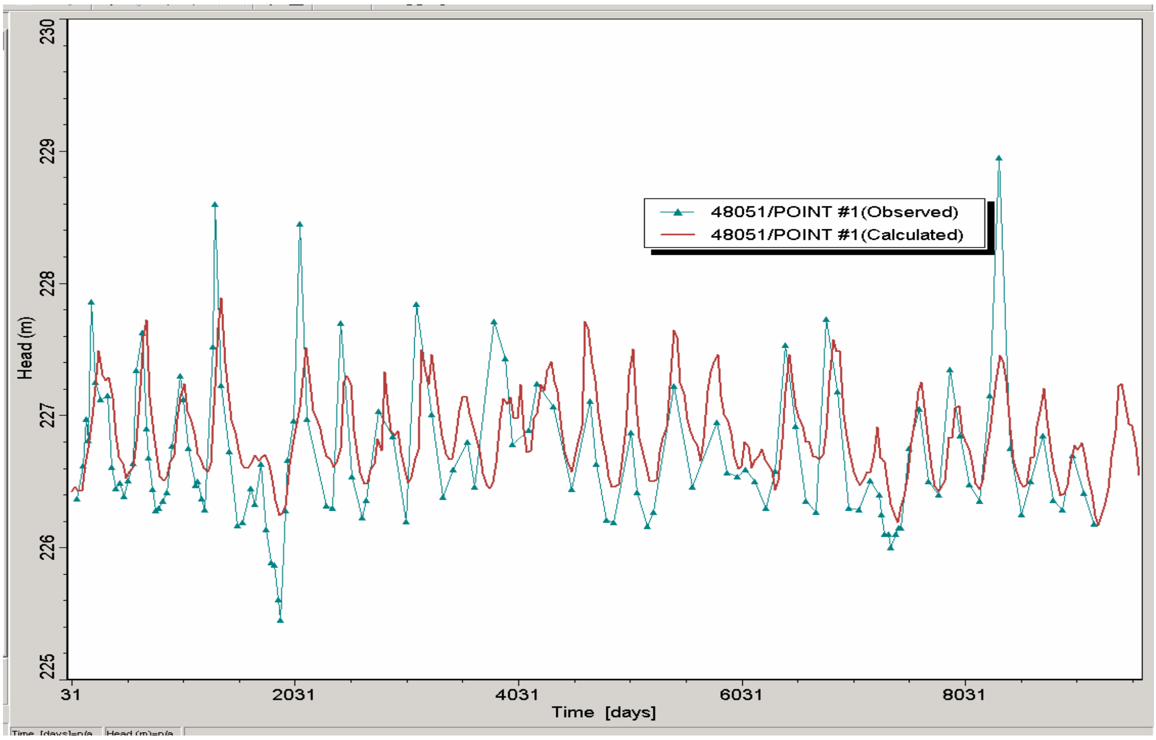


- **Figure 25 Extraction and Observation Bores Included in the Calibration Model**

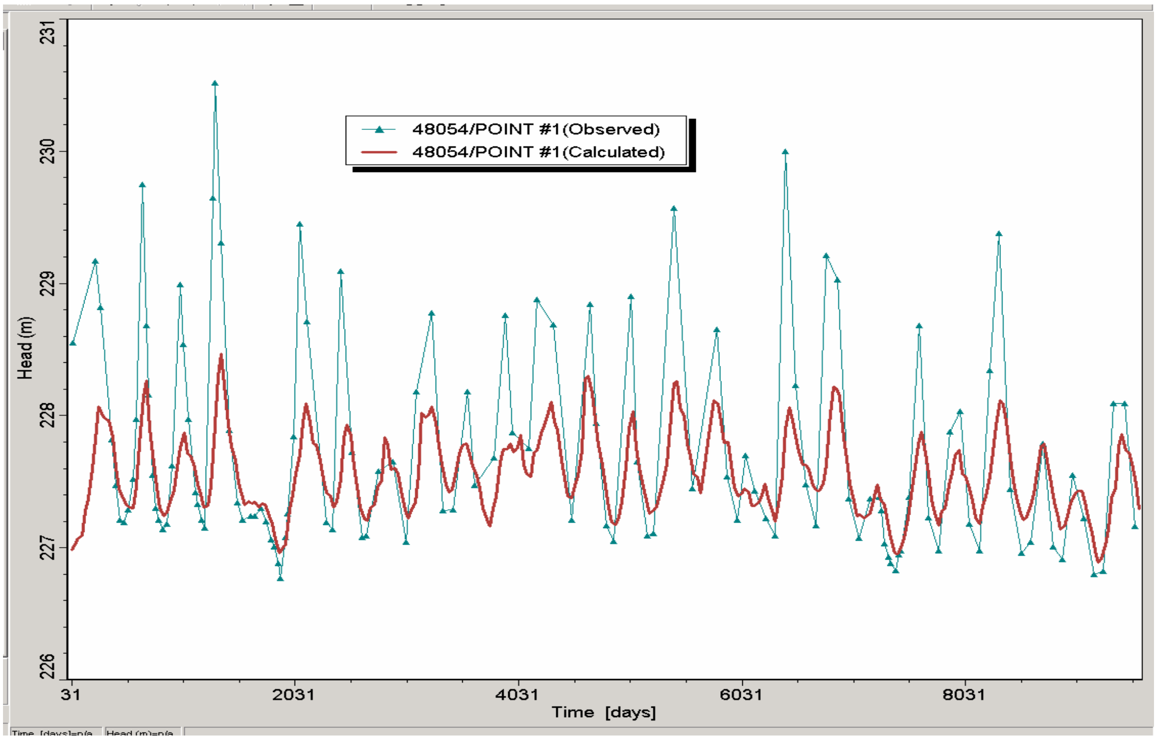


Calibration models were run over a 26 year period from 1979 and predicted heads at the locations of the observation bores were compared to measured groundwater heads. Hydraulic conductivity and aquifer storage parameters were varied until an acceptable match to observations was obtained. It was found that constraints in stream bed conductance (ie, river bed permeability) were required to be minimal in order to achieve calibration (ie, river bed permeability was not low relative to the aquifer). This result matches the conceptual understanding of the river base, which is relatively sandy/gravely and any accumulated silts would be seasonally flushed by large winter and spring flows. This reflects short timelags between stream level changes and impacts on the groundwater system, and vice versa. The results are presented in Figure 26 and Figure 27. The distribution of hydraulic conductivity and storage parameters resulting from calibration are shown in Figure 28 and Figure 29 respectively.

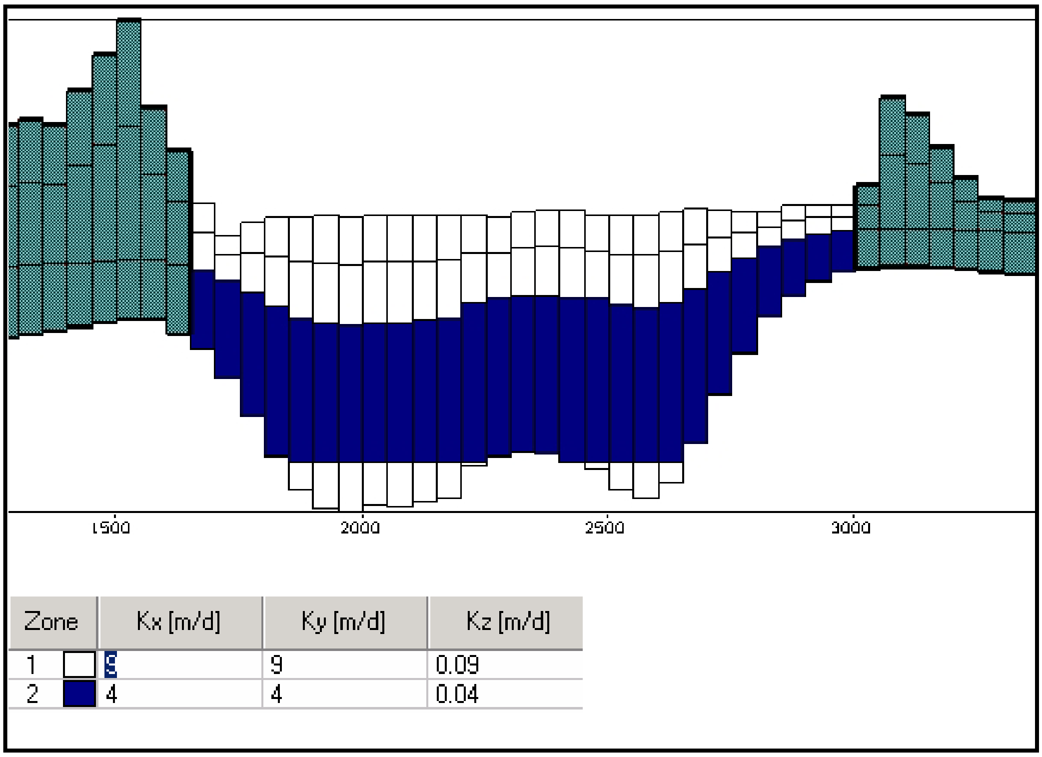
- **Figure 26 Calibration Results for Observation Bore 48051 (Layer 3)**



- **Figure 27 Calibration Results for Observation Bore 48054 (Model Layer 3)**

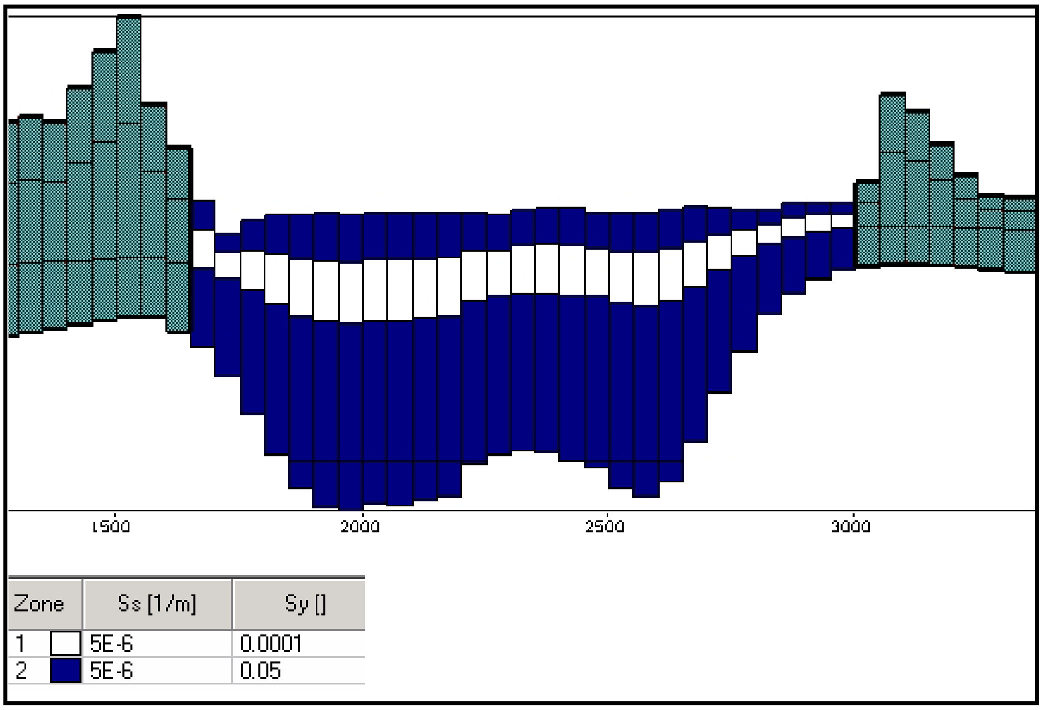


- **Figure 28 Hydraulic Conductivity in Cross Section**



Zone		Kx [m/d]	Ky [m/d]	Kz [m/d]
1	⬜	9	9	0.09
2	🟦	4	4	0.04

- **Figure 29 Storage Parameters in Cross Section**

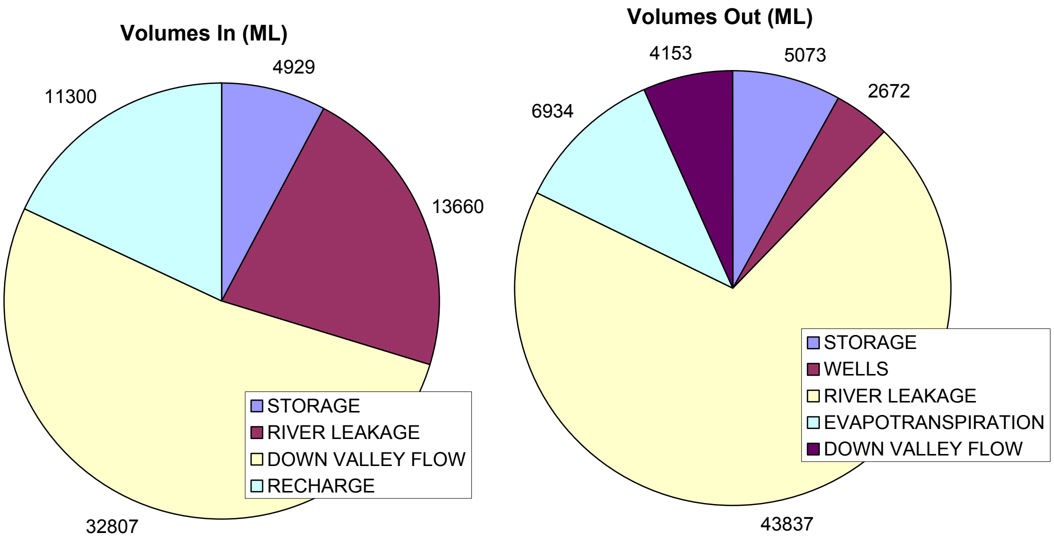


Zone		Ss [1/m]	Sy []
1	⬜	5E-6	0.0001
2	🟦	5E-6	0.05

The water balance for the transient calibration model is shown in Figure 30. It can be seen that inflows to the aquifer occur through down valley flow river leakage and recharge (from irrigation and rainfall). Inflows associated with change in storage reflect changes in groundwater levels in the aquifer throughout the duration of the model and are balanced by outflows associated with change in storage.

Outflows from the aquifer are dominated by groundwater discharge to the river. Other outflow components of the water balance include groundwater extraction from bores, evapotranspiration and down valley flow.

- **Figure 30 Mass Water Balance for Transient Calibration Model**



7.5 Predictive models

The calibrated model was run in predictive mode to assess the impacts of various groundwater extraction scenarios on river flows. The following scenarios have been run:

Forty year (30 day time-step) model

- Scenario 1 – All existing groundwater licences,
- Scenario 2 – All existing groundwater licences plus all river water diverters converted to groundwater extractions at a distance of 300m from the river,
- Scenario 3 – All existing groundwater licences plus all river water diverters converted to groundwater extractions at a distance of 600m from the river.

One year (daily time-step) model

- Scenario 4 – Scenario 2 repeated with a more refined time discretisation. This model was run for a period of one year and incorporated a stress period of one day. This model includes detailed representation of expected irrigation demand patterns over the period 1 July 2002 to 30 June 2003. It assumes that the actual surface water diversions (with restrictions applied during the summer) would have been taken from groundwater.
- Scenario 5 – The same as Scenario 4 except that there is no restriction on groundwater extractions. In this case the full irrigation demand is borne entirely by groundwater extraction.
- Scenario 6 – The same as Scenario 5 except that conversion of surface water diversions to groundwater extractions occurs at the time that surface water diversion restrictions were implemented. In this case the full irrigation demand is borne by a combination of groundwater extraction and surface water diversion.

Scenarios 1 to 3 were run from 1960 to 2000 and incorporated measured climatic data over this period discretised into monthly stress periods and assumed demand from 2002/2003.

Scenarios 4 to 6 were run with a more refined time discretisation in an attempt to illustrate implications for daily river flows during a particularly dry irrigation season. The climatic and river flow conditions included in these scenarios are considered to be typical for periods when the river is stressed and therefore represent a period when restrictions on river diversions and groundwater extraction would be applied under a streamflow management plan.

7.5.1 Scenario 1 – present day extractions

The layout of bores is the same as that shown Figure 25 and corresponds to the existing licenced extractions in the model domain. License #48180 was included with a reduced extraction rate as described in Section 7.4. This model forms the base case against which Scenarios 2 and 3 are compared.

7.5.2 Scenario 2 – Surface water diverters converted to groundwater extractions 300m from the river

Layout of production bores included in Scenario 2 is shown in Figure 31. This scenario includes the three existing groundwater licences together with eleven additional bores each relating to an existing surface water extraction licence. These “surface water substitution” bores are each located approximately 300 m from the river at points that are close to existing surface water diversions. The results are therefore indicative of the groundwater response that would be expected if all surface water diverters were required to obtain their water from bores located approximately 300 m from the river. The licensed diversions within the model area are summarised in Table 3.

- **Table 3 Summary of Surface Water Diversions in Model Area**

Licence No.	Easting	Northing	Entitlement [ML/yr]	Average Usage [ML/yr]	Model ID
832596	479928	5948126	130	0	N/A
836362	479928	5948126	49	0	N/A
753483	480042	5947928	28	28	SWD01
819301	480734	5947666	37	31	SWD02
831735	481405	5947577	52	52	SWD03
832154	482001	5947482	28	28	SWD04
831638	482001	5947482	28	0	N/A
831492	482463	5947315	15	15	SWD05
	483643	5946195		84.4	SWD6
	483683	5946278		84.4	SWD7
	482914	5946717		84.4	SWD8
	482428	5947140		84.4	SWD9
833533	481651	5947370	589	84.4	SWD10
	481780	5947310		84.4	SWD11
	484159	5946145.00		84.4	N/A
	481651	5947370		84.4	N/A

The average annual usage figures shown in Table 3 have been obtained from meter readings for the period 2002 to 2005. Those licensed diversions which have not been active in the last three years have not been included in the model. Also note that Licence No. 833533 refers to eight separate points of diversion, six of which are within the model domain. Usage data for this licence is not recorded for each diversion point and hence it is assumed that total usage is shared equally amongst the eight diversion points.

It is assumed that all extraction bores (ie those existing bores and the additional surface water diversion substitution bores) extract their annual usage volumes in the period 1 November to 30 April each year.

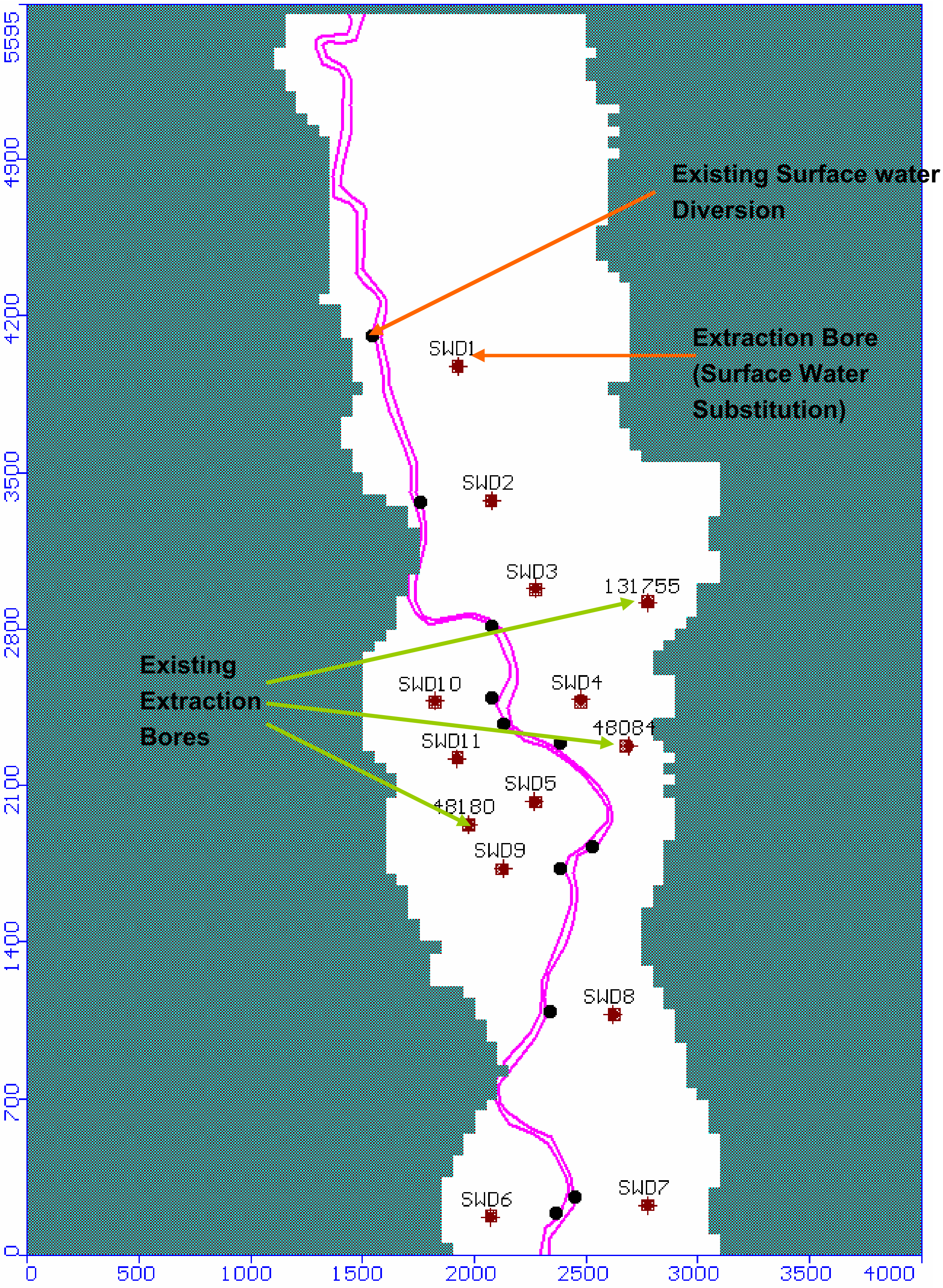
The results of Scenario 2 can be understood by comparing the predicted model results with those of the base case (Scenario 1). Of particular interest is determining the mechanisms and respective magnitudes of water yielded from the model to meet the specified groundwater extractions. This analysis was undertaken by comparing the various components of the water balances for Scenarios 1 and 2 such that the differences in model fluxes indicate the relative magnitude of water obtained from various mechanisms that combine together to yield the volume of water extracted from the surface water diversion substitution bores. The major sources of capture identified in the model to achieve groundwater extraction include:

1. River depletion by intercepting baseflow discharge to the river and by increasing stream leakage to groundwater,
2. Changes in down valley groundwater flow including reduced outflow at the model's downstream boundary and increased inflow at the upstream boundary,
3. Reduction in water discharge through evapotranspiration associated with a depressed water table,
4. Changes in groundwater storage associated with a depressed water table in response to pumping.

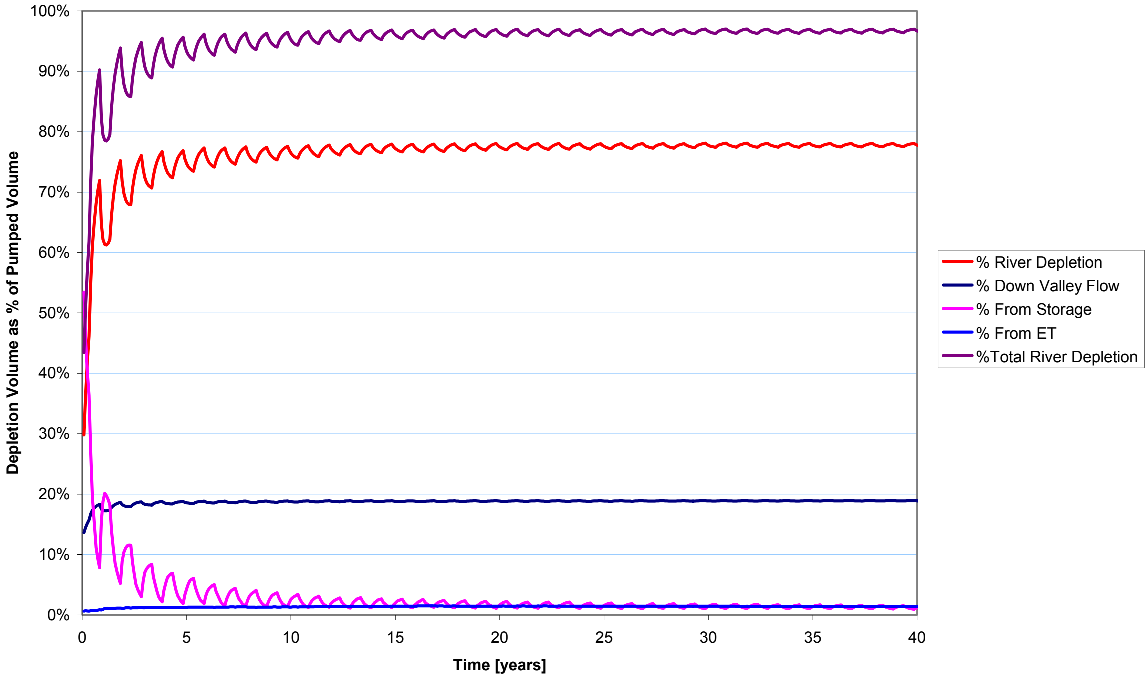
The magnitude of each of these sources expressed as a percentage of the water extracted from the bores is shown graphically in Figure 32. Here it can be seen that the principal change in water balance is the river flow depletion and this mechanism accounts for approximately 78% of the water extracted from the surface water diversion substitution bores. It should be noted that the "down valley flow" component of the Water Balance as shown in Figure 32 is an artefact of the model boundary conditions. In reality the "down valley flow" component or induced flow across the model boundaries, represents a flux of water that mostly would be expected to have been derived from baseflow or stream leakage had the model extended further upstream and downstream. In this case the effective river depletion term is given by the sum of the "river depletion" and "down valley flow" components (which include 1 and 2 above) and amounts to approximately 97% in the long term. This can be seen in Figure 32 as the "Total River Depletion" curve that represents the sum of the direct streamflow depletion and the change in down valley flow.

It is of interest to note the changes in flux with time in Figure 32. It can be seen that with bores located approximately 300 m from the river it takes between five and ten years before the total streamflow depletion reaches the long term average of 97%. The annual fluctuations that can be seen in the river depletion and groundwater storage curves are due to the cyclic nature of the pumping and the amplitude of these fluctuations decrease with time as the cumulative groundwater extraction increases.

- **Figure 31 Extraction Bores Included in Scenario 2 Model**



- **Figure 32 Changes in Water Balance to Meet Groundwater Extraction – Scenario 2**



The ultimate objective of substituting groundwater extractions for surface water diversions as a management tool is to reduce impacts of extraction on streamflow in critical times. To this end it is necessary to compare river flows with predictions of streamflow depletion and with the saving in streamflow achieved by the elimination of direct diversions from the river. Measured flows at Myrtleford between 1960 and 2000 are shown graphically in Figure 33.

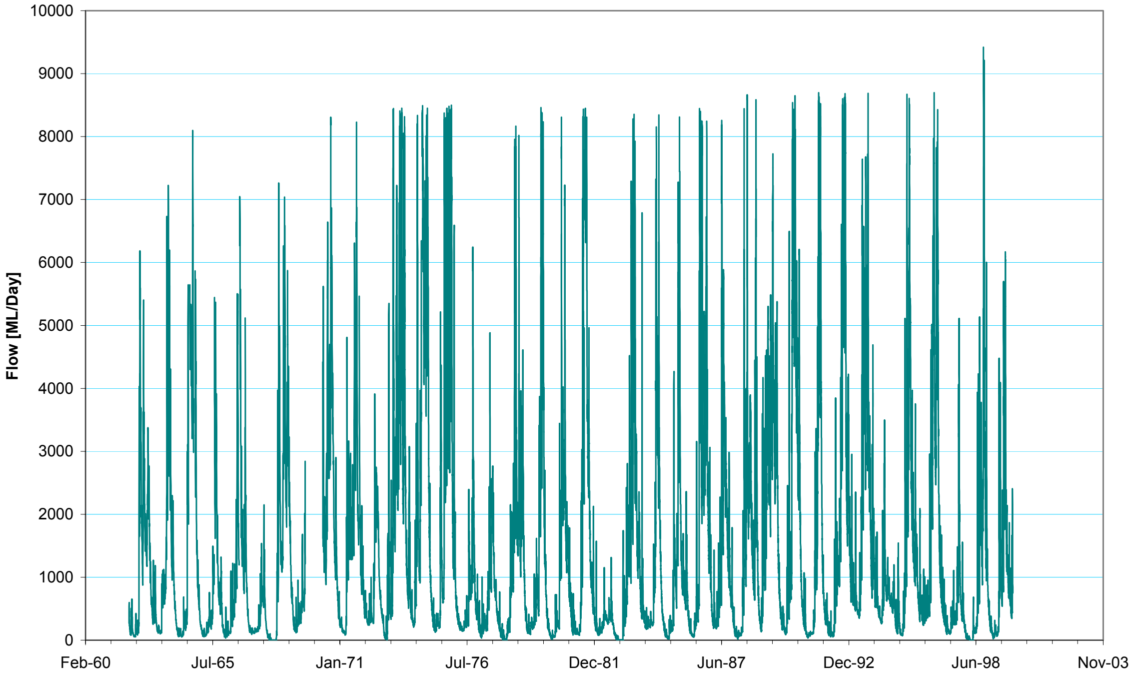
The river is unregulated above Myrtleford and accordingly flows vary dramatically. River flow is almost always greater than 100 ML/day which is significantly greater than the combined surface water diversions within the model domain as shown in Table 3 (ie. 660 ML/year or 3.6 ML/day average usage during the irrigation season). There are occasions, however when the river flows are extremely low at Myrtleford and it is at these times that it is of interest to consider the potential benefits of substituting groundwater for streamflow diversions.

To further illustrate this issue the Scenario 2 model results and measured streamflows in the driest summer on record (1982/1983) were plotted in detail. Figure 34 shows the measured flows and daily averaged flows at Myrtleford in the summer of 1982/83. It also presents the predicted streamflow depletion obtained from Scenario 2 model results for this year (being model year 22). The streamflow depletion represents the reduction in river flow that can be attributed to the surface water diversion substitution bores. Also shown on Figure 34 is an adjusted mean daily river flow. This represents the amount of flow that would have been present in the river had the river water diversion substitution been in place at the time. It has been calculated by adding the total unrestricted surface water diversions to the measured flow (assuming that the current diversion estimates were active over the period) and then subtracting the calculated streamflow depletion. The calculation does not take into account any restrictions that were applied to river diversions during that summer. The amount of increased flow in the river is given by the difference between the measured or average daily flows and the adjusted mean daily flow. In this particular period the streamflow depletion, the substituted diversions (3.62 ML/d) and the measured river flows are all of similar magnitude and as such a substantial improvement in river flow (at low flow) can be realised by substituting river diversions by groundwater extraction.

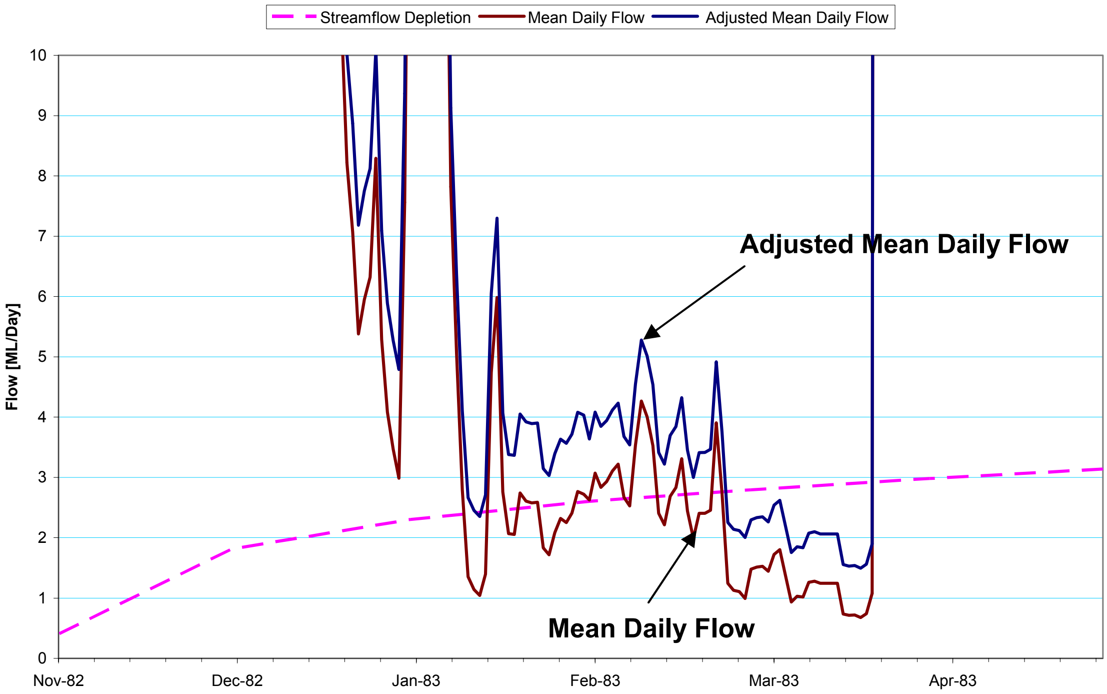
The results presented in Figure 34 indicate that even though the cumulative volumes pumped from groundwater are almost entirely derived from streamflow depletion (approximately 97%), the time lag between the extraction and the onset of streamflow depletion is such that some benefit in streamflow may be expected.

While relatively modest levels of potential streamflow benefit have been predicted, these results must be scaled up to account for the fact that the model represents a small portion of the total stream reach upstream of Myrtleford and incorporates a small portion of the total surface water diversions.

- **Figure 33 Ovens River Flow at Myrtleford**



- **Figure 34 River Flows and Streamflow Depletion During the Summer of 1982/83**

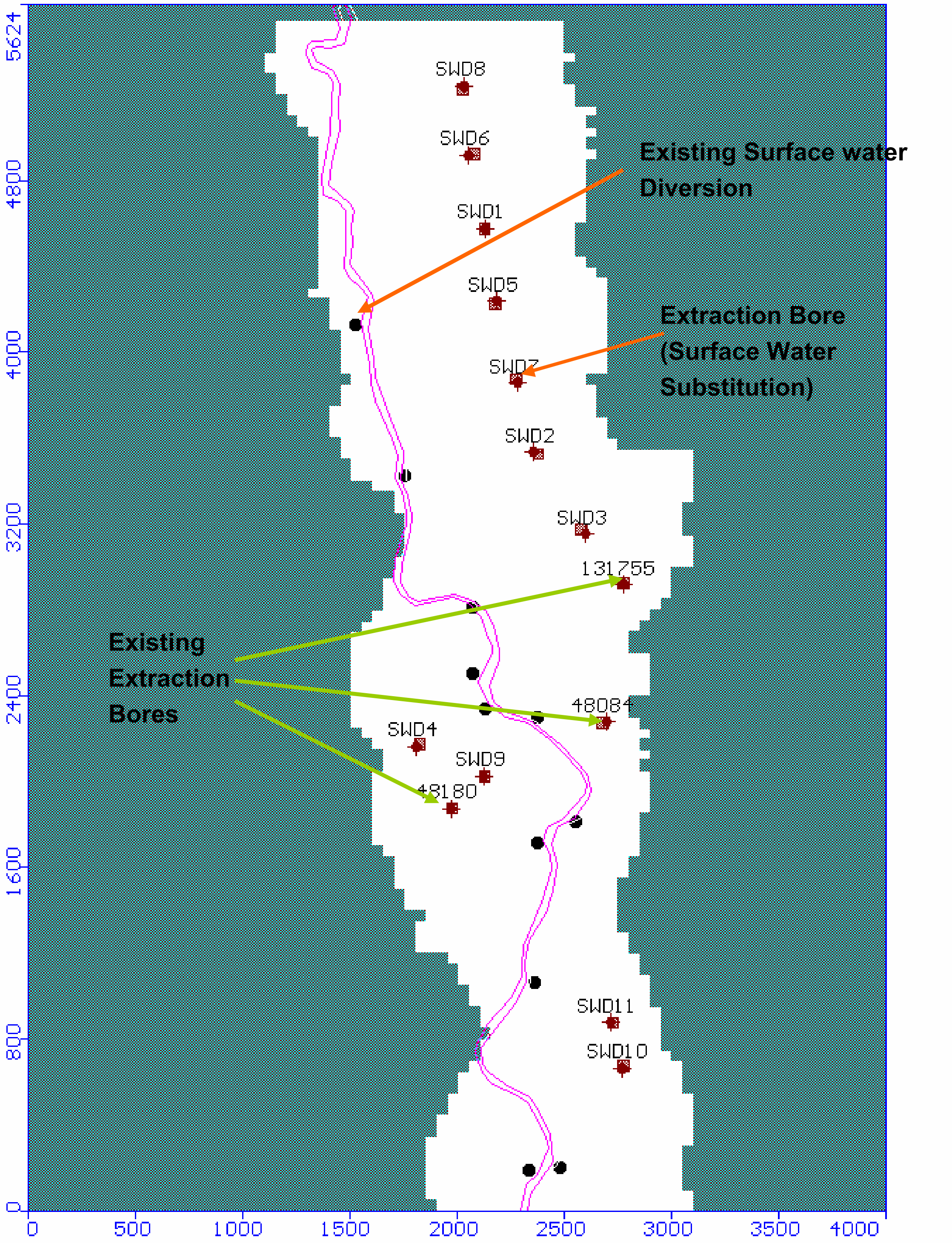


7.5.3 Scenario 3 – Surface water diverters converted to groundwater extractions 600m from the river

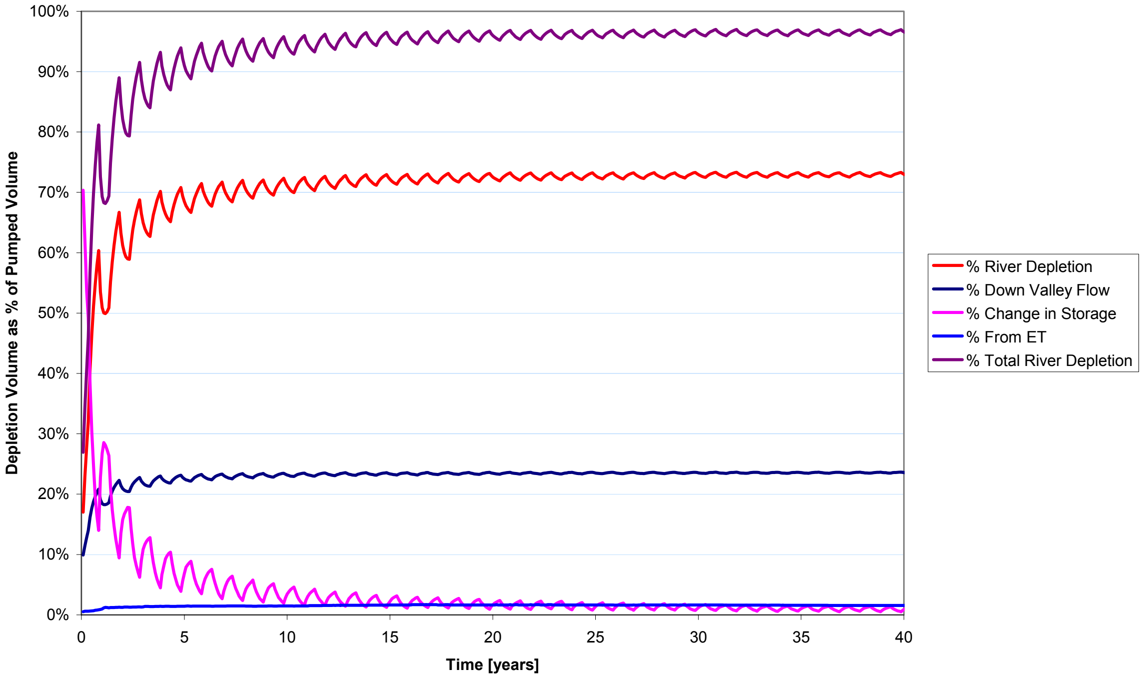
The third scenario considered in this study is essentially the same as Scenario 2 except that the substitution bores are considered to be approximately 600 m from the river. The locations of groundwater extraction bores included in the Scenario 3 model are shown in Figure 35. It should be noted that in order to obtain the required separation between the river and the substitution bores within the relatively narrow valley, it was necessary to relocate some of the bores some distance up or down-valley from the point of river diversion.

Results are presented in Figure 36 in the form of the various components of net water yield that, in combination allow for the groundwater extraction included in the Scenario 3 model. Here it can be seen that streamflow depletion stabilises at about 97% which is the same as that predicted for Scenario 2. A comparison of predicted streamflow depletions for Scenarios 2 and 3 is shown in Figure 37. In general it can be seen that as the bores are located further from the river there is a marginal increase in the time lag between the onset of pumping and the associated streamflow depletion.

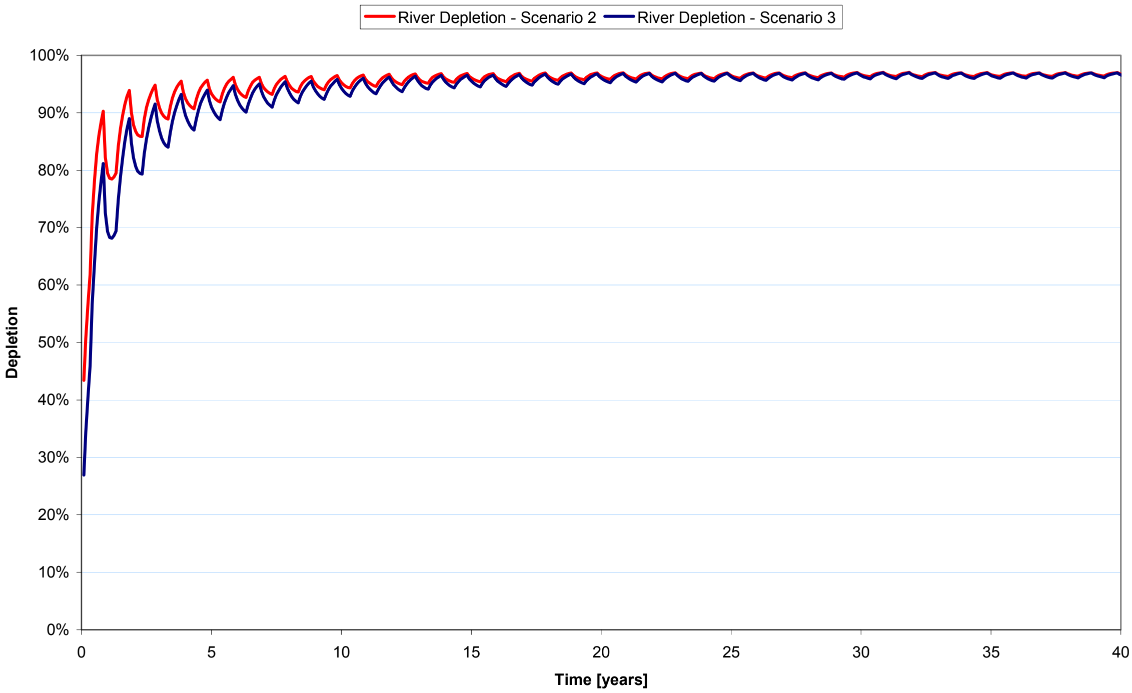
- **Figure 35 Production Bores Included in Scenario 3 Model**



- **Figure 36 Changes in Water Balance to Meet Groundwater Extraction – Scenario 3.**

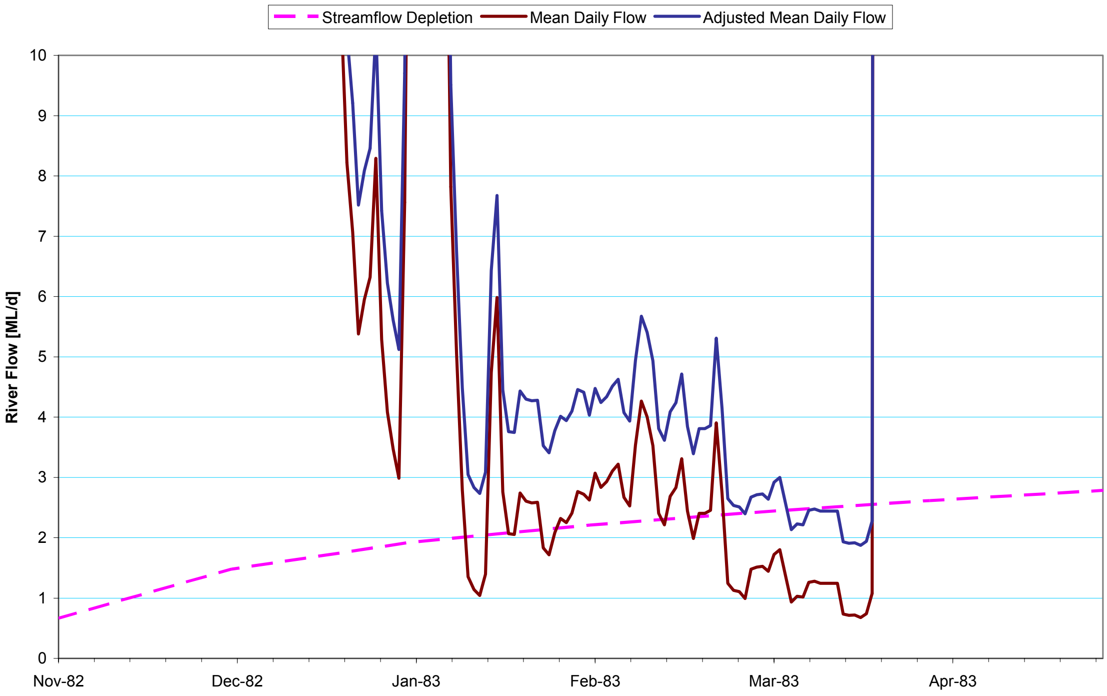


- **Figure 37 Comparison Between Predicted Streamflow Depletion for Scenarios 2 and 3**

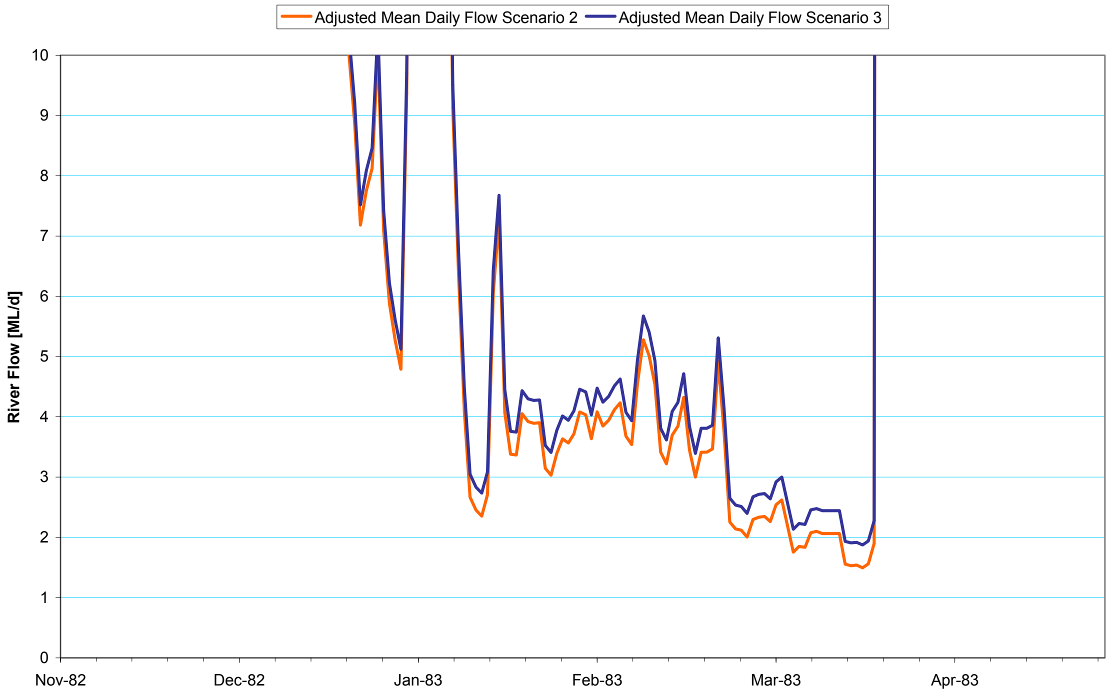


The model-predicted streamflow depletion, measured flows, daily average flows and adjusted daily average flows for the Ovens River at Myrtleford in the summer of 1982-83 are shown in Figure 38. The adjusted mean river flow is that which would have been measured had the surface water diversions been substituted by groundwater extractions located approximately 600 m from the river. While the result is similar to that predicted for Scenario 2 (refer to Figure 34), it is apparent that Scenario 3 results in a higher adjusted mean river flow than that realised in Scenario 2. This difference is shown graphically in Figure 39.

- **Figure 38 River Flows and Streamflow Depletion During the Summer of 1982/83**



- **Figure 39 Comparison Between Predicted River Flows in Scenarios 2 and 3**



7.5.4 Scenario 4 – Daily Time Step Model with surface water diverters converted to groundwater extractions 300m from the river

The apparent benefits to streamflow predicted for Scenarios 2 and 3 during particularly dry summers are of sufficient magnitude to warrant further investigation of the merits of surface water conversion to groundwater. To this end a more detailed model was developed to investigate potential streamflow benefits within a drought year.

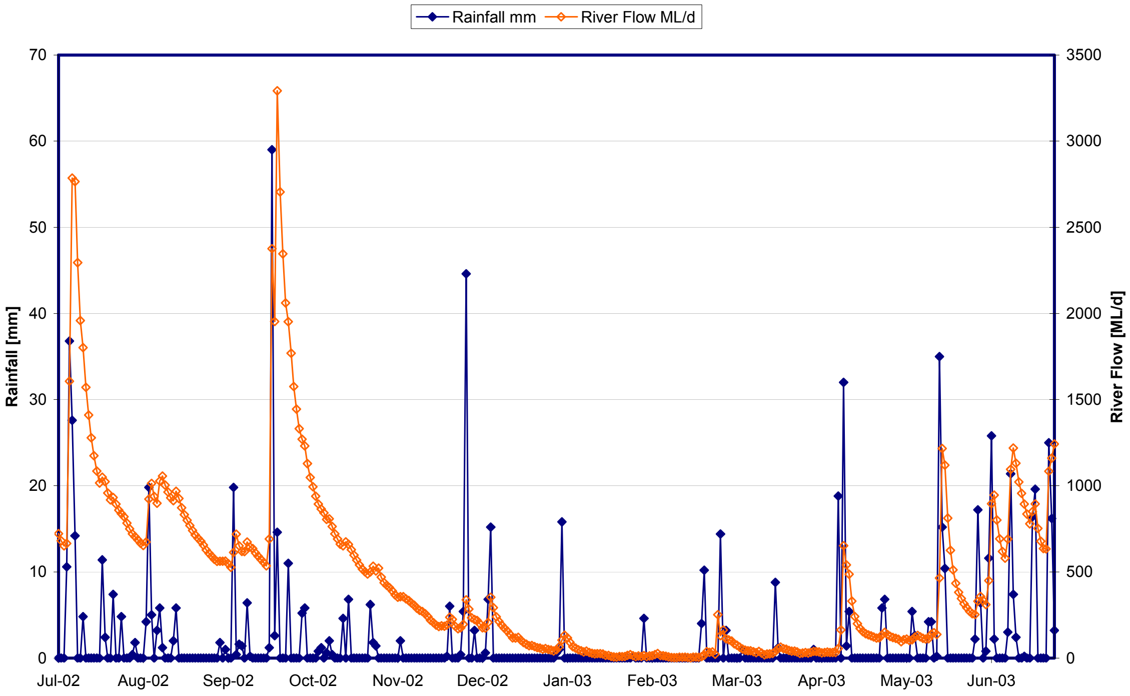
The model was reconfigured in order to assess the impacts on river flows within a relatively short time scale coinciding with severe drought conditions and extreme low river flows. It is in such conditions that relatively small improvements in Upper Ovens river flow are most important and water resource management issues such as groundwater river interaction are most critical. To this end the model was re-discretised to a daily stress period for a one year duration. The period 1 July 2002 to 30 June 2003 was chosen for this model. The 2002/03 year was particularly dry and was selected for modelling so that the model can explore the influence of groundwater pumping on river flows at a time of particularly low river flow because more accurate estimates of actual stream diversion are available (than were available for 1982/83). Rainfall and river flows for the period of the model are shown in Figure 40. It can be seen that there was little rainfall in the period December 2002 to April 2003 and river flows were extremely low throughout this period.

The low river flows experienced over this period led to the progressive implementation of diversion restrictions through the summer months. The history of diversion restrictions over the modelled period is documented in Table 4 (from G-MW (report in preparation).

- **Table 4 History of streamflow rosters and diversion restrictions for 2002-2003**

Start	Finish	Roster	Restriction
1 July 2002	17 December 2002	None	None
17 December 2002	6 January 2003	Stage 1	Restricted Hours
6 January 2003	20 January 2003	Stage 2	75% of Allocation
20 January 2003	12 February 2003	Stage 3	50% of Allocation
12 February 2003	1 May 2003	Stage 4	25% of Allocation
1 May 2003	30 June 2003	None	None

- **Figure 40 River Flow at Myrtleford and Rainfall for Duration of Detailed Model**



The locations of all surface water diversions within the model area are listed in Table 5.

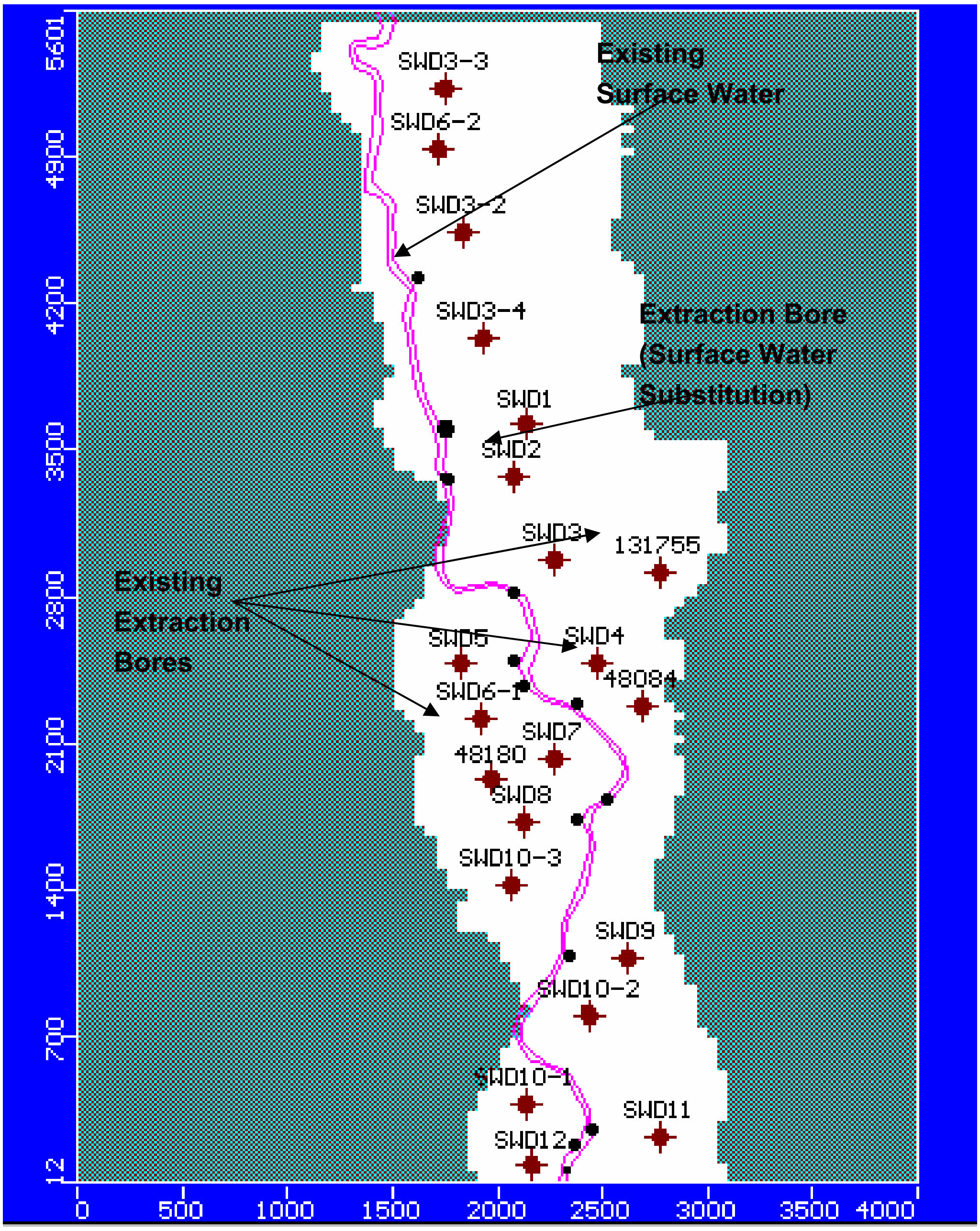
Figure 41 shows the location of the extraction bores simulating SW diversions. In order to avoid unsustainable groundwater pumping rates in the model, some of the surface water diversions were represented by multiple groundwater abstractions. The locations of some of the larger groundwater abstractions were spatially redistributed to reduce mathematical convergence problems associated with over-extraction of the aquifer within the model.

The surface water diversions (SWD) from the Ovens River were estimated on a daily basis for the simulation period. They were derived from a ten day irrigation cycle developed for every licence based on an assumed crop water demand (D. Lovell, GMW, *pers. comm.*). The pumping cycle for each diversion was then applied over the irrigation season as estimated for each crop. The pumping rates were then scaled down in the times corresponding to the periods in which there were restrictions applied to all surface water diversions (refer to Table 4 for details of restrictions). The resulting extraction regime for each diversion was then applied to the groundwater model as a groundwater extraction rate from the appropriate surface water substitution bore. (Note that these extraction figures from the local GMW diversions officer (supplied via D. Lovell, GMW, *pers. comm.*) include some winter groundwater extraction, presumably for irrigation of winter crops). The combined pumping rate from all bores is shown in Figure 42.

- **Table 5 Summary of Surface Water Diversions in Model Area**

License No.	Pump No.	EASTING	NORTHING	Model ID
831743	12400	483876	5946183	SWD12
833533	12416	483796	5946465	SWD11
833533	12417	483029	5946906	SWD9
833533	12418	482540	5947317	SWD8
833533	12419	483756	5946344	SWD10
833533	12420	481883	5947497	SWD5
833533	12435	481763	5947557	SWD4
831492	12430	482576	5947499	SWD7
831638	12440	482113	5947659	SWD6
8000734	12448	481463	5947759	SWD3
831735	12450	480861	5947797	SWD2
819301	12460	480688	5947934	SWD1

- **Figure 41 Extraction bores included in Scenario 4 model**

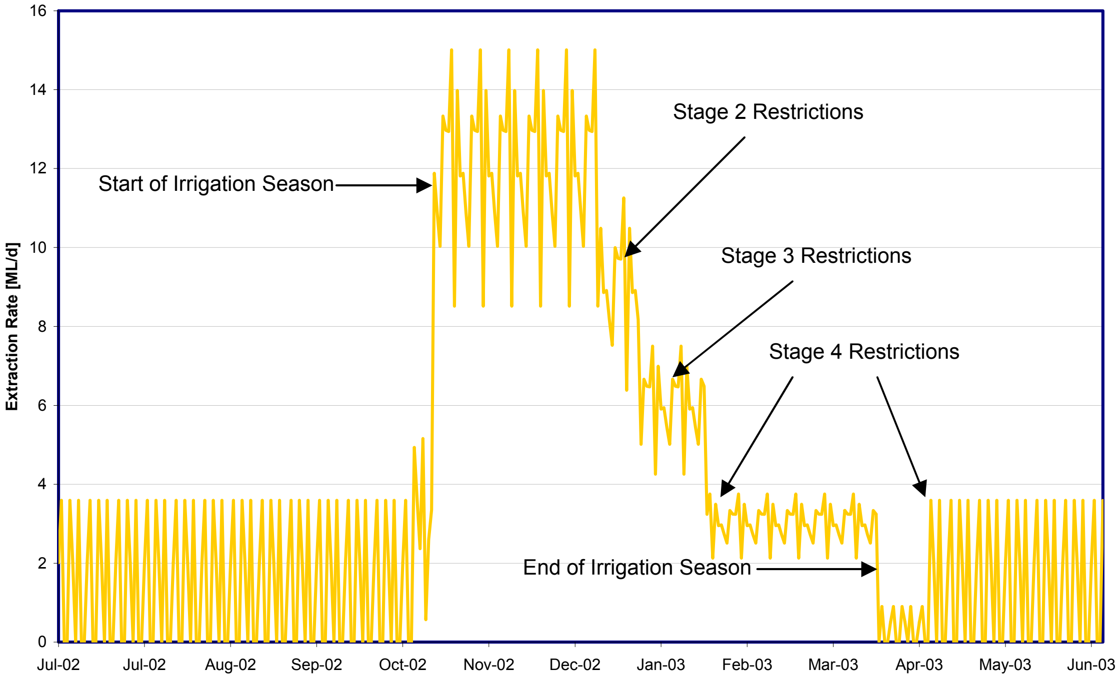


Existing Surface Water

Extraction Bore (Surface Water Substitution)

Existing Extraction Bores

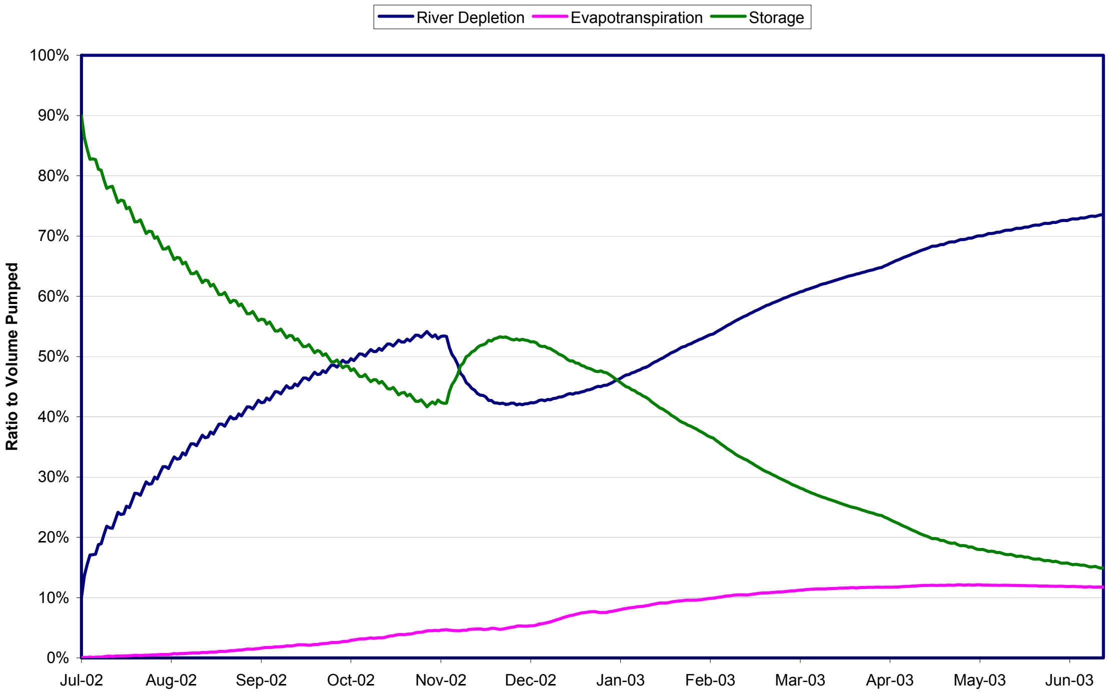
- **Figure 42 Combined groundwater extraction rate – daily stress period model**



The daily time step model was also run with no surface water diversion substitution so that effects attributable to the substitution can be distinguished. By comparing the mass balance components in the surface water substitution and non-surface water substitution models, it is possible to define a series of mass balance component changes that account for the substitution pumping independent of existing groundwater licences. Figure 43 shows the changes in mass balance components expressed as a percentage of the cumulative groundwater pumping. The cumulative river depletion (the combined reduction in base flow and increase in leakage from the river) accounts for approximately 75 % of the water extracted from the bores at the end of twelve months. Other mass balance changes of note include groundwater storage and changes in evapotranspiration. The model predicted change in down valley flow has been incorporated in the river depletion curve shown in Figure 43.

One obvious feature of Figure 43 is the progressive change in dependence from groundwater storage to streamflow depletion. At the start of the model almost all of the water discharged from the bores is obtained from storage and there is very little streamflow depletion. As pumping progresses the importance of streamflow depletion increases and that of storage changes decreases. The change in trends at the start of the pumping season (November-December) reflects the initial increased dependence on storage depletion before increased drawdown ultimately captures baseflow and induced stream leakage.

- **Figure 43 Changes in water balance to meet groundwater extraction – Scenario 4**



A more detailed analysis of the surface water groundwater interaction processes during the summer period is shown in Figure 44 and Figure 45. Figure 44 shows the calculated streamflow depletion and river flow at Myrtleford on different scales. Figure 45 presents the same information for the summer months at the same scale for both river flow and streamflow depletion. It can be seen that for most of the year the streamflow depletion is negligible compared to river flow. However for the period January to March 2003 the streamflow depletion resulting from surface water diversion substitution is significant compared to river flow measured at Myrtleford.

The benefits in river flow can potentially be realised by way of the fact that when there is surface water diversion substitution the water is not being taken directly from the river. Hence the potential increase in River flow can be calculated as the difference between the surface water diversion volumes and the predicted streamflow depletion. This can be seen in Figure 46 showing the combined diversion flows (equal to “substitution pumping”), the predicted streamflow depletion and the difference between these fluxes being the potential saving in river depletion. Positive values of potential increase in river flow in Figure 46 indicate periods when the river flow would be increased if all surface water diversion were substituted. When the potential increase in river flow is negative the river flow would be reduced by full substitution of surface water diversions.

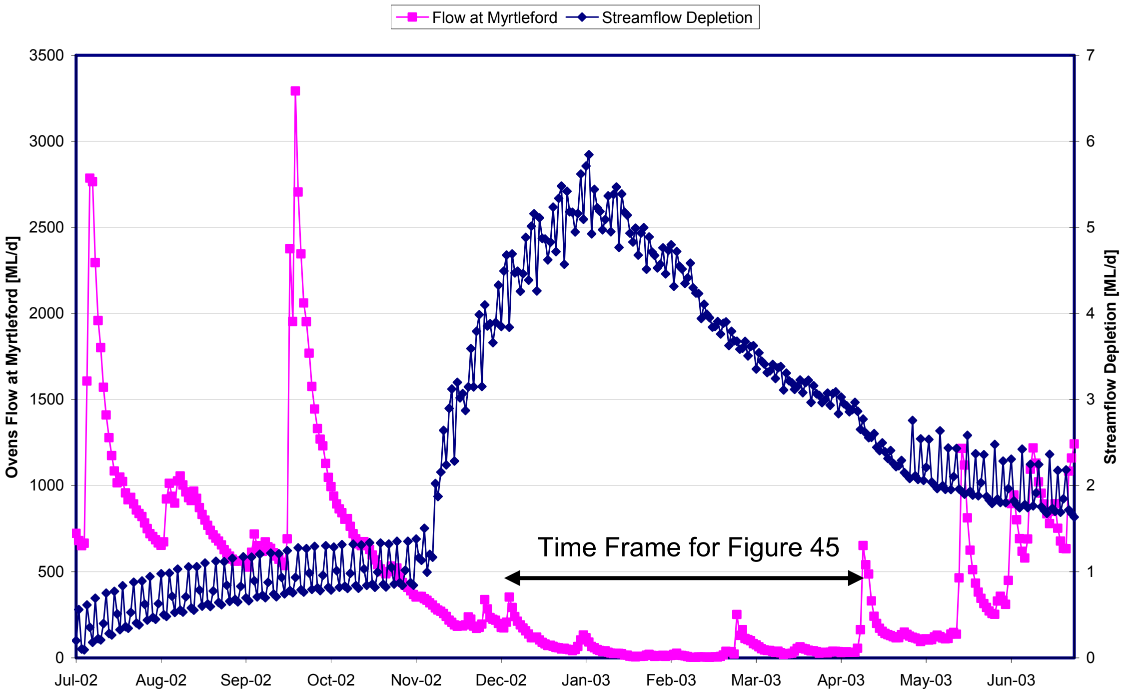
It is interesting to note that almost all of the benefit in surface water diversion substitution is realised in the early part of the summer when diversions are high and the groundwater pumping has yet to be fully felt as streamflow depletion. As the drought progresses the diversions decline as restrictions on surface water diversions take effect and the streamflow depletion rises in response to early season groundwater extraction. The streamflow depletion is slow to respond to the decline in groundwater extraction and during the latter part of the drought the river flow would actually be lower than with no substitution.

While not possible to model without using an integrated surface water/groundwater hydrological model, in an extreme season, groundwater extraction may also lower the watertable such that initial stream flows following autumn rains would be required to "re-prime" the groundwater system before desired minimum streamflows could be re-established. Anecdotal evidence from the 2002/2003 drought is that this scenario occurred in the lower Ovens when voluntary rosters were ineffective in reducing irrigation demand leading to a significant decline in river flow. Increased releases down Buffalo River took several days longer than expected to reach Wangarratta. This was thought to be due to the initial dam releases preferentially filling laterally connected gravel beds (that had been drained as a consequence of groundwater pumping and low streamflows) prior to the releases being effective in increasing downstream flow (Goulburn-Murray Water, report in preparation).

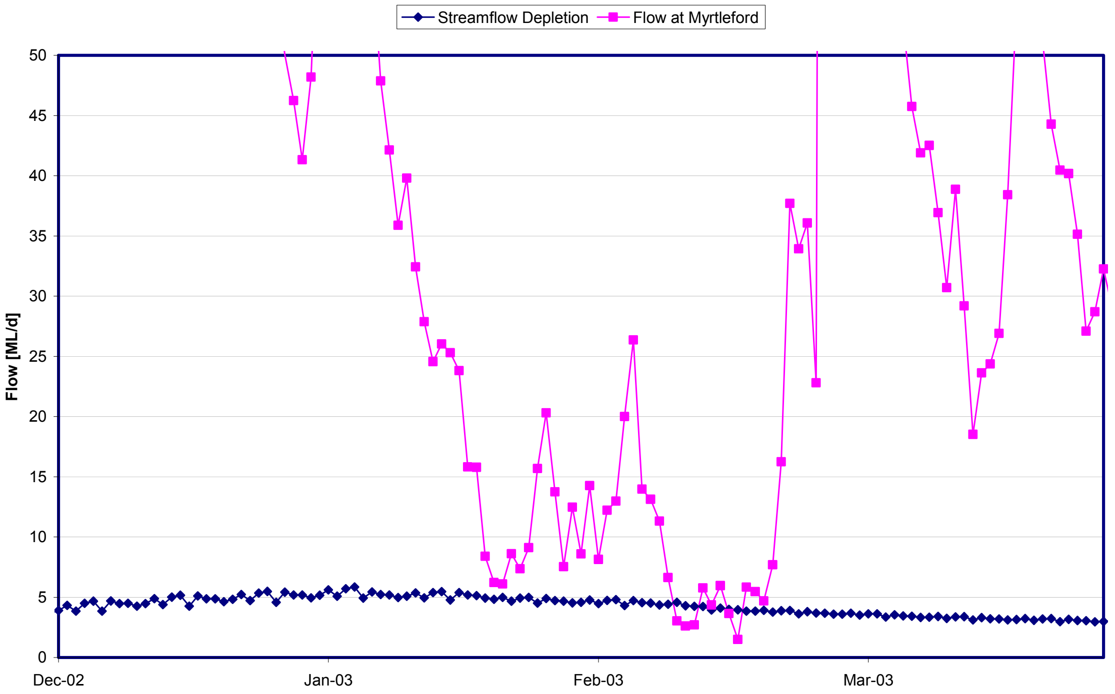
It may be concluded from this analysis that the surface water diversion substitution rules would need careful design in order to avoid reduced river flows in the mid and late summer. A management response to this potential problem may be to authorise substitution only beyond mid summer such that the disbenefits associated with substitution later in the irrigation season would be shifted further into the autumn period, when in most years, autumn rainfall would offset the time lag impacts of late summer groundwater extraction.

The differences between results of Scenario 4 and Scenario 2 as presented in Figure 46 and Figure 34 respectively are due to the fact that the daily time step model includes a more detailed and more accurate representation of the volume and timing of diversions that occurred during the year. Furthermore the time lag between groundwater extraction and streamflow depletion is more precisely predicted in Scenario 4. Total benefits to the river in each of the scenarios is approximately the same, however Scenario 4 shows that these benefits are not evenly distributed throughout the irrigation season.

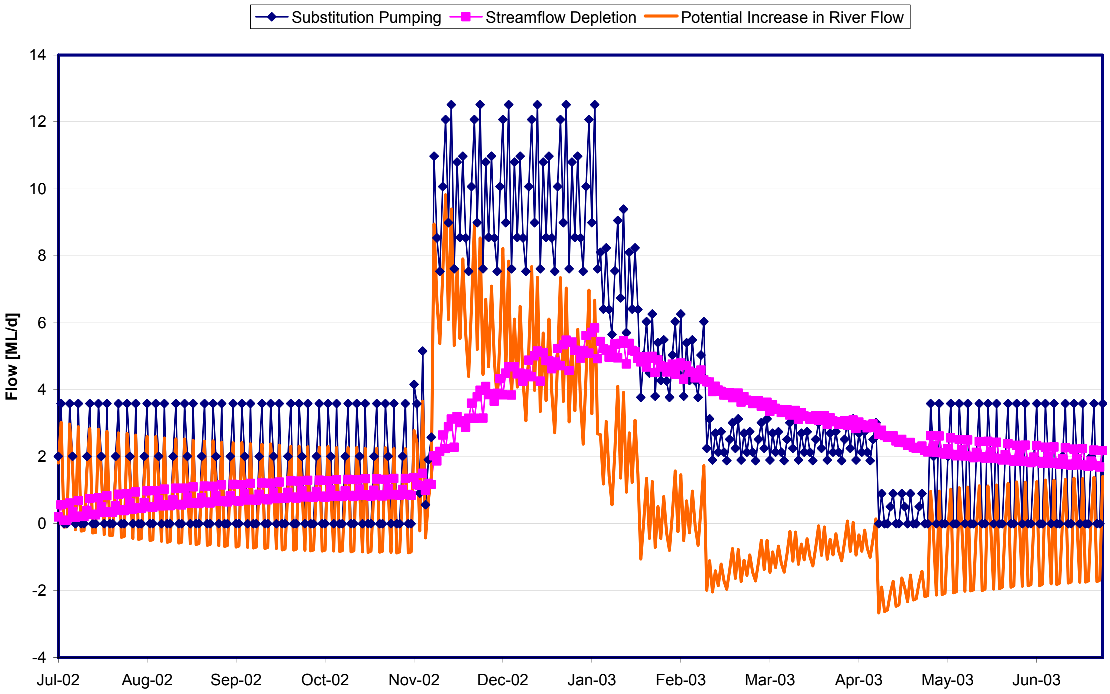
- **Figure 44 River Flow and Stream depletion During the period 2002/2003**



- **Figure 45 River Flow and Stream depletion during the summer period 2002/2003**



- **Figure 46 Potential Increase in River Flow Arising From Substitution of River Diversions**



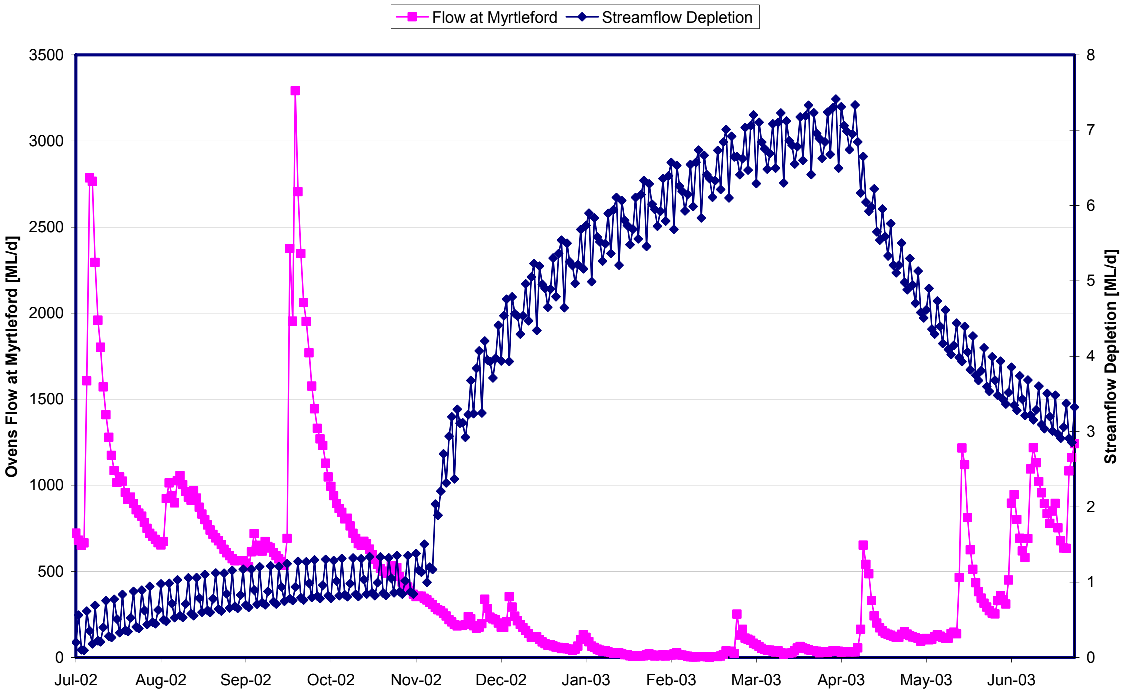
7.5.5 Scenario 5 – Daily Time Step Model with surface water diverters converted to groundwater extractions 300m from the river with no restrictions

Scenario 5 explores the impacts on river flow that would accrue if all surface water diversions were converted to groundwater extractions at a distance of 300m from the river with no restrictions applied to the volumes of water extracted. This scenario is consistent with there being no economic impact associated with the management of the water resources of the valley as it assumes that the irrigation requirements are fully met for the entire year.

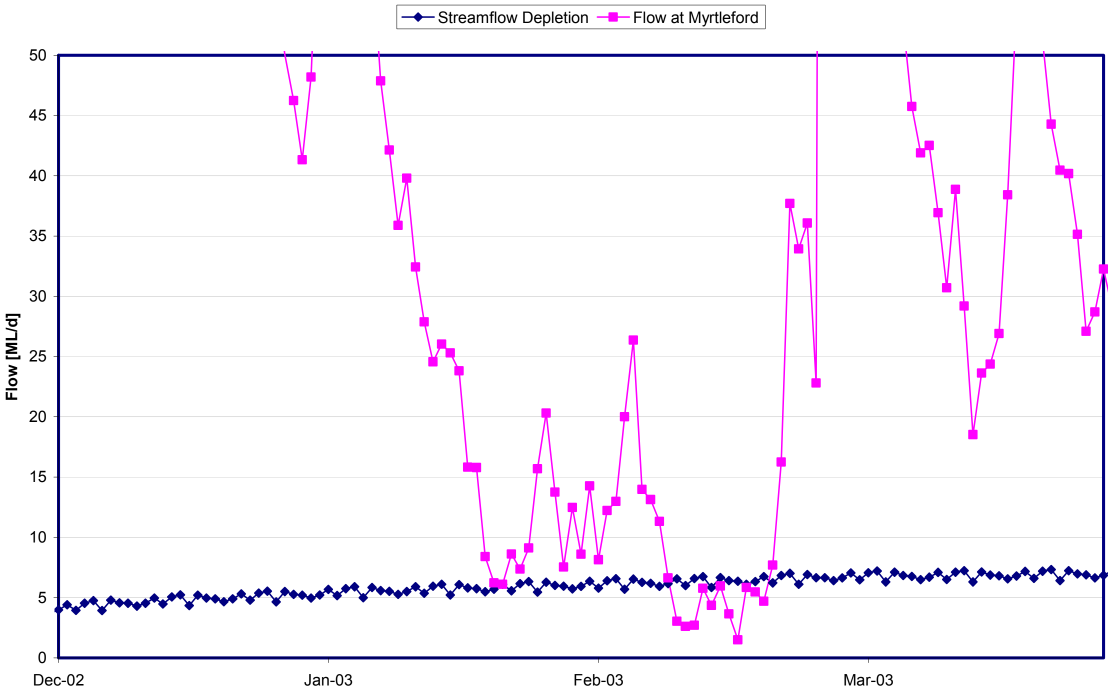
Results of this scenario are presented in Figure 47, Figure 48 and Figure 49. Figure 49 shows that there are clear streamflow benefits resulting from substitution from November through to mid-January. Table 6 indicates net savings of river flow of around 430 ML in this period, which is around 5.6 ML/d. If full substitution was modelled for the entire Upper Ovens, savings in river flow of around 1,700 ML, or 22 ML/d would be achieved over the November to mid-January period (refer Table 7). During the mid-January to mid-February period, river flow was not affected either way by substitution (ie neutral impact). However during the period mid-February to early April, river flow suffered due to substitution by a total of around 326 ML (refer Table 7). This represents river depletion of about 5.9 ML/d, or 23 ML/d for full substitution, over the period.

The net savings for the river over the entire irrigation season are 104 ML, or about 400 ML if full substitution was implemented. This represents an average additional river flow of 2.6 ML/d. These are moderately significant savings in the context of low river flows.

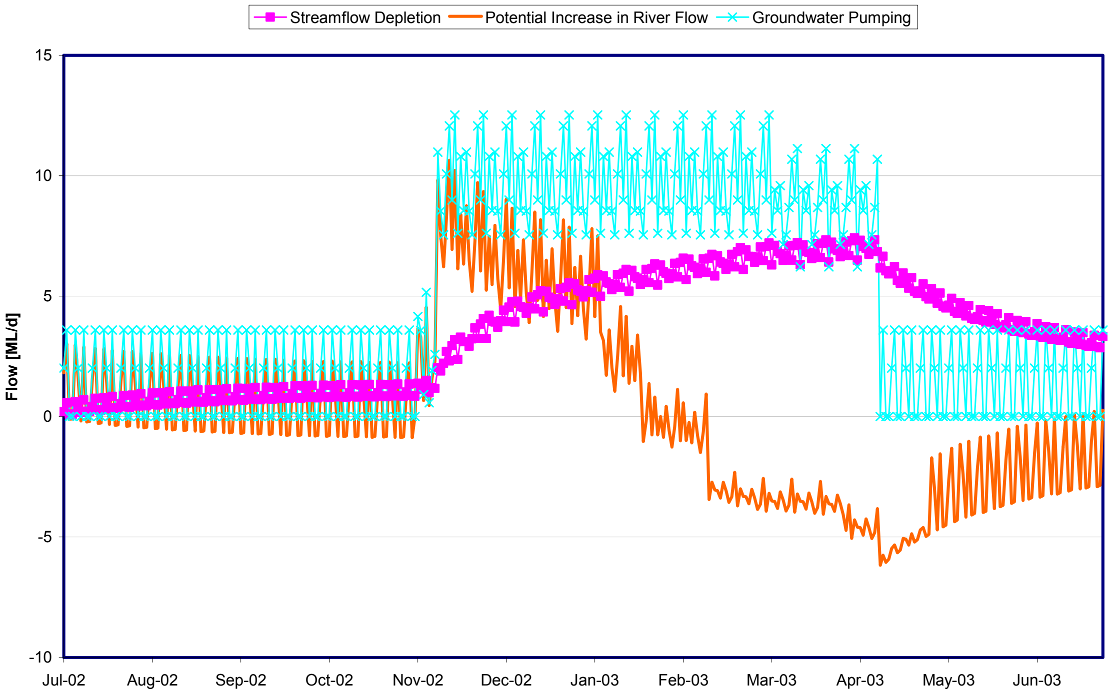
- **Figure 47 Streamflow depletion and measured flows at Myrtleford**



- **Figure 48 Streamflow depletion and river measured flow at Myrtleford in Summer**



- **Figure 49 Net savings in river flow for Scenario 5**

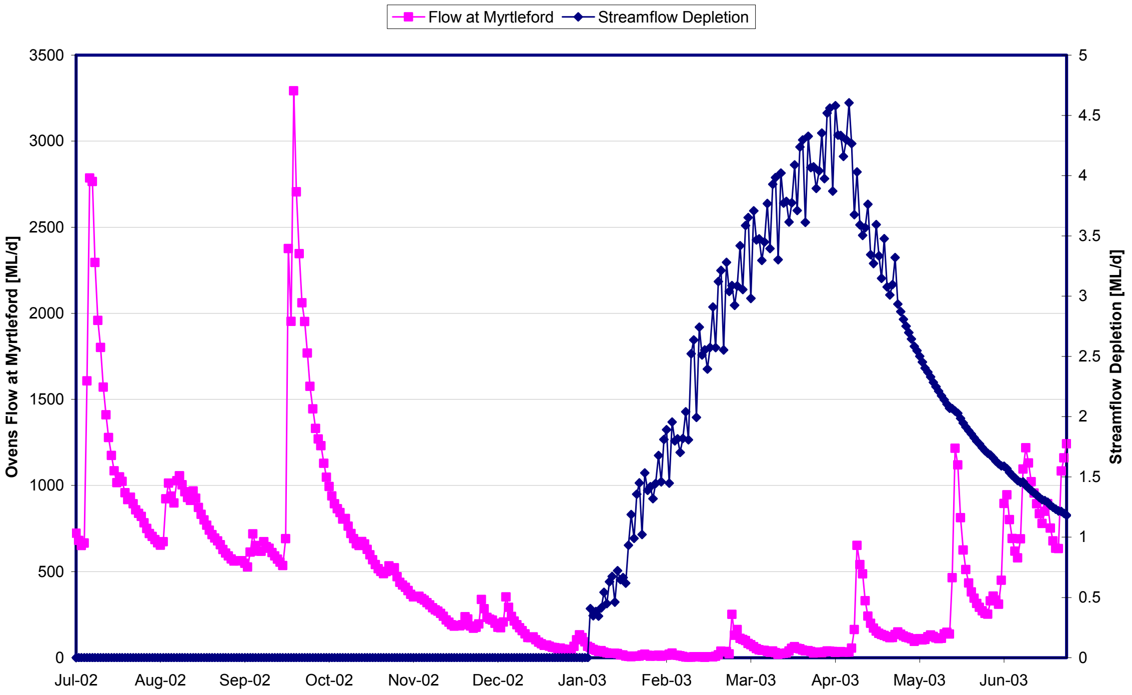


7.5.6 Scenario 6 – Daily Time Step Model with surface water diverters incrementally converted to groundwater extractions 300m

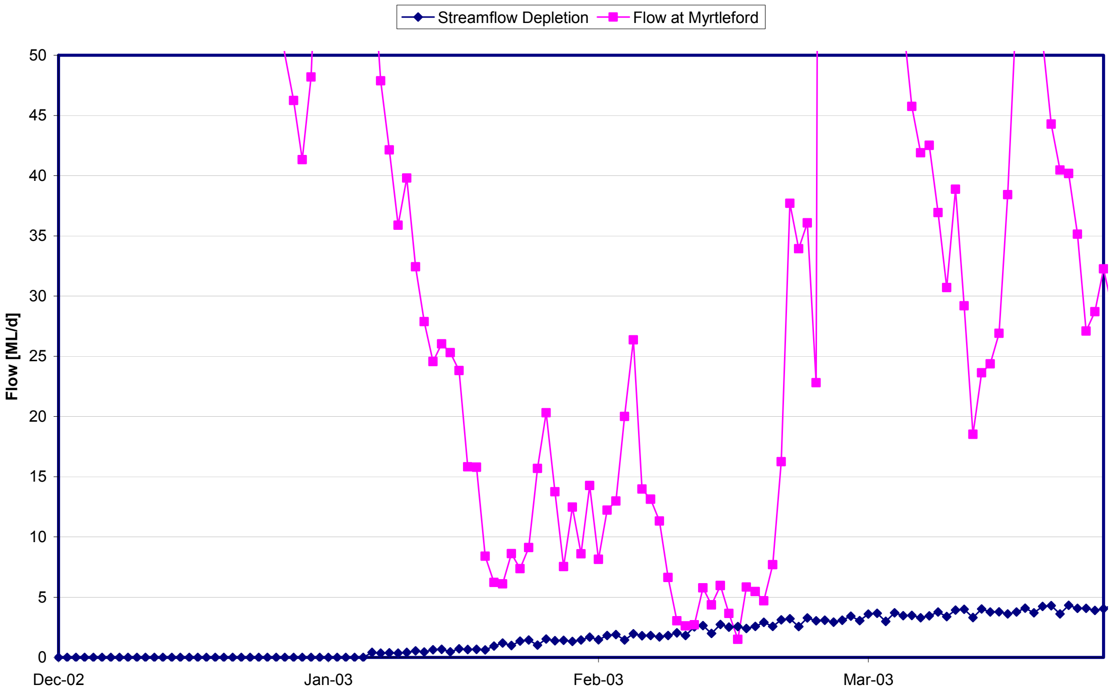
Scenario 6 considers the impacts on river flow resulting from the progressive conversion of surface water diversions to groundwater extractions at a distance of 300m. It is assumed that conversions occur at the time surface water restrictions are implemented and the volumes of groundwater pumping are equivalent to the reduction in volume of surface water diversion. This scenario is consistent with there being no economic impact associated with the management of the water resources of the valley as it assumes that the irrigation requirements are fully met for the entire year.

Results of this scenario are presented in Figure 50, Figure 51 and Figure 52. Figure 52 shows that compared to the surface water restriction scenario, there is no additional water for the river. In fact, the river will be depleted during the season by around 317 ML from January to early April, which is an average of about 3 ML/d (1,250 ML and 12 ML/d respectively for full conversion) as shown in Table 7. A different comparison however is the benefit to the river compared to all diversions being extracted from the river. This comparison (discussed further in Section 9) shows there are clear benefits to the river even under Scenario 6.

- **Figure 50 Streamflow depletion and measured flows at Myrtleford**



- **Figure 51 Streamflow depletion and river measured flow at Myrtleford in Summer**



- **Figure 52 Net savings in river flow for Scenario 6**

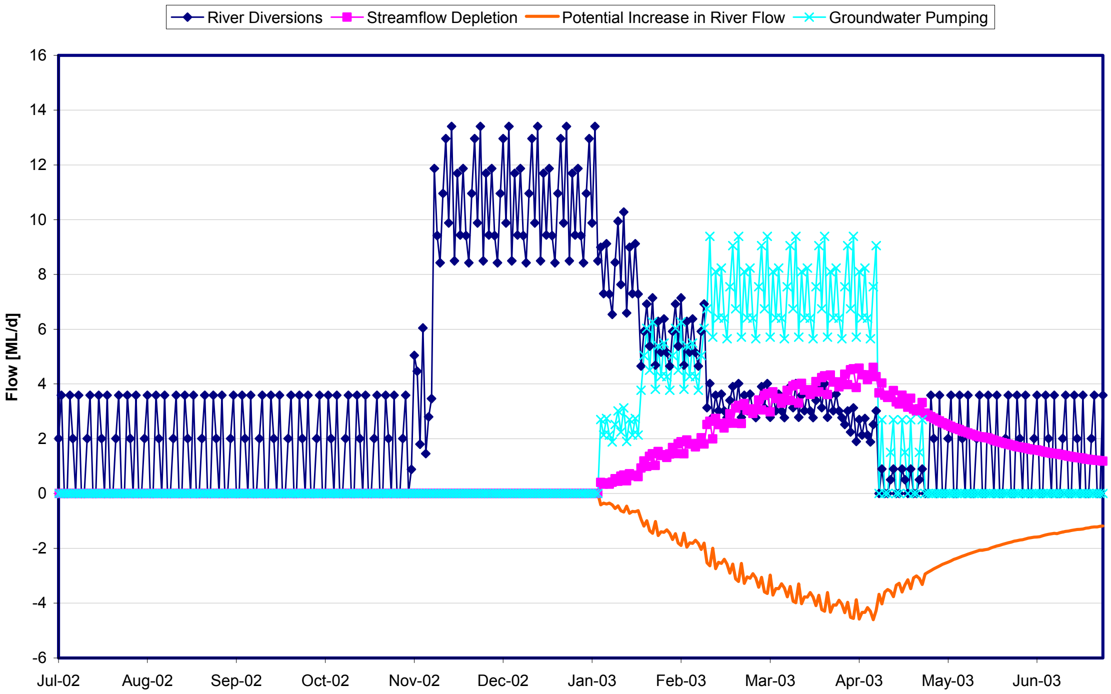


Table 6 Summary of Streamflow Benefits for Scenarios 4, 5 and 6

Scenario	Description	Cumulative Increase in Streamflow	Cumulative Decrease in Streamflow	Net Change in Streamflow[ML]
4	Groundwater Substitution with Restrictions	377	102	275
5	Groundwater Substitution No Restrictions	430	326	104
6	Incremental Groundwater Substitution	0	317	-317

Table 7 Summary of Streamflow Benefits for Scenarios 4, 5 and 6, With Impacts Assigned to Period within Irrigation Season and Extrapolated to the Entire Upper Ovens Catchment

Dates	Days	Scenario 4				Scenario 5				Scenario 6			
		Modelled Area		Upper Ovens		Modelled Area		Upper Ovens		Modelled Area		Upper Ovens	
		Nett	ML/d	Nett	ML/d	Nett	ML/d	Nett	ML/d	Nett	ML/d	Nett	ML/d
Nov to mid-Jan	77	377	4.9	1,508	19.6	430	5.6	1,720	22.3	0	0.0	-	0.0
Mid-Jan to mid-Feb	26	14	0.5	56	2.2	-0.5	0.0	-2	-0.1	0	0.0	0	0.0
Mid-Feb to early April	55	-102	-1.9	-408	-7.4	-326	-5.9	-1304	-23.7	-317	-5.8	-1268	-23.1
Entire Season	158	275	1.7	1,100	7.0	104	0.7	416	2.6	-317	-2.0	- 1,268	-8.0

It is important to understand the differences between the modelling results of Scenario 2 and 3 and Scenario 4, 5 and 6, and why they appear to present different outcomes regarding the benefits of substitution, ie Scenario 2 and 3 appear to show substitution more positively than Scenario 4, 5 and 6). In Scenario 2 and 3 the difference between river flow and the adjusted river flow due to substitution does not include adjustment for the restricted river flow, whereas presentation of the results for Scenario 4, 5 and 6 does include restriction impacts. The main difference therefore is that Scenario 2 and 3 represent average diversions benefits across the irrigation season, whereas Scenario 4, 5 and 6 results are more detailed and show that the benefits (compared to restricted surface water diversion) change during the season.

7.6 Principal findings

Modelling has demonstrated the following:

- Continuous pumping of groundwater from the relatively narrow alluvial aquifer gives rise to significant streamflow depletion. After 5 to 10 years of six month groundwater extraction and rest cycles the volumes of water extracted from bores is almost entirely sourced from streamflow depletion.
- Although long term pumping considerations indicate little streamflow benefit in replacing river diversions by groundwater pumping there are small scale time lags that provide an opportunity for improving river flows through conversion of surface water diversions to groundwater extractions some distance from the river.

- Models aimed at investigating, in detail, the short time lags over particularly dry summer months were developed. These model results suggest that within the Upper Ovens Valley, substitution will provide a greater total summer flow, but risks greater stream depletion in the late summer period due to the cumulative impact of early season groundwater extraction. In designing substitution rules, it is therefore imperative to understand the particular environmental objectives and whether there are environmental tradeoffs in having greater early season river flows but the risk of late season lower flows. In other words, do early dry season benefits outweigh late season disbenefits which will only materialise in extended long dry seasons when very low flows would be expected anyway? If these late season environmental risks are considered too great, then the design of substitution rules may limit application to the late summer early autumn period.
- Due to the apparent late season impacts of the time lag in the Upper Ovens, it is clear that a substitution approach would have greater application in a wider alluvial valley where the time lag would be expected to be longer.

7.7 Conclusions

Modelling has demonstrated that groundwater extractions from the aquifers in the Upper Ovens River valley have a direct impact on river flows. It was found that in the long term, almost all the water extracted from bores is derived from river depletion as indicated by a reduction in baseflow or increase in stream leakage. Scenario modelling of long term impacts of pumping featured constant pumping during the summer and minimal or no pumping outside the irrigation season. Under this extraction regime there is a lag of at least five to ten years before the river flow depletion equals the total groundwater pumping rate.

Modelling was used to investigate potential benefits of converting river water diversions to groundwater extractions. It is clear that in terms of long term large scale catchment yield, there is little benefit associated with substitution because in the long term almost all (more than 95%) of the groundwater extraction is sourced from river depletion. There is however some benefit that can be realised in terms of increasing short term river flows during drought years. Results of this study have shown conversion of river diversions to groundwater extractions may lead to substantial increases in mean daily river flows at times of extreme drought. Not withstanding the potential to make use of the time lag in this way, design of such substitution regimes would need careful consideration of the overall impacts. Modelling suggests that conversion of diversion extraction to groundwater extraction may have positive impacts early in the season offset by negative impacts on streamflows late in the season when demand for water has fallen, but the earlier groundwater extractions impacts are realised at the stream. This is clearly an issue in extended drought years such as 1982/83 and 2002/03.

8. Comparison of Numerical and Analytical Model Results

8.1 Introduction

The impact of groundwater pumping on streamflow in the Upper Ovens Valley has been assessed using a numerical model. This type of modelling is very useful in assessing streamflow impacts because it can simulate complex hydrogeological conditions, variable pumping schedules and multiple pumping bores. However as indicated at the start of this report (Chapter 1), there will always be gaps in our understanding of groundwater stream interaction and the resources for extensive studies of complex systems are invariably limited. It is therefore preferable for simple analytical models to be available for assessing the impacts of groundwater pumping on streamflow due to their low cost and ease of use.

The most commonly used analytical model is the Jenkins model which assumes the aquifer is unconfined, of infinite size, and comprises uniform hydraulic properties. The following is a comparative assessment of the Jenkins analytical model against the results of the numerical modelling undertaken for the Upper Ovens in Chapter 7 of this report. The purpose of this assessment is to evaluate the applicability of the Jenkins model in a hydrogeological setting where the aquifer is of limited size and comprises differing hydraulic properties (ie conditions where the main assumption underpinning the model are violated).

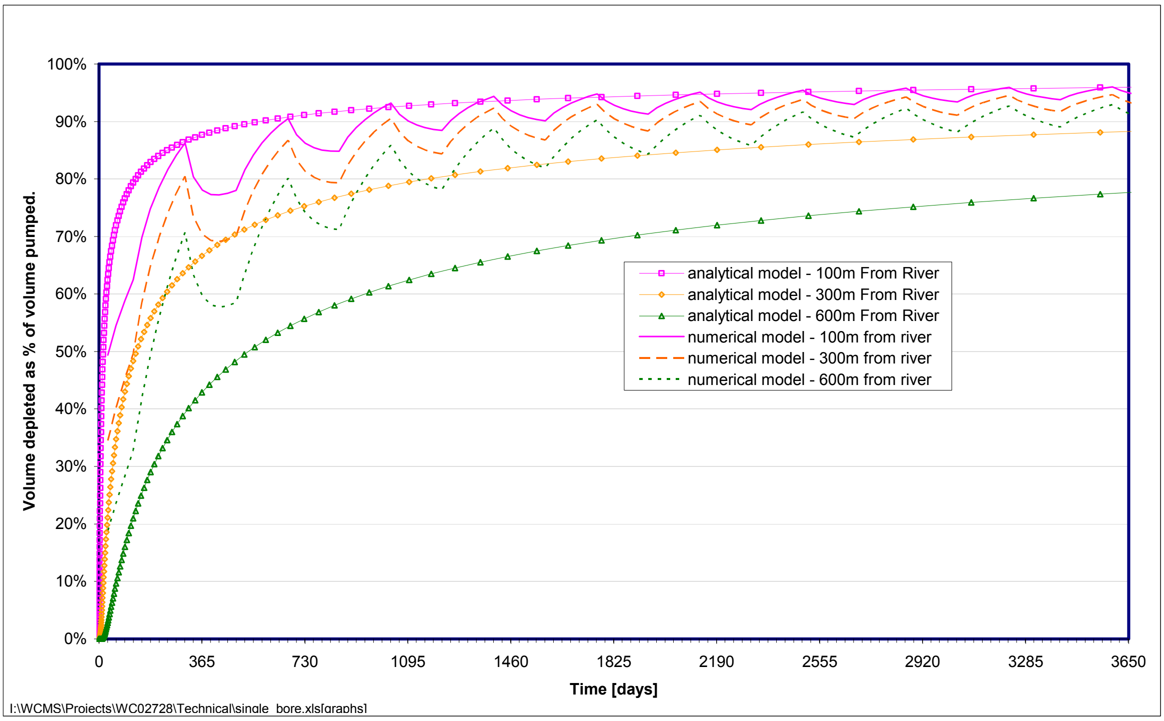
8.2 Single Pumping Bore

The numerical model was designed to reflect the geometry of the aquifer, which in general comprises an elongate aquifer system containing 4 aquifer layers underlying the Ovens River. The aquifer system is approximately 900 m wide and bounded on each side by lower permeability bedrock. The average transmissivity of the four layers is 200 m^2/day, and the upper layer has a specific yield of 0.1. In the simple longer term model (scenario 1 – chapter 7) for each 12 month period there is 6 month period of continuous pumping followed by a 6 month non-pumping period. A more detailed description of the aquifer and numerical model is discussed in the Chapter 7. The Jenkins model assumes there is only one layer that is of infinite size and pumping is continuous (it is possible to simulate periods of non-pumping with the Jenkins model, but this requires a very high level of computational effort. An average aquifer transmissivity of 200 m^2/day and a specific yield of 0.1 was applied to the Jenkins model for this assessment.

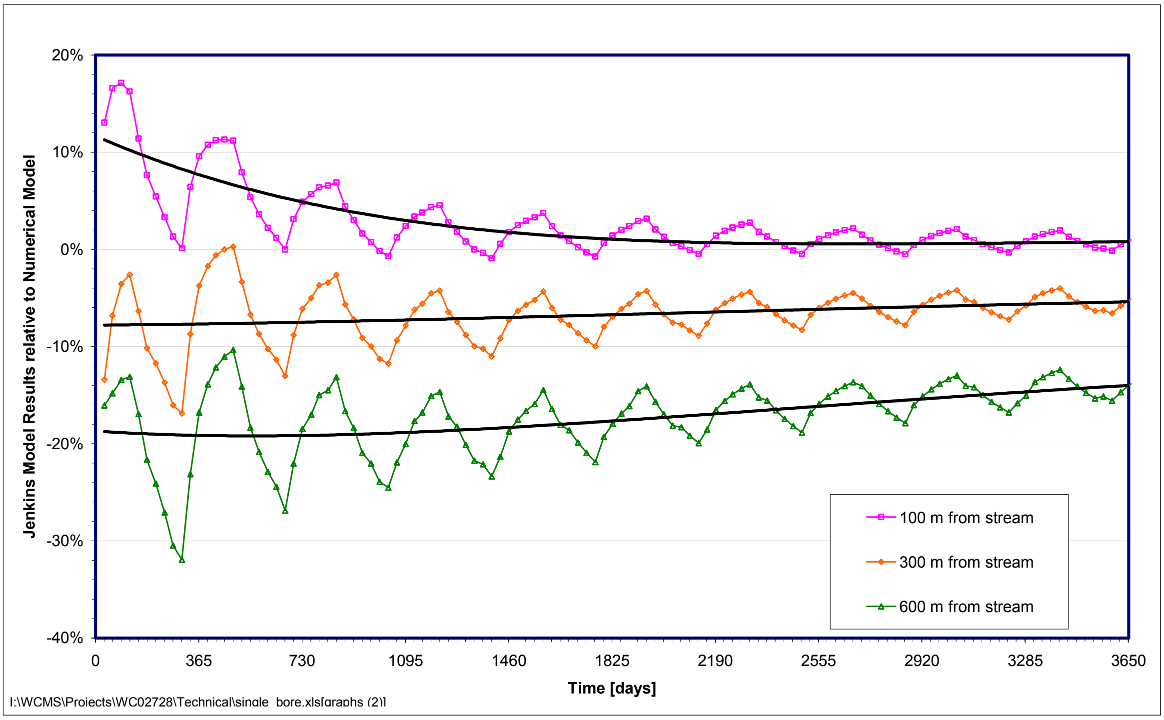
The most obvious difference between the results of the two models is the sinusoidal nature of the numerical model (Figure 53). However, this only reflects how pumping is simulated in each model and does not reveal any fundamental differences between the model results. The analysis results show the Jenkins model to be more sensitive to the distance between the pumping bore and the stream, and as such tends to under-estimate stream flow depletion for a bore located at a distance greater than 100 m from the stream (Figure 53). At a distances less than 100 m the Jenkins model appears to over-estimate streamflow depletion (Figure 53). The degree of over or under estimation by the Jenkins model decreases over time, with the mean difference for the 100 m and 300 m bores ranging from 10% to -10% in the first year decreasing 1% and -7 5% in the fifth year, and then to less than 1% and -5% after 10 years respectively (Figure 54). For a bore located 600 m from the stream the mean differences are greater at -20% in the first year decreasing to -16% after 5 years and -14% after 10 years. The range between the mean difference (ie solid black line in Figure 54) and the actual difference (ie sinusoidal lines in Figure 54) also decrease over time which indicates that, when assessing long term impacts on streamflow, knowledge of the actual pumping schedule is less significant than knowledge of the annual volume pumped.

The greater sensitivity of the Jenkins model to the distance between the stream and the bore is most likely a result of the aquifer being limited in size (ie bounded), which would cause the numerical model to calculate a greater amount of drawdown and, hence, a greater amount of streamflow depletion than the Jenkins model (which assumes an infinite aquifer). This is a similar result to that obtained by the Braaten and Gates (2004) study on surface water and groundwater interaction. It may be possible to adjust the Jenkins model output by using a “corrected” value for the distance between the bore and stream or by using an adjusted transmissivity or storage co-efficient. This could be done by using a numerical model to simulate streamflow depletion for several bounded aquifers with different widths and comparing those results with Jenkins model results. Results from the current numerical model indicate that if the Jenkins model were used where the Upper Ovens Valley aquifer is approximately 900 m wide, the mean error per year would be less than 10% provided the distance between bore and stream did not exceed 300 m. However, this is a relatively crude approach and more detailed assessment, using the numerical model, would be required to provide a more refined correction method.

- **Figure 53 Streamflow depletion from a single bore at increasing distance from the stream**



- **Figure 54 Jenkins Model results relative to the Numerical Model results**

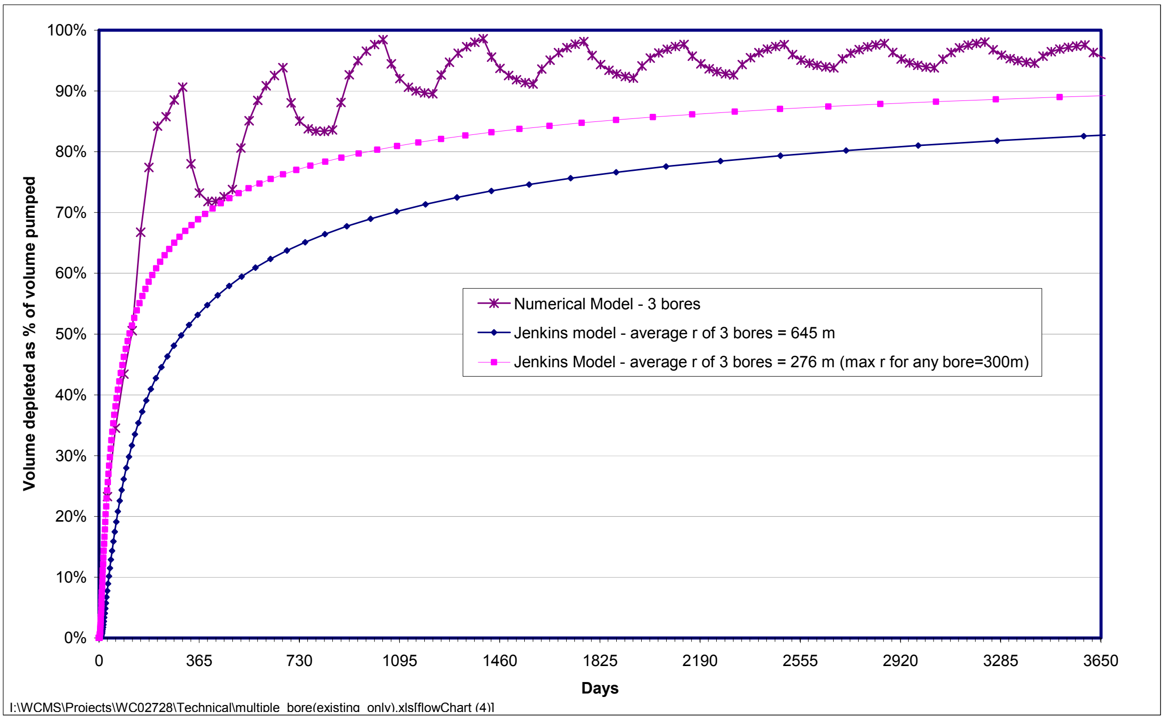


8.3 Multiple Pumping Bores

The impact of multiple bores on streamflow can be assessed relatively easily using a numerical model. Analytical models can only incorporate single pumping bores and, as such, may be unsuitable for assessing the impacts of multiple pumping bores. To evaluate this issue the Upper Ovens Valley numerical model was used to calculate the impact of three existing pumping bores on stream flow, which was then compared with results from the Jenkins analytical model. The three bores were located at distances of 227 m, 496 m, and 645 m from the Ovens River with an average distance of 456 m and an average pumping rate of 108.1 m^3/day. The average distance between the stream and the three bores was used in the Jenkins model to calculate streamflow depletion.

The results show that the Jenkins model significantly under-estimates the streamflow depletion with a mean difference of more than -20% in the first 5 years reducing to -14% after 10 years (Figure 55 and Figure 56). The difference between the two models is most likely due to the bounded nature of the aquifer as described in the previous section. If, as suggested in the previous section, an adjustment is applied when using the Jenkins model (ie the maximum distance between bore and stream is limited to a maximum of 300 m when assessing this section of the Ovens River, which reduces the average to 276 m) the mean difference between the numerical and Jenkins model is reduced to -10% (Figure 55 and Figure 56). This suggests that the Jenkins model could be used to assess the impact of multiple bores, but there would need to be a detailed evaluation on the most suitable method for adjusting the Jenkins model to allow for the bounded aquifer conditions.

- **Figure 55 Combined streamflow depletion from 3 bores**



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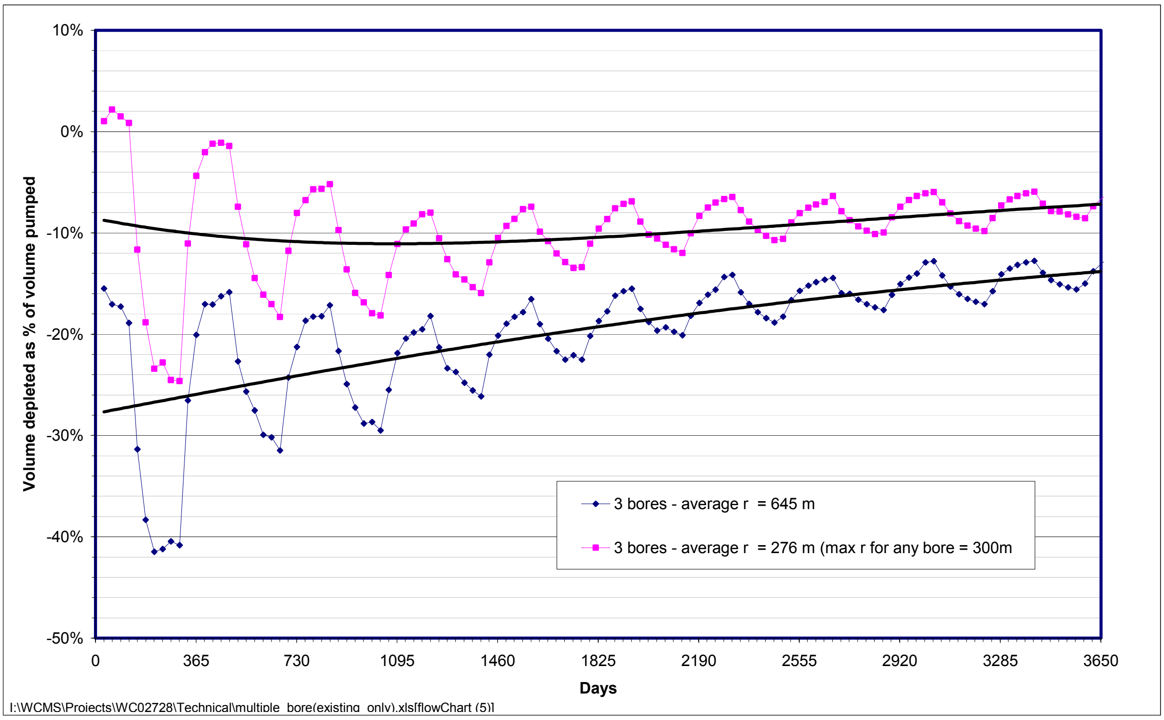
- **Figure 56 Jenkins Model results relative to the Numerical Model results**



8.4 Conclusions

In a bounded aquifer, such as that underlying the Upper Ovens River approximately 10 km upstream of Myrtleford, the Jenkins analytical model tends to under-estimate the amount of stream flow depletion. A similar conclusion was obtained in a research paper prepared by Braaten and Gates (2004) on the effect of a bounded aquifer on surface water/groundwater interaction.

The degree of under-estimation is less than 10% for bores located within 300 m of the stream. At 600 m from the stream the impact were under estimated by 20%, although this decreased to about 15% after 10 years pumping. An assessment of multiple bore pumping was similar to the single bore case. A correction factor could be developed to reduce the difference between the numerical and analytical model, which would significantly improve the applicability of the Jenkins model to the Upper Ovens catchment. It is likely that other analytical models for unconfined and infinite sized aquifer would also under-estimate the amount of streamflow depletion.

An area of study where numerical modelling is likely to have a significant advantage over analytical models is where detailed assessments of the impacts of pumping over short time frames (eg months) are required.

9. Methods for Applying Conjunctive Management in the Upper Ovens Catchment

9.1 Introduction

In the context of the modelling results in Chapter 7, this section describes how the four management methods discussed in Chapter 6 might apply to the Upper Ovens River to achieve the objectives of a future Streamflow Management Plan (SFMP). The minimum passing flow proposed in the draft Upper Ovens Streamflow Management Plan (2003) was proposed to be 100 ML/day which would be expected to lead to a significant decline in reliability of supply to surface water diverters (Holland et. al, 2005; Sinclair Knight Merz, 2005). In the event that these or similar minimum stream thresholds are adopted, it is imperative that water resources of the catchment are managed conjunctively as time lags arising from groundwater pumping impacts are likely to be short. Differences in institutional management arrangements, such as licence conditions, are also required to be technically defensible rather than being residues of an earlier and less informed management era.

Given the above, the next section in this chapter describes why it is essential that groundwater management arrangements for the Upper Ovens Valley are integrated with the emerging surface water management regime. The third section summarises Upper Ovens hydrology and key elements of the draft Streamflow Management Plan. The remaining sections discuss in turn how each of the four methodologies discussed in Chapter 6 might assist in meeting the minimum streamflow objectives of a future Streamflow Management Plan, whilst maximising the reliability of supply to surface water and groundwater diverters.

9.2 The basis for including groundwater management in the Streamflow Management Plan

The modelling presented in Chapter 7 has demonstrated that groundwater pumping, even at some distance from the river, has a significant impact on streamflow in the Upper Ovens catchment during the irrigation season.

The draft Upper Ovens SFMP (2003) did not include regulation of groundwater pumping to manage impacts on the river because of a poor understanding of the time lag between abstraction and its effect upon the stream, and uncertainty as to the magnitude of the impact, particularly during critical low stream flow periods when environmental risks are greatest.

While in part the draft 2003 Plan recognised that ‘the taking of groundwater from a dragline hole or a shallow bore effectively takes water from the same resource’, other sections of the Plan suggest that the high connectivity is not fully appreciated. For example, with respect to the likely increase in severity of restrictions that could be imposed under the draft Plan, the Plan refers to groundwater as a release valve for these restrictions: '*Despite the possibility of bans on extraction being applied, improvements in flow management, such as pumping from the Harrietville dredgeholes, will significantly reduce this risk*'(draft Upper Ovens River Stream Flow Management Plan, 2003). In other words, the draft Plan suggests that although the new surface water restrictions may be harsh, substitution to groundwater may be a solution to reduced reliability of supply. While Chapter 7 of this report indicates that there maybe some merits in substitution, the need for careful design is also identified. There are considerable risks to plan objectives if substitution is put forward on the basis of groundwater and surface water being conceptualised as separate hydraulic systems.

While the impact of groundwater pumping within the irrigation season in the Upper Ovens is not a one to one ratio (over the course of the year impacts are essentially one to one), for near river users, modelling suggests that the majority of groundwater pumped is either sourced from the river or captures groundwater fluxes that would ultimately contribute to baseflow within the irrigation season. Even at 600m from the river, modelling indicates that over the course of the season, approximately 40% of groundwater pumped contributes to streamflow depletion within the irrigation season.

One of the important objectives of the draft Streamflow Management Plan is 'to provide equitable flow sharing arrangements between all stakeholders'. As there is evidence that groundwater pumping impacts upon the Upper Ovens River (and possibly also other Groundwater Dependent Ecosystems) within a short time frame, and that both equity and sustainability are key objectives of statutory based water resource management plans (Water Act 1989 - Section 32A(1)), it is critical that both surface and groundwater licences are considered in the development of prescribed rules and conditions to achieve stream flow outcomes. This is the premise of this chapter.

9.3 Upper Ovens Hydrology, Streamflow Management Plan and Estimated Groundwater Use

Typical of unregulated catchments in Northern Victoria, flows in the Upper Ovens River are highly variable, differing considerably between years, seasons and months. Mean annual streamflow for the Upper Ovens River is 570,000 ML/yr (measured at Myrtleford), but total surface water extraction licences (8,575 ML/yr) make up only 1.5% of average annual flow (draft Upper Ovens River Streamflow Management Plan, 2003). Total surface water use is estimated to be approximately 30-60% of entitlement, depending on rainfall within the season (D.Lovell, GMW, *pers. comm.*). As the draft Streamflow Management Plan indicates, the key issue with respect to the Plan is therefore not about the total volume of commitments, but the problems relating to the impact of extraction rates on streamflow because generally demand is greatest over the low flow period of the year.

Currently restrictions are enforced when river flow at Bright drops below 10 ML/d. The draft 2003 Streamflow Management Plan recommended an environmental water provision (EWP) of

100 ML/d. This provision was to be phased in over a 5 – 10 year periods, with the ultimate objective of a complete ban on any direct extraction when river flows at Myrtleford are under 100 ML/d. However the draft plan also recognised that to achieve such a management regime, significant public scale investment would be required in providing alternative supply options for irrigators. The Government has since maintained its commitment to develop a Streamflow Management Plan for the Upper Ovens River and is in the process of determining the environmental water requirements.

In understanding the social issues associated with achieving minimum streamflows likely to be faced under a management plan, it is worth comparing the total surface water entitlement and usage relative to groundwater entitlement and estimated usage. The following categories of groundwater entitlement were provided by GMW (D.Lovell, GMW, *pers. comm.*):

1) **Irrigators with groundwater and surface water supplies** (it is expected that the surface entitlement is utilised first then the groundwater is used as a secondary source or for backup): 676 ML/yr of groundwater entitlement. For estimation purposes assume 20% of this groundwater entitlement is regularly used (135 ML/yr) , and on average a further 50% of this is actually used (68 ML/yr)
2) **Irrigators using groundwater as primary source**: 1,820 ML/yr of groundwater entitlement. For estimation purposes assume that on average 50% of this entitlement is used (910 ML/yr).
3) **Groundwater primary source but use of entitlement not known** – (no knowledge of whether water is used / not used): 490 ML/yr. For estimation purposes assume 40% of these entitlements are actually used, and of those, on average 50% are used within any one year (100 ML/yr)
4) **Sleeper licences** (entitlement not used): 410 ML/yr
5) **Stock and domestic:** 64 ML/yr. Assume 50% of this is used in any one year (32 ML/yr)

Based on the information and assumptions outlined above, it is estimated that there are approximately 2,920 ML/yr of groundwater entitlements in the Upper Ovens. Groundwater entitlements therefore make up about 25% of total water entitlements in the Upper Ovens. If it is assumed 50% of these entitlements are used on average, this represents usage of around 1,460 ML/yr.

Groundwater sleeper licences are known to be at least 410 ML/yr (item 4 above), but really the estimated proportion of licensees not using their entitlement in item 3 (refer above) should also be added to this. It is estimated this could be 60% of the 490 ML/yr: 290 ML/yr. The total volume of sleeper licensed entitlement is really therefore more like 700 ML/yr.

9.4 Permanent restrictions on entitlement

Permanent (or semi-permanent) restrictions on entitlement are only likely to be proposed and adopted in catchments or aquifers where there is general acceptance that a system is significantly over allocated such as in some of the Deep Lead systems in northern Victoria (eg the Katunga Water Supply Protection Area (2006)).

In the Upper Ovens, where catchment yield is high and annual flow highly variable, future management is expected to have a strong focus on low flow maintenance. It is therefore generally recognised that with respect to surface diversions, it is the timing of extraction that is critical rather than the volume of entitlement (draft Upper Ovens River Streamflow Management Plan Report, 2003). Permanent restrictions on entitlements (for either groundwater or surface licences) would therefore need to be sizeable to be effective in low flow years but would then necessarily be excessive in the majority of years.

The extent of sleeper licences (estimated to be around 700 ML/yr as discussed above) within the Upper Ovens is a further deterrent for using permanent restrictions to achieve streamflow management plan outcomes. As these licences are activated, they could undermine the permanent entitlement restrictions imposed, and hence further management actions would be required.

Given the above, the technical basis for permanent or semi-permanent ‘Katunga’ type restrictions aimed at delivering streamflow outcomes would be poorly targeted and hence would be expected to have a low economic cost-benefit outcome compared with options better targeted towards environmental objectives. Options that achieved the desired outcomes whilst minimising economic costs would clearly be more politically and socially acceptable to the community at large.

9.5 Substitution

Aside from identifying the long term impacts of pumping current groundwater commitments within the Upper Ovens Valley, the modelling in chapter 7 was focussed on assessing the potential for substitution of surface water diversion for groundwater extraction in the Upper Ovens to reduce streamflow impacts. The following sub-sections consider the implications of modelling scenarios 4, 5 and 6 (chapter 7) for groundwater management in the Upper Ovens catchment.

Scenario 4 - Groundwater Substitution with Restrictions

This scenario simulated substitution from surface water diversion to groundwater pumping (300m from the river), using actual volumes estimated from the 2002-03 irrigation season. As surface water diversion was restricted in the 2002-03 season, the substituted groundwater pumping was also restricted by the same amount. Figure 46 shows that there are clear streamflow benefits resulting from substitution from November through to mid-January. Table 6 and Table 7 indicates net savings of river flow of around 377 ML in this period, which is around 4.9 ML/d. However it must be remembered that the modelling in Chapter 7 represents only about one quarter of surface water diverters. Therefore if full substitution was modelled for the entire Upper Ovens, savings in river flow of around 1,500 ML, or 20 ML/d may be achieved over the November to mid-January period.

During the mid-January to mid-February period, river flow was marginally benefited by substitution, by around approximately 0.5 ML/d, or 2 ML/d if full substitution was implemented. However during the period mid-February to early April, river flow marginally suffered due to substitution by a total of around 100 ML (refer Table 6 and Table 7). This represents river depletion of about 1.9 ML/d, or 7.4 ML/d for full substitution, over the period.

The net savings for the river over the entire irrigation season are 275 ML, or about 1,100 ML if full substitution was implemented. This represents an average additional river flow of 7 ML/d. These are significant savings in the context of low river flows. The trade-off for these benefits is reduced flow later in the season which could have negative impacts in the late summer if the season remained dry. For the 2002-03 irrigation season, Figure 45 shows that the reduced late summer flow would have most impact in the middle two weeks of February, when flows at Myrtleford were generally between 3-6 ML/d. It is important to note however, that actual streamflow for this period already partially represent streamflow conditions under substitution, as a number of irrigators commence pumping from bores and draglines when direct diversion is restricted (D.Lovell, pers. comm.,25 May 2006).

The fundamental question of whether this substitution scenario (ie restricted substitution) is ‘good’ for the river, depends on the environmental tradeoffs and values. If the exclusive goal was avoidance of critical low flows at any cost (say less than 5-10 ML/d), then full licence conversion in the Upper Ovens may not the best management technique due to late season impacts. However if higher summer flows for a large part of the summer period provided greater environmental benefit than the disbenefit of critically low flows at the end of severely dry summers, substitution may be considered viable from an environmental perspective whilst also delivering higher reliability of supply to irrigators..

Scenario 5 - Groundwater Substitution with No Restrictions

This scenario simulated substitution from surface water diversion to groundwater pumping (300m from the river), during the 2002-03 irrigation season. No restrictions were applied to simulated groundwater pumping, despite the fact that surface water diversions were restricted in the season.

Figure 49 shows that there are clear streamflow benefits resulting from substitution from November through to mid-January. Table 6 indicates net savings of river flow of around 430 ML in this period, which is around 5.6 ML/d. If full substitution was modelled for the entire Upper Ovens, savings in river flow of around 1,700 ML, or 22 ML/d would be achieved over the November to mid-January period (refer Table 7).

During the mid-January to mid-February period, river flow was not affected either way by substitution (ie neutral impact). However during the period mid-February to early April, river flow suffered due to substitution by a total of around 326 ML (refer Table 7). This represents river depletion of about 5.9 ML/d, or 23 ML/d for full substitution, over the period.

The net savings for the river over the entire irrigation season are 104 ML, or about 400 ML if full substitution was implemented. This represents an average additional river flow of 2.6 ML/d. These are moderately significant savings in the context of low river flows.

The above comparison is between full groundwater substitution (ie, no restrictions), and restricted surface water diversion. Given that this scenario represents no economic impact (ie irrigation requirements fully met), an alternate and perhaps fairer comparison is between this scenario and full diversion from the river. Under the full diversion scenario, around 1,530 ML of water is extracted from the river during the irrigation season. Under this substitution scenario (to 300m), around 870 ML of water is depleted from the river during the irrigation season. This is a net saving of 660 ML (or 43% of pumped volume) to the river. This equates to about 4.3 ML/d, or 17 ML/d when the results are extrapolated to the entire Upper Ovens. This comparison shows that if full irrigation is to be maintained throughout the season, then substitution is clearly more beneficial to the river than direct diversion.

However full substitution without restrictions will not achieve environmental objectives for critically low flow maintenance, as very low flow in drought years will be significantly effected. This is due to the physical nature of the Upper Ovens catchment and associated relatively short time lag. When compared to the Scenario 4, it is seen that substitution with restrictions is partially effective at protecting late season low flows because of this short time lag.

Scenario 6 – Substitution: Incremental Conversion to Groundwater

Scenario 6 simulates conversion from surface water to groundwater (300m from river) at the time of surface water restrictions. The volumes of groundwater pumping are equivalent to the reduction in volume of surface water diversion, so that as per scenario 5, all irrigation requirements are met for the season.

Figure 52 shows that compared to the surface water restriction scenario, there is no additional water for the river. In fact, the river will be depleted during the season by around 317 ML from January to early April, which is an average of about 3 ML/d (1,250 ML and 12 ML/d respectively for full conversion). As discussed for Scenario 5, a different comparison is the benefit to the river compared to all diversions being extracted from the river. Under the substitution Scenario 6, around 1,180 ML of water is depleted from the river during the irrigation season, compared to 1,530 ML if directly extracted from the river. This is a net saving to the river of 350 ML over the irrigation season (or 23% of pumped volume). This equates to about 2.2 ML/d, or 9 ML/d if the results are extrapolated to the entire Upper Ovens. This comparison shows there are clear benefits to the river even under Scenario 6, although the savings are less than for Scenario 5.

Initially this method of substitution appears to have little benefit compared to the complete conversion scenario (Scenario 5). While there are no benefits early in the season, the one potentially important advantage is that the maximum impact of the substitution is delayed until later in the irrigation season. In the critical mid-February period of 2003, the negative impact on the river under Scenario 5 is around 3.7 ML/d, whereas under Scenario 6 is only 2.5 ML/d. When multiplied out under the full conversion scenario this is a difference of around 15 ML/d compared to 10 ML/d. In summary, the potential benefit of Scenario 6 compared to Scenario 5 is that in Scenario 6, the worst impact of delayed effects of substitution occur later in the season, by which stage autumn rains could be expected in most years to have ended the drought period such that the time lag impacts of early groundwater extraction becomes irrelevant.

Summary
Substitution of surface water diversion licences to groundwater licences may be a useful management option contributing to achieving environmental flow objectives in the Upper Ovens. If the exclusive objectives are to minimise critically low flows (say less than 5-10 ML/d, which typically occur approximately 1 in 10 years), then full season substitution may not be appropriate because the groundwater pumping time lag impact upon the stream does not appear to be sufficiently long to avoid late summer flow impacts. However, cumulative streamflows appear to benefit from substitution over the duration of the extraction season. It is therefore critical to understand the environmental tradeoffs involved. As the negative tradeoffs would be most apparent in extended drought periods, an analysis of the environmental benefits/disbenefits of the substitution approach would need to consider different types of seasons. The disbenefits could also be minimised if it were practically feasible to adopt substitution during the middle of the season, thereby pushing the river impacts away from the summer period towards autumn and winter when river flows can be more reliant on rainfall runoff rather than baseflow.

In the event that substitution is given greater consideration, investigations as to the practicality at a local scale would require investigation. Even where practical, significant capital investment is likely to be required. Cost sharing principles would therefore need to be explored.

9.6 Trading

Trading groundwater away from the river in the Upper Ovens catchment will realise a net benefit to streamflow over the course of the irrigation season, as some of the impacts are delayed until the winter period. Hence it would be a useful management tool to help regulate groundwater impacts on the river. In an unrestricted groundwater environment, trading away from the river will always produced stream flow benefits, provided there is no increase in the volume of water pumped (ie, release of sleepers). However, if trading occurs in a restricted groundwater extraction environment, there is a danger in encouraging trade away from a ‘controlled’ zone (ie, where restrictions apply) near the river, in that it could be difficult to manage delayed impacts felt late in the irrigation season. Under this scenario, trading would be most beneficial if it occurred in the second half of the irrigation season, or alternatively if the outer zone to which the licence is traded is restricted to manage late season impacts.

The issues associated with the design of transfer rules for the Upper Ovens are very similar to those arising from substitution. The main difference is that any benefits associated with substitution would be slower to be realised through trading (because market forces would take time to operate). A precedence exists for transfer conditions under a management plan to incorporate rules on reduced entitlement as a condition of transfer (eg Katunga Water Supply Protection Area (2006)) as a possible means of countering increased reliability of supply that may arise from conversion from surface water to groundwater through transfer. Therefore the application of this tool could incorporate some of the benefits of substitution and permanent restrictions on entitlement. The disadvantages are that such constraints may reduce the uptake of trade and therefore impinge upon regional development.

9.7 Restrictions

9.7.1 Introduction

Given the general acceptance of the need for restrictions on direct stream diversion to ensure water sharing and environmental objectives, and that most existing groundwater users are likely to be impacting upon the stream within a relatively short timeframe, rules for restrictions on groundwater users commensurate with their impact upon the stream during critical times, must form the central plank of conjunctive management in the Upper Ovens River. This is because:

- Permanent (or semi-permanent) restrictions on groundwater entitlement are not sufficiently targeted to minimise the critical low flow periods of the Upper Ovens River without being unnecessarily harsh in the majority of seasons.
- Substitution rules may be a useful management tool in reducing the impacts on surface water users on the stream, however practical difficulties means that it is likely to be an opportunistic rather than a blanket approach. The demand for direct diversion will remain, requiring prescribed restriction rules to achieve environmental outcomes. As indicated in section 9.1.1, comparable rules are required for groundwater users to ensure equitable treatment of those impacting upon the stream.
- Significant streamflow outcome achievements through transfer could be achieved in the longer term by developing appropriate trading rules, however such measures will not deliver short to medium term outcomes for the stream.

In contrast to the above three methods, restrictions offer a targeted approach to achieving SFMP outcomes in the short term. Examples of how the method may be applied in the Upper Ovens catchment is discussed below. Additional technical work may be required to develop this approach more fully, and clearly consultation with the community and Catchment Management Authority is critical to further progressing these proposals.

9.7.2 Restrictions Based on Zonal Approach

The simplest type of restriction would be to restrict all groundwater users in accordance with rules prescribed for surface water users. However, such an approach may not be technically sound if, for example, a groundwater user 300m from the river has a different impact to a user 10m from the river. Such differences are likely to be in terms of total stream flow depletion during the irrigation season and in the timing of the stream depletion. While modelling for the Upper Ovens has shown that after 5-10 years, virtually all groundwater pumped causes streamflow depletion, in a catchment where total consumptive use is only a few percent of total streamflow, this fact is somewhat irrelevant. The important statistic is the streamflow depletion during the irrigation season (ie, summer/autumn). A bore 10m from the river essentially causes 100% of the pumped volume to reduce river flows during the irrigation season, whereas a bore 300m from the river depletes river flow by about only 65% of the pumped volume during the irrigation season. Further, the timing of the impact for a bore 300m from the river is delayed to later in the season, compared to a bore adjacent the river whose impact is virtually immediate.

If these differences are important in terms of management objectives, then some form of differential treatment (such as a zonal approach) may be warranted. In the narrow alluvial valley of the Upper Ovens, a maximum of two zones is proposed to deal with these differences. The near river zone (Zone 1) may be managed consistent with surface water licences. Zone 2 could be managed to reflect the lower but delayed impact on the stream. Zoning of bores screening deep aquifers requires further technical work as the timing of impacts upon the stream may be a function of the degree of confinement as well as the distance from the stream.

As the water management plan for the Upper Ovens catchment is also expected to incorporate areas of bedrock, some assessment of the timelag associated with licensed extraction from the bedrock will also be required. No work has been conducted on bedrock aquifers to date, but the volume of licensed commitments from bedrock bores is small and as most of the non alluvial catchment is forested there is limited potential for increased groundwater pumping activity from these areas.

9.7.3 Definition of Zone 1 and 2

Based on the modelling results it is suggested that the differential zone 1/zone 2 boundary would be required to be at least 200m from the stream. If adopted, the 200m width should extend to 350 m if the stream was less than 350 m from the bedrock outcrop. This is partly for practical and administrative reasons but also reflects the fact that a closer valley wall will result in greater boundary effects (ie increased drawdown leading to a more rapid transmission of pumping impacts to the stream). In other words, a bore located 300m from the river and 50m from the alluvial-bedrock margin will cause greater streamflow depletion than a bore 300m from the river but 200m from the alluvial-bedrock margin.

In assessing the appropriateness of a given boundary it is apparent that a trade-off is required. The advantage of a narrow zone 1 (say within 100m) is that:

i. groundwater users close to but not immediately adjacent the river (100-200m) are differentiated from groundwater users adjacent to the river. For example, a bore 100m from the river in the Upper Ovens River effectively sources about 75-80% of pumped water from the river during the irrigation season. Depending upon management objectives and the environmental tradeoffs of the management plan, this 20% difference in impacts from users very close to the river may be sufficient for differential treatment of licences.

ii. Socially and politically, a narrow zone 1 and the application of common surface and groundwater management rules to those within this zone is likely to acceptable to the community who, with their practical local knowledge, are aware of the interaction and support common rules where they are clearly justified.

However as the difference in impact of those marginally beyond 100 metres will be negligible from that caused by closer bores, stream flow objectives may be compromised unless a similar magnitude of restrictions are also applied to Zone 2. Conversely, relatively tight restrictions in Zone 2 to effectively manage those close to the zone 1 boundary will overtly constrain those bores further away. The actual width chosen for the zone, may therefore be in part a function of the numbers of bores within the proposed boundary area and other components of the suite of rules contained within the wider management plan, such as the extent of substitution and trading rules. In application of the zonal framework, it is therefore critical to recognise the potential need for a fuzzy zonal boundary as alluded to in section 4.2.

9.7.4 Management of Zone 2

The potential application of short term restrictions on timing or the rate of application to achieve streamflow outcomes within Zone 2, were outlined in Chapter 6. Data sets that have the potential to be used to trigger restrictions in Zone 2 of the Upper Ovens include:

- *Real time data* – A trigger based on data recorded during the pumping season. This means that the trigger and associated restriction can occur at any time during the irrigation / pumping season.
- *Recent historical data* – This is a trigger based on the immediate period leading up to the pumping season. (This is a type of leading indicator. Leading indicators are those that provide data / information concerning targets prior to adverse conditions arising).

Real time data is not considered practical for the reasons outlined in chapter 6. However in considering the potential for historical data, it is noted that Figure 46 indicates that the lagging impact of groundwater pumping in zone 2 (300m from the river) is still evident in late February and March, to the extent that even though the pumping rate in this period was reduced to 25% of the rate at the start of the season, the impact on the river ranged from 25-40% during this period. In other words, the lag has negative impacts late in the season which cannot be controlled by changing pumping rates and could be deleterious to the river if coincident with low stream flow. The only way to manage these late season impacts is to predict the low flow in advance via use of a leading indicator or provide access to surface water early in the season with substitution late in the season. For the reasons discussed in chapter 6, cumulative rainfall or trends in the rainfall residual mass warrants further investigation .

The way that rainfall records could be used to determine the need for restrictions is not, strictly speaking, a ‘trigger’ in the sense that at the specific time the data is assessed, restrictions would either apply or not apply, ie the trigger cannot occur at any time. Once the review had been conducted, it would be necessary to establish whether a further review was warranted that would either lift or apply restrictions.

Number of Review Periods

It was suggested in Chapter 6 that due to the time lag effect, only one review and announcement of restrictions would be practical (ie, a mid-season review would be too late to realise streamflow benefits). In light of the modelling results from Chapter 7, a mid-season review of restrictions may be able to deliver streamflow benefits and where restrictions are lifted, ease the economic impacts of earlier restrictions if they had been applied. This is best seen by comparing the streamflow depletion curve in Figure 46 to that of Figure 49. The streamflow depletion curve in Figure 46 responds relatively rapidly to the reduction in pumping rates. While the impact is still 25-40% during the latter part of the season, by comparison, Figure 49 illustrates that the corresponding impacts when there was no restriction to groundwater pumping were around 50-65%. Hence a mid-season review could justifiably change management decisions and therefore should be considered in the development of appropriate rules.

The use of rainfall records from the Upper Ovens in the manner proposed in this report clearly requires additional work. A statistical assessment of the correlation of rainfall datasets with mid-season and late season streamflow in the Upper Ovens catchment would form part of this work. An integral part of that assessment should be examination of the potential for robust indicators that are sufficiently early to allow irrigators to plan for the forthcoming irrigation season. It would also be critical to understand the general water demand patterns of the key crops grown in the valley to ensure that any triggers took into account the timing of water requirements in the area. Other options that may be worth exploring include:

i. Use of another leading indicator such as the Southern Oscillation Index (SOI). Negative values of the SOI over a period of time often indicate El Nino episodes, which are characterised by a reduction in rainfall over eastern and northern Australia. By observation of the SOI, it may be possible to predict when seasons of drought are imminent in the Upper Ovens.

ii. A revised assessment of the potential for real time indicators such as groundwater levels.

Restriction Magnitude

The final aspect to be considered is the magnitude of restriction, and whether a single restriction percentage is imposed, or whether the size of the restriction is calculated based on a sliding scale depending on the relative magnitude of the rainfall index relative to particular thresholds.

If a seasonal allocation approach is adopted, simplicity may suggest a single percentage annual allocation. (Use of a sliding scale would imply a greater level of confidence in the accuracy of the leading indicator than is warranted). Something in the order of an 80% restriction may be appropriate, however the effectiveness of this approach is clearly dependent upon the amount of sleeper licences and cannot therefore be adequately designed until metering data provides an indication as to what effective reduction in pumping would arise from an application of a given allocation.

If an entitlement share approach were used as currently is applied to surface water diverters (and discussed in section 6.4.3), the extent of sleeper licences are less critical as the restriction rules are targeted at current levels of development.

The level of restrictions required to be applied to groundwater extraction may be lower than the effective restriction applied to surface water diverters (& therefore zone 1 groundwater users) because:

1) The time lag means groundwater extraction has a reduced impact on the river during the irrigation season.

2) Groundwater restrictions, if imposed, would occur from the start of the irrigation season, whereas surface water restrictions are almost always imposed several months into the season.
3) There will be occasions when, due to error in the cumulative rainfall method of predicting streamflow, groundwater restrictions will be called, when in fact stream flow does not reach critical levels and surface water restrictions are not called. Indeed, the groundwater restrictions may in part contribute to surface water restrictions not being required.

However additional work is required to progress this reasoning, particularly if the environmental impacts arising from a late season depletion in flows were deemed to be more detrimental to environmental objectives than a more consistent drop in flow as a result of surface water and Zone 1 groundwater use.

9.8 Communication / consultation

Clearly the issues associated with conjunctive management in the Upper Ovens are complex and require a considerable amount of additional work in order to progress to a practical level. Initiating dialogue and generating discussion on the methodology and tools presented in this report is therefore critical to achieving community support, input and acceptance.

An initial step towards this goal would be development of a brochure outlining basic hydrogeological principles (in particular the process of groundwater surface water interaction), presentation of case studies where significant stream depletion has occurred together with some of the concepts presented in this report. Key messages that could be communicated include:

- why conjunctive management is being considered for the Upper Ovens River.
- Federal and State government policy driving the management actions, and the fact that this is emerging as a big issue at a national level across Australia,

Development of future management arrangements will also be required to include public meetings and possible development of field trials which will assist in enhancing community understanding of groundwater-surface water interaction (eg, refer Recommendation 17)

9.9 Conclusions

Conjunctive management of groundwater and surface water in the Upper Ovens is critical given that modelling (chapter 6) suggests significant interaction between these two resources. The modelling results are consistent with the general acceptance of high level interaction, both within agencies and the Ovens community, and therefore support an integrated groundwater/surface water management plan being developed for this sub-catchment, consistent with policy initiatives documented in Our Water Our Future (DSE, 2004).

Integrated management has the potential to ensure that pumping of existing licensed entitlements in the catchment are managed to assist in achieving agreed environmental objectives. Integrated management also has the potential to provide options for reducing the economic cost of achieving minimum environmental flows, by providing options for trading or conversion of surface water licences to groundwater licences.

If groundwater use is found to be high within the catchment, then restrictions must form the basis for achieving environmental streamflow objectives, because in the long run essentially all groundwater pumping causes the equivalent amount of streamflow depletion, but more importantly also demonstrates that bores distant from the river cause only a proportion of this depletion during the irrigation season. Depending upon environmental objectives and environmental tradeoffs, bores distant from the river may require different management from bores closer to the river.

Short term restrictions on groundwater users commensurate with their impact upon the stream during critical times must form the central plank of conjunctive management in the Upper Ovens River. Other methods discussed in this report are unlikely to be the principal management tools, because:

- Permanent (or semi-permanent) restrictions on entitlement are not sufficiently targeted to minimise the critical low flow periods of the Upper Ovens River without being unnecessarily harsh in the majority of seasons.
- Substitution rules may be a useful management tool in reducing the impacts on surface water users on the stream, however practical difficulties means that it is likely to be an opportunistic rather than a blanket approach.
- Significant streamflow outcome achievements through transfer could be achieved in the longer term by developing appropriate trading rules, however such measures will not deliver short to medium term outcomes for the stream.

Short term restrictions are best implemented in a zonal framework to allow for differing impacts of different groundwater users. Subject to further investigations (particularly ground-truthing), two potential zones are proposed for consideration. Zone 1 is for bores up to 200m from the river, extending to the bedrock interface where the alluvial - bedrock boundary is 350m or less. Within this zone, similar management rules would be expected to that which applies to surface water users. Alluvial sediments outside this range would be classified as Zone 2. Ideally, further investigations are required to establish whether vertical zoning is warranted. This will depend upon the degree of confinement. A separate zone may also be required for bedrock aquifers.

Once management objectives have been developed for the area, additional technical work is warranted to ‘road test’ the above zoning proposals and design proposed management rules to achieve these objectives. These management rules may include restrictions and rules on trade and substitution. The development of restriction rules will also require additional technical work to assess whether rainfall indices can be used as a predictor for the likelihood of low summer streamflows.

Finally, the potential for this proposed approach to be significantly undermined by sleeper / dozer licences needs to be recognised. Section 9.3 indicates that sleeper (allocation not used at all) and to a greater extent dozer licences (only a part of allocation used) are a significant proportion of total allocation within the Upper Ovens catchment. Actions to bring allocation and use into line or methods of restriction based on usage rather than allocation, are likely to be required in order for restrictions to be effective.

10. Conclusions

10.1 General conclusions regarding management options for managing groundwater extraction impacts on unregulated streams

Four options for managing groundwater pumping impacts on unregulated streams to achieve streamflow management objectives have been considered. Some of the methods (substitution and trading) are opportunistic, and hence by themselves may not be able to deliver the desired outcome in the short term. However in the long run they can assist in achieving streamflow outcomes. Conclusions regarding three of the four options are summarised below:

- Permanent (or semi-permanent) restrictions on entitlement are not sufficiently targeted to provide the types of streamflow objectives likely for an unregulated stream. The imposition of such measures are unlikely to be able to achieve stream protection without very large economic costs (and little environmental benefit) in most years, and would therefore be very difficult to sell to the community.
- Trading over the long term, could be important in reducing summer stream impacts but demand for trade over the short term will be small and therefore targeted rules will be ineffective in delivering short term benefits to the stream.
- Where the practical obstacles to substitution can be overcome, it may be a useful management tool. Its potential influence is increased in wide alluvial catchments where the time lag is of sufficient magnitude to move stream impacts from early season pumping into the winter period. In narrow catchments, careful design will be necessary so that conversion does not lead to unacceptable late season stream impacts arising from the timelag effect of early season pumping.

The most suitable method for addressing current groundwater user impacts on the stream is that of short term restriction, in conjunction with restrictions to surface water users. However, the potential exists to complement such reactive management measures with trading and substitution rules, which over a longer timeframe have potential for improving overall water access to all users, thereby reducing the severity and frequency of short term restrictions.

Of the options available for imposing restrictions, trigger based restrictions are considered the best primary method for managing these impacts because it is technically the most defensible option, as it can be targeted to deliver protection to the stream when required, yet minimise impacts on groundwater users at other times. A fixed restriction period / volume has the same problem as permanent restrictions in being poorly targeted to the unique conditions of a particular year and therefore economically costly in years when streamflows are not significantly compromised by groundwater extraction.

A trigger based on recent historical data, applied shortly before the start of the irrigation season is considered the best form of trigger to deal with the time lag issue. Rainfall records would seem to be the most appropriate parameter to use for this trigger, as it is a leading indicator of likely baseflow conditions. Further, the data is widely available and easily collected.

10.2 Numerical Groundwater Modelling in the Upper Ovens

Modelling was used to investigate potential benefits of converting river water diversions to groundwater extractions. It is clear that in terms of total annual flow, there is little benefit associated with substitution because in the long term almost all (more than 95%) of the groundwater extraction is sourced from river depletion. There is however considerable benefit that can be realised in terms of increasing short term river flows during drought years. Results of this study have shown conversion of river diversions to groundwater extractions may lead to an increase in mean daily river flows at times of extreme drought, but that the timing of these benefits is not evenly distributed throughout the irrigation season. Hence, some late summer/early autumn flows may be less than would occur without substitution (in years where surface water restrictions are required).

10.3 Using Analytical Models to Estimate Numerical Modelling Results

In a bounded aquifer, such as that underlying the Upper Ovens River approximately 10 km upstream of Myrtleford, the Jenkins analytical model tends to under-estimate the amount of stream flow depletion. A similar conclusion was obtained in a research paper prepared by Braaten and Gates (2004) on the effect of a bounded aquifer on surface water/groundwater interaction.

The degree of under-estimation is less than 10% for bores located within 300 m of the stream. At 600 m from the stream the impacts were under estimated by 20%, although this decreased to about 15% after 10 years pumping. An assessment of multiple bore pumping was similar to the single bore case. A correction factor could be developed to reduce the difference between the numerical and analytical model, which would significantly improve the applicability of the Jenkins model to the Upper Ovens River. It is likely that other analytical models which assume unconfined and infinite sized aquifers would also under-estimate the amount of streamflow depletion.

An area of study where numerical modelling is likely to have a significant advantage over analytical models is where detailed assessments of the impacts of pumping over short time frames (eg months) are required.

10.4 Recommended Approach in the Upper Ovens Catchment

A recommended approach for further developing conjunctive management in the Upper Ovens catchment is outlined in section 9.7.

Progressing these recommendations are critical to the development of a conjunctive water management plan for the catchment.

11. Recommendations

The recommendations arising from this investigation are outlined in two categories; those directly related to the Upper Ovens catchment, and those related to the general advancement of integrated groundwater and surface water management across Victoria.

11.1 Upper Ovens Catchment

11.1.1 Management of Groundwater

With respect to management of groundwater in the Upper Ovens catchment, this investigation recommends that:

1. The proposed new Upper Ovens Streamflow Management Plan incorporate conjunctive surface and groundwater management.
2. Environmental management objectives be developed for the Upper Ovens catchment to allow further development of local scale conjunctive management methodologies to contribute to achieving these objectives.
3. Detailed investigations be conducted on the potential application of substitution and trading rules to encourage surface water and Zone 1 groundwater licences to be transferred to Zone 2. The investigations should clearly document the potential benefits and pitfalls associated with such rules for the Upper Ovens, and a proposed package should be developed in the context of contributing to environmental management objectives (currently under development by the Catchment Management Authority).
4. That community engagement be initiated in the Upper Ovens on technical and equity issues associated with conjunctive water management.

11.1.2 Desktop Investigations

‘Desktop’ investigations are required to enhance understanding and management of groundwater in the Upper Ovens catchment. These investigations should include (in order of higher to lesser priority):

5. an assessment of an appropriate leading indicator of low stream flow (ie, investigation of the ability of indicators to predict low stream flow well in advance of occurrence). Methods investigated should include cumulative rainfall and rainfall residual mass balance. If neither of these are found to be suitably accurate indicators then the use of the SOI should also be investigated. The assessment of these leading indicators should firstly involve experimentation to determine the most accurate index, and secondly a statistical analysis of the accuracy of the index, assuming it had been adopted as a predictor for the

last 40 years. Viable triggers are required as a basis for early season restrictions as well as the basis for a mid-season review.

6. A review of the monitoring bore network be undertaken, to determine its suitability for assessment of groundwater surface water interaction. This review should include assessment of bore density, locations, depths and monitoring frequency. An expected output of the report would be to recommend the best location for one or more new transects of monitoring bores (and associated stream level monitoring gauge if appropriate) , with the specific goal of providing data to assist in measuring groundwater – surface water interaction.

7. Numerical modelling of the proposed groundwater restriction measures be undertaken (using the existing model developed in this study), to assess the actual streamflow impacts of the management measures proposed in this assessment. This would include modelling under a range of steamflow events to evaluate the long term benefit of groundwater restrictions and substitution to streamflow. The leading indicator developed in Recommendation 5 should be used to assess when Zone 2 restrictions would have historically been applied under this indicator. This modelling should also include scenario runs assuming a certain percentage of surface water diverters convert to substitution over time. Testing of the proposed 200m location of the Zone 2 boundary should form part of this modelling.

8. The analytical modelling undertaken in this assessment be further developed into a more ‘user friendly’ process / tool for wider catchments where it would be expected to have greater application as a management tool. This should include development of a guidelines document as to how, when and where analytical modelling can be used to assess stream depletion, and the strengths and weaknesses of this approach compared to numerical modelling.

9. An economic assessment of the implications of Zone 1 and Zone 2 restrictions be undertaken. This will require an assessment of the frequency that the restrictions would be enforced, and could utilise outputs from Recommendation 7.

10. A broader desktop assessment of GDEs in the Upper Ovens be undertaken. The main river channel is only one of four or five potential GDEs within the catchment. Wetlands / marshes, terrestrial and riparian vegetation and stygofauna are other potential environmental users of groundwater. If substitution is to be encouraged as part of the SFMP, a desktop assessment to identify potential GDEs should be undertaken. Development of a depth to watertable map for the Upper Ovens is likely to be an important part of this assessment.

11.1.3 Field Work / Investigations

With respect to field work and field investigations to advance understanding and management of groundwater in the Upper Ovens catchment, it is recommended that:

11. The zoning proposed in this report (two zones for groundwater management) be further investigated through site based investigations to prove the timelag predictions derived from modelling. These investigations should include one or more of the following:
    a. Hydrochemistry sampling and analysis be undertaken of the river and selected groundwater bores next summer, during the typically lowest flow period. The aim of this work is largely for community education, to demonstrate that during periods of low flow, most of the water in the river is comprised of groundwater.
    b. Intensive monitoring of groundwater observation bores (ideally with data loggers), in an area of intensive groundwater use in the Upper Ovens. This would include metering (and continuous logging) of nearby groundwater extraction bores. This task would serve the dual purpose of providing data for more accurately calibrating the groundwater model to support Recommendation 7, and providing the community with confidence that the predicted time lags are comparable with those measured in the field.
12. The implementation of metering of groundwater bores in the Upper Ovens be accelerated to provide an understanding of groundwater use relative to entitlement in the Upper Ovens catchment.

11.2 General

11.2.1 Desktop

To advance integrated management of groundwater and surface water across Victoria, it is recommended that:

13. A baseflow/rainfall analysis be conducted for the Upper Ovens River to understand the reliability of seasonal and historic rainfall records (eg, in August/September) as an indicator of critically low summer flows. The analysis would be expected to be carried out on a range of different seasonal events to establish whether the relationship is a robust basis for announcing restrictions. Seasonal events that might be considered include:
    - Very low winter and spring rainfall (eg 1982/83 & 2002/03)
    - average to low winter/spring rainfall.
    - High winter/spring rainfall.

14. Numerical modelling be undertaken of wider alluvial valleys to determine the approximate valley width (for different aquifer hydraulic properties) at which point the time lag is greater than about six months. For these valleys, substitution may be a more effective tool in delivering environmental outcomes than in the Upper Ovens, as the bulk of groundwater pumping (utilised for irrigation) impacts would be delayed until the winter period. This should also include assessment of the impact of semi-confining layers on zone localities.
15. A methodology be developed for managing groundwater interaction in regulated catchments. This assessment has focussed on development of a methodology applicable to unregulated systems. In regulated systems the management objectives and the means to achieve them are likely to be different, eg the emphasis at some times is more likely to be on managing river losses.

11.2.2 Field Work

16. A groundwater/stream monitoring site (probably a bore transect) be established in a fractured rock aquifer (in an unregulated catchment of relatively high groundwater use) to assess the impact of stream interaction in fractured rock environment.
17. A groundwater/stream monitoring site (probably a bore transect) be established in a semi-confined aquifer, in an unregulated catchment of relatively high groundwater use, to asses the impact of stream interaction in a semi-confined environment.

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Appendix A Discussion on the Calculation of Streamflow Depletion

Review

Methods to calculate the impact of pumping on stream flow have been developed since Theis developed the solution to transient groundwater flow. Initial investigations by Theis (1941), Glover and Balmer (1954) developed an analytical solution for an idealised case where the stream fully penetrates the aquifer, the water table is flat (ie the stream is neither gaining or losing), and the streambed is not clogged with low permeability sediments. A flat water table is used in the model because the Theis solution does not incorporate natural recharge or discharge (ie recharge or discharge can only be simulated using a bore). As a result, the streamflow depletion can only be represented by the model as increased recharge. However the distinction between increased recharge and reduced discharge is unnecessary because the mechanism for these processes are the same (ie intersection of the stream by a drawdown cone). What is unknown is the proportion of streamflow depletion that is derived from reduced discharge and increased recharge respectively. Using this model these investigators showed the proportion of the pumped groundwater derived from streamflow (as either reduced discharge or increased recharge) to be a function of aquifer diffusivity (ie both aquifer transmissivity and storage co-efficient) and the square of the distance between the bore and the stream (ie a ten fold increase in distance causes a 100 fold time delay from the start of pumping till the commencement of reduced streamflow. From this simple model Jenkins (1968) and Glover (1974) developed an analytical solution for calculating stream flow depletion from a well discharging at a constant rate at a fixed distance from a stream.

Many methods for assessing more typical[4] cases have been developed by various researchers. According to Bakker and Anderson (2003) the significance of streambed clogging on flow across a streambed (and, hence on groundwater flow to the well) was identified by Kazman (1948) and Walton (1963), who developed a method using extended flow lengths to simulate clogging. Hantush (1965) developed an analytical method that dealt with clogging more directly by assuming a thin layer of low hydraulic conductivity and no storage separates the aquifer from a fully penetrating stream. Analytical solutions for a partially penetrating stream have been developed by Hunt (1999), Zlotnik and Hung (1999), Butler et al (2001), and Fox et al (2002) using different assumptions regarding stream width and drawdown on the non-pumped side of the stream. The influence of other factors on streamflow depletion such as the direction of groundwater flow

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[4] Where the stream is in a more typical situation, such as partially penetrating an aquifer or has a “clogged” stream bed.

(towards or away from the stream), stream gradient (Bakker and Anderson, 2003), and intermittent pumping (Darama, 2001) have also been examined.

Due the complexity and variability of the natural environment there is no single robust and technically simple tool for predicting the impact of groundwater pumping on streamflow. In the following sections the solution to the idealised case (ie the method by Glover and Balmer, 1954) will be described and the level of error introduced by factors such as streambed clogging and partial penetration will be examined.

Idealised Case

Using the Theis solution Glover 1974 developed a model to calculate the volume of streamflow depletion due to pumping from a single bore. To use the Theis solution the model needed to incorporate a recharge source to ensure the water balance is maintained. To do this the model is constructed with an injection bore to simulate recharge and a pumping bore to simulate discharge. The stream is represented as an imaginary line located half way between the pumping bore and the injection bore. When the pumping (and injection) commences a cone of drawdown and a cone of impression form around the respective bores and the outer edge of each cone migrates towards the stream. The water balance is maintained because injection and pumping commence at the same time and operate at the same rate. After a period of pumping the two cones intersect at a point on the stream directly opposite the pumping and injection bores. When this occurs water from the cone of impression is diverted into the cone of depression slowing the rate of drawdown in the pumping bore (and slowing the rate of impression in the injection bore). It is important to note that the model calculates streamflow depletion using drawdown NOT groundwater level. As a consequence the model does not differentiate between the two forms of steamflow depletion; reduced baseflow and increased stream leakage. As the two cones continue to expand the amount of water transferring from the injection bore to the pumping bore increases until 100% of the pumped water is derived from the injection bore (ie the stream). When this occurs the two cones cease to expand (ie the rate of streamflow depletion is equal to the rate of pumping). The rate at which streamflow depletion increases is proportional to the change in rate of drawdown in the pumped bore (Figure 57). The rate of streamflow depletion changes in a similar manner as the slope of the time drawdown curve in Figure 57 and follows the shape of the curve shown in Figure 58 (in a dimensionless form). The duration of pumping required before streamflow depletion begins is dependent on the storage co-efficient, transmissivity, and the location of the bore. The pumping rate does not influence the rate at which the drawdown cone spreads and as such does not influence the timing at which streamflow depletion commences. By keeping the transmissivity and storage co-efficient constant the curve in Figure 58 can be split into a series of curves which show the effect of distance between the bore and the stream on the duration of pumping before streamflow depletion begins (Figure 59). These curves can also be used to calculate the volume of streamflow depletion. For example, a bore located 500 m from a stream that has been pumped for

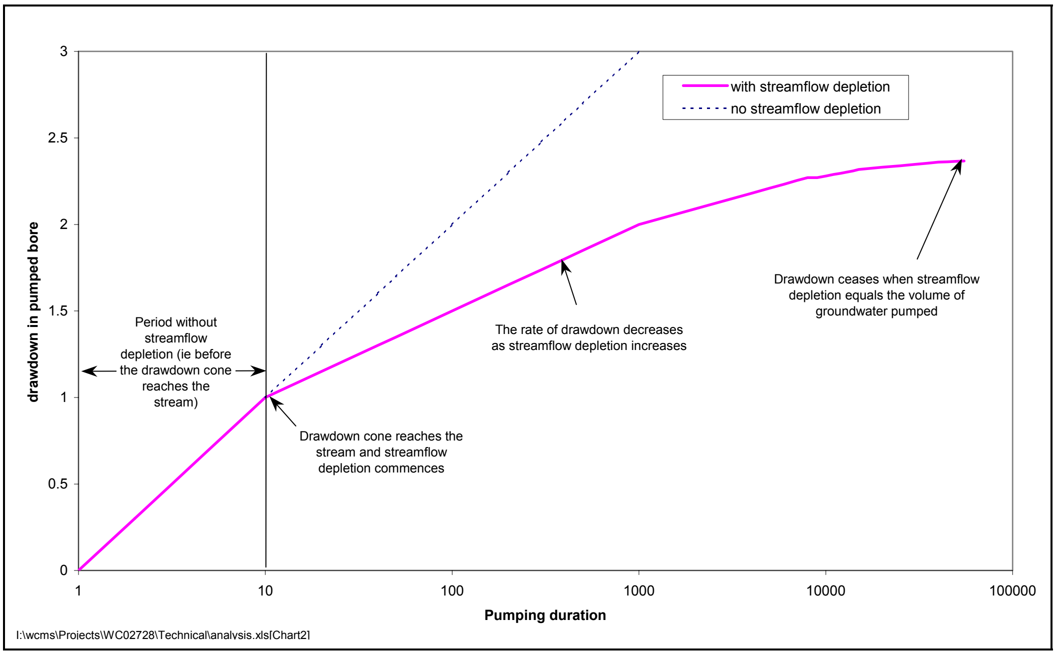
36 days (0.1 year) from an aquifer with a transmissivity of 100 m^2/d and storage co-efficient of 0.1 will begin to deplete streamflow after 11 days pumping (0.03 years on Figure 59). The amount of streamflow depletion will increase as pumping continues, reaching 7% on day 36 (0.1 year). If the pumping rate is 550 m^3/d (200 ML/year) the streamflow depletion rate, on day 36, will be 38.5 m^3/d (Figure 59). Curves showing the total volume depleted can also be calculated ((Figure 60 [log scale] and Figure 61 [linear scale]). After 36 days pumping the total volume depleted from streamflow is 0.386 ML or 1.9% of the total volume pumped (Figure 60).

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

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

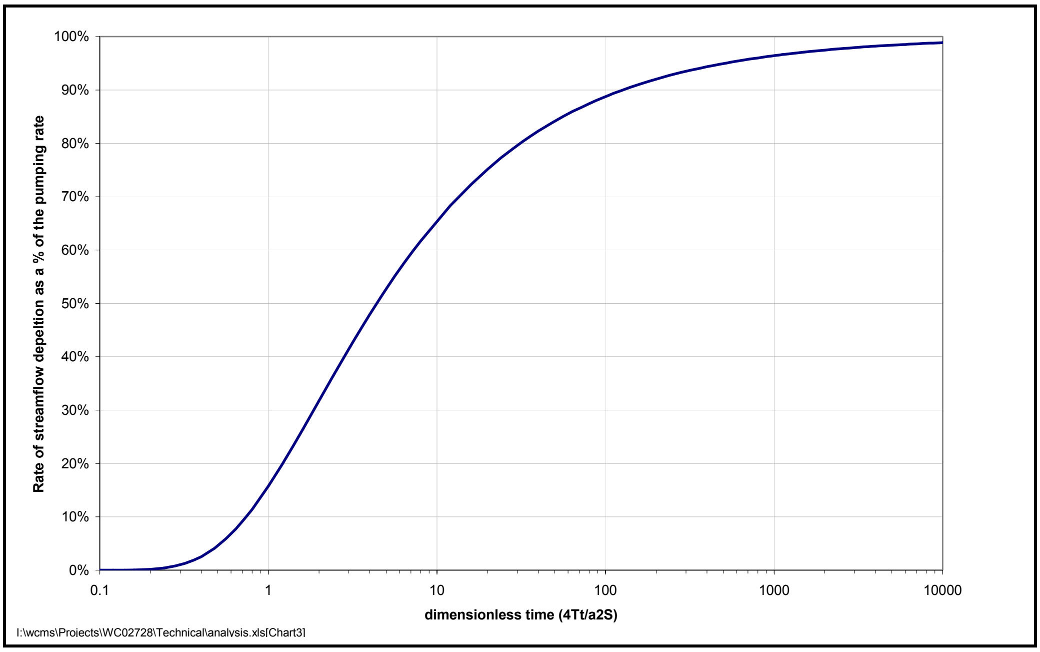
- Groundwater is extracted from a bore at a constant rate,
- The stream is represented as a straight line at some distance from the pumped bore,
- The source of increased recharge is represented as an image bore (ie an injection bore rather then the stream itself) located on the opposite side of the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

- **Figure 57 Effect of induced recharge on drawdown in the pumped bore**



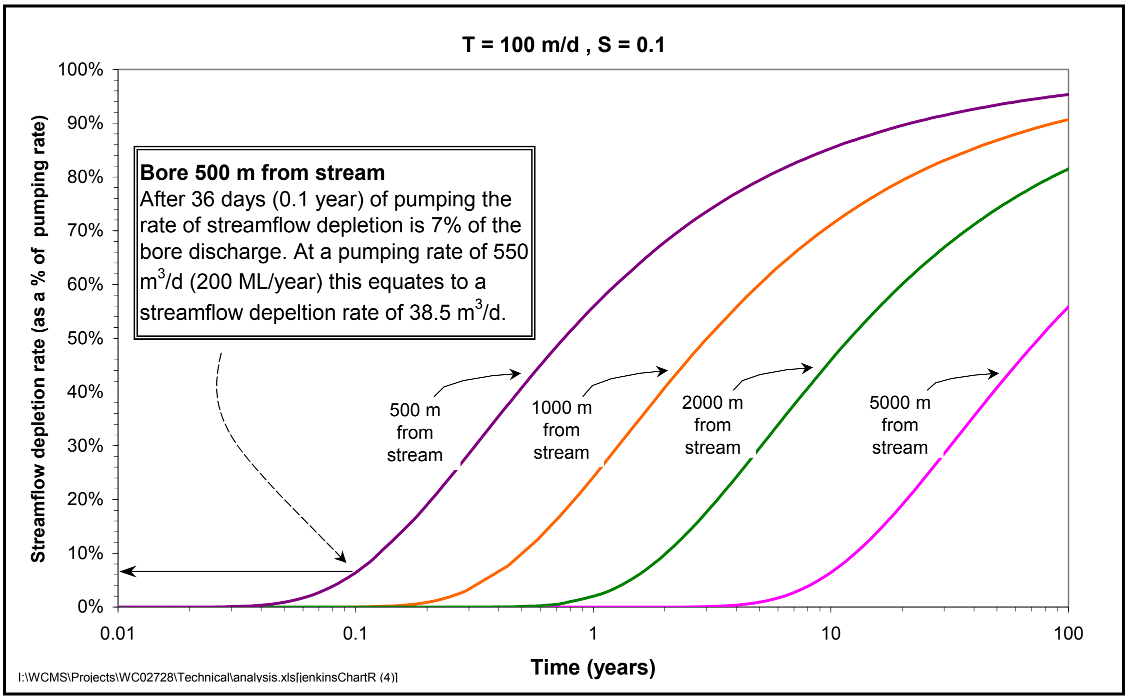
I:\wcms\Projects\WC02728\Technical\analysis.xls[Chart2]

- **Figure 58 Change in the rate of streamflow depletion as a percentage of the pumping rate after Jenkins, 1968 (ie change in the slope of the drawdown curve in Figure 57).**



I:\wcms\Projects\WC02728\Technical\analysis.xls[Chart3]

- **Figure 59 The delay before streamflow depletion commences at increasing distance between the bore and stream (with a T = 100 m^2/d and S = 0.1).**



Bore 500 m from stream
After 36 days (0.1 year) of pumping the rate of streamflow depletion is 7% of the bore discharge. At a pumping rate of 550 m^3/d (200 ML/year) this equates to a streamflow depeltion rate of 38.5 m^3/d.

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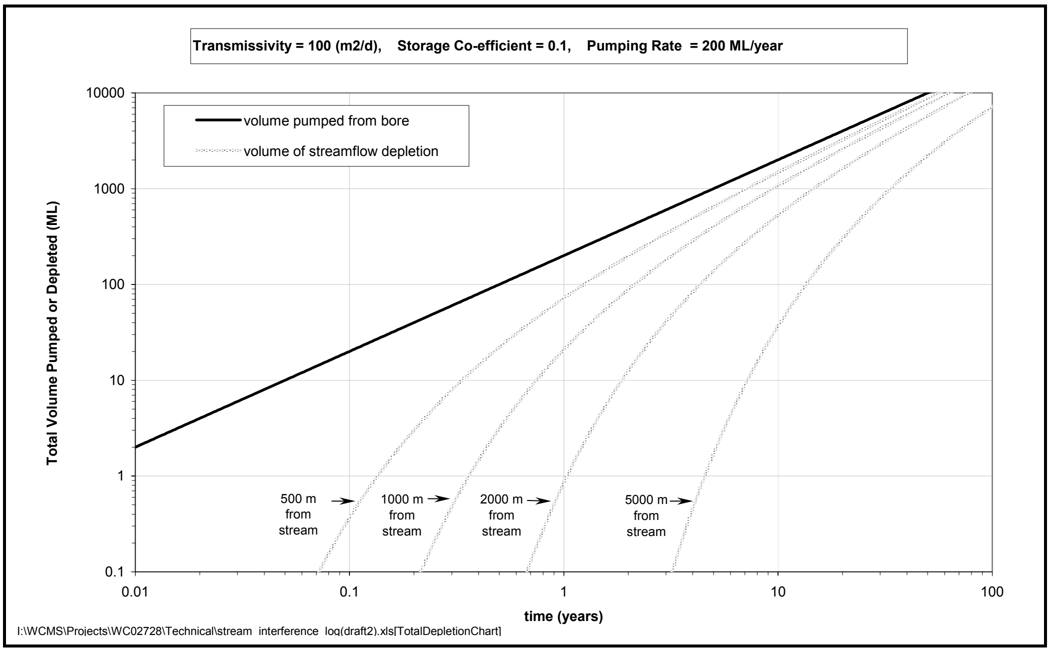
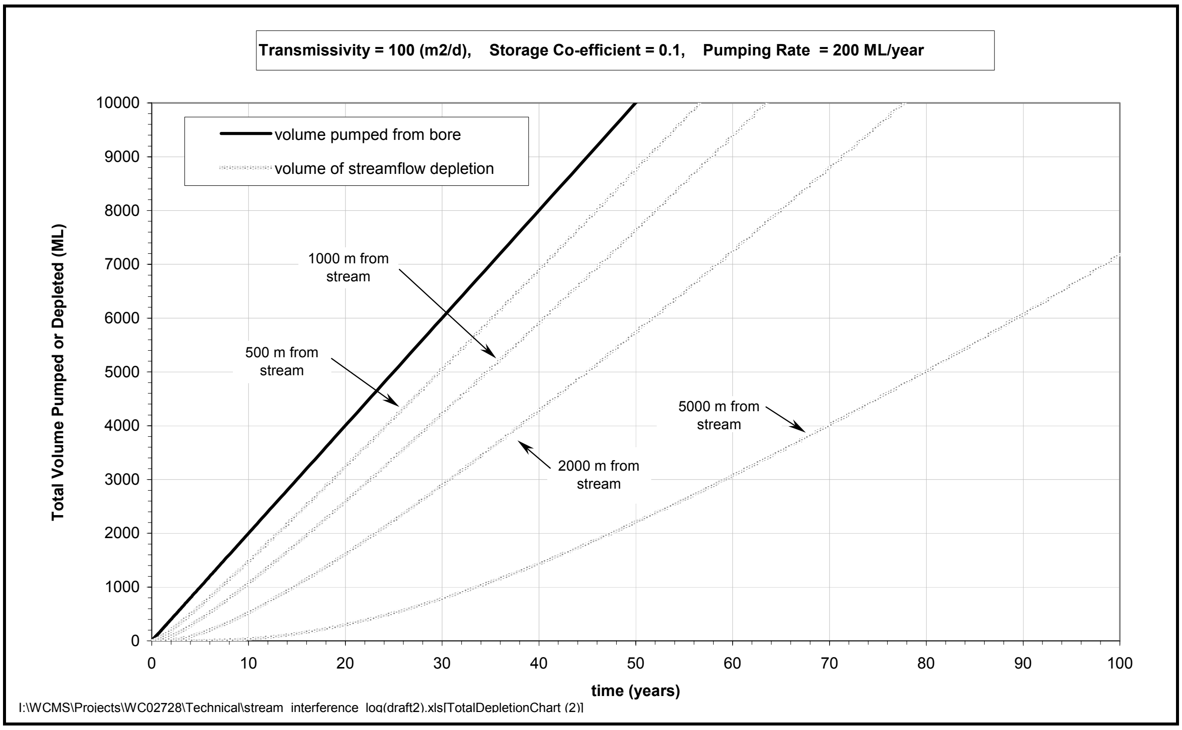
- **Figure 60 The volume of streamflow depletion over time at increasing distance between the bore and the stream (with a T = 100 m2/d, S = 0.1, and pumping rate = 200 ML/year) – log axes**



I:\WCMS\Projects\WC02728\Technical\stream_interference_log(draft2).xls[TotalDepletionChart]

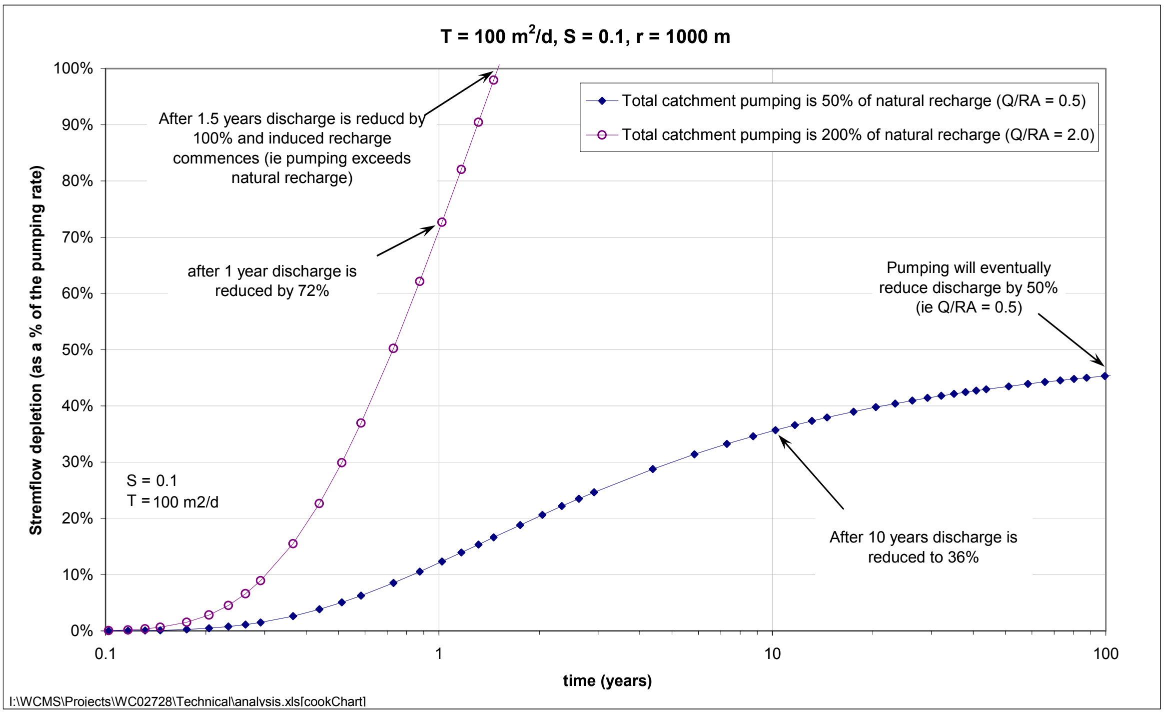
- **Figure 61 The volume of streamflow depletion over time at increasing distance between the bore and the stream (with a T = 100 m2/d, S = 0.1, and pumping rate = 200 ML/year) – linear axes**



Idealised Case - Modified

In the idealised case by Glover (1974) (& described in the previous section) the model assumes there is no natural recharge. Invoking a sloping water table onto the Jenkins (1968) model implies that there is a source of recharge (to sustain the water table slope in the absence of pumping). Using research by Knight et al (2002), Cook and Lamontange (2002) have incorporated natural recharge (ie recharge from rainfall) into the idealised case (ie all of the assumptions of the Jenkins (1968) model remain except for the “flat water table”). By incorporating natural recharge Cook and Lamontange (2002) have shown that the total pumped volume must exceed the total “natural” recharge volume before there is a net induced recharge from the entire river system (Figure 62). Induced stream leakge only occurs if the pumping rate exceeds the total “natural” recharge to the catchment (Figure 62). Note; the model also shows reduced base flow occuring in the same manner as in the Jenkins (1968) model. This model provides a means for assessing the stress status of an entire catchment. However, the Cook and Lamontange (2002) model cannot be used for assessing the impact of pumping on a specific reach. Cook and Lamontange (2002) have also shown that the distribution of bores within a catchment can have a significant impact on the timing of reduced discharge and induced stream leakage. Hence in simple terms, for most hydrogeological situations the greater the distance the extraction bore from the river the longer the time for the effect to be felt at the river, ie. distance equals time. The time frames may be many years. For example the “drying” of the upper parts of many catchments in the United States took many decades (Sophocleous, 2002b).

- **Figure 62 Effect of different ratios of pumping to recharge on stream impacts (modified after Cook and Lamontange, 2002)**



1. “r” represent the distance all pumping occurs from the river (all bores are located at this distance)

Typical Case

As described in the review, streams and aquifers are not typically configured in the manner described for the idealised case. As a result the predictions using the idealised case may be in significant error. An evaluation by Sophocleous *et al.* (1995) identified the range of discrepancy between the idealised case without recharge (Jenkins, 1968) and simplified typical cases. A summary of these results are presented in Table 8. The features that introduced the most significant error (>10% error in the predicted streamflow depletion) were streambed clogging, partial penetration of the aquifer, and aquifer heterogeneity. In each instance except transverse aquifer heterogeneity the idealised case over-estimated the stream depletion. On the basis of the assessment by Sophocleous et al. (1995) it could be concluded that more sophisticated solutions should be used to evaluate stream depletion. However, the evaluation by Sophocleous *et al.* (1995) was undertaken using a stream/bore configuration that achieved 95% stream depletion over a 2 month period (ie a bore very close to the stream). If, however, the modelling was conducted over a longer period of time and/or at greater distances from the stream it is likely that the level of error would be lower, and if the distance and/or time were sufficiently great then the difference between the models would be negligible (ie at steady state the volume pumped equals the volume recharged irrespective of the source of the recharge). Aside from stream and aquifer configuration, Sophocleous *et al.* (1995) has also identified a key issue regarding the assessment of stream depletion which is; should transient or steady state conditions be used to assess the impact of stream depletion, and if transient conditions are to be used what period of time is representative of a typical pumping period?

It is clear that there are many issues that require further examination to determine whether the idealised case is appropriate (ie is the level of error using the idealised case acceptable).

It is recommended that the amount to which streambed clogging and partial penetration reduce streamflow depletion be evaluated for typical pumping durations, aquifer characteristics, and stream/aquifer configurations in northern Victoria. The effect of aquifer heterogeneity is not considered worth investigating due to the impracticability of identifying heterogeneity at any specific site within northern Victoria. It is likely that the non-pumping or recovery period would also need to be incorporated into the assessment of transient conditions (ie typical pumping durations).

- **Table 8 Potential error of idealised case (after Sophocleous et al., 1995)**

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

1. only one feature was evaluated at a time

Appendix B Restriction Types and their Potential for Application

- **Table 9 Options for applying restrictions. Streamflow is managed using engineering structures and planned allocations .**

Option	Impact Category	Pros	Cons
Restrict pumping in response to a trigger	Technical	If appropriate triggers can be found then restrictions would have a strong technical basis compared with other options. Possible triggers could be short term or a single annual indicator (eg groundwater level in August).	• Time delay means defensible triggers may be difficult to identify, particularly flexible triggers that facilitate a response to worsening or improving streamflow conditions. ▪ Triggers may be necessary to both apply and lift restrictions.
	Economic		Increase in groundwater management costs for implementation and compliance (in comparison to current costs)
	Environmental	• Restrictions could be applied in response to observed indicators that have a real impact upon the stream.. • Could provide flexibility to deal with worsening or improving streamflow situations.	• Likely to have minimal benefits during the later part of the irrigation season because a late introduction of restrictions may mean that the season may be over before any stream benefits are realised.
	Social	▪ Community is likely to see the need for a restriction when the trigger occurs (ie greater community acceptance of restrictions based on objective measurements) ▪ Surface water users are likely to support a move to incorporate all water users to share responsibilities for streamflow management (unless they are also groundwater users). ▪ This method deemed to be most equitable with restrictions to surface water users (ie restrictions to surface water users are also triggered by objective measurements).	Groundwater users are not "used" to restrictions and would be expected to resist their implementation (the level of resistance is likely to reflect the ratio of groundwater users to surface water users. ie low resistance where surface water users out number groundwater users). Note that this situation is likely to occur when introducing a system of restrictions regardless of the restriction system adopted As a result, this point has not been repeated for other options.
Implement a pre-determined restriction for a fixed period of the year (eg pumping duration restricted by 75% in February, or full summer period)[1].	Technical	Relatively simple to identify "critical" stream flow periods as target periods for the protection of base flows	Technically difficult to determine what level of restriction (and when) would deliver the required outcome at the stream
	Economic	• Easy for irrigators to plan for restrictions • Relative low cost to implement as costs are largely limited to initial set up costs.	▪ Increase in groundwater management costs for implementation and compliance. To a large degree implementing a restriction system will always increase management costs. As a result this comment is not repeated for other restriction types, although it may be applicable. ▪ If the restriction period is long then the building of storages could circumvent the restriction ▪ Restrictions in a given year may be found to have been unnecessary as the period targeted to benefit the stream may in any given year, to be a stress period for the stream.
	Environmental	• Some benefit but probably the least effective compared to the other methods (might be to early to say this – we might need to look at some stream flow data to show that the timing of critical stream flows for a given stream is regular/irregular – this would determine whether restrictions could be justified on a seasonal basis). • Not flexible to deal with worsening or improving situations for a stream	• Restriction could be circumvented with on farm storages if the restriction period is short (ie pump more frequently outside the restriction period) • Doesn't benefit stream in other low flow periods that are not targeted by the defined restriction season.

	Social	▪ Surface water users are likely to support a move to incorporate all water users to sharing the responsibilities for streamflow management ▪ Groundwater restrictions could be set at less than the full amount required to achieve the stream flow objective. This would be in recognition of the fact that the restrictions will sometimes have been unnecessary. This may provide a means of achieving greater equity with surface water restrictions and therefore generate wider support. (to some degree this could also be applied to the other options, eg the criteria for a trigger could be altered if it were seen to cause unnecessary restrictions in a preceding year)	▪ Community may not understand why a restriction is being applied at certain times (ie if a restriction is active but the streamflow does not come under stress). There will inevitably be criticisms through examples of how both the restriction period and the period targeted to benefit the stream are misaligned to actual stream stress periods. ▪ Surface water users tend to be on restrictions that are “trigger” based, so there may be a perception of inequity if groundwater users are restricted in the different manner, particularly if surface water users are restricted while groundwater users are permitted to pump (and vice versa).
Allow Winterfill only	Technical	Relatively simple justification based on summer being high risk period for streams.	▪ Technical basis may be weak in catchments with limited groundwater pumping or where effects of pumping can extend into summer (but in these catchments we may simply narrow the width of zone 2, ie winterfill bores that impact into summer get put into zone into zone 3) ▪ The winterfill period would need to be defined for each catchment (ie it could be that winterfill in some areas is really late summerfill). Alternatively the size of zone 2 could be set to ensure the impacts of winterfill pumping do not occur outside the currently defined winterfil period [this a potential definition for zone 2]
	Economic	▪ Long term security to new groundwater users if confident that long-term supply is certain. ▪ Low compliance costs compared to "trigger" or “pre-determined” restrictions (except for pre-determined cases where there is a total ban for a certain time period).	▪ Large impact on existing groundwater users ▪ May be very expensive where soil types are ill suited to construction of storages ▪ Cost share arrangements likely to be necessary to gain support for implementation.
	Environmental	Significant benefit to streamflow during the summer months (probably greatest benefit compared to other methods) if technical assessment is correct.	In “dry” winters there may be significant impacts on streamflow.
	Social	There may be some support from surface water users, particularly in areas where there is significant winterfill pumping of surface water	Significant community resistance where there is a high proportion of groundwater users
Implement a permanent restriction all year round.	Technical	Relatively simple to calculate based upon broad assumptions.	▪ Not targeted to specific low flow periods so assumptions likely to be easily challenged. ▪ May be very conservative ie if targeted to years of relatively low flow may mean reduced pumping in many years when there is no problem.
	Economic	▪ Long term security to new groundwater users if confident that long-term supply is certain. ▪ Low compliance costs compared to "trigger" or “pre-determined” restrictions (except for pre-determined cases where there is a total ban for a certain time period).	▪ Relatively high compliance costs (similar to “trigger” and “pre-determined” restrictions) ▪ Likely to be lowest benefit/cost compared with other methods because likely to be the most extended period of restriction without achieving environmental benefits.
	Environmental	▪ Significant benefit to streamflow likely, if restrictions sufficiently severe but probably to a lesser extent than “winterfill” ▪ Benefit provided all year round and therefore provides protection to the stream during infrequent low flow events in normally high flow periods (eg dry spring). ▪ Potentially provides down catchment benefits at times when benefits are not apparent locally.	▪ Environmental benefits may not be realised if restrictions are softened for social or economic reasons. ▪ Relatively crude approach because it doesn’t allow for actual rainfall/recharge conditions or target high risk periods. ▪ Not flexible to deal with worsening or improving situations

	Social	▪ Easily understood and easily defined. ▪ Groundwater restrictions could be set at less than the full amount required to achieve the stream flow objective. This would be in recognition of the fact that the restrictions will sometimes have been unnecessary. It may therefore provide a means of achieving greater equity with surface water restrictions.	Likely to be deemed inequitable compared to surface water restrictions which are reactive to real events compared to this method which is proactive but poorly targeted.

1. the extreme extensions of this approach are "winterfill only" or a "permanent restriction". These 2 special cases are dealt with separately.

- **Table 10 Options for identifying timing of restrictions**[1]

Trigger		Pros	Cons
Historical Data[2]	Analysis of historic rainfall as a means of identifying at risk months.	■ Could use widely accepted forecasting – eg tighter restrictions required in El Nino ■ Is available for most catchments ■ Tools such as Rainman could be used ■ Could be used to identify a deficit in groundwater storage which could be used as a trigger	■ Could introduce restrictions that are out of phase with surface water restrictions – ■ Data may need manipulation to determine affect of historic rainfall on stream flow – might be a challenge for some catchments. ■ Would require adaptive management in response to climate change.
	Analysis of historic streamflow data as a means of identifying at risk months.		■ Could introduce restrictions that are out of phase with surface water restrictions ■ It doesn't indicate the potential for "low flow" in the following season(s)- not sure what this means (ie streamflow in one season cant be used for forecasting in a following season) ■ Some streams may not have detailed historic flow data ■ Would require adaptive management in response to climate change.
	Historical groundwater levels (this would probably be used as an index to identify whether current levels are above or below a (pre-determined) critical baseflow or seepage condition)	If available , it is highly valuable data that can be used to evaluate the current impact of historical groundwater pumping	■ Could introduce restrictions that are out of phase with surface water restrictions – see above. ■ Generally not available for most catchments ■ Technically difficult to apply to a catchment where hydrogeological parameters are strongly heterogeneous
	Historical groundwater pumping This would be difficult to apply, but could be used in 2 different ways 1. if we calculated a maximum allowable volume that could be pumped over a fixed period (say 5 years), and then simply restrict users to that volume (very diffciult to apportion the volume to each user), or 2. use this data as a tool to calibrate observed groundwater levels	■ Very useful for determining the high risk periods for the stream ■ Useful for checking/calibrating the relationship between the volume pumped after a restriction is applied and the impact on streamflow.	■ Could introduce restrictions that are out of phase with surface water restrictions ■ Highly unlikely that time series extraction volumes are available on a seasonal basis. ■ Difficult to apply
Real Time Data (ie during pumping period)	Rainfall during irrigation season. Establish a trigger based upon cumulative rainfall for any period?	High probability that groundwater restrictions will be in phase with surface water restrictions – not if allow for lag time (ie we are talking about Zone 2) the restrictions would be in phase but the benefit to streamflow would be out of phase	■ Would require predicting low flow events caused directly and indirectly by rainfall (ie reduced runoff and increased demand for surface water), as well as providing for lag time between groundwater pumping affecting the stream. ■ Lagging influence of pumping on the stream means that restrictions may be in place but not effective late in the irrigation season(& early in the season if no lag allowed for as suggested in the middle column)[1] ■ Would need to make sure that winter pumping was not used to circumvent restrictions.
	Streamflow during irrigation season	High probability that groundwater restrictions will be in phase with surface water restrictions. BUT the benefit to streamflow at the critical time may be limited.	Lagging influence of pumping on the stream means that restrictions will probably be ineffectual in critical flow periods– ie low stream flow event may have already caused environmental problems before impact of restriction on groundwater users has any impact on the stream ie unlikely to be effective in achieving outcomes (this is an issue for all "real time" triggers because the surface water restrictions are often imposed and then relaxed on very short time frames. So we really need to used some form of predictive method using historical data or forecasting, in conjunction with real time data).
	Groundwater levels during irrigation season	Reflective of pumping as well as recharge/rainfall (ie could be used as a composite indicator).	■ Restrictions during some periods likely to be out of phase with surface water restrictions ■ Difficult to identify a site (particularly in fractured rock systems) where the groundwater levels will be representative of the "average" groundwater status. ■ Increased observation bore network likely to be required for most catchments.

	Groundwater pumping volume during irrigation season (ie after a certain cumulative volume is extracted by all pumpers, restrictions will be introduced).		▪ High cost in obtaining seasonal time series pumping data ▪ Not linked at all to current surface flows which are more responsive to rainfall than groundwater pumping. ▪ Would need to be linked to entitlement, otherwise would encourage individuals to use a high volume early in the season to make most use of water before restrictions introduced. (ie dilemma of common property)
Combination of Historical and Real Time Data	Combination (of some or all other triggers except an arbitrary trigger)	▪ Greatest flexibility ▪ Incorporates influences of earlier pumping and climate as well as the current "situation" ▪ Could be used to modify restriction in the following year if a "real time" trigger occurs late in the irrigation season and, as a result, restrictions are not instigated. ▪ Potential for a smaller lag effect compared to stand alone options. (eg low winter rainfall could be used as a signal to impose restricyion before low streamflows occur during the irrigation season).	▪ May be overly complex and, hence, difficult to apply to a restriction system (eg rosters)

1. To some degree all options are ineffectual at reducing impacts when the "lag" become "large". However this exercise is targeted at Zone 2 where the lags is likely to be a few weeks to months.
2. All historical data would need to be used in conjunction with "real time" data otherwise there is a large risk of restrictions being out of phase with surface water restrictions (ie ineffectual or perceived to be ineffectual).

▪ **Table 11 Possible types of restrictions**

Option	Impact Category	Pros	Cons
Rosters[2] (including bans)	Technical		More technically complex to develop than non-roster options
	Economic	▪ If the application of the restriction is based on "historical" or combination of "historical and real time" triggers this allows for a longer notification period for impending restrictions and, hence, a greater opportunity for irrigators to plan for restrictions	▪ Compliance costs may be high (ie checking on pump operation) ▪ Large impact on irrigators if there is only a short notice of restrictions (ie based on "real time trigger" only)
	Environmental	▪ If combination of "historical and real time" triggers are used then lag effect could be minimised (ie restrictions could be introduced before streamflow becomes critical and, hence, reduce the time difference between the impact of surface water restriction and groundwater restrictions). ▪ Applicable to all licensed users including sleepers. Rosters can be progressively tightened if use increases as a consequence of TWE or activation of sleeper licences. ▪ Provides control over the duration of pumping so potentially more effective than other option	Reduction in pumping impacts upon the stream may be minimal if roster is implemented late in the season (this is particularly the case if the triggers are based on "real time" data only)
	Social		
Restrict use to portion of entitlement (including bans)	Technical		Sleepers and trade could potentially undermine desired outcomes. Would therefore need restrictions calculated on the basis of entitlement or make some assumptions on use and restrict TWE.
	Economic	▪ Simple low cost to implement ▪ Gives high degree of flexibility to irrigators with respect to when they will use their remaining allocation	Compliance costs may be very high because the frequency of bore inspection required (probably equal or greater than for a roster) This is a PCV approach where the PCV may be less than current entitlements. Suspect we would probably require modelling to demonstrate an increase in environmental flows, and provide evidence that timing of environmental flows will be appropriately targeted. (you may need to do this regardless of approach adopted)
	Environmental	Some benefit would be obtained because pumping occurs during the irrigation season (unless winter storage involved) when stream flows are most vulnerable.	▪ May not achieve desired outcome because there is no control on when pumping occurs ▪ In many areas current use is significantly less than entitlement, so there may be no reduction in pumping unless restrictions are severe (ie >50% as a minium)
	Social		▪ If high levels of sleeper licences, restrictions on entitlement will require tightening as sleepers are activated. This will affect security of entitlement. ▪ Constraints on TWE to limit activation of sleepers and preserve security of existing entitlements will be at the expense of improved efficiencies.
Introduce a "winterfill" licence[3]	Technical	As per winter fill section in "Options for applying restrictions"	As per winter fill section in "Options for applying restrictions"
	Economic	As per winter fill section in "Options for applying restrictions"	As per winter fill section in "Options for applying restrictions"
	Environmental	As per winter fill section in "Options for applying restrictions"	As per winter fill section in "Options for applying restrictions"
	Social	As per winter fill section in "Options for applying restrictions"	As per winter fill section in "Options for applying restrictions"

2. A roster is, in effect, a restriction on the duration of pumping and, hence, a reduction in the volume pumped for the period a roster is implemented.

3. Strictly speaking this is not a restriction because "winterfill only" would be the terms of the licence. However, if existing groundwater users could be encouraged to convert to "winterfill" licences this would be a form of "self imposed restriction" and, hence, is included here as a "restriction"