



# Sustainable Groundwater Yield Assessment Woolshed Sub-Catchment, ACT

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iCAM is a group of researchers specialising in integrated catchment modelling at the Australian National University. We work on a project basis with Government Agencies and industry to provide support for decision making. We are committed to developing tools which are useful for considering social, economic and environmental impacts resulting from changes in factors such as policy, climate or land use. We aim to develop such tools with the participation of policy makers as well as industry.

## PREFACE

The following report provides the results of two discrete but related pieces of work undertaken for Environment ACT on the sustainable management of groundwater resources in the Territory. The two pieces of work are presented in an amalgamated report to ensure that the sequential linkage between the two can be retained.

### Phase 1

Phase 1 is work that was undertaken in early 2004 aimed at deriving the volume of groundwater that could be extracted from the aquifer system of specific sub-catchments in accordance with the ACT Water Resources Management policy of 10% of annual recharge. This work has been reported separately to Environment ACT and is presented here without alteration from that earlier publication.

### Phase 2

Phase 2 represents work undertaken in July 2005 aimed at assessing the impacts on streamflow of groundwater pumping at the rate recommended from the 2004 work. Specifically, the phase 2 work attempted to quantify the impacts of pumping on the baseflow character of the subcatchment streams, and to identify changed flow attributes that could be used to assess associated ecological consequences.

## GLOSSARY OF TERMS

**Aquiclude:** Impermeable beds of geologic material that usually prevent groundwater movement. Sometimes used interchangeably with aquitard and confining unit/layer.

**Aquifer:** a geologic formation(s) that is water bearing. A geological formation or structure that stores and/or transmits water, such as to wells and springs. Use of the term is usually restricted to those water-bearing formations capable of yielding water in sufficient quantity to constitute a usable supply for people's uses.

**Aquitard:** A confining bed that retards but does not prevent the flow of water to or from an adjacent aquifer; a leaky confining bed. It does not readily yield water to wells or springs, but may serve as a storage unit for ground water. Sometimes used interchangeably with aquiclude and confining unit/layer.

**Baseflow:** Contribution to streamflow from groundwater

**Cone of depression:** The zone around a well in either an unconfined or confined aquifer where the water surface dips down to form a cone shape. The shape of the cone is influenced by porosity and the water yield or pumping rate of the well. In a confined aquifer the cone of depression forms in the potentiometric surface and the aquifer remains fully saturated while ever the drawdown remains above the top of the aquifer. In an unconfined aquifer, the cone of depression forms in the watertable and the aquifer that is normally saturated becomes unsaturated as a well is pumped.

**Connected system:** River (or lake) section that is linked to groundwater by a continuous saturated zone.

**Confined aquifer:** (also known as artesian or pressure aquifers) exist where the groundwater is bounded between layers of impermeable substances like clay or dense rock. When tapped by a well, water in confined aquifers is forced up, sometimes above the soil surface. This is how a flowing artesian well is formed.

**Confining layer:** Geologic material with little or no permeability or hydraulic conductivity. Water does not pass through this layer or the rate of movement is extremely slow. Sometimes used interchangeably with aquiclude and aquitard.

**Discharge:** An outflow of water from a stream, pipe, groundwater aquifer, or watershed; for an aquifer, discharge is the opposite of recharge.

**Discharge area:** The area or zone where groundwater emerges from the aquifer. The outflow maybe into a stream, lake, spring, wetland, etc.

**Disconnected system:** River (or lake) sections that are separated from the groundwater in the adjacent aquifer system by an unsaturated zone.

**Dividing flow lines:** Boundary of groundwater flow. This may be located on ridge lines where groundwater flow is typically away from the dividing line, or at streams, lakes etc where groundwater flow direction may be towards (water bound is a sink for groundwater) or away from (water body is a source of groundwater) the dividing line.

**Drawdown:** A lowering of the groundwater level caused by pumping.

**Evapotranspiration:** The loss of water from the soil through both evaporation and transpiration from plants.

**FDC (flow duration curve or flow exceedence curve):** cumulative probability distribution of flow.

**Hydraulic Conductivity:** A specific measure of permeability, derived from the proportionality constant from Darcy's Law relating hydraulic gradient to specific discharge which for an isotropic medium and homogeneous fluid, equals the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

**Intrinsic Permeability:** a specific measure of permeability. A porous medium has an intrinsic permeability of 1 darcy when a pressure gradient of 1 atm/cm on a rock sample of 1 cm<sup>2</sup> cross section will force a liquid of 1-cp viscosity through the sample at the rate of 1 cc per sec.

**Normal variate:** variate derived for a normal distribution  $z=(x-\mu)/\sigma$  (i.e. a value of 1 corresponds to 1 standard deviation above the mean value of the distribution)

**Piezometric head:** The pressure that exists in a confined aquifer. Specifically, it is the elevation above a datum plus the pressure head.

**Permeability:** A measure of the rate at which water will flow into or through soil or rocks.

**Potentiometric surface:** The potential level to which water will rise above the water level in an aquifer in a well that penetrates a confined aquifer; if the potential level is higher than the land surface, the well will overflow. See confined aquifer. Also known as piezometric surface.

**Quickflow:** Rapid component of streamflow; can include runoff, interflow and a rapid response from groundwater (if this exists)

**Recharge:** Water added to an aquifer. For example, when rainwater seeps into the ground. Recharge may occur artificially through injection wells or by spreading water over groundwater reservoirs.

**Robustness:** Ratio of aquifer storage to recharge (storage/recharge). A very large value (much greater than 20) implies that the aquifer is well buffered against variations in recharge. A small value (<20) indicates the aquifer is not well buffered and the effects of annual fluctuations in recharge are immediately apparent

**Slowflow:** Slow component of streamflow; can include baseflow, interflow, industrial releases/leakages and urban leakage

**Static water level:** (1) Elevation or level of the water table in a well when the pump is not operating. (2) The level or elevation to which water would rise in a tube connected to an artesian aquifer or basin in a conduit under pressure. Also referred to as Standing Water Level (SWL).

**Storage Coefficient:** The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head, related to porosity and aquifer thickness (virtually equal to the specific yield in an unconfined aquifer). Expressed as an absolute value normally from 0.00001 to 0.002 for confined aquifers and from 0.02 to 0.35 for water table aquifers.

**Transmissivity:** A measure of the capability of the entire thickness of an aquifer to transmit water, calculated as the hydraulic conductivity times the saturated aquifer thickness. Also known as coefficient of transmissivity.

**Unconfined aquifers:** An aquifer in which the water table is at or near atmosphere pressure and is the upper boundary of the aquifer. Because the aquifer is not under pressure the water level in a well is the same as the water table outside the well.

**Underflow:** Groundwater discharge that flows beneath the stream gauge site, and is hence not recorded.

**Variate (z):** A random variable with a numerical value that is defined on a given sample space

**Water table:** The top of an unconfined aquifer; indicates the level below which soil and rock are saturated with water. The upper surface of the saturation zone.

# Phase 1

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## INTRODUCTION

The groundwater resources of sub-catchments in the ACT are coming under demand pressures as the groundwater systems reach their limit for allocation. Under the Water Resources Management Plan for the ACT, 10% of average annual recharge has been adopted as the sustainable yield for groundwater abstraction. The volume of average annual recharge for each sub-catchment has previously been derived using a mass balance approach, and verified by a rainfall recharge method.

Demand for groundwater in some sub-catchments is such that there is a backlog of applications for bore construction and licences to take water in sub-catchments where the sustainable yield has already been allocated. If granted, these would increase the use past the level specified. As well, there are likely to be abstraction from bores, in some sub-catchments, by groundwater users who were active before the legislation controlling groundwater use was passed. These users are not subject to the legislation.

In light of this development history and the pending proposals, Environment ACT wishes to revisit the previous derivation of sustainable yield for eight sub-catchments as a priority. In particular, Environment ACT has contracted this work to describe and confirm the previous conceptual model for each sub-catchment in terms of its groundwater dynamics and water balance. Further, it would like a review of the previous approach and a confirmation of the estimates of sustainable yield derived.

Finally, Environment ACT would like the consultants to provide some views on ongoing monitoring, field assessment and/or management actions.

The eight sub-catchments subject to analysis in this project are Coppins, Fyshwick, Lake Burley Griffin, Lake Ginninderra, Sullivans, Woolshed, Woden, and Weston. Each sub-catchment is dealt with by a separate report. This report details the analysis for Woolshed sub-catchment.

## Background

Groundwater management in Australia is undergoing change as part of the Council of Australian Government's (COAG) initiative on water reform. Primary amongst the changes is the requirement that all aquifers are managed sustainably with groundwater allocated according to a sustainable yield, and that the sustainable yield for an aquifer must include provision for the environment.

Two pieces of legislation relevant to the sustainable use of groundwater in the ACT are the Environmental Flow Guidelines (1998) and Water Resources Management Plan (WRMP), 2004.

The WRMP identifies integrated catchment management as a key factor for sustainable use of natural resources. Management within a catchment context is essential for assessing the interplay between surface water and groundwater. The amount of groundwater available for extraction under the Plan is set at 10% of groundwater recharge, until research in a specific sub-catchment determines that a higher value of groundwater use is sustainable.

There are issues for management consideration related to the spatial distribution of current groundwater use, and the possibility that local hotspots of groundwater drawdown may have been produced due to the history of bore development. That is, there may be uneven withdrawal of groundwater from the aquifer such that some areas are providing a disproportionately large part of the overall sub-catchment yield. In particular, the consultants will provide advice on the volumes of groundwater that might be available for areas within the various sub-catchments and compare this with the actual amounts of withdrawal. This information could be used by Environment ACT to better manage the impacts of resource use, both on the aquifer itself, and on wider environmental values. Though the nature of the way in which the resource is accessed is important, and the continued access to the resource is a priority, the issue of uneven access to the resource is of low priority.

Given the previous nature of groundwater development, there is a lack of comprehensive information detailing groundwater withdrawal.

## Scope of Report

The deliverables for the project are:

- Methods utilised for the assessment;
- Hydrogeological information about each sub-catchment including average annual recharge, aquifer management issues, existing use, ability to meet any likely future demand, and advice on sustainable groundwater yields, including advice on a spatial basis within the sub-catchment;
- Calculation of relevant parameters, including run-off, rainfall, evapotranspiration, recharge, yields and sustainable yields;
- Comparison of calculations undertaken within the consultancy, including a discussion on differences resulting from different models, the most appropriate method to select and reasoning supporting this selection;
- Comparison of Water Resources Management Plan 2004 calculations with those undertaken within the consultancy;
- Impacts of implementation of consultancy calculations versus those of the Water Resources Management Plan 2004; and
- Any future recommendations for ongoing monitoring, field assessment and/or management actions.

## Methods and approaches

The methods employed for the project fall into two parts – the hydrogeological conceptualisation and commentary on aquifer performance; and the hydrologic analysis that will lead to definition of baseflow as an independent check on groundwater recharge.

### *Hydrogeological Conceptualisation*

The approach to the conceptualisation of the hydrogeology will draw upon the experience of the team in ACT and region hydrogeology. The area will be partitioned into hydro-lithologic units based on their aquifer behaviour. Aquifer parameters will be estimated based on previous experience in these terrains. All available information will be analysed and spatial patterns of withdrawal will be compared with available groundwater level information.

A major issue in aquifers where usage is approaching sustainable yield is that of groundwater head decline due to the uneven abstraction of water. If the entire sustainable yield is abstracted from only a small part of the aquifer, significant head loss can occur, with resultant inter-well impacts. Critical in this study will be the spatial nature of both current and potential future abstraction.

In two Sub-Catchments, Sullivans and Woolshed, the groundwater flow was simulated in a simple cross-section using the numerical simulation model MODFLOW. This modelling was not carried out in any other Sub-Catchments due to the lack of data.

### *Hydrologic modelling*

The baseflow component of the stream flow generated within the sub-catchments will be estimated using a baseflow filtering approach. This will provide an estimate of the baseflow index for each stream at the

relevant gauging station. This baseflow index can be interpreted as representing groundwater discharge. In a groundwater system that is in equilibrium the discharge is generally matched by the recharge (assuming sub-surface outflow is negligible). This relationship allows the baseflow index to be used to estimate recharge quantities.

Flow duration curve analysis of gauged sites will be used to explore the differences in distributions of flow volumes between catchments. Combined with the estimated baseflow, this will be used to explore potential means of estimating the baseflow volume at ungauged sites.

## GROUNDWATER SUSTAINABILITY

There are two stages to deciding upon a sustainable yield that a groundwater resource might provide. In this context sustainable yield is defined to represent the volume of groundwater that can be taken from the resource to satisfy economic development (that is, non-environmental uses) for long periods of time. This means that volumes of groundwater required to satisfy the environmental uses have already been deducted from the overall resource available.

In some sense the term sustainable is applied too broadly. In the strictest sense, sustainable development of groundwater resources means that the resource continues to be available in perpetuity. However, the principles of Ecologic Sustainable Development have been applied to groundwater development to mean that the use of the groundwater has to lead to sustainable ecologic outcomes. That is, not only will the groundwater resource be sustainably available for extractive users, it will also continue to sustain the ecosystems that rely upon it. In most cases, this duality is not possible.

For the extraction of a sustainable yield to be truly sustainable in the long term (that is, the volume is available to be withdrawn from the aquifer for the foreseeable future, with no consideration of the impact of the withdrawal on processes outside the aquifer), the amount extracted cannot exceed the long-term recharge rate to the aquifer. However, due to the closed nature of the water balance, the amount extracted has to come from some other use supplied by the aquifer.

Whenever a megalitre of groundwater is extracted via a pumped bore, a megalitre of groundwater is lost from some other part of the aquifer system. In the early stages of pumping the extracted groundwater comes from a reduction in aquifer storage in close proximity to the bore (usually observed via a reduction in groundwater levels in the vicinity of the bore). But, over longer time, this storage is balanced by a decrease in groundwater discharge, or by induced recharge, depending whether the reduction in groundwater levels can intercept a source of surface water. Examples of induced recharge would include increased leakage from a creek or river, or direct leakage from a lake. These surface water bodies may have been recharge sources under natural conditions, or they may have been discharge sites where a falling groundwater level has reversed the hydraulic gradient causing water to flow backwards as it were.

At the broad aquifer level, the ultimate control on the amount of groundwater available is the size or quantity of the water balance. Nature will limit the amount of water sustainably available to the natural recharge volume plus any captured recharge or discharge.

Thus, the first, and most important, step in arriving at a sustainable yield is the quantification of the volumetric components of the water balance. These components will include recharge sources such as rainfall, rivers and lakes, irrigation returns and leakage from surface infrastructure, as well as leakage from other aquifers. Balancing this will be the components of discharge, including discharge to rivers and lakes, discharge via evapotranspiration through groundwater dependent ecosystems, and discharge via surface infrastructure in urban environments (leakage into storm water and sewerage systems). Changes in storage within the system can also be influential, especially if there are finer grained semi-confining layers involved that have a potential to be dewatered (providing a one-off volume of induced leakage water).

Detailed information that sets out the water requirements for each groundwater use needs to be available so that an informed decision can be made about the acceptability of the trade-off process. Again, in most cases, the water requirements of the ecosystem assets are usually a major knowledge gap. It is within this context that Governments usually apply the precautionary principle – that is, in the face of scientific uncertainty about the consequences of actions, coupled with the prospect of harm (especially to the environment), there should be a cautious approach (the act of preventative anticipation).

The Water Resources Act (1998) provides for the protection of the environment through recognising water for environmental purposes as a legitimate use of the resource (VRMP, 2004), as well as giving clear priority to environmental water provisions. This priority is established through the Environmental Flow Guidelines. The Environmental Flow Guidelines have been interpreted such that a decision was made that 10% of surface water flows above the 80<sup>th</sup> percentile flow have been selected as suitable for allocation in most sub-catchments. This flow will be made up from surface water flows generated by run-off process, and from baseflow generated by groundwater discharge. In addition, the amount of groundwater available for extraction from each sub-catchment will also be limited to 10% of groundwater recharge (VRMP, 2004) as an extra measure to manage the impacts of groundwater withdrawal on the lower 20% of surface water flows. It is assumed in this work that this 10% determination is a decision taken with a view to the precautionary principle.

The key question then becomes, how much has the sustainability of the dependent ecosystems been affected by the reduction of discharge by 10% of the total? The corollary to this, then, is this an acceptable trade-off? A subsidiary question also arises – has the integrity of the aquifer system (that is, the groundwater sustainability as opposed to its dependencies) been similarly reduced? Does the extraction cause any deleterious effects?

The first set of questions related to impacts on the integrity of the environmental values can only be answered with recourse to information that show the performance of the ecosystems involved under changing flow regimes due to groundwater development. This data is not available for the consultant's work.

The second set of questions, regarding aquifer impacts and whether groundwater users can continue to withdraw at the level set by current estimates of sustainable yield, becomes the major sustainability issue for advice in this report.

## Areal Sustainability

An estimate of sustainable yield is usually made for a complete aquifer system – that is, an area that can be conceptualised as a discrete groundwater flow unit where there are specific recharge and discharge areas. In fractured rock terrain where the aquifer is un-confined or semi-confined, the shape of the watertable is controlled to a large extent by the topography and, the hydraulic conductivity in particular is low, groundwater flow can be compartmentalised into a number of areas. Major dividing flow lines under natural conditions – usually related to broader topographic features such as ridgelines or streams, bound these areas.

Groundwater flow in each area is driven by recharge that is specific to that area, with little interchange of groundwater between areas under natural conditions – this is especially the case if the areas are defined by a dividing flow line.

When the groundwater resources of an aquifer are developed, the natural flow system is changed. This means that the dividing flow lines used to define flow areas, as described previously, will also change in response to the pumping. In an aquifer where the hydraulic conductivity is low (as described above) the scale of the influence of pumping is small. Low hydraulic conductivity aquifers are characterised by steep drawdown cones. A bore located close to a flow line boundary will have an effect on that boundary, but the scale of the change will be small when compared to the size of the flow system.

When groundwater is pumped near a dividing flow line at the discharge end of the aquifer, such as a stream or lake, the scale of the effect of the pumping will depend largely on the “strength” of the stream or lake. The “strength” can be viewed as the amount of water available in the surface water body, the ease with which it can be drawdown by a groundwater gradient, and the hydraulic conductivity of the aquifer. Where the “strength” of the surface water body is low, there will be the possibility for the effects of pumping of groundwater to extend beyond the surface water body. However, the scale of the impact will depend on the hydraulic conductivity. In this case, the volume of water in the low “strength” surface water body would be substantially impacted – that is, a large proportion, if not all, of the flow in the stream would be lost underground.

Where the surface water body is of a high “strength” the impact of groundwater pumping will not extend past it. In terms of groundwater pumping in a low hydraulic conductivity aquifer, the surface water body will act as an infinite source – that is, it will never dry up, though the pumping will capture substantial volumes of water when compared with the aquifer water balance.

For the Woolshed Sub-Catchment, the middle to lower reaches of Woolshed Creek will act as a very low strength dividing flow line. Bores immediately adjacent to the Creek (between 200 and 400 metres) will have an influence either side of the Creek, but that influence will be limited. It is likely that bores will affect the flow in the Creek substantially depending on the rate at which the bore is pumped and the relative flow in the Creek.

Bores in other areas away from the Creek in the same middle to lower reaches, will have little effect on the other side of the Creek. In the upper parts of the Sub-Catchment, bores will capture groundwater flow that originates up-gradient from the drawdown cone developed around the pumping bore.

### Management the Spatial Nature of Extraction

The spatial arrangement of groundwater extraction points can lead to local areas where the aquifer is placed under more stress than elsewhere. This occurs due to overlapping drawdown cones that produce greater water level falls.

This occurrence can lead to two types of impacts – impacts on the aquifer itself, and impacts on the user’s access to the groundwater. The former impact is of a higher priority to Environment ACT, whereas the latter issue is of lower priority and will not be discussed further in this study. Implementation of specific management actions related to the latter impact will be required if the priority for this increases in the future.

In principle, the approach to minimising the potential for overlapping drawdown cones is to administer bore spacing via minimum bore separation distances. This issue is further developed below. As well, there will be need to consider that in these unconfined fractured rock aquifers, most groundwater that is extracted from a bore will originate as recharge immediately up-gradient from the bore.

For example, the situation where a bore is sited down the hydraulic gradient from another bore (and outside the advised bore separation distance) will produce a greater drawdown effect in the aquifer than two bores pumping the same amount but lying across the hydraulic gradient.

## SUB-CATCHMENT HYDROGEOLOGIC FRAMEWORK

The Woolshed Sub-Catchment covers the catchment of Woolshed Creek, which is a northern tributary of the Molonglo River, entering in the very upper part of Lake Burley Griffin. The catchment area is 61.08 km sq, and is dominated by rural land use, with minor conservation and forestry land uses also occurring.

### Recharge and Groundwater Flow considerations

The Woolshed Sub-Catchment is underlain by complex sequence of rocks, which trend in a north south direction. The sequence is cut by the Sullivans Fault, a major regional structure separating rocks of the Mt Ainslie Volcanics and Canberra Formation of Silurian age to the west from older sedimentary rocks of the Adaminaby Group of Ordovician age to the east. The Greenwood Granite intrudes the Adaminaby Group in the north eastern parts of the Sub-Catchment.

There are deposits of recent sediments in the lower parts of the Woolshed Creek floodplain. Limited borehole evidence has shown substantial layers of gravel within a sequence of sands and clays, but these gravels appear to be localised.

The Adaminaby Group is comprised of well-bedded, fractured sandstones, shales and mudstones and forms the slightly higher relief country to the east. Generally, the Mt Ainslie Volcanic units are reasonably massive extrusive welded ignimbrites. The sediments of the Canberra Formation, which is found in the valley floor of Woolshed Creek and lying between two distinct areas of Mt Ainslie Volcanics (the Mt Ainslie – Mt Majura Ridgeline to the west and a sequence of low hills to the east), are relatively less massive, tending to be well bedded through the catchment. The Greenwood Granite is a massive intrusive complex.

Generally, the volcanic units are reasonably massive extrusive welded ignimbrites. The sediments of the Adaminaby Group and the Canberra Formation are relatively less massive, tending to be well bedded through the catchment.

The rock sequence has undergone major tectonism that has produce folds and faults. The rock mass is said to be a fractured rock aquifer. Fractures are usually open to some depth, but invariably, the effective depth of open fractures that will permit water movement in substantial quantities is limited to depths of between 60 and 100 metres. The rock type controls the degree to which the fractures are open to a large extent. The Mt Ainslie Volcanics, for instance, is generally less fractured, and is therefore tight (or doesn't contain usable amounts of groundwater), whereas, the sediments of the Adaminaby Group can be well fractured, and therefore contain relatively more groundwater.

The rocks have undergone periods of erosion and weathering. This has left a weathered layer that can also be several metres in thickness.

The Sub-catchment is characterised by undulating topography, with dominant surrounding ridgelines, flowing to a subdued flatter valley floor. The catchment is not incised into its floodplain to any great degree in its lower reaches.

Water will infiltrate below the root zone of the catchment's vegetation cover and move through zones of increased porosity under the influence of gravity. In these types of terrains, water flow will be along lateral boundaries such as the base of the soil, or the base of the weathered zone, as well as the base of the openly fractured zone. In general, the majority of water will flow at depth through the fractured rocks.

Discharge from this deeper aquifer will generally occur at the lower parts of the landscape.

The watertable surface will generally be a subdued reflection of the topographic surface, with flow mirroring the hillslopes. The lower reaches of Woolshed Creek will be the ultimate destination of the groundwater flow,

with virtually all the water that infiltrates to the groundwater system exiting via the Creek before the Sub-Catchment outlet. That is, there is little opportunity for flow between sub-catchments.

Woolshed Creek can also be thought of as a dividing streamline. That is, groundwater flow on one side of the Creek will not bypass it to influence flow on the other side of the Creek – this is more so in the lower parts of the Sub-Catchment. This means that recharge that occurs on one side, is of no benefit to groundwater users on the opposite side of the Creek. In the upper parts of the Sub-Catchment, groundwater flow will probably be radially towards the middle portions of the Creek – the Creek would be accepting groundwater discharge in its lower half or so.

Woolshed Creek can also be thought of as a hydraulic boundary under natural groundwater flow conditions, as discussed in an earlier section. That is, natural groundwater flow on one side will not bypass it to influence flow on the other side – this is more so in the lower parts of the Sub-Catchment. This means that recharge that occurs on one side, is of no benefit to groundwater users on the opposite side of the river, except in the case where bores, which are drilled immediately adjacent to the Creek, can access some groundwater from the other side of the Creek and possibly water from the Creek itself. In the upper parts of the Sub-Catchment, groundwater flow will probably be radially towards the upper to middle portions of the Creek – the Creek would be accepting groundwater discharge for a large proportion of its length.

The fractured rock aquifers of the catchment are characterised by low hydraulic conductivity (that is, the ease with which groundwater moves through the aquifer) and extremely low storativity (or storage capacity). The ratio of aquifer storage volumes to annual recharge volumes (or aquifer robustness) would be low – the consequence of this is that the aquifer is highly sensitive to the difference between recharge and pumping over a pumping season. The aquifer will be vulnerable to groundwater level depletion in a succession of dry years, as the capacity for aquifer storage to buffer withdrawals is low.

### Surface water-groundwater interaction

The Woolshed Sub-Catchment will discharge to Woolshed Creek as described in the preceding section. There is opportunity for the Creek to act as a source of groundwater recharge in the lower flatter parts, especially where there are reasonable thicknesses of sediments associated with its bed. However, in general the Creek is a gaining stream (the stream gains groundwater) in its lower half.

### Existing groundwater development and use

There are currently five licensed groundwater users in the Woolshed sub-catchment. Three users have a groundwater only licence for a total allocation of 9 ML/yr, while there are 2 combined surface water and groundwater licences with a total allocation of 182 ML/yr. The current estimate of average annual groundwater use in the catchment is 96 ML/yr (data supplied by Environment ACT, 2005).

### IMPACT OF CURRENT GROUNDWATER PUMPING

The analysis in the following sections is based on the assumption that the baseflow as derived from the various techniques represents groundwater discharge. Further, it is assumed that under steady state conditions, that the volume groundwater discharge is in equilibrium with the volume of recharge, and that this recharge volume occurs at an equal rate across the entire catchment area.

In some Sub-Catchments, groundwater extraction has been occurring for some years. However, the analysis below relies on the fact that the effects of pumping have not been observed in the Creek. This means that the base flow estimates derived are a minimum in this regard.

**STREAMFLOW DATA**

As there are no streamflow gauges in the Woolshed sub-catchment (see Figure 1), an alternative approach is needed to estimate the recharge. Three methods were employed: adopting the results from a gauged catchment with similar attributes, particularly land use; using a water balance approach based on the empirical evapotranspiration/rainfall relationship of Zhang *et al.* (2001); and using the MODFLOW model to reproduce measured groundwater levels in the aquifer by simulating appropriate levels of recharge.

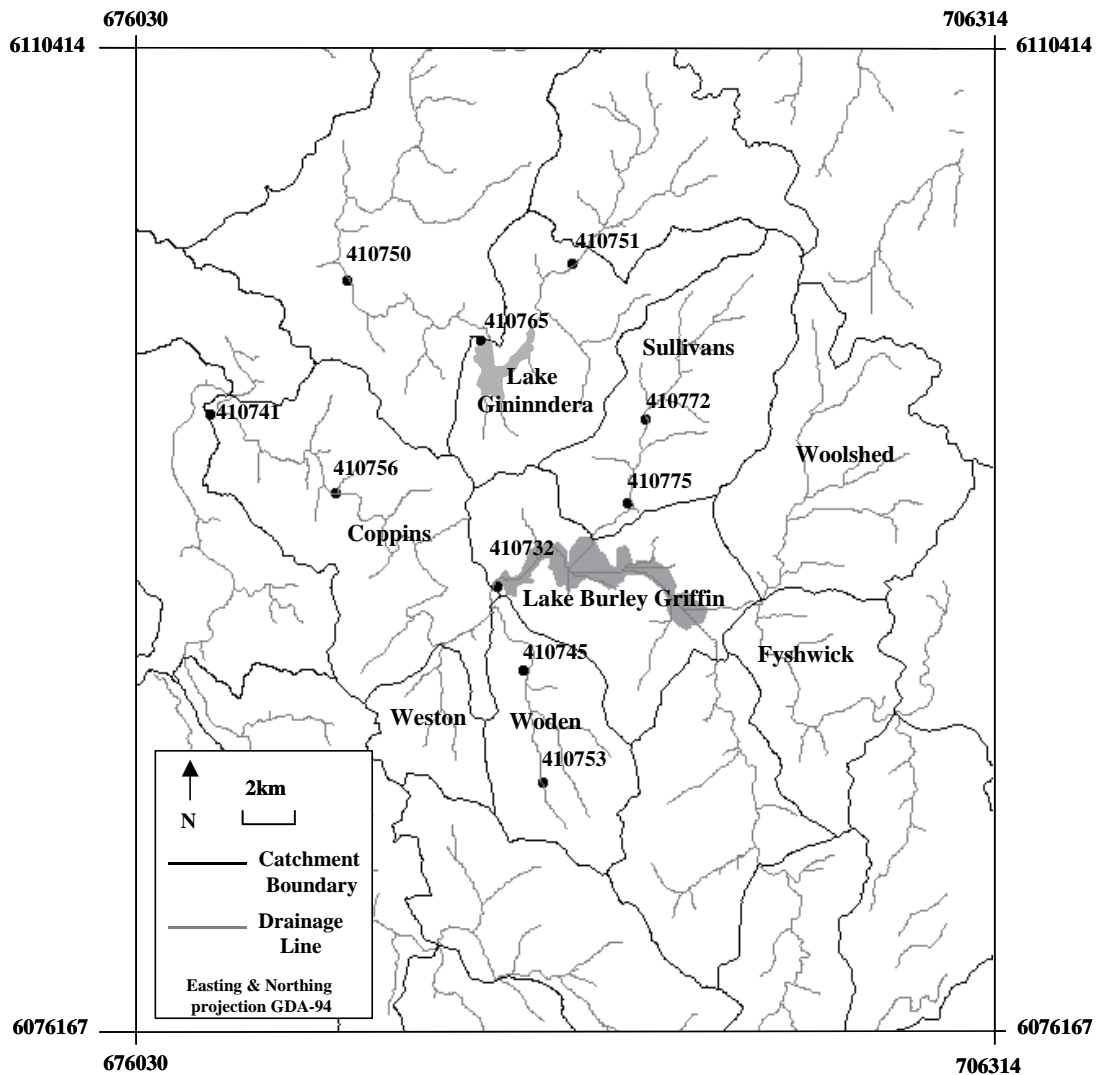


Figure 1: Sub-catchment boundaries and location of gauges used in this study.

**Transfer from similar catchment**

The geology, physiography and land use of the Woolshed Sub-Catchment is very similar to the Sullivans sub-catchment. Assuming that the two sub-catchments are likely to have similar recharge processes based on these similarities, the estimated recharge for the Sullivans sub-catchment has been adopted. The section below (see Flow Duration Analysis) outlines the hydrology of Sullivans Creek within the context of the broader hydrology of the other eight Sub-Catchments.

## Water balance

The water balance equation for a catchment over some period  $T$  can be written as:

$$Q = P - E - Q_s - \Delta S \tag{1}$$

where  $Q$  is the total streamflow,  $P$  is the total rainfall,  $E$  is the total evaporative loss,  $Q_s$  is the total subsurface outflow and  $\Delta S$  is the change in water stored in the catchment (final - initial). Assuming negligible subsurface outflow and change in storage over the period  $T$  gives:

$$Q = P - E \tag{2}$$

An estimate of  $E$  can be obtained using the evapotranspiration/rainfall relationships of Zhang *et al.* (2001). When calibrated on data for Australian catchments presented in the same work, the parameters of the Zhang *et al.* relationships are given in Table 1 (I. Hume, pers. comm.).

Table 1: Modified parameters used in the empirical relationships of Zhang *et al.* (2001)

	Grass cover	Trees
$E_0$	1400	1800
w	0.5	4

Estimates of the grass and tree coverage in each catchment were made based on the available land use coverages given in Table 2.

Table 2: Land use estimates for study catchments (note the values for Fyshwick are uncertain due to the lack of data for the NSW portion of this sub-catchment)

Catchment	Urban	Rural	Forestry	Conservation
	Fyshwick	0.1	0.85	0.05
Sullivans	0.4	0.34	0	0.26
Weston	0.79	0.04	0.06	0.11
Woden	0.74	0.11	0.02	0.13
Woolshed	0	0.78	0.07	0.15
Coppins	0.01	0.68	0.27	0.04
Lake Burley Griffin	0.67	0.11	0.07	0.15
Lake Ginninderra	0.64	0.22	0	0.14

Estimates of the impervious area, as well as the area covered by trees and by grass only were made using the following rules:

Table 3: Impervious, grass and tree fractions for each land use class

	Urban	Rural	Forestry	Conservation
Impervious	0.3	-	-	-
Grass	0.4	0.7	-	0.2
Trees	0.3	0.3	1	0.8

The estimated streamflow at the gauged sites (allowing for evaporative loss from the lakes, but ignoring extractions) matched the observed values to within a few percent for most of the sites (flows at Parkwood and Sullivans Creek were over-estimated). The runoff coefficient for the Woolshed sub-catchment was estimated at 0.12. Assuming baseflow comprises 20% of the total flow, this gives a recharge for the Woolshed sub-catchment of 15 mm/yr or an available groundwater resource of 94 ML/yr. There is considerable uncertainty in both the estimated discharge and the adopted baseflow fraction, and the values given here should be considered upper limits.

## MODFLOW

MODFLOW is a commercially available software product for modelling aquifer response, and is widely used in the hydrogeological community. It is capable of 3-D modelling of an aquifer, but here has been used to model a 2-D slice of the catchment down the stream. The slice runs from the northwest of the catchment down the stream to the bottom of the catchment. The slice was 1250m wide and 11750m long and the topography was determined from the catchment DEM.

The model was constructed based on the following assumptions:

- 1) Constant groundwater head imposed by the water level in Lake Burley Griffin;
- 2) Zero groundwater flow boundaries on the sides of the slice;
- 3) A 2m deep drain existed in the centre of the slice with a horizontal conductivity of 200m/day to simulate groundwater discharge to a stream;
- 4) The aquifer was 70m thick with a uniform hydraulic conductivity of 1m/day;
- 5) The initial hydraulic head was defined using water level data from existing bores.
- 6) No water was being removed from the aquifer from pumping.

The simulations were run for a year at a daily timestep, with recharge set to be uniform over the slice at the equivalent of 20mm/yr applied daily. This value was selected based on the estimate from the annual water balance. Figure 2 shows that this recharge underestimates the measured water level in the upper catchment. The slopes in the upper catchment are quite steep and it is expected that lateral flow to the modelled slice would contribute a significant volume of water. Therefore it was necessary to incorporate the larger contributing area by effectively altering the width of the cells in the upper catchment by a factor of four. With this recharge the modelled response had a better fit to the observed bore water levels in the upper catchment (20mm/yr area adjusted in Figure 2).

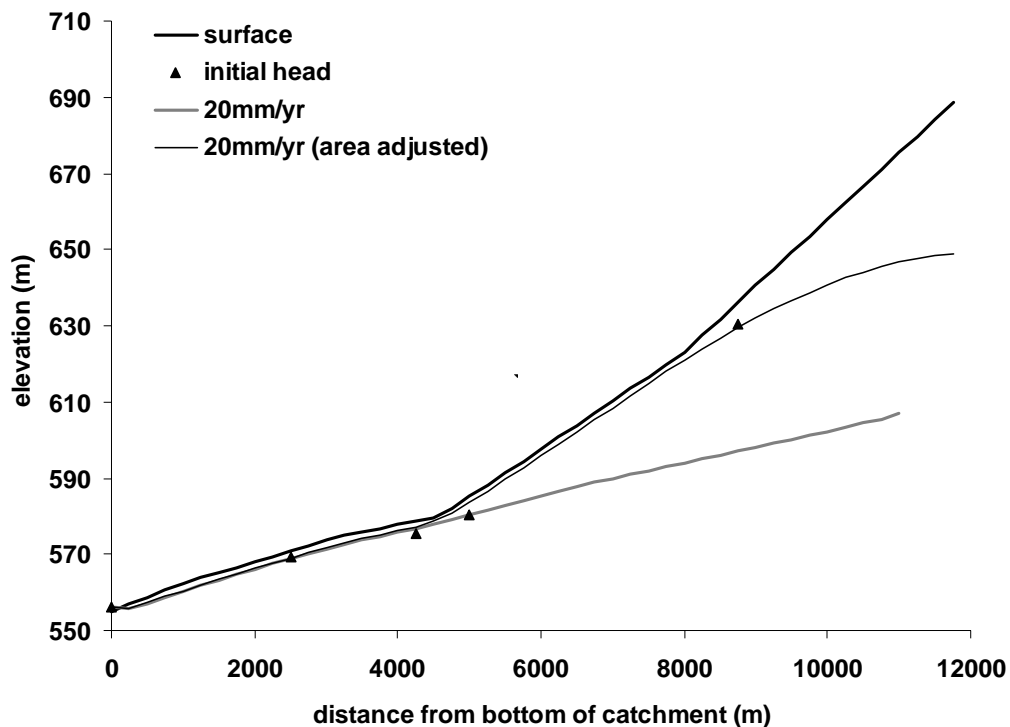


Figure 2: Watertable response in Woolshed Creek catchment from MODFLOW simulations with different catchment recharge.

This indicates that the contributing area of groundwater flow to the stream in the upper-woolshed catchment is substantial, and that the catchment recharge is approximately 20mm/yr.

## FLOW DURATION ANALYSIS

The following section details a general analysis of Flow Duration Curves (FDC) for surface water gauging sites either in the Sub-Catchments or in adjacent relevant Sub-Catchments. This was used as a basis for comparison of flow characteristics between Sub-Catchments.

In order to be able to confidently compare FDCs from different gauges the curves should be generated from the same period of data as the flow data used to derive a FDC is strongly dependent on the occurrence of rainfall in that period. Therefore a common gauging period was selected, which also avoided extended periods of poor quality data defined with a quality code of 255 in the records for gauges 410741 (Molonglo River near confluence with Murrumbidgee River), 410732 (water level in Lake Burley Griffin at Scrivener Dam) and 410750 (Parkwood - gauge locations and sub-catchment boundaries are shown in Figure 1).

The period from June 1, 1989 to October 31, 2002 was chosen to generate FDCs for each gauge. Any additional poor quality data within that period was removed from the data set, including 40 days prior to the start and 40 days after the end of the poor quality data period.

Finally the data set for each gauge was checked manually to ensure that any records showing zero flow were a reflection of no flow and not just missing data. Zero flow data preceded by a steady decline in flow, particularly in dry seasons, was considered to be real data. High flow rates that dropped to zero within a timestep, and rapidly returned to a high flow rate was considered to be erroneous and the data was removed with the same window of 40 days prior and after the erroneous data period. Using this subjective method data was removed from the 410741, 410772 and 410775 gauge records for one time period each. All other zeros were believed to be real data and were left in the data sets to generate the FDCs to reflect the transient nature of the creeks and tributaries in the ACT.

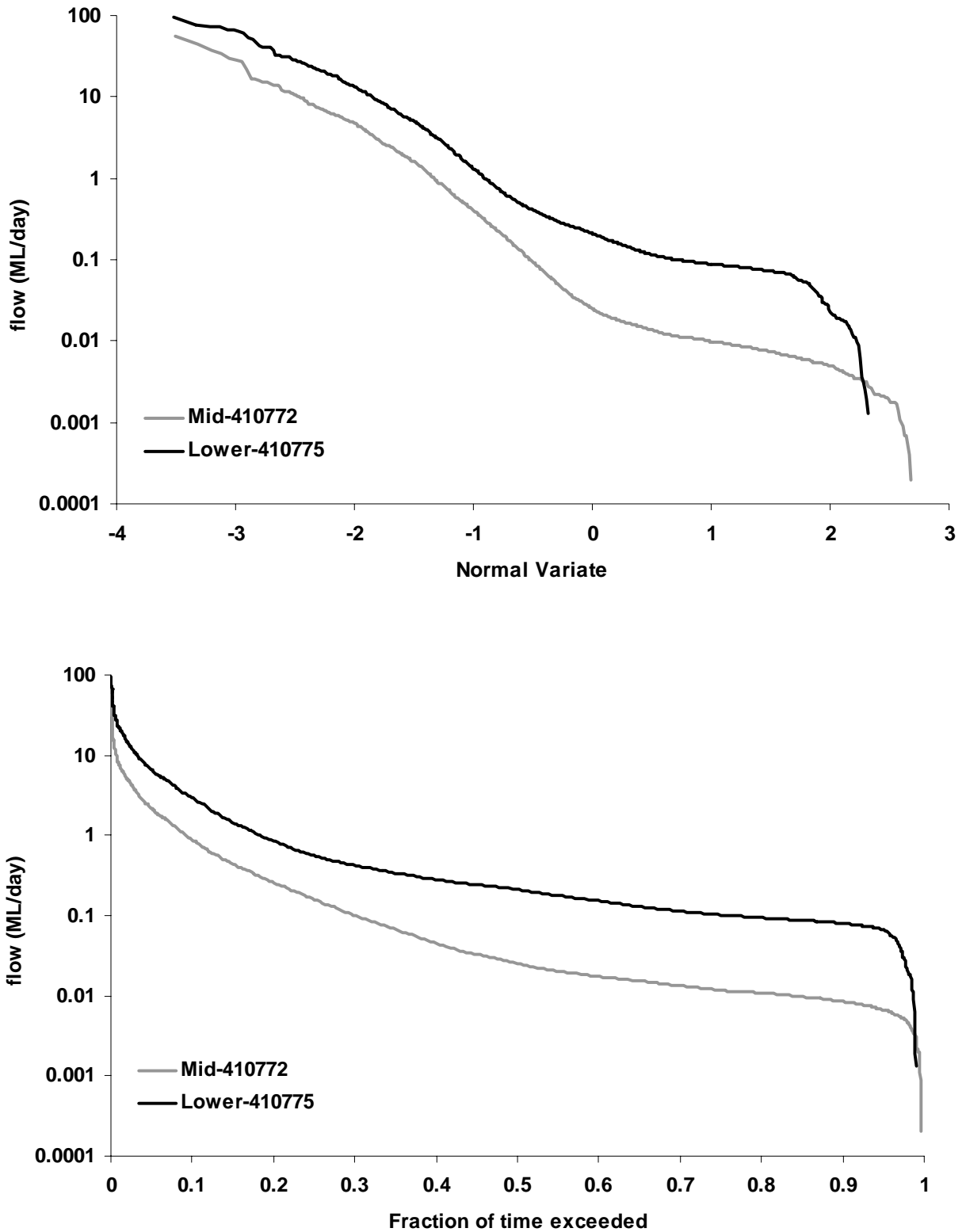


Figure 3: Flow duration curves for gauges in Sullivans Sub-Catchment. Top panel shows the FDC plotted as flow against the normal variate, while the bottom panel shows flow plotted against fraction of time exceeded.

Table 4: Conversion of normal variate to probability

Normal Variate	Probability	Normal Variate	Probability
-4	0.003	4	99.997
-3.5	0.023	3.5	99.977
-3	0.135	3	99.865
-2.5	0.62	2.5	99.38
-2	2.3	2	97.7
-1.5	6.7	1.5	93.3
-1	16	1	84
-0.5	31	0.5	69
0	50		

Figure 3 shows the flow duration curves for the two gauges in Sullivans Sub-Catchment (Table 4 shows the conversion of the normal variate to probability). The lower gauge has a higher flow duration curve than the upper gauge even after allowance for the change in catchment area is made. This is due to the difference in land use between the upper and lower gauges, with the upper catchment area predominantly rural while the lower catchment is mostly urban. The effect of urbanisation on a catchment's response is complex. Urban areas have a higher fraction of impermeable areas which act to reduce recharge and hence baseflow. However, leakage from water pipes, and irrigation of gardens and parks acts to increase recharge, as well as potentially simulating a baseflow component. Converting streams to stormwater channels will likely result in a decrease in recharge from the stream to the streambank (and the aquifer in areas where the watertable is below the channel bed). However, there is not likely to be a significant impact on the discharge from the aquifer to the stream in areas with high watertables as the channel bed, while made of concrete, is not totally impervious. The partial sealing of the channel bed will result in a slight increase in the groundwater level until a new equilibrium is reached between recharge and discharge.

The low flow volumes are enhanced for the lower gauge, though there is a slightly higher zero flow fraction (99.0% versus 99.6%) though this may be due to data errors. Figures 4, 6 and 8 show the FDCs of all gauged sites for observed flow, and estimated quickflow and baseflow components respectively while Figures 5, 7 and 9 show the corresponding normalised relative FDCs (FDC for each gauge divided by the FDC for gauge 410756, with the low probability tails (probability between 0.135 and 6.7%) normalized. Figure 10 shows that there are two classes of Sub-Catchments: those with comparable flow to 410756, and those with significantly stronger baseflow components. The nature of the curves in Figure 8 suggests that the baseflow filter is not adequately extracting the baseflow component, but this does not reflect the uncertainty in the total baseflow estimates.

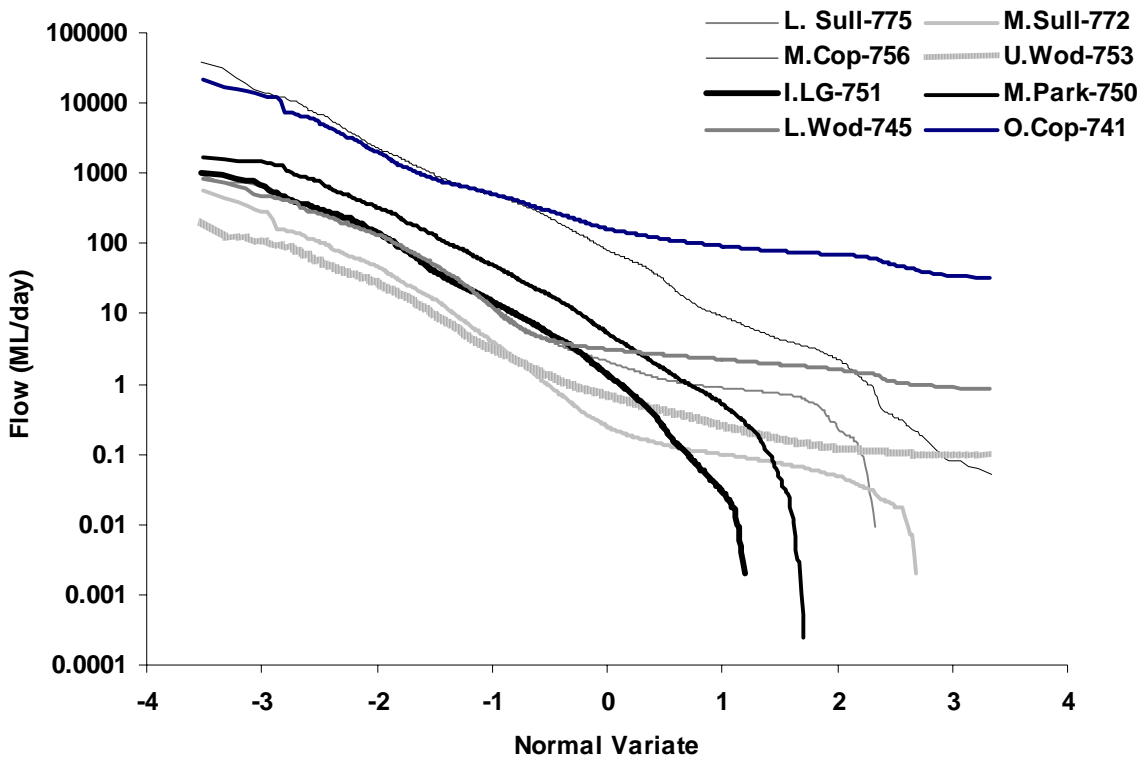


Figure 4: Flow duration curves for all gauges sites

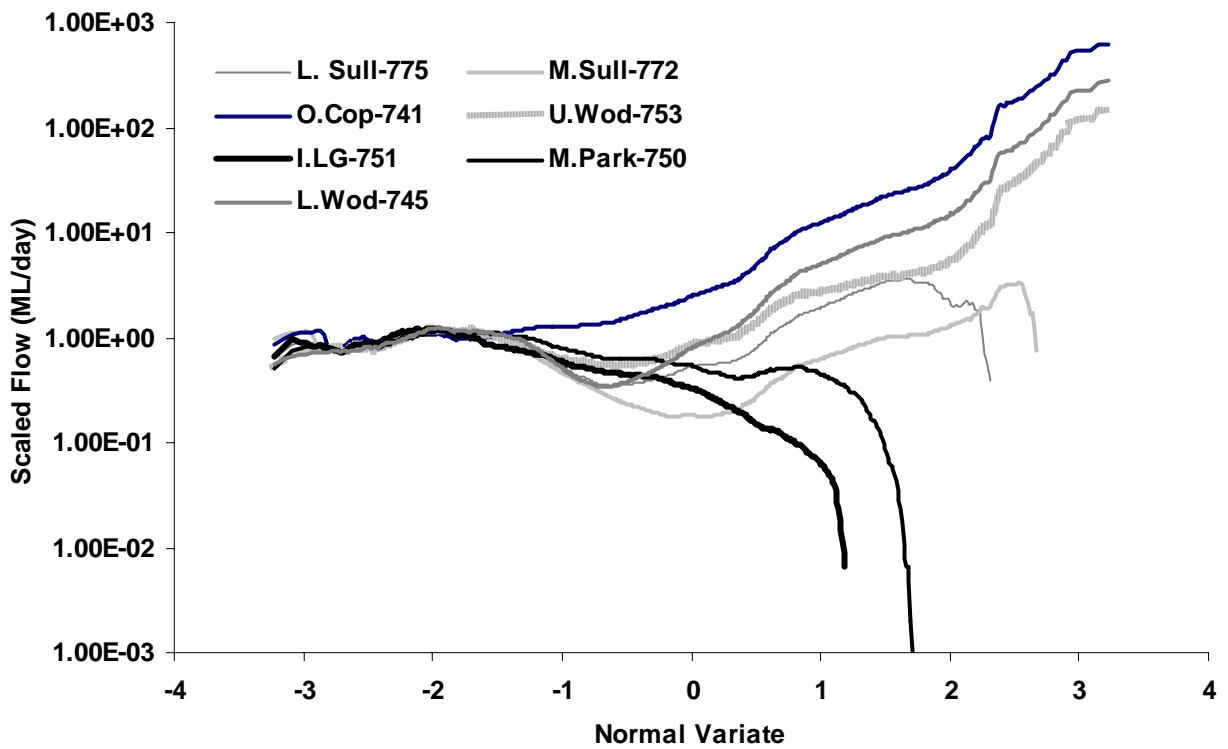


Figure 5: Normalised relative flow duration curves (observed FDC divided by FDC for 410756, with high flow portion (Normal variate between -3 and -1.5) normalised).

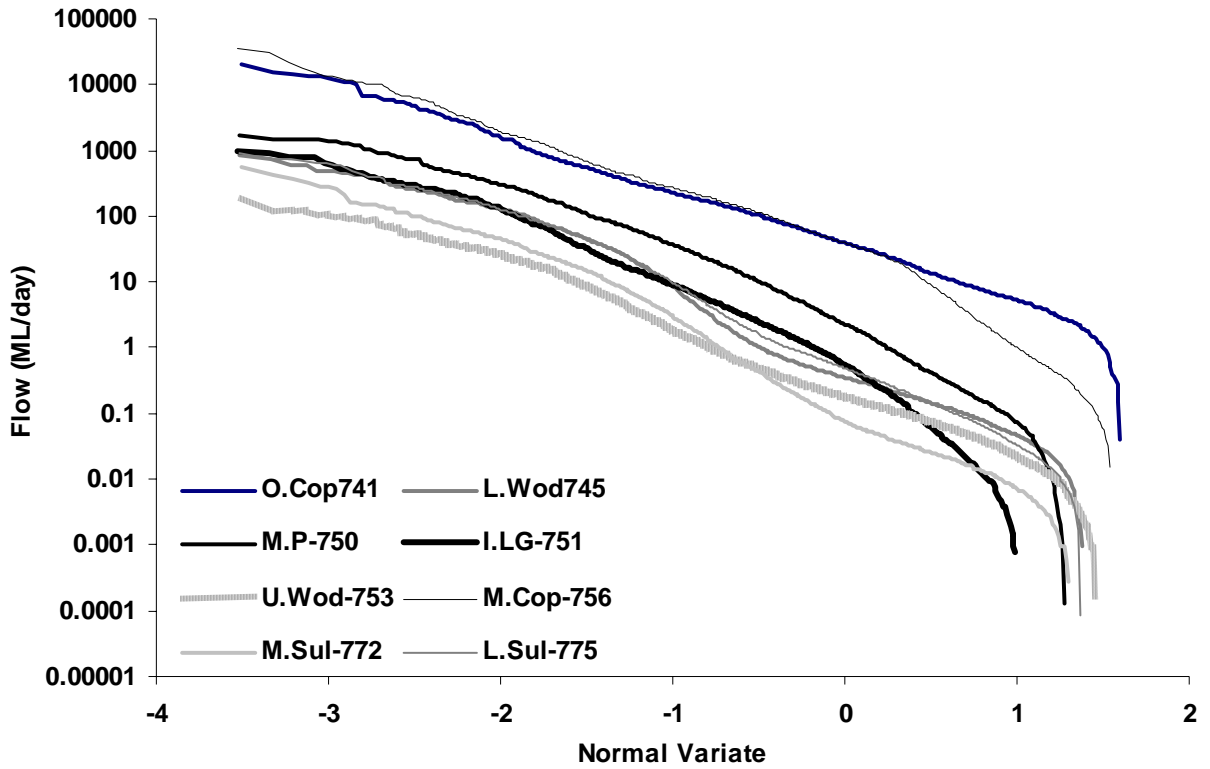


Figure 6: Flow duration curves of quick flow component for all gauges sites

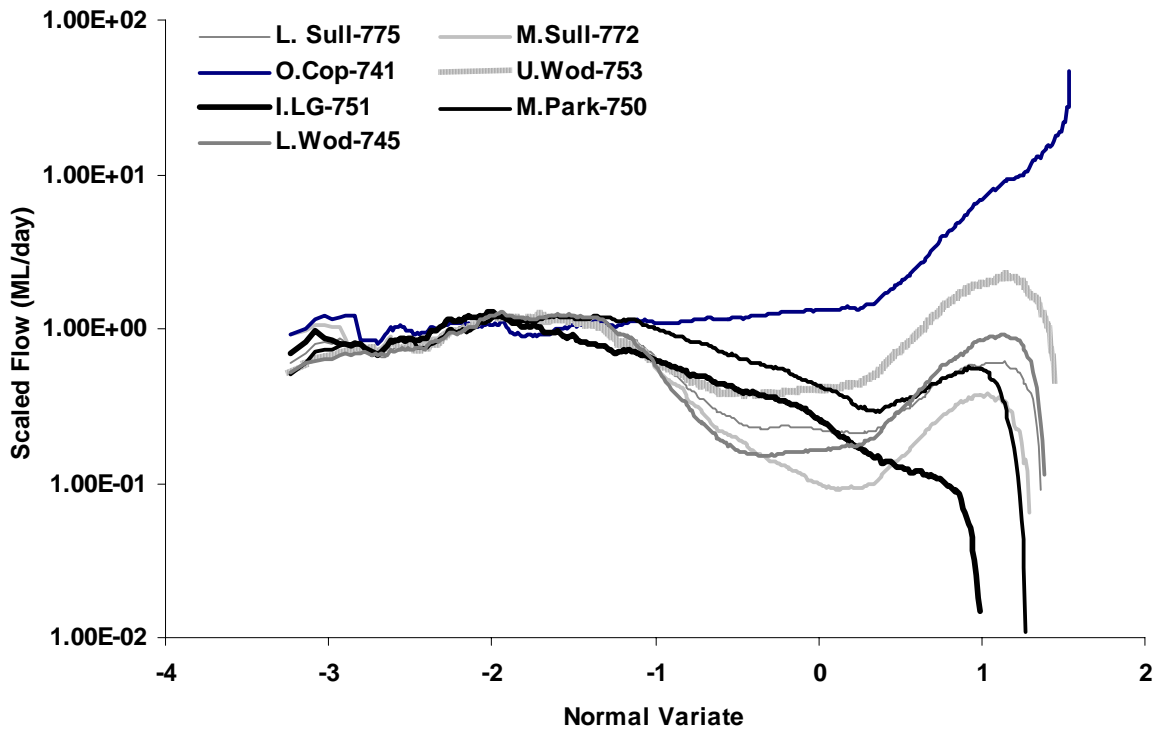


Figure 7: Normalised relative quick flow FDC (observed quick flow FDC divided by quick flow FDC for 410756, with high flow portion (Normal variate between -3 and -1.5) normalised).

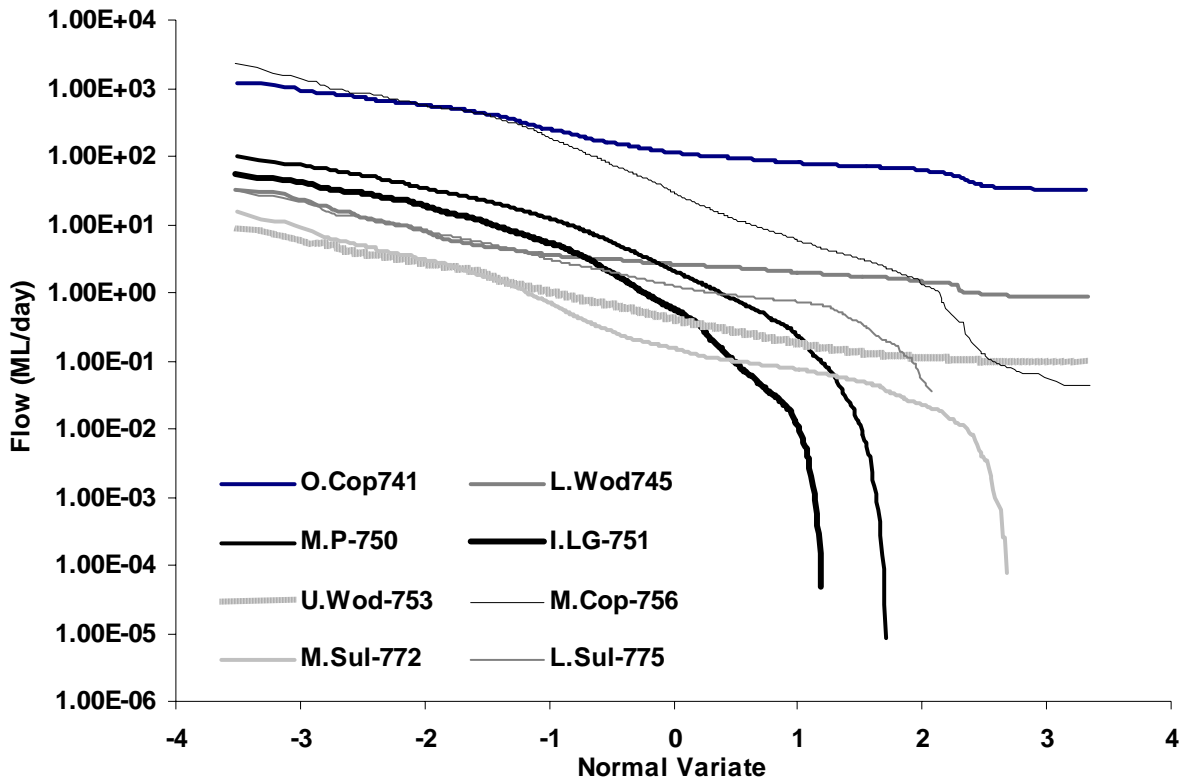


Figure 8: Flow duration curves of estimated baseflow component for all gauges sites

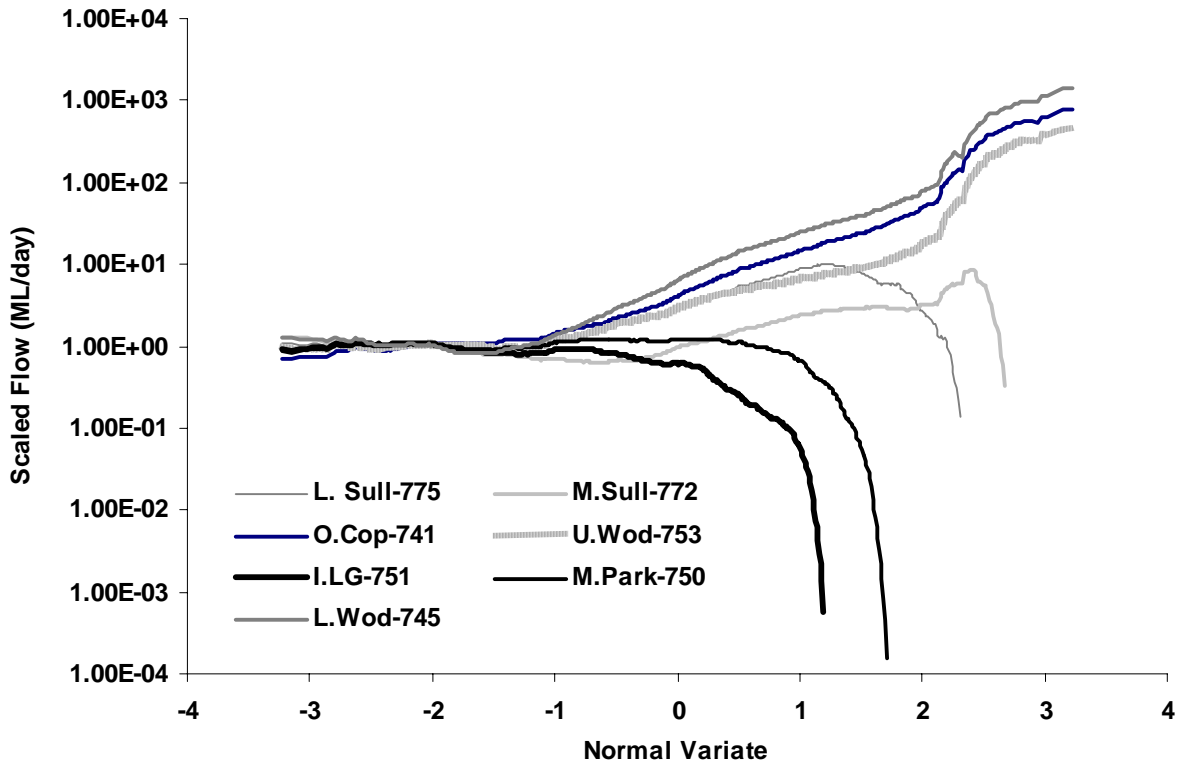


Figure 9: Normalised relative baseflow FDC (observed baseflow FDC divided by baseflow FDC for 410756, with high flow portion (Normal variate between -3 and -1.5) normalised).

Table 5: Scale factors used for normalising high flow portion of FDCs

gauge	total FDC	quick FDC	slow FDC
410741	0.807	0.055	0.014
410745	0.048	0.136	0.059
410750	0.125	0.054	0.032
410751	0.051	0.011	0.005
410753	0.010	0.763	0.939
410772	0.017	0.019	0.005
410775	0.049	0.056	0.014

Comparison of the flow duration curves for all gauge sites included in the study suggests that there are 3 classes of catchments: those with significantly stronger baseflow than that observed at gauge 410756 (corresponding to lower Coppins, and the gauges in Woden catchment), catchments with similar baseflow contribution (gauges in Sullivan's) and catchments with a much weaker baseflow component (gauges 410751 and 410750). It should be noted that the baseflow component for gauge 410741 (lower Coppins) is strongly affected by the sewerage treatment plant located just upstream of the gauge). The weaker baseflow components have considerable periods without flow (12% for gauge 410751 and 4.5% for gauge 410750). The low baseflow volume for these gauges could be due to a significant subsurface flow bypassing each gauge.

The flow duration curves for the two gauges in Sullivans Sub-Catchment suggest that there is evidence of a contribution of groundwater to streamflow between the two gauges, though the contribution from other sources (e.g. leakage from water supply and sewerage pipes, external water use) are unknown.

## BASE-FLOW AND SUSTAINABLE YIELD VOLUMES

Assuming that all recharge within a catchment appears as baseflow at the gauge (as discussed in an earlier section), baseflow filtering can give an estimate of the recharge within the catchment. The presence of a sub-surface flow out of the catchment, which bypasses the gauge site, will result in the recharge being underestimated. The potential for sub-surface outflow (or inflow) is highest in low relief areas. Alternatively, the contribution from leakage from water pipes and drainage from the outdoor use of water (watering, washing cars etc.), which have not been accounted for, will result in an overestimation of the recharge derived from baseflow filtering.

## Methods

There are a number of baseflow filtering algorithms available. Some are purely mathematical in nature (e.g. Lyne and Hollick (1979), Gustard *et al.* (1992), Croke *et al.* (2001)), while others attempt to have a more physical basis by using an assumed functional relationship for the discharge of groundwater to the stream (e.g. Chapman 1999, Croke *et al.* 2002). This review of techniques is not exhaustive, giving only a sample of the types of filters available.

### *Mathematical filters*

#### Lyne-Hollick filter

The paper by Lyne and Hollick (1979) was one of the first attempts at using a digital filter for estimating the baseflow, and used a filter developed for signal processing. The filter has one parameter (value lies between 0 and 1) which determines the degree of smoothing applied to the data (large values result in stronger smoothing, and a smaller baseflow component). The recommended value of the parameter for daily data is 0.925 (Nathan and McMahon, 1990, Grayson *et al.* 1996).

The filter function is:

$$q_f(i) = \alpha q_f(i) + (q(i) - q(i-1)) \frac{1 + \alpha}{2} \quad (3)$$

where  $q_f$  is the estimated quickflow response,  $q$  is the observed streamflow, and  $\alpha$  is the filter parameter. If the derived value of  $q_f$  is negative, then  $q_f$  is set to zero. Similarly, if  $q_f > q$ , then  $q_f$  is set to  $q$ . The baseflow is then given by  $q_s = q - q_f$ . The filter is applied in three passes. For the second pass, the filter is used backwards ( $i+1$  is used instead of  $i-1$  in equation 1). In both the second and third passes, the observed streamflow is replaced with the estimated baseflow from the previous pass.

### BFI filter

This filter was developed by Gustard *et al.* (1992). The procedure is to divide the observed timeseries into non-overlapping blocks of 5 timesteps, and determine the minimum value in each timestep (and the timestep corresponding to the minimum value). The baseflow timeseries is then estimated by interpolating between values. It is designed to be used with daily data.

### Minimum filter

This is a two-step filter developed by Croke *et al.* (2001) for the estimation of recharge in the Jerrabomberra Creek catchment. The first step is a running minimum filter of width  $2n+1$  timesteps. At each timestep  $i$ , the minimum of the observed flows from timestep  $i-n$  to  $i+n$  is determined. The resulting timeseries is then smoothed using a running average (or boxcar) filter of the same width. For the study of the Jerrabomberra Creek catchment, a filter width of 5 timesteps ( $n=2$ ) was adopted (increasing the value of  $n$  to 3 resulted in a 13 to 19% decrease in the estimated baseflow volume). This filter is easily applied at any temporal resolution, with the filter width scaled by the timesteps in 1 day.

As a precursor to applying this filter, it is sometimes helpful to remove spurious low values in the observed flow timeseries (actually, this can be of benefit for any of the mathematical filters). This is done by comparing the flow at each timestep with the immediate neighbouring timesteps. If the flow for the current timestep is less than both the neighbouring flows, the flow is set to the average of the value for the neighbouring timesteps.

## Physically-based filters

### Boughton

This filter comprises of an instantaneous quick flow component (entire of quick flow generated in a timestep leaves the catchment within that timestep) and an exponentially decaying baseflow and is based on the model developed by Boughton (1993). The filter has two parameters, the decay constant for the baseflow and the ratio of baseflow to total flow. Chapman (1999) gives a detailed description of this filter and the IHACRES filter. The baseflow estimated using the Boughton filter may include the interflow component as well as the baseflow component, and hence will tend to over-estimate the recharge.

### IHACRES

This filter is based on the IHACRES model of Jakeman *et al.* (1990) and Jakeman and Hornberger (1993). The filter is a slight generalisation of the Boughton filter in that an exponentially decay quick flow component is used, thus relaxing the assumption that the entire of the quick flow generated in a timestep leaves the catchment within that timestep. As a result, the filter has three parameters with the additional parameter being the decay constant for the quick flow component. This filter will be less likely to include the interflow component (depending on the quick flow time constant adopted) and so should give a more reliable estimate of the baseflow. Chapman (1999) compared the performance of the Boughton and IHACRES filters, and concluded that the Boughton filter is preferable.

## Furey-Gupta

A recent addition to the physically based baseflow filters is the filter developed by Furey and Gupta (2001). This filter is essentially the Boughton filter with a one-timestep delay between rainfall and its influence on baseflow.

## Generalised

Croke *et al.* (2002) and Croke (2004) have derived a generalised physically-based baseflow filter that encompasses the Boughton, IHACRES and Furey-Gupta filters, as well as modifying the functional relationship of the baseflow discharge to the solution to the Dupuit-Boussinesq equation for a homogeneous aquifer (spatially uniform transmissivity, effective porosity and recharge) obtained by Sloan (2001). In addition, the filter can be constrained to force the effective rainfall (fraction of rainfall that will eventually become streamflow) to be less than or equal to the observed rainfall, thus increasing the physical basis of the filter.

## Recommended method

While the physically-based filters have a stronger theoretical basis, they can have problems when used on ephemeral streams due to the assumed exponential decay in baseflow. If the temporal distribution of baseflow were of importance, then the physically-based filters would be preferable. The main difficulty with the physically-based filters is that they generally assume a constant partitioning of effective rainfall between quick flow and baseflow. This causes the filters to occasionally under- or over-estimate the baseflow component.

Since only the long-term recharge volume is of interest in this work, the mathematical filters (which are easier to apply) are preferable. For the purpose of estimating the recharge in streams in the ACT, it is recommended that the Lyne-Hollick filter be used with a parameter value of 0.925. This parameter value was recommended by Nathan and McMahon (1990). The BFI and Minimum (when applied with a filter width of 5 days) filters potentially include shallow subsurface flow as well as baseflow, and hence will tend to overestimate the baseflow. Thus the Lyne-Hollick filter is considered to give a more reliable estimate of the baseflow volume (and hence recharge volume) coming from the "slowest" part of the groundwater discharge process, which can be viewed as being derived from the deeper aquifers of the relevant catchments. It is these deeper aquifers that are the groundwater resource being developed for extractive use.

If the effect of climate variability on recharge and sustainable extraction is needed, then the CMD version of the non-linear module in the IHACRES rainfall-runoff model should be used, though this is beyond the scope of this study.

## Results

The estimated baseflow volumes for each gauging station in Sullivans Sub-Catchment are given in Table 6. The area draining to each gauge is 31.9 and 49.2 km<sup>2</sup> for 410772 and 410775 respectively. The baseflow component for the upstream gauge (410772) corresponds to a recharge depth of 5.2 mm/yr, while the corresponding recharge depth for gauge 410745 is estimated at 14.4 mm/yr – note that the area used here is the total area above the lower gauge, which includes the area above gauge 410772. The lower baseflow volume in the upper catchment may be due to subsurface bypass flow at the site of the 410772 gauge. Alternatively, the lower volume maybe due to the impacts of water extraction from both Sullivans Creek and the aquifers in the surrounding area. Most of the development in the Sullivans Sub-Catchment occurs in the region above the upper gauge.

The recharge rate adopted for the Sullivans Sub-Catchment is 14.4 mm/yr (iCAM, 2004).

Table 6: Baseflow for gauges in the Sullivans Sub-Catchment. The first column gives the filter used (LH = Lyne-Hollick filter, Min = Minimum filter, BFI = Baseflow Index filter) and the parameter value used.

Filter	410772		410775	
	$Q_s/Q$	$Q_s$ (ML/day)	$Q_s/Q$	$Q_s$ (ML/day)
LH(0.9)	0.11	0.52	0.15	2.14
LH(0.925)	0.09	0.46	0.14	1.94
LH(0.95)	0.08	0.38	0.12	1.70
Min (5)	0.15	0.72	0.19	2.71
Min (7)	0.11	0.51	0.15	2.18
Min (9)	0.09	0.43	0.14	1.94
BFI	0.11	0.53	0.16	2.25

The three analysis methods used to derive recharge estimates for the Woolshed Sub-Catchment provided varying values – between 14 and 31 mm/yr as transferred from Sullivans Sub-Catchment gauges (Baseflow Filtering), 20 mm/yr (MODFLOW watertable fitting) and 15 mm/yr (water balance).

It is proposed that the recharge estimate of 15 mm/yr be adopted for the Woolshed Sub-Catchment until further investigation is able to provide a recharge rate that has a higher level of confidence. The reasoning behind the adoption of the 15 mm/yr rate is based on a conservative approach towards the lower end of the estimates.

### Sustainable volumes for the Sub-Catchment

Based on the recharge rate of 15 mm/yr from the analysis above, the total recharge to the Sub-Catchment is 916 ML/yr. Based on the current policy the sustainable volume of groundwater available for the Sub-Catchment is 92 ML/yr.

## CURRENT SY ESTIMATES FROM WRMP 2004

### Current volumes allocated

The WRMP makes provision in Woolshed sub-catchment for an allocation based on preserving baseflow in the Molonglo River. Total recharge in the Woolshed catchment is estimated in the WRMP to be 29 mm/yr using a gross water balance model. This translates to a groundwater volume of 64 ML/yr for use (that is, 10% of total recharge) which appears to be in error – the actual volume according to the WRMP should be 177 ML/yr.

### Discussion of implications of this study

The volume of groundwater identified as being available for sustainable extraction is larger than the volume derived for the WRMP (see Table 7). This effectively allows more groundwater to be accessed, if these volumes are adopted.

Table 7: Summary of Groundwater Information for Woolshed Sub-Catchment

Current Groundwater Yield Estimate (WRMP) ML/yr	Current Allocation ML/yr	Groundwater Usage ML/yr (average for 2001 to 2003)	Groundwater yield Estimate this report ML/yr
64	64	unknown	94

The volume of groundwater that is being proposed in this work is a volume that can be sustainably extracted based on the current policy settings within the ACT. There has been no analysis of the impacts of extraction of this volume on environmental values both within and outside the Sub-Catchment. The information to undertake such an analysis is not available to the project. The estimate of a sustainable extraction volume has also been derived using a long term average annual approach. A rate of extraction of groundwater higher than 10% might be possible, and could be considered sustainable in most years. However, extraction at higher rates would reduce the security of access to the groundwater and result in more severe drawdown levels, and reduced yields, in dry years.

Some groundwater use in the Woolshed Sub-Catchment is located close to the boundary with the neighbouring Fyshwick Sub-Catchment in the Pialligo area. Some consideration should be given to rationalising the impacts across the Sub-Catchments' boundary. Specifically, there may be water level impacts due to groundwater extraction, occurring in this region that is 'blurring' the intent of the Sub-Catchment approach. That is, the drawdown across the boundary may be causing groundwater to flow from one catchment to the other and confusing the sustainable yield approach.

## LOCAL SCALE IMPACTS OF GROUNDWATER USE

The aquifers throughout the sub-catchments of the ACT are either unconfined or only marginally semi-confined. As such, recharge occurs over a large proportion of the landscape, rather than in one discrete area. The long-term sustainability of groundwater extractions will depend on the amount of recharge that occurs in the area of the aquifer that is hydraulically up-gradient from the point of extraction.

### Impacts around pumping bore

The impact of groundwater extraction, at the estimated sustainable yield, on the integrity of the aquifer will manifest as either a reduction in aquifer storage (as a result of minor compaction) or as an increase in groundwater salinity due to increased hydraulic gradients drawing in more saline groundwater. The likelihood of aquifer compaction is extremely low. If compaction does occur it most likely be noticed as a reduction in aquifer storage – the impacts at the land surface would most likely be unnoticeable.

The likelihood of increasing groundwater salinity will be higher, but the process will not be uniform across the Sub-catchment. Effects will be highest where changing hydraulic gradients can easily activate salt stores within the sub-surface. These salt store areas are generally associated with more deeply weathered materials.

Consideration should be given to limiting groundwater withdrawals in areas where groundwater salinities have been shown to be increasing over a time span of a number of years. This will require specific changes to licence conditions and may not be possible within the current licensing system. Movement to this restriction will also benefit from education of the groundwater user community as to the reasons for the management change.

### Minimum bore separation

One possible management response to avoid the development of local drawdown impacts is to impose a minimum bore separation distance on new applications. It is recommended that a minimum bore separation distance of 200 m be applied – this would equate to a radius of influence of 100 metres for each of two adjacent bores.

## FUTURE DATA REQUIREMENTS

### Resource assessment data

Resource assessment data will greatly increase the ability to manage the aquifer. The data would enable a better understanding of the impacts of groundwater extraction on stream flows using more quantitative analysis techniques.

Some data is being collected from bore owners at the time of construction of new bores. This data collection should be continued and efforts made to ensure compliance with this requirement.

Additional data related to aquifer performance should be considered. This data includes monthly groundwater levels and six-monthly salinities across a broader area related to extraction, especially where there are associated surface water systems. In some cases hydraulic parameters will be required to allow a more quantitative analysis of the impacts of groundwater extraction. This data would include aquifer thickness, hydraulic conductivity and specific yield.

### Monitoring data

Aquifer response data needs to be collected from bore owners as part of their licence condition, as well as from public funded observation bore networks. The data should include:

- Usage data – 6 monthly (quarterly is preferred) metered usage, drawdown level under normal pumped conditions, water level under non-pump conditions, salinity;
- Observation bores will provide monitoring data that will allow seasonal drawdown and salinity distribution to be described.

The consultants understand that some of this information is currently being collected as part of existing licence conditions, and also that changes to licence conditions to include new measurements is a complex process requiring user consent which may result in those changes not occurring. Nevertheless, the information will be required and collection of such is in the best interests of all users.

## RECOMMENDATIONS

It is recommended that:

1. A recharge rate of 15 mm/yr be adopted for the Woolshed Sub-Catchment for management purposes until better estimates are available, reflecting the result of a conservative approach based on the water balance analysis;
2. Based on the preferred method, a sustainable groundwater extraction limit of 94 ML/yr be adopted;
3. A minimum bore separation distance of 200 m be adopted, being equivalent to a radius of influence of 100 m. Further, it is recommended that where possible within existing licensing constraints, volumes of groundwater allocated to new users, or when existing allocation schemes are able to be altered, should also have regard to the volume of recharge up-gradient of the bore;
4. Environment ACT invest in a program of investigations that would increase the knowledge base concerning the processes driving the aquifer. Specifically, these works would include monthly monitoring of groundwater levels and six-monthly monitoring of groundwater salinities in areas of groundwater extraction; similar groundwater monitoring between areas of groundwater extraction

and Lake Burley Griffin, and the introduction of six-monthly groundwater salinity measurements on all licensed abstraction bores.

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## Phase 2

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## EXECUTIVE SUMMARY

Baseflow volumes vary between catchments and between seasons. Catchments with predominantly volcanic geology have baseflow fractions of about 0.23, while catchments with predominantly sedimentary geology have slightly more variable baseflow fractions between 0.1 and 0.2. Seasonal variations in the baseflow fraction are apparent, with baseflow fraction strongest in the winter/spring due to reduced evapotranspiration.

None of the ACT catchments (excepting Murrumbidgee and Molonglo gauges) have significant buffering of the baseflow. That is, the variations in annual climate are apparent in baseflow volumes in the current year.

The impact from groundwater extraction on surface water flows is most likely to be the result of captured groundwater discharge, than of induced recharge from the stream. The impact is a long lived process, with the time to full impact varying depending on the volume pumped and the distance of the pumping from the stream. However, there is little difference between pumping close to a stream as opposed to further from a stream when compared to the variability due to annual rainfall fluctuation. As well, groundwater extraction in wet years will have an influence on baseflow in succeeding dry years.

The impact on flows within a sub-catchment will depend on the location of the groundwater extraction points relative to the longitudinal profile of the stream in the sub-catchment. If extraction occurs higher in the catchment (closer to the headwaters) the likelihood of impact on the stream within the catchment is greater. If extraction is concentrated closer to the catchment outlet, the impact will be felt only at the catchment outlet. The largest influence on the absolute volume of baseflow in a sub-catchment is from recharge variability (linked to rainfall variability), though the proportion of baseflow to total flow does not vary substantially with rainfall. The aquifer has low storage and can be classified as having low robustness (the ratio of storage to annual recharge). This means that aquifer storage provides a low buffer capacity against a sequence of years with low recharge.

The geology, physiography and land use of the Woolshed Sub-Catchment is very similar to the Sullivans sub-catchment. Assuming that the two sub-catchments are likely to have similar recharge processes based on these similarities, the estimated recharge for the Sullivans sub-catchment has been adopted. The section below (see Flow Duration Analysis) outlines the hydrology of Sullivans Creek within the context of the broader hydrology of the other eight Sub-Catchments.

## INTRODUCTION

Environment ACT engaged iCAM and Salient Solutions Australia to undertake work to support a second generation of sustainable yield estimates for groundwater in sub-catchments in the ACT. This work involves tasks to better define the influence of groundwater pumping on riparian ecosystems in the nine sub-catchments that have already been studied as part of a previous project to define sustainable yield estimates for groundwater.

The following discussion is generic to all catchments in the ACT, except where specific gauge data has been analysed for particular catchments. These catchment specific discussions are contained within the sections on Baseflow Fraction, Cease to Flow and Seasonal or Climatic influences on Baseflow.

## CONCEPTUAL MODEL OF GROUNDWATER – SURFACE WATER CONNECTION

A conceptual model has been developed to characterise stream-groundwater interactions in the major streams and rivers of the ACT. Specifically, the streams being discussed in the following section include the Murrumbidgee and Molonglo Rivers, as well as the major streams of the sub-catchments identified in the Water Resource Management Plan, for example, Jerrabomberra, Yarralumla, Tuggeranong, Sullivans, Woolshed and Ginninderra Creeks.

All of the main ACT streams are regarded as gaining streams. That is, groundwater discharge occurs to higher order streams over much of the year under natural conditions. Groundwater does not discharge to the entire length of the stream course; rather it is concentrated on the lower parts. The exact length of stream course that accepts groundwater discharge is unknown.

The conceptual model also assumes that all groundwater is discharged to the stream. That is, there are no other processes whereby groundwater can be discharged without appearing in the stream network.

It is assumed that the groundwater discharge rate reflects the amount of groundwater discharging from the *productive* aquifer in any sub-catchment, where the *productive* aquifer is the deeper groundwater flow system. That is, there are no other groundwater sources in the sub-catchment that contribute to discharge but cannot be accessed by pumping.

If all groundwater is discharged to the stream, then the volume discharged should be the same as the volume recharged to the aquifer over long time periods (so that changes in storage are negligible).

In summary, the analysis method employed in this and other work carried out to quantify the recharge rates to the aquifer rely on a sequence of assumptions (see below). These assumptions are considered applicable to the ACT groundwater and surface water sources, and there is high confidence that these are valid based on the knowledge and data currently available.

1. All recharge to the aquifer is manifest as discharge from the aquifer under steady state conditions;
2. The discharge is from the aquifer which is being pumped or subject to management (there are no other groundwater sources that cannot be accessed by pumping);
3. This groundwater discharge has occurred to streams in individual sub-catchments before the stream exits the sub-catchment;
4. All groundwater discharge appears as a component of streamflow. That is, there are no other discharge pathways;
5. Baseflow in the stream adequately represents the contribution of groundwater discharge to streamflow;
6. The baseflow filtering technique can partition the true amount of baseflow from the measured hydrograph; and
7. There are no impacts from groundwater pumping on the baseflow derived from the observed record.

These assumptions may be contravened in some cases. For instance,

- There may be some cases where groundwater is evaporated or transpired in a disconnected wetland or swamp prior to reaching a stream;

- In some areas, well developed regolith may transport groundwater through shallow flow paths that are not fully connected with the fractured rock aquifer and are therefore not accessible to pumping bores;
- In some urbanised catchments the leakage of water from anthropogenic sources and activities may be accounted as part of the baseflow component of the observed hydrographic record;
- Groundwater extraction may be causing a diminution of baseflow; and
- There may be analytical errors in the filtering techniques used to partition baseflow from the observed record.

The occurrence of these circumstances is unknown, but considered to be rare.

### GROUNDWATER DISCHARGE AND BASEFLOW

Specific information was required to better understand the role of groundwater discharge to better identify the relationship between this and baseflow in the streams. In particular, does groundwater compose the majority or all of the true baseflow in ACT streams, and does the baseflow as defined by the analysis represent the true baseflow in the stream? Is the groundwater discharge able to be attributed to the aquifer from which groundwater is being pumped?

Baseflow is comprised of those sources of water that come from the slow processes contributing water to a stream. Traditionally these have been defined as coming from groundwater. In practice, baseflow is probably better defined as that part of the streamflow that is not contributed by surface runoff. If this definition is accepted, then baseflow must be comprised of only groundwater.

The complicating issue is that there may be more than one source of groundwater inflows. In some sub-catchments, there may be a shallow zone related to more deeply weathered regolith that acts as a conduit for lateral transmission of infiltrating water. This shallower aquifer will usually be above the main zone of production for pumping bores, but will contribute groundwater discharge to the streams. The relative volume of water in each of the shallow and deep aquifers is unknown.

There may be other sources of slowly varying discharge in urban catchments. These include: leakage from water supply and sewer systems, runoff into storm drains from daily water use (e.g. washing cars, footpaths and watering of gardens - if excessive) and industrial sources (e.g. discharge from LMWQCC). In the existing water shortages, the effect of daily water use will be less, but may be a potential contributor in historical data.

The question above also asks whether the baseflow as derived by the analysis represents the true baseflow in the stream.

The baseflow estimates used in this study are based on application of the Lyne-Hollick baseflow filter (Nathan and McMahon, 1990). As this is not a direct measurement of the baseflow volume, the resulting estimate of baseflow may include contributions from other components of flow (e.g. interflow), or may underestimate the baseflow contribution. In addition, errors in the observed streamflow can result in an underestimation in the estimated baseflow. While positive errors (overestimation of streamflow) will only affect the baseflow fraction for that timestep, negative errors (underestimation of streamflow) can result in an underestimation of the baseflow over a significantly longer time due to the properties of the filter.

The baseflow estimates given here should be viewed as the best estimate given the available data and current state-of-the-art analysis techniques. While other baseflow filters are available, the Lyne-Hollick filter is a widely accepted filter within Australia.

Conversion of estimated baseflow into recharge requires information on the subsurface flux of water out of the catchment. As such data is not available, and given the characteristics of the catchments within the ACT, it was assumed that any such subsurface outflow would be negligible compared to the estimated baseflow.

## BASEFLOW FRACTIONS

Analysis of the baseflow fractions for gauged sites in the ACT show that there is variation in the baseflow fraction between streams (see Table 2.1). Ignoring gauges with extremely large contributing areas (i.e. gauges on the Molonglo and Murrumbidgee rivers), gauges to the south of Lake Burley Griffin appear to have a fairly constant baseflow fraction of approximately 0.23 (range from 0.20 to 0.24). Gauges located north of Lake Burley Griffin have lower baseflow fractions (0.1 to 0.18). This difference is correlated with a difference in the geology of these catchments, and suggests that catchments in the region dominated by sedimentary rocks may have a lower baseflow fraction to catchments dominated by volcanic rocks.

**Table 2.1 Long term mean baseflow fraction for all gauges used in the study (1996 to 2004)**

Gauge	Location	Baseflow fraction	Dominant Geology
410772	Sullivans Creek at Southwell Park	0.10	Sedimentary
410775	Sullivans Creek at Barry Drive	0.14	Sedimentary
410750	Ginninderra Creek upstream of Charnwood Road	0.16	Sedimentary
410751	Ginninderra Creek upstream of Barton Hwy	0.18	Sedimentary
410779	Tuggeranong Creek upstream Sewer Crossing	0.23	Volcanic
410753	Yarralumla Creek at Mawson	0.20	Volcanic
410745	Yarralumla Creek at Curtin	0.22	Volcanic
410790	Jerrabomberra Creek at Hindmarsh Drive	0.24	Volcanic
410756	Molonglo River below Coppins Crossing	0.28	Mixed
410741	Molonglo River at Sturt Island	0.37	Mixed
410761	Murrumbidgee River below Lobbs Hole Creek	0.43	Mixed

A study of baseflow characteristics of unregulated rivers and streams in the Murray Darling Basin has been carried out on streamflow records for the period 1990 to 1999 (SKM 2001). No records for gauging sites in the ACT were included, but the summary for NSW streams can be viewed as providing context for the study reported here.

The study derived Annual, Summer, Autumn, Winter and Spring baseflow indices using filtering techniques for 91 gauging stations in NSW. Baseflow indices for the upper Murrumbidgee, upper Murray and upper Lachlan Rivers are thought to be relevant to ACT stream analysis (representing 35 gauging stations).

Derived data for these stations showed:

- A range in the annual baseflow index of 0.19 to 0.56 (0.09 to 0.59 for summer; 0.1 to 0.68 for autumn; 0.24 to 0.51 for winter; and 0.24 to 0.56 for spring);
- A median annual baseflow index of 0.27; and
- Median baseflow indices of 0.2 (summer); 0.22 (autumn); 0.29 (winter); and 0.3 (spring).

The data derived by SKM shows consistency with the baseflow fractions derived during this work, and also highlights that the variation due to seasonality is not as large as the variability between gauges.

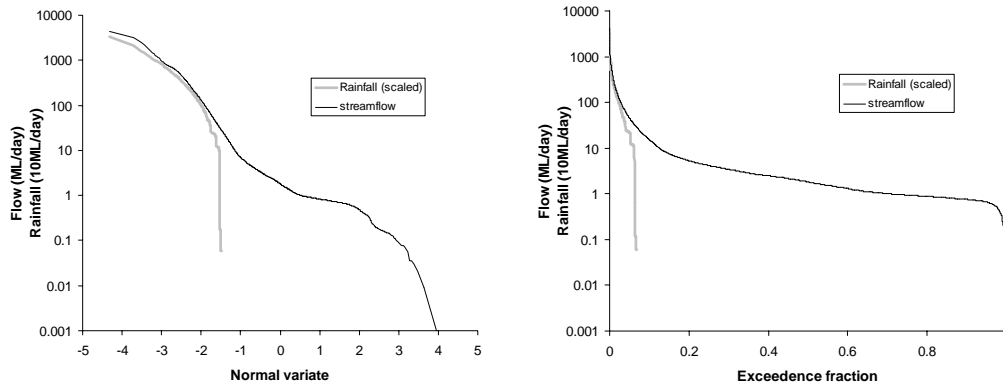


Figure 2.1: Flow and rainfall duration curves (or exceedence curves) for Sullivans Creek at Barry Drive (gauge 410775) derived from hourly data.

Figure 2.1 shows the rainfall and flow duration curves for Sullivans Creek at Barry Drive (gauge 410775). The rainfall exceedence curve has been converted into ML/day, and scaled by a factor of 10, which corresponds to a runoff coefficient of approximately 0.1 (ignoring the influence of unit hydrograph). The high flows are dominated by the rainfall duration curve (exceedence fraction < 3.3%, normal variate < -1.84). There are two changes of slope in the log-normal flow duration curve, one at normal variate = -0.975 and the other at 0.5 (exceedence fractions = 16.5% and 69% respectively). Assuming these changes in slopes correspond to shifts in dominant flow generation processes it is suggested that the first change is due to the transition between runoff and interflow dominance, and the second change between interflow and baseflow dominance.

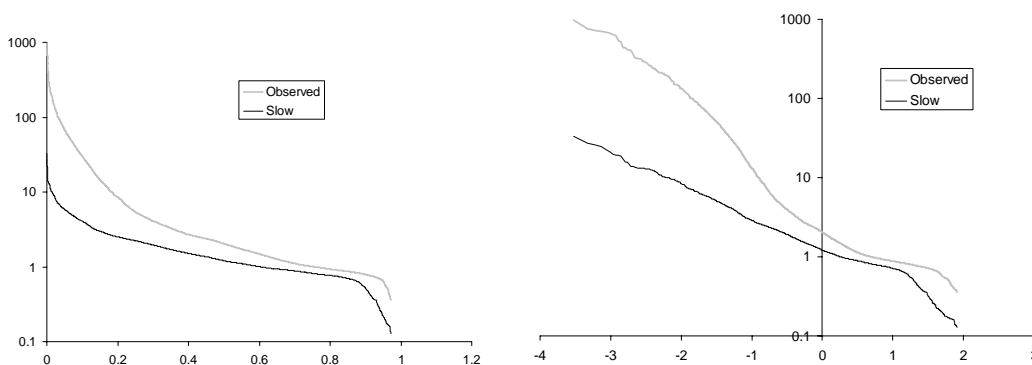


Figure 2.2: Flow and baseflow duration curves for Sullivans Creek at Barry Drive (gauge 410775) derived from daily values.

Figure 2.2 shows that the majority of the observed flow is baseflow approximately 24% of the time (based on daily data); with evidence of a slight underestimation of the baseflow produced by the baseflow filter (by approximately 20%).

The lowest observed value in the FDC shown in Figure 2.2 is 0.036 ML/day (this is not the minimum observed flow however). This corresponds to approximately 0.4L/s. If this corresponds to a constant “leakage” term (actually leakage minus loss from stream through evaporation and infiltration) from within the catchment, then the leakage term is a minor contributor to the baseflow (estimated volume ~2ML/day). However, if data errors cause the decrease in observed flows near 1, then the minimum flow corresponds to the plateau between 0.8 and 0.9 – i.e. approximately 1ML/day. This is then a significant fraction of the estimated baseflow. It should be noted that there is no apparent lowflow limit in the hourly data. This implies that either the lowest values are the result of data errors, or that there is no significant constant contribution to streamflow in the catchment.

For Sullivans Creek (gauge 410775) the mean baseflow index (BFI) estimated using the baseflow filter is 0.14, and corresponds to a mean baseflow volume of approximately 730 ML/yr (corresponding to a mean annual recharge of 15 mm/yr). There does not appear to be a significant steady influx to the stream from urban water use/supply (estimated volume is 0.036 ML/day, or 1.8% of the estimated baseflow). The baseflow is the dominant contributor to observed streamflow approximately 30% of the time, with some evidence that the baseflow volume estimated using the baseflow filter underestimates the actual baseflow by approximately 20%. If this is correct, then the baseflow volume is approximately 880 ML/yr (corresponding to a mean annual recharge of 18 mm/yr), and the corrected value of the BFI is 0.17.

### CEASE TO FLOW CHARACTERISTICS

Analysis of the hourly observed streamflow data for Sullivans Creek (gauge 410775) shows that between 1987 and 2004, there were 50 periods when flow ceased (Figure 2.3), the longest duration being almost 16 days (April/May 2000).

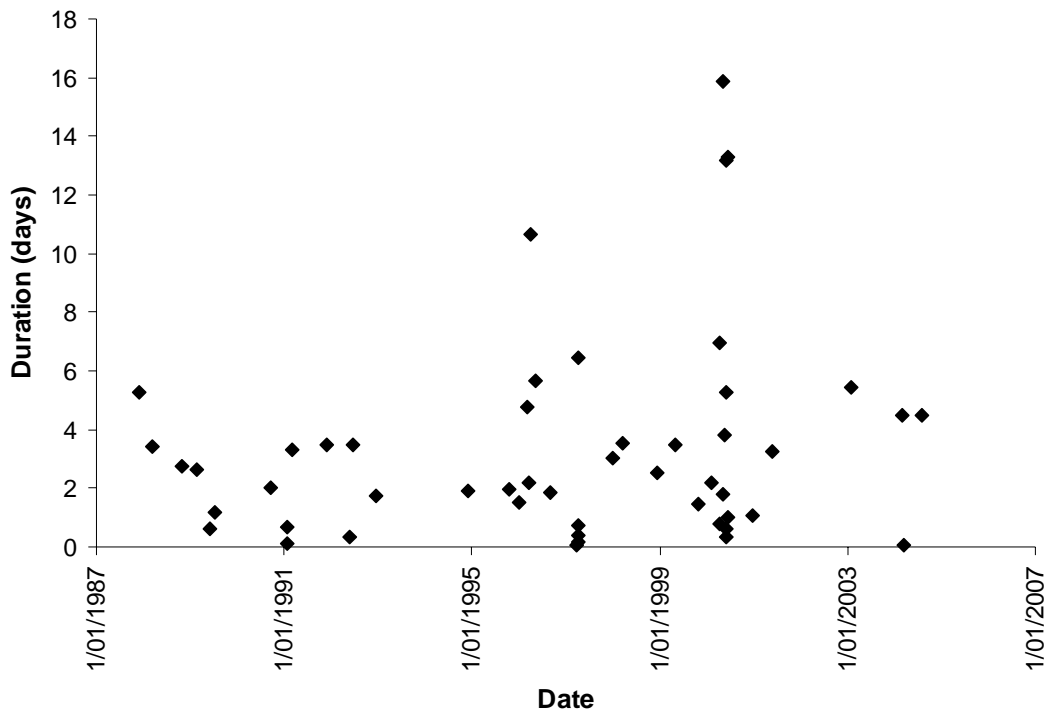


Figure 2.3: Duration of no-flow periods for Sullivans Creek at Barry Drive (gauge 410775).

While there are a significant number of occasions when no flow is recorded at gauge 410775, most of these are short in duration (less than about 4 days), and only 4 periods lasted for more than one week. It should be noted that a recording of no-flow may not necessarily correspond to zero flow, but that the flow was below the detection threshold of the gauge.

## HYDROLOGY OF POOLS

The hydrology of pools or ponds in the bed of a stream is poorly understood. The level of the water in a pond/pool will be controlled by the difference between the inputs and outputs of water to and from the pond. The major input to the pond/pool once cease to flow conditions have occurred will be from groundwater seepage. The amount of groundwater seepage will be constrained by the local hydraulic gradient around the pond/pool and by the hydraulic character of the materials immediately adjacent to the pond. The major outputs from a pond/pool will be via evapotranspiration and by seepage to the groundwater on the downstream side.

If the pond/pool remains connected to the local watertable as the cease to flow conditions occur, then it is likely that evapotranspiration will be a small component of the water budget, with the main control being the throughflow nature of the groundwater in the pond/pool. That is, groundwater is effectively passing through the pond, and the water level in the pond is an expression of the free water surface.

If the pond becomes disconnected from the watertable, then the rate of drying of the pond/pool will depend on the rate at which water in the pond can infiltrate to the unsaturated zone around the pond, and the evapotranspiration of water from the pond/pool. Typically, the infiltration loss will dominate over the evaporative loss.

In some cases the rate at which a pond dries will be determined by a reduction in the amount of groundwater seeping into the pond. This seepage can be reduced as the hydraulic gradient of the groundwater around the pond is lowered due to pumping. However, the hydraulic gradient will need to be lowered by a considerable amount so that evapotranspiration can dominate over seepage inflows.

The location of the pond along the stream trace is also critical. The conceptual model of groundwater flow suggests that the watertable may be connected to the stream for the lower half to two-thirds of its course in a sub-catchment. This suggests that the watertable may be able to disconnect from the stream more frequently in upper sub-catchment positions, as opposed to those in the lower sub-catchment. This means that a pool/pond in the mid to upper reaches may be prone to higher rates of drying than a pool/pond in the lower parts. Thus, groundwater pumping around the sub-catchment outlet is likely to have a larger impact on ponds/pools.

Information on the frequency and duration of ponds drying out and the groundwater conditions in the immediate vicinity of the pond is necessary before conclusions can be made concerning the impact of groundwater use on the ponds and the habitats they support. At this stage, this information is not available and the issue will require future monitoring and research to address this question.

## IMPACTS OF GROUNDWATER PUMPING ON STREAM POOLS

This is a complex issue that may require more detailed site specific analysis.

Generally, the issue being explored relates to the impact from groundwater pumping on ephemeral groundwater-fed pools in a stream once flow has ceased. In particular, will the pool dry faster when impacted by groundwater pumping? Pools that are fed only from surface water are not considered in this discussion.

In the case where the impact from pumping is via interception of groundwater discharge, the impact on any specific pool will be to lessen the hydraulic gradient to the pool. This means that the groundwater flow will diminish, but not cease. Thus, the size of the impact will be proportional to the ratio of the size of the diminution of groundwater inflows to the pool, to the evaporation rate. Where the groundwater seepage to a pool falls below the evaporation rate, it is likely that the pool will then dry out.

Given the hydraulic gradients likely in most of the sub-catchments in the ACT, it is difficult to conceive of a situation where the hydraulic gradients can be lowered to the point that groundwater flux is lower than about 6 mm/day (the average summer daily evaporation rate).

There will be a larger likelihood of impacts where groundwater extraction induces recharge from the surface water body. This will occur where pumping occurs close to a stream and causes the watertable to be drawn down immediately under the stream. For a drawdown of 1 metre at the stream, the distance of pumping from the stream is a function of the pump rate and the hydraulic parameters of the aquifer. Generally, pumping at rates of about 5 m<sup>3</sup>/day or higher and within 100 metres of a stream in a fractured rock environment will probably induce recharge from the stream.

In these latter situations, it is likely that the impact of pumping will be to increase the rate at which a pool dries out. The actual timing will be different for each pool.

There will be a spatial difference between the behaviour of pools within a sub-catchment. It is more likely that pools in the upper parts of a subcatchment are going to be dominated by surface inflows (that is, stranded above the regional watertable), while those pools at the bottom of the subcatchment are more likely to be dominated by groundwater seepage. This is essentially the difference between ephemeral and perennial flow.

The location of the extraction bores in the catchment will also be influential on the particular reaches of a stream that are affected. Groundwater extraction will not affect stream flow higher in the sub-catchment than where the extraction occurs. This means that if extraction is concentrated towards the sub-catchment outlet, the impact will be felt mainly at the outlet, with little reduction to flows above that point, whereas a different impact will be felt within the sub-catchment if the extraction points were concentrated in the sub-catchment headwaters.

## SEASONAL OR CLIMATIC INFLUENCES ON BASEFLOW

For the gauged sites in the ACT sub-catchments, there does not appear to be a significant variation of the annual average baseflow fraction when plotted against annual rainfall (e.g. Figure 2.4 for Sullivans sub-catchment). This is also the case when 2 or 3 year average rainfall, or if the difference between this years and last years rainfall, are used as the abscissa. This suggests that the baseflow closely follows the annual rainfall, that is, the aquifers are not providing a strong buffer between recharge and discharge for the sub-catchments. This implies that the storage capacities of the aquifers for the observed catchments are not sufficiently larger than the annual fluxes through the aquifers to allow observable buffering of the system.

Seasonal variations in the baseflow fraction are observable, with the peak in baseflow fraction typically occurring in August/September. This is likely to be a response to the decreased evaporative loss in the winter, as well as the influence of typically higher rainfall intensities in the summer (resulting in a potential increase in the runoff component). The exception to this is gauge 419790 (Jerrabomberra Creek) where the seasonal signal is broader and less distinct.

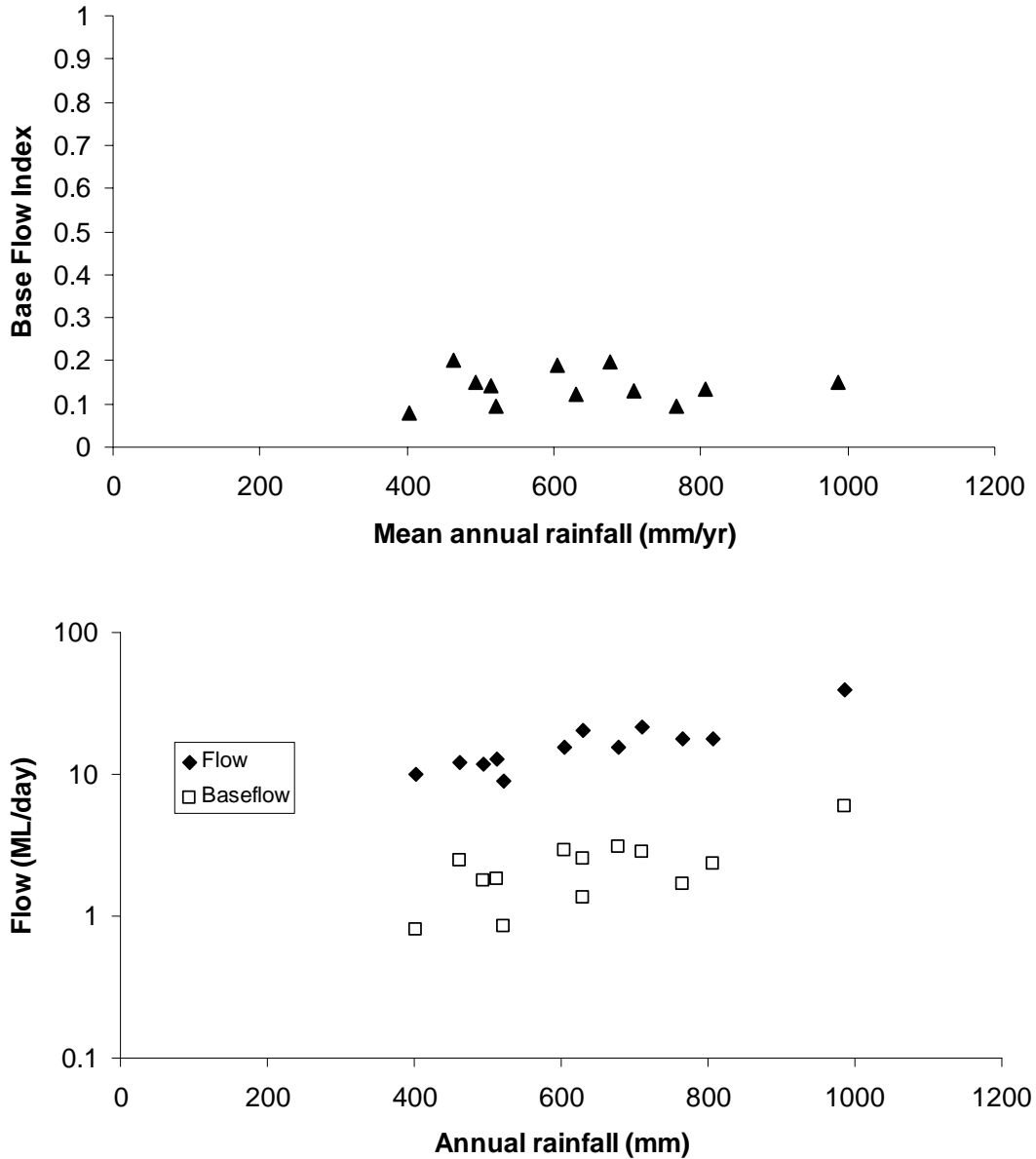


Figure 2.4: Baseflow fraction and total annual observed flow and baseflow for 410775.

While there is no detectable variation in annual baseflow fraction between years with significantly different annual rainfall, dry years tend to have a greater proportion of time when the streamflow is dominated by baseflow.

Figure 2.5 shows the rainfall and streamflow duration curves for Sullivans Creek at Barry Drive for the years 1994 (dry year) and 1995 (wet year). The curves show that the wet year had a higher runoff coefficient, as expected for a catchment with higher soil moisture content. The wet year (1995) has a greater persistence in the high flows, suggesting that there is an interflow component contributing in wet years. The influence of this intermediate flow component is not observed in 1994. The dry year (1994) has a greater fraction (approximately 86%) of time when baseflow dominates (see Figure 2.6) compared with 1995, where baseflow dominates the observed streamflow approximately 20% of the time.

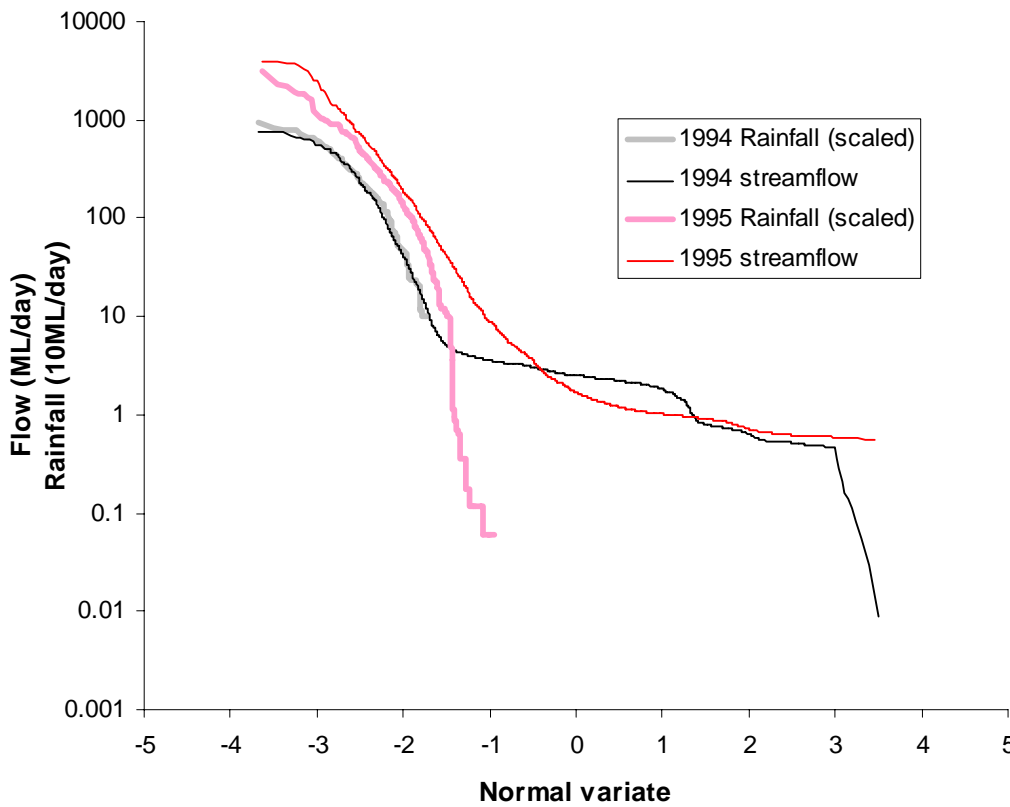
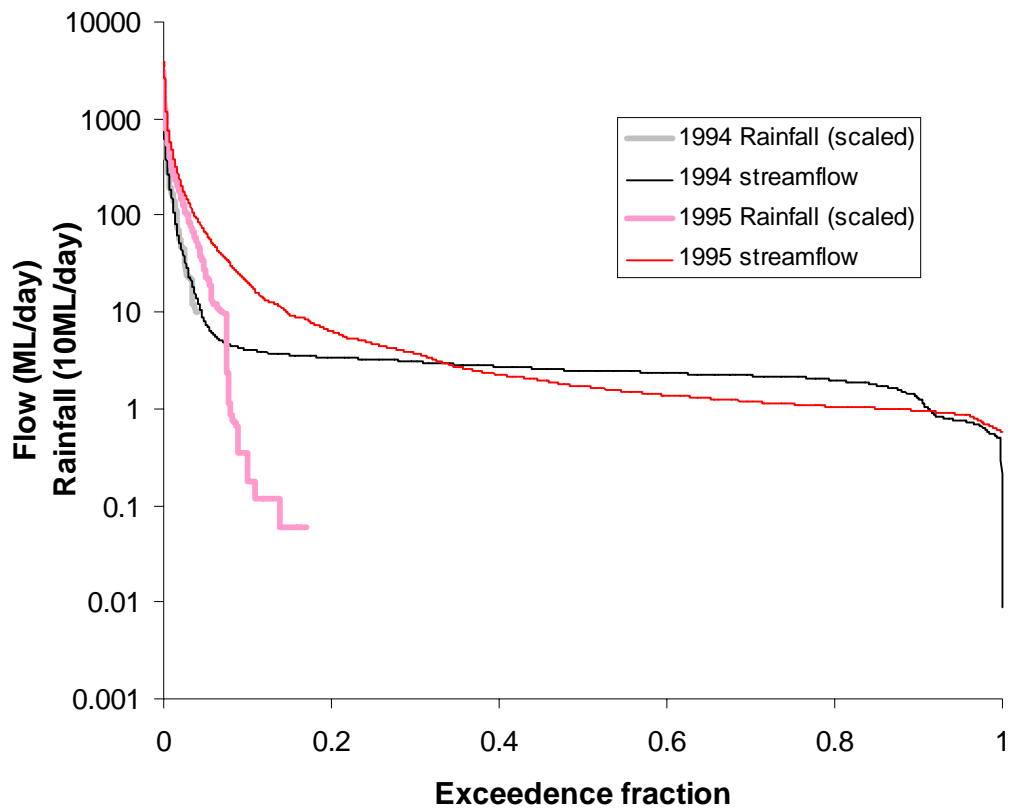


Figure 2.5: Rainfall and streamflow duration curves for Sullivans Creek at Barry Drive (gauge 410775)

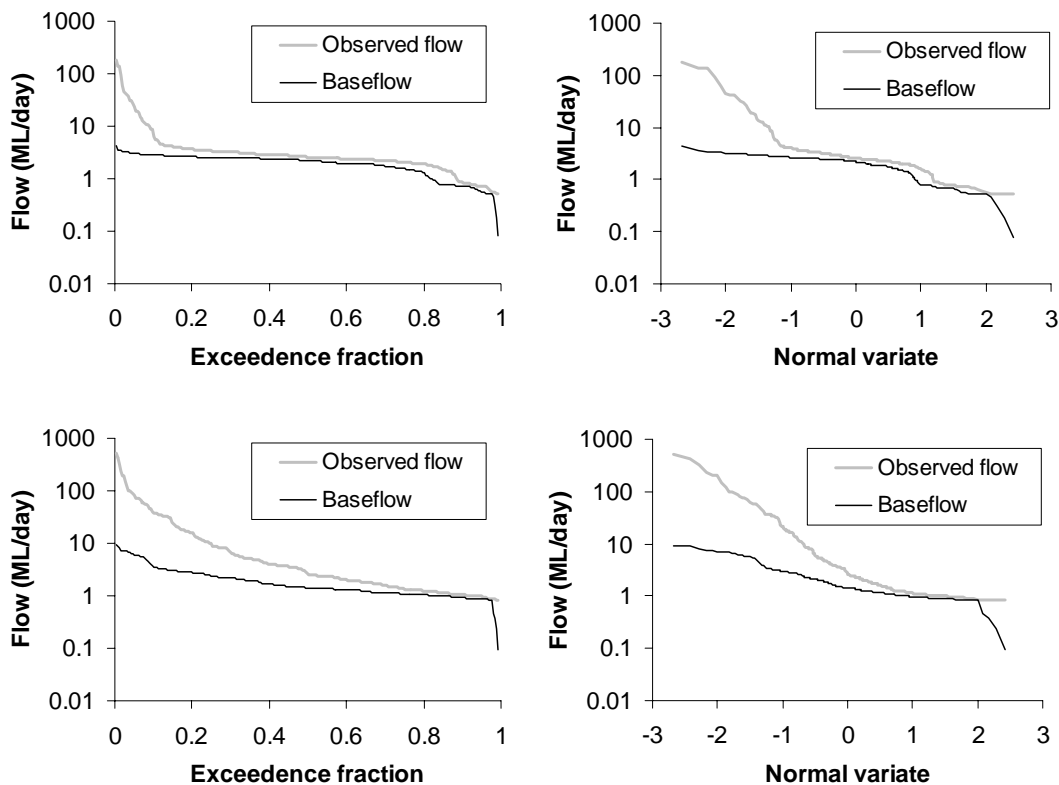


Figure 2.6: Streamflow and baseflow duration curves for Sullivans Creek (gauge 410775). The top plots show the results for 1994 (annual rainfall at Canberra airport 383 mm), while the bottom plots correspond to 1995 (annual rainfall 801 mm).

The results presented above are consistent with discharge from an aquifer that has a low robustness. Robustness is a term developed during work on characterising sustainable yield of aquifer systems in the Murray-Darling Basin (REM, 2002, Middlemis *et al.*, 2004) and relates to the ratio between aquifer storage and the long term annual recharge volume – this is effectively a dimensionless number. A robust aquifer system has a high ratio of storage to recharge, where an aquifer system with low robustness has a low ratio. These authors suggested a threshold value for low robustness aquifers of between 10 and 20.

The fractured rock aquifers of the ACT are characterised by a thickness of about 70 metres with a storage coefficient of 0.01, which equates to storage of about 700 mm per unit area. Using a typical average annual recharge volume of 40 mm/year, the robustness measure is 17.5. The robustness measure will vary as the recharge rate varies between wet and dry years, assuming that recharge increases linearly with increasing rainfall. This variation may be by a factor of 4 or more, from values of about 10 during wet periods, to values of about 45 during dry periods.

This low robustness measure underlines the need to manage groundwater extractions carefully, and further lends weight to the adoption of the low percentage of annual average recharge as the determinant of sustainable yield as being a prudent decision. That is, by only allowing 10% of annual average recharge to be extracted from the groundwater, the robustness of the aquifer has been increased effectively by an order of magnitude.

## GROUNDWATER EXTRACTION EFFECTS ON STREAM FLOW

As an aid to understanding the issue of the impact from groundwater pumping on streamflow, a simple numerical model was developed that simulated the groundwater conditions in ACT sub-catchments. A specific sub-catchment, Woden, was chosen to be the basis for the model. This allowed sub-catchment specific attributes such as topographic shape, recharge rate and baseflow to be assigned. However, the model exercise was not an attempt to replicate the conditions of the Woden sub-catchment.

The model simulated a typical sub-catchment in the ACT, and comprised a one layer, 100 m thick, unconfined aquifer. The downstream boundary to the model was set as a constant head cell, with all other boundaries set to no flow. The constant head cell was set with an elevation consistent with the elevation of the Molonglo River at the confluence with Yarralumla Creek. A stream in the sub-catchment was simulated via a drain, with the water level in the drain set just below ground level.

The sub-catchment was portrayed using topographic data for the Woden sub-catchment.

The aquifer hydraulic conductivity was set at 0.5 m/day and the aquifer that was considered was isotropic (that is, hydraulic conductivity was constant in all directions). A storage coefficient of 0.01 was also assigned.

Recharge was set to 39 mm/yr – consistent with the Woden sub-catchment.

The model was first run at steady state to allow visual calibration of the modelled groundwater levels against current understanding of the groundwater conditions in the sub-catchment. The model was also calibrated against the baseflow component of the Woden sub-catchment derived from earlier streamflow analysis. The steady state model runs derived an outflow of 3.67 ML/day, with 95% of the flow occurring through the model stream. This matches the previous analysis of the Woden sub-catchment.

The resultant head distribution was then used as the starting heads for a number of transient model runs.

### Base Case

A base case was run in transient mode to confirm the model stability and to generate a base case of streamflow for future comparison with pumping scenarios.

The model was run for 300 years with no groundwater extraction to allow groundwater discharge to come to quasi-equilibrium and ensure there were no artefacts of groundwater storage change in the results.

The base case confirmed that the stream was accepting 3,506 m<sup>3</sup>/day as a steady state groundwater discharge. The remainder of flow out of the model was due to the constant head cell at the downstream end, and could be thought to represent underflow to the Molonglo River.

### Extraction Scenarios

Extraction scenarios were run for 325 years. The first 200 years were modelled with no extraction to allow the model to reach steady state.

Two types of extraction scenarios were then imposed. Firstly, one year of pumping at a rate of 10% of recharge from one bore was used to gauge the time response of the stream to groundwater pumping. This one year of pumping was followed by 125 years of no pumping. In the second type of extraction scenario, pumping was held constant at 10% of recharge for the full 125 years to gauge the long term impact on streamflow.

In both scenarios, the impact of pumping from different distances from the stream was tested by placing the abstraction well either 500 metres or 2 km from the stream. In the case of the 2 km pumping distance, the pumping was split between two pumping bores to avoid instabilities caused by being too close to the model boundary.

The effects on streamflow at the catchment outlet from pumping groundwater at the sustainable limit of 10% of recharge are independent of the number of bores used to attain the extraction volume. This is based on the principal of linear superposition. This principal is based on the laws of mathematics and effectively states that the impacts from two separate actions are the same as the impact from the sum of the actions. Thus, linearity dictates, for example, that the impacts from one bore pumping at the maximum rate will be the same as the impacts from ten bores pumping at one-tenth the rate.

*Impact of one year of pumping*

The impact of one year of pumping is shown in Figure 2.7.

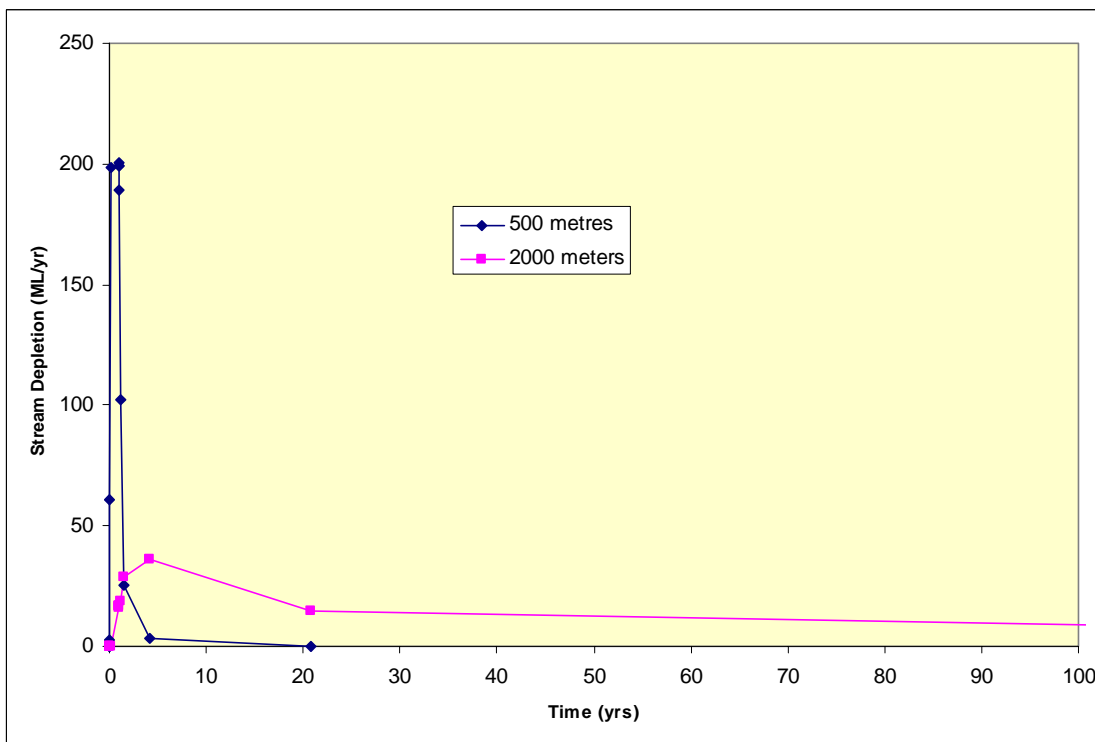


Figure 2.7: Stream depletion impact due to pumping at a rate of 367 m<sup>3</sup>/day for one year at two different distances from a stream.

The main feature to be noted from Figure 2.7 is the time lag in the response of the stream to the pumping and the length of time it takes for the full impact to be felt. The closer the bore is to the stream the faster the impact and the quicker the time to full impact. At a distance of 500 metres from the stream the full impact of one year of pumping is effectively detected within about 5 years, whereas, the full impact of extraction for one year at 2 km is ongoing for considerable time.

This importantly shows that the impact of pumping is not confined to the year in which the pumping occurs. Rather, the impact is spread over many years and is proportional to the distance from the stream. Figure 2.7 also shows that the impact in any one year from pumping some distance from the stream is small.

### Impact of continuous pumping

The impacts of pumping from the aquifer at the rate of 10% of recharge per year for many years are shown in Figure 2.8.

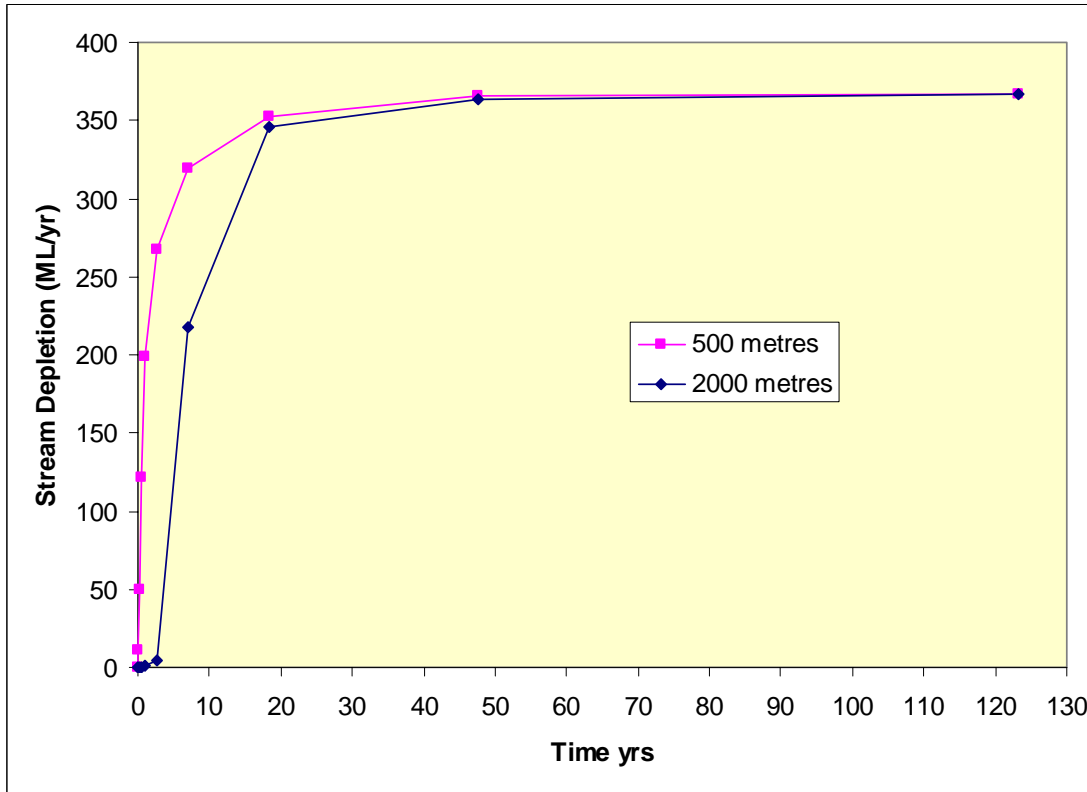


Figure 2.8: Stream depletion as a result of annual extraction of 367 m<sup>3</sup>/day for 125 years

Figure 2.8 shows that the impact of continuous pumping takes a number of years to build to a constant depletion of streamflow at the rate equal to the pumping rate. Again the nature of the impact is dependent on the distance of pumping from the stream.

The key finding from these scenarios is that there is a time lag involved in the impacts of pumping on streamflow that extends over many years. This results in a legacy of impact due to previous years pumping.

The impact on streamflow in these scenarios is via the capture of groundwater discharge that would have otherwise reported to the stream. The process of induced recharge (that is, the induced movement of water out of the stream due to the presence of a drawdown cone below the stream) is thought not to be operating in this simulation.

### Variable recharge

The model was run for the same period as previously, but using a variable annual recharge amount based on the annual rainfall measured at Canberra Airport. The variable annual recharge commenced at year zero in the model, while pumping commenced at year 200.

The annual recharge was derived by using a factor based on the long term recharge rate of 39 mm/yr divided by the long term annual rainfall value. A recharge sequence was constructed by cycling the 66 years of record from Canberra Airport to make up the complete input sequence over the 325 years.

Groundwater extraction was set to 367 m<sup>3</sup>/day at 500 m and 2,000 m from the stream. To test the sensitivity of the impact on groundwater discharge, extraction was increased to 734 m<sup>3</sup>/day for both distances as well.

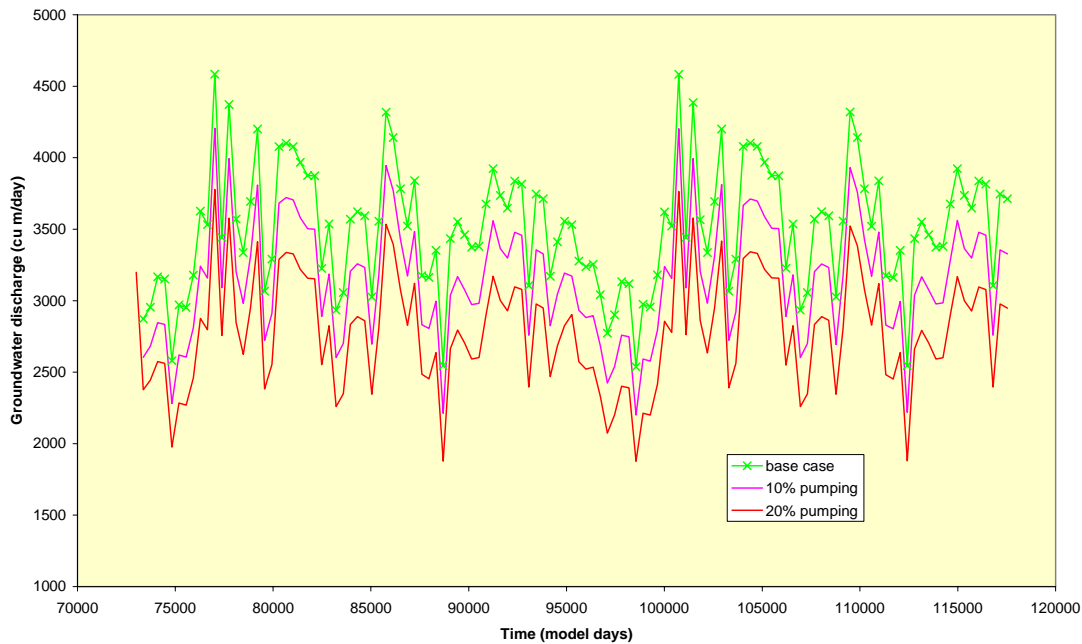


Figure 2.9: Time series of groundwater discharge for different pumping rates – pumping 500 m from the stream.

Apart from the first few time steps, Figure 2.9 shows that the impact of extraction at the different pumping rates has the same form over time, being proportional to the recharge volume in any year, but varies by a constant amount related to the extraction volume. The peaks in the time series are due to the variability of rainfall from year to year, while the downward shift in the overall times series is caused by the extraction of groundwater. The trends show that the major influence on modelled baseflow is the variation in recharge from year to year due to the large variation in annual rainfall. That is, the normal sequence of wet and dry years can introduce an almost 3-fold variation in recharge to the aquifer. This assumes that the variation in recharge is linearly related to the annual rainfall.

The impact of groundwater extraction, when compared to the variation due to annual rainfall variability, is a second order influence, particularly at the lower rate of 10% of annual recharge. Specifically, pumping at this rate introduces a linear 10% change in baseflow, compared with up to 300% change in recharge due to rainfall fluctuation.

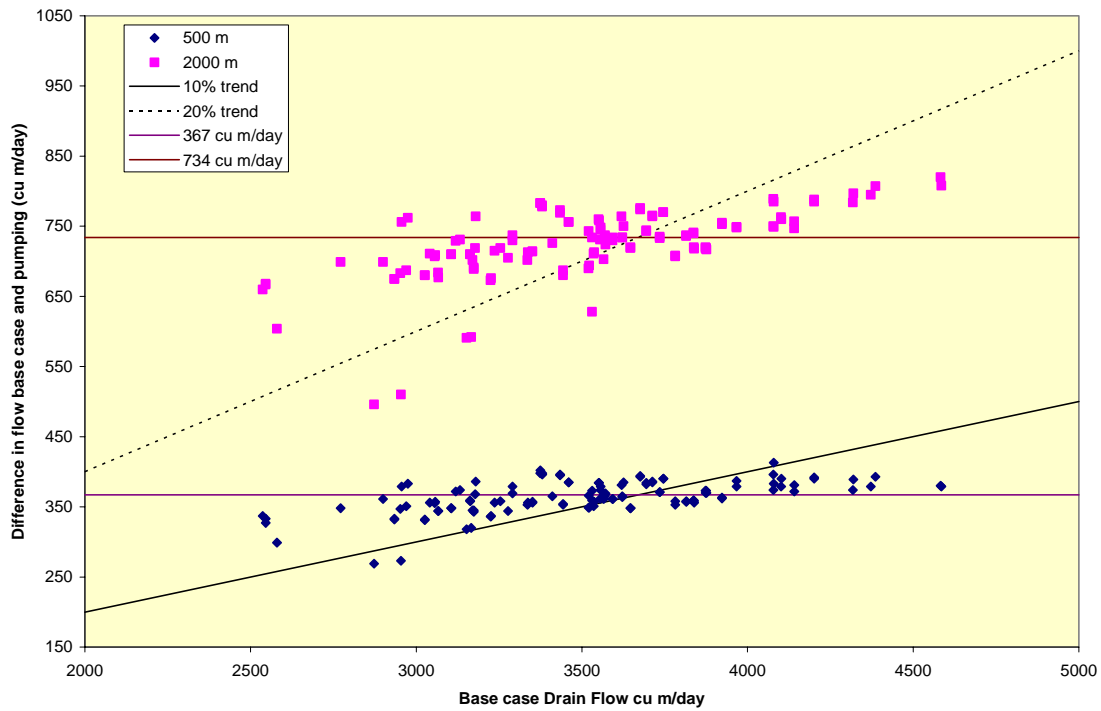


Figure 2.10: Difference in groundwater discharge compared with the base case of no pumping, for extraction at 367 m<sup>3</sup>/day and 734 m<sup>3</sup>/day – pumping 500 m from the stream. The horizontal lines represent the constant level of pumping for both cases (367 and 734 m<sup>3</sup>/day). The 10% and 20% trend lines are also shown.

Figure 2.10 shows the difference in annual groundwater discharge between the base case and both the 367 and 734 m<sup>3</sup>/day extraction cases. When recharge is high in wet years (represented by the higher groundwater discharge values in the base case) the impact on the stream is higher than the amount pumped, and conversely, in dry years, the impact of pumping is lower than the amount pumped. For instance, when considering the case for pumping at 367 m<sup>3</sup>/day, it can be seen that when rainfall is higher (corresponding to higher baseflow values), the impact of groundwater pumping on streamflow is greater than the 367 m<sup>3</sup>/day extracted. Conversely, for dry years, the impact on streamflow is less than the amount pumped. This result stems from the role of storage depletion and addition. In dry years, proportionately more groundwater comes from storage during extraction, and during wet years recharge is required to satisfy the storage deficit, thus diverting it from becoming discharge. This means that pumping will have the effect of reducing baseflow by a high proportionate amount during wetter years than during dry years. This result further highlights the role groundwater storage plays in the overall dynamics of the water system, and reinforces the importance of matching the extraction rate to the robustness of the aquifer.

Figure 2.10 also shows the effect of commencement of extraction and the lag in the impacts being felt in the stream. This is evident in the values that fall well below the main trends in each scenario.

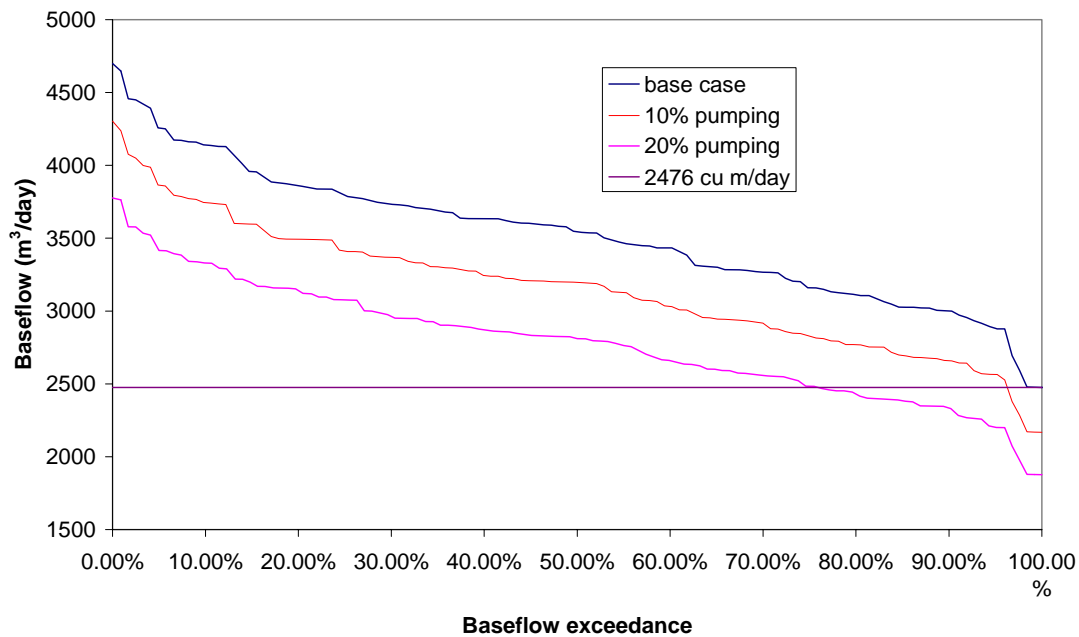


Figure 2.11: Flow duration of modelled annual baseflow for different pumping scenarios 500 m from the stream.

There is virtually no information available to describe when a stream dries, so it is assumed that in the driest years under the natural conditions the ecosystem is able to survive. If groundwater abstraction results in the baseflow falling below the lowest value for the base case too often, then the ecosystem is likely to be severely impacted by the extraction. This is based on the viewpoint that the ecosystem has evolved to manage to survive the driest years, and make maximum use of the wet years. If the severity and frequency of the low baseflow years is increased, then the ecosystem will be affected to some extent. Figure 2.11 shows the changes in annual baseflow for the modelled sub-catchment. The lowest annual baseflow volume is 2476 m<sup>3</sup>/day. If this is taken as the lowest baseflow threshold (or an *ecosystem acceptable* baseflow), the reduction in baseflow due to pumping at 10% of annual recharge potentially results in an increase frequency by 3.45% in below acceptable level conditions, whereas pumping at 20% of annual recharge results in a reduction in the flow duration of 24.5%. Below acceptable conditions may equate to no flow conditions in some circumstances, but not enough information is available for this to be determined.

It is also assumed that the distribution of baseflow during the year doesn't change between scenarios. That is, at a particular annual baseflow volume, there is a similar distribution of baseflow throughout the year for all scenarios.

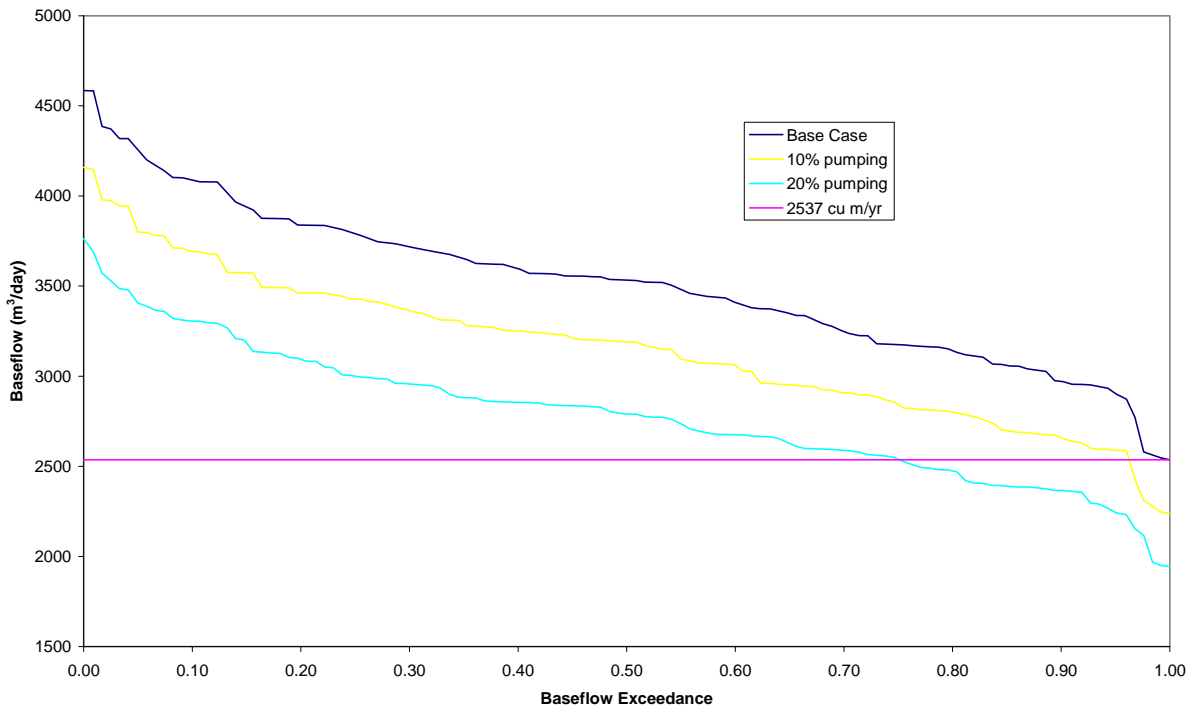


Figure 2.12: Flow duration of modelled annual baseflow for different pumping scenarios 2,000 m from the stream.

Figure 2.12 shows the annual modelled baseflow duration for different pumping rates when extraction occurs 2,000 m from the stream. The impact on the baseflow character is exactly the same as for the 500 m extraction distance.

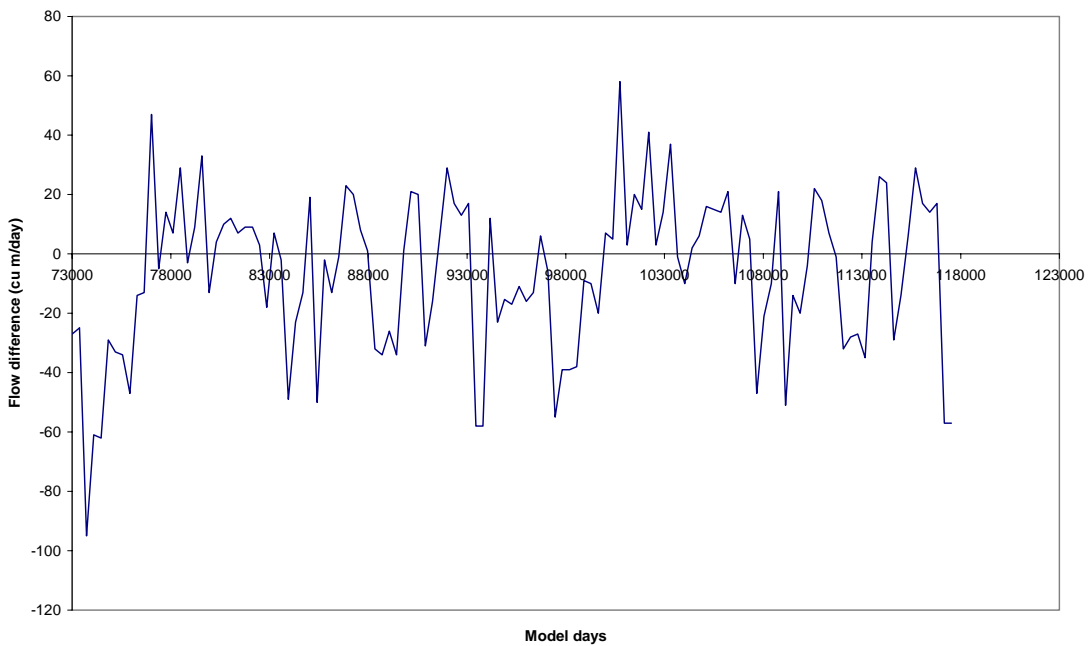


Figure 2.13: Baseflow difference between 500 m and 2,000 m extraction scenarios at 10% pumping case.

Figure 2.13 shows the difference between the modelled annual baseflow for pumping at 500 m from the stream versus pumping at 2,000m from the stream, at different times, for the 10% pumping case. Positive differences occur when the impact on the stream is greatest for the 2,000 m pumping scenario (that is, when pumping further from the stream reduces the baseflow amount by the larger value) and negative differences occur when the converse is true. The data shows that the overall difference is not large, between  $\pm 60 \text{ m}^3/\text{day}$  in any one case. Further, there is a trend correlated with wet and dry years. In wet years the impact of pumping further from the stream is greater than closer to the stream, whereas this is reversed during dry years. The reasons for this difference are not fully understood, but may be related to the buffering effect of aquifer storage. The lag between the impact on the stream from the two distances is also obvious during the first 5,000 days or so, with relatively large negative differences.

The overall magnitude of the difference between the two distances indicates that the impact on the stream will not be sensitive to the distance of extraction from the stream.

### SURFACE WATER USER PROVISIONS APPLIED TO GROUNDWATER USERS

The issue of when a groundwater user should be dealt with as accessing surface water will be decided by the time frame of the impacts of the water use on surface water.

The most immediate impact on surface water will occur where groundwater extraction causes induced recharge from a stream or water body. Where the impact of this induced recharge is fast (say, a three month period for the full impact to eventuate), then the user is behaving as a surface water user. In essence the best measure of impact will be a critical distance between a pumping bore and the surface water body.

The timing of the impacts of groundwater extraction is controlled by the rate at which a bore is pumped and the hydraulic parameters of the aquifer – that is, the values of transmissivity and storage coefficient.

There are two common types of aquifers in the ACT – a general fractured rock aquifer, and an unconsolidated sediments aquifer associated with alluvial deposits on the Murrumbidgee and Molonglo Rivers. The fractured rock aquifer has transmissivities of between 25 and 50  $\text{m}^2/\text{day}$ , and storage coefficient values of 0.01. The alluvial aquifers have transmissivity of about 200  $\text{m}^2/\text{day}$  and storage coefficients of 0.1.

Simple rules could be developed that applied a buffer zone around surface water bodies, where groundwater users within those buffer zones were classed as surface water users. The width of the buffer zone would be a function of the amount proposed to be pumped and the aquifer parameters, such that there was at least 0.1 metres of drawdown predicted at the surface water body within 3 months. Figure 2.14 shows a simple nomograph that combines these conditions for three different combinations of aquifer parameters, which are considered to cover the conditions likely to be found in the ACT. The lines on Figure 2.14 show the distance from a stream that would satisfy the conditions expressed above (0.1 metres drawdown within 3 months) for a given pumping rate, transmissivity and storage coefficient. As an example, the critical distance from a stream is about 60 m for a bore that is pumping at  $10 \text{ m}^3/\text{day}$  in an aquifer that has a transmissivity of 50  $\text{m}^2/\text{day}$  and a storage coefficient of 0.01. Thus, any bore within this distance might be considered to have such an impact on the stream that a licence to extract should be treated as a surface water licence.

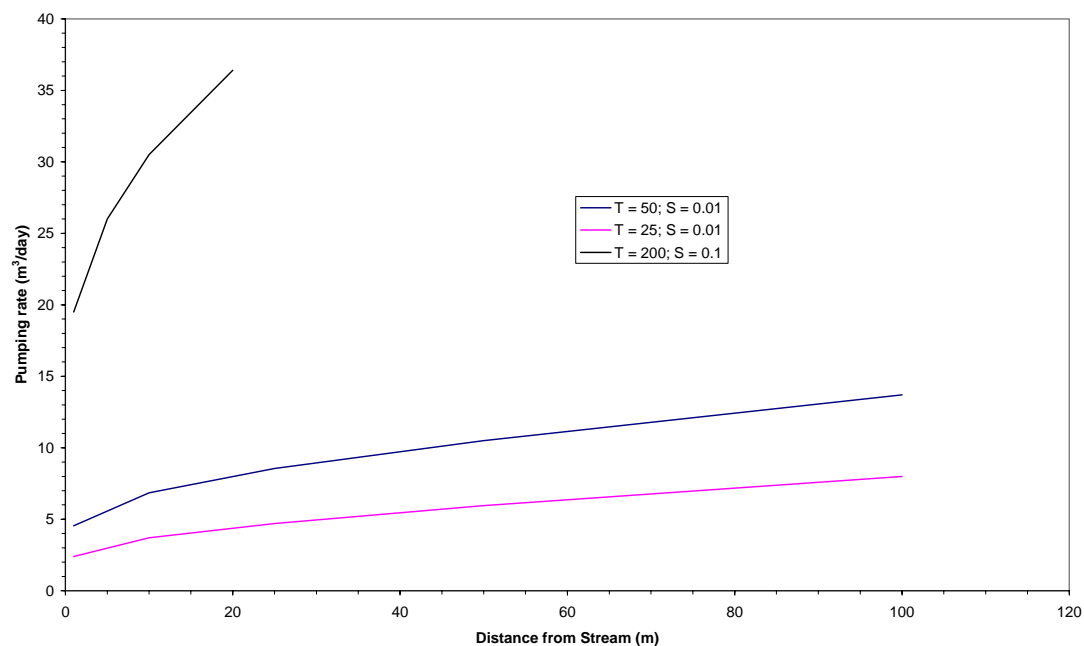


Figure 2.14: Nomograph relating the rate of pumping, distance from the pumped bore for a drawdown of 0.1 metres and the aquifer properties.

## GENERAL CONCLUSIONS

A number of general conclusions can be made based on the analysis undertaken.

- Catchments with predominantly volcanic geology have baseflow fractions of ~0.23.
- Catchments with predominantly sedimentary geology have more variable baseflow between 0.1 and 0.2.
- None of the ACT catchments (not including Murrumbidgee and Molonglo gauges) have significant buffering of the baseflow (i.e. variations in annual climate are apparent in the current year).
- Seasonal variations in the baseflow fraction are apparent, with baseflow fraction strongest in the winter/spring due to reduced ET.
- The impact on surface water flows is most likely to be the result of captured groundwater discharge, than of induced recharge from the stream.
- The impact of groundwater extraction is a long lived process, with the time to full impact varying depending on the volume pumped and the distance of the pumping from the stream.
- Groundwater extraction in wet years will have an influence on baseflow in dry years
- Aquifer storage has a low capacity to buffer a sequence of years with low recharge and is said to have a low robustness.
- There is little difference between pumping close to a stream as opposed to further from a stream.
- The impact on flows within a sub-catchment will depend on the location of the groundwater extraction points relative to the longitudinal profile of the stream in the sub-catchment.
- The largest influence on the absolute volume of baseflow in a sub-catchment is from recharge variability (linked to rainfall variability), though the proportion of baseflow to total flow does not vary with rainfall.

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