Recharge Estimation for Jerrabomberra Creek Catchment, the Australian Capital Territory

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Abstract: 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. The recently implemented Water Resources Management Plan (WRMP) for the Australian Capital Territory (ACT) limits groundwater abstraction across the entire ACT to 10% of annual recharge. This assumes that most groundwater recharge will eventually be manifested as base flow in regional streams, and hence the use of groundwater is akin to extraction of base flow. This study, commissioned by Environment ACT in the light of rising demand for bore-water allocation, comprises a review of the estimate of recharge for the Jerrabomberra Catchment in the ACT and recommendations for future management. The current estimate of mean annual recharge (25 mm) has been derived using a mass balance approach, and verified by a rainfall recharge method. Estimates of recharge derived in this study were obtained using a variety of methods. Firstly, a filtering procedure was used to partition streamflow at gauged sites into surface runoff and base flow leading to an estimate of the contribution of the ACT portion of the Jerrabomberra catchment to streamflow at gauging site 410790 at Hindmarsh Drive. Secondly, the IHACRES rainfall-runoff model was used to partition rainfall into actual evapotranspiration, surface runoff and recharge, with the resulting baseflow calculated using a physics-based groundwater discharge function. Finally, an independent estimate of recharge was derived using Darcy's Law for the region draining through the Capital Golf Course, a subsection of the aquifer of interest. These estimates indicate that the mean annual recharge is between 50 and 100mm/yr.

Keywords: Groundwater; Recharge; Sustainable yield; Modelling

1. INTRODUCTION

The groundwater resources of the Jerrabomberra Creek Catchment in the ACT are coming under development pressures as proposals to increase the existing groundwater use are considered by the ACT Government. Current groundwater use exceeds the limits set for allocation via the Water Resources Management Plan (WRMP) for the catchment. Under the WRMP, 10% of groundwater recharge has been set as the sustainable yield for groundwater abstraction. This figure has been derived using a mass balance approach, and verified by a rainfall recharge method. This paper summarizes a study of the recharge in the Jerrabomberra catchment [Evans et al., 2001].

The catchment is composed of a sequence of predominantly volcanic rock types with some interbedded ash-stones and sediments. The rocks have been fractured and faulted to varying degrees and can be considered a fractured rock aquifer covering a broad zone. The Jerrabomberra Creek valley floor is covered with a minor amount of alluvium that may contain some small sand and gravel lenses. The upper catchment (in NSW) was assumed to not be a significant contributor to groundwater resources in the ACT portion, with most of the recharge appearing as baseflow within the upper catchment.

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Hydrogeologically, the rocks behave as a fractured aquifer, with minor unconsolidated sediments along the creek line. The aquifer is usually about 60 m thick on average, with the occasional bore being drilled to depths greater than 100m. It is rare for bores of this depth to increase their yield significantly from the deeper drilling.

Recharge to the unconfined aquifers of the Jerrabomberra Creek Catchment occurs as diffuse leakage through soil material. The rate of recharge will depend on a number of variables including climate, vegetation and soil physical properties. Once within the aquifer, groundwater will flow downhill towards the discharge areas. This flow will mirror the topography, with flow lines being generally at right angles to the topographic contours.

Jerrabomberra Creek is the major discharge point, with most groundwater flow ending at the Creek. Since the aquifer is unconfined, and the catchment has reasonable relief, this implies that the Creek acts as a hydraulic divide – that is, the groundwater flow on the west side of the Creek can be considered independent of the flow on the east side. This model of recharge and flow also implies that the contributing zone for any point within the aquifer is generally the area that is immediately upslope orthogonally to the Creek.

The immediate ramification from this is that recharge occurring to the east of the Creek is not available to be used to the west of the Creek. Equally, recharge that occurs significantly across slope from an area is not available to be utilised within that area.

Thus, whilst the catchment-wide recharge volume is important in defining the sustainable yield of the Catchment, it is not the only consideration that needs to be made when allocating volumes of groundwater to be utilised in smaller sub-regions of the Catchment. Rather, the Catchment-wide recharge volume can be thought of as one of a number of end-of-valley sustainability targets that must be met. That is, it is a necessary condition that catchment recharge must not be exceeded to attain sustainable development, but it is not sufficient to meet this condition alone. It is also necessary to meet sub-regional targets to assure sustainable conditions everywhere.

The topography and geological formations within the catchment suggest that for groundwater management purposes, the catchment should be sub-divided into three broad aquifer zones (see Figure 1).

Significant development has already occurred in the Narrabundah-Symonston Zone; with 10 productions bores allocated 246 ML/yr. The annual metered usage figures are not available for any of the bores. Estimated usage is close to allocated volume. The volume allocated within this zone is already in excess of the allowable allocation for the ACT portion of the Jerrabomberra Creek catchment of 121 ML/yr as published in the WRMP.

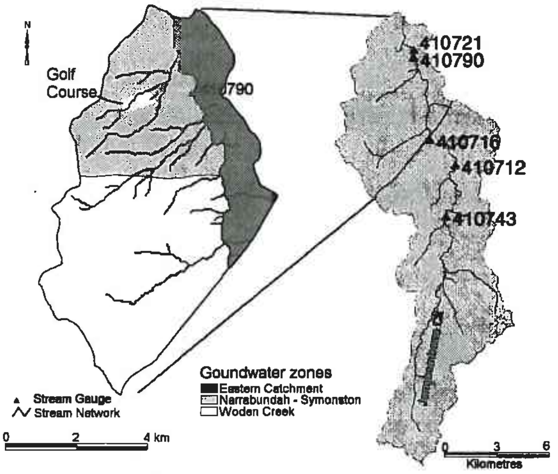

Figure 1. ACT portion (and entire catchment on right) of the Jerrabomberra Creek catchment, showing the groundwater zones, stream gauges and location of the golf course.

2. STREAMFLOW

The average annual runoff quantity was calculated from the observed record at gauging station 410743. This was adjusted to reflect total catchment flow using a weighting equation based on proportionate catchment area:

$$R_{ug} = R_g \times (A_{ug} / A_g)^{0.7} \qquad (1)$$

where the ungauged and gauged catchment is represented by the subscript ug and g respectively, and R is the runoff, and A is the area.

In order to estimate recharge for the ACT portion of Jerrabomberra Creek, the contribution to the flow at station 410790 from the ACT region was estimated by subtracting the flow at the ACT/NSW border. This flow was estimated from station 410743 using equation 1 for surface runoff (quickflow component), and allowing for the relative increase in the slowflow component noted in section 4.

3. MASS BALANCE

One method for estimating recharge is a simplified steady state mass balance between rainfall, runoff recharge and evapotranspiration. The assumptions of the mass balance approach used is that the interception storage is zero, and there is no change between initial and final storage for each timestep.

Average annual evapotranspiration was derived using the Thornthwaite method based on average monthly data. The potential evapotranspiration value derived was adjusted to reflect actual evapotranspiration, using the average monthly rainfall deficit from evapotranspiration.

The mass balance method is a quick and simple method for calculating recharge and has been accepted as an industry standard when the absence of more detailed data that would allow a more mechanistic approach. However, the primary disadvantage of the method is that recharge is the difference of two very large numbers (rainfall minus streamflow and ET) that are usually almost equal. This results in large variations in recharge as a result of small variations in the dominant terms of the mass balance equation. The accuracy of the method relates directly to the accuracy of the estimates of the other terms in the mass balance equation.

There are also errors associated with the estimation and/or measurement of the other parameters, with these errors accumulating in the recharge estimate. For example, if the error in any parameter value is of the same size as the recharge, then the error in the recharge will be 100%. The errors in rainfall measurement can be of the order of 5% [Ward et al., 1998]; the errors in streamflow measurements can be as high as 25%; and errors in the Thornthwaite ET estimate are equally as high. With the recharge estimate for the catchment being only 3.7% of rainfall, and 4.5% of ET, it is highly likely that the error in recharge is conservatively of the order of 100%.

The choice of average annual estimates of the input values may also introduce uncertainty into the recharge estimates. It is likely there will be much greater fluctuation in annual conditions that might make an average annual analysis a poor estimator of recharge. An iterative approach using smaller time steps may be more useful.

The mass balance method assumes that the initial and final conditions (most importantly soil moisture) are the same. For this reason, the hydrological year should be used, with the inherent assumption that the conditions during the dry season are the same from year to year. If this is not the case, then the mass balance will be missing a term, resulting in an additional error in the derived recharge.

There are also some questions regarding the use of the Thornthwaite ET estimator. Better estimators to use would be Priestly-Taylor (Zhang, pers. comm.) or Penman-Monteith.

The WRMP quotes a value of recharge of 25 mm/yr. It appears that this value should in fact be 29 mm/yr (see Table 1), as the proportionate area factor of 86.3% was also applied to the per unit area recharge value.

Finally, the volume of sustainable yield derived via the mass balance method has been assumed to be available from anywhere within the ACT portion of the catchment. This assumption does not fit well with the conceptualisation of the way recharge occurs and the way it is then transmitted through the aquifer as described earlier.

Table 1. Average annual parameter values for the period 1970 to 1996 used to generate recharge for ACT WRMP [Environment ACT, 1999]

Parameter	Value	
	ML/yr	mm
Streamflow	4,710	95
Actual Evapotranspiration	27,145	550
Precipitation	33,265	674
Recharge	1,410	29

4. BASEFLOW FILTERING

Long-term baseflow volume can be used as an indicator of long-term recharge providing that there are no losses from the aquifer (e.g. abstraction of groundwater or subsurface flow out of the catchment). One method of determining the baseflow component in a record of observed streamflow is to use a filter. There are a number of filters that have been described in the literature. Generally, these filters are based on assumptions about the structure of the baseflow hydrograph, or the physical processes involved. Here we will present the results for a simple mathematically-based filter (one that makes no assumption about the form of the baseflow).

Table 2. Fraction (%) of baseflow component in the total flow for the 3 stations, and 3 values of L

Station	L (days)		
	5	7	9
410743	21	17	14
410721	33	27	24
410790	30	26	24

4.1 Description of filter

The base flow component was determined from the total streamflow using the assumption that baseflow component can be obtained by determining the minimum value of streamflow discharge for a selected time interval with given width L. The second step of the filter used in this study was smoothing these minimum values using a boxcar filter of width L. The baseflow-filtering algorithm was employed for all three stations

(410721, 410790 and 410743) where the streamflow records were available using 3 values of the parameter L (5, 7 and 9 days, see Table 2).

4.2 Results

Using a filter width of 5, the filtering process suggests that the baseflow volumes at stations 410721 and 410790 are approximately 30% of the total flow, giving an estimated recharge of 26mm (see Table 1). However, this applies to the entire catchment draining to this point. The contribution from the area within the ACT is likely to be higher as the baseflow contribution is significantly stronger at these sites than at the upstream site (410743). Using the area method (equation 1), the flow at 410743 would be increased by a factor of 1.7 to give the flow at gauge 410721. Analysis of the observed flow shows that the quick flow component does scale by about this amount, but the slowflow component increases by a factor of 3.3, or almost twice the quick flow increase. If all of this increase were attributed to the area within the ACT, the estimated recharge within the ACT would be approximately 54mm/yr. Thus the filtering of baseflow gives an estimate of between 26 and 54mm/yr of recharge, depending on the assumed baseflow strength at the ungauged border site (see Table 3).

Table 3. Volumes of quick (Q_Q) and slow flow (Q_S) components for selected sites. Note that the area of the ACT fraction is based on the area of the catchment above gauging site 410721.

Station	Area	Q_S		Q_Q	
	km^2	ML/yr	mm	ML/yr	mm
410743	55.3	941	17	3835	69
410721	119.4	3113	26	6644	56
NSW fraction	85.8	1280	15	5215	61
ACT fraction	33.6	1833	54	1429	43

5. RAINFALL-RUNOFF MODELLING

One of the limitations of the mass balance method is the assumption that the initial and final conditions are the same. The most important of these is the soil moisture content. If the mass balance is calculated over a period (usually the hydrological year) where the initial and final states are very dry, then a simple mass balance calculation will be possible. However, if there is a significant difference in the initial and final volumes of water stored within the catchment (ignoring groundwater) compared with the value being determined, then a more detailed accounting scheme must be employed. Simple rainfall-runoff models can give a more reliable mass balance in such cases.

5.1 IHACRES

The IHACRES model [Jakeman and Hornberger 1993] is a simple rainfall-runoff model that uses measured rainfall and temperature to simulate streamflow using 5 or 7 parameters, depending on the number of exponential stores used in the linear routing module. The parameter values are estimated by calibrating the model against recorded streamflow for typically 2 years, and the model performance tested for a separate simulation period that also has recorded streamflow. The model used here is a modification of the catchment moisture deficit (CMD) version of Evans and Jakeman [1998].

The CMD version of IHACRES does not explicitly model recharge. Rather the model assumes that the only means of water leaving the catchment is through evapotranspiration and surface discharge at the catchment outlet. Here, the IHACRES model has been modified to include a groundwater discharge to the stream using a modified version of the model developed by Sloan [2000]. The Sloan model estimates the baseflow based on the modelled recharge, and steady state groundwater storage. For this study, the steady state term is ignored as it cancels with one of the terms in the non-steady state calculation. Here, the baseflow was modelled assuming constant recharge, transmissivity (T=300m^2/day) and effective porosity (g=0.5%). It should be noted that if the Sloan model is used to estimate the baseflow only (i.e. ignoring water table fluctuations), then the model is sensitive only to the ratio $T/(gL^2)$ where L is the length of the hillslope.

Due to time and data limitations, we adopted a 2-hillslope model (1.5 and 8.5km), optimising the relative areas to reproduce the observed streamflow (optimised value was 95% of recharge going to 1.5km hillslope). Further development of this model could include use of a high resolution DEM (25mx25m) to determine the distribution of distances from the stream network removing the need to optimise some of the parameters of the groundwater model.

In addition to the inclusion of the groundwater model, an estimate of the potential evapotranspiration (PET) was used instead of temperature. Daily PET estimates were obtained using the Penman-Monteith method for grass 0.12m high [Grayson et al., 1996]. The daily net surface radiation needed for this was derived using an adaptation of model 2 in Vardavas et al. [1997] [Croke, Hatzidimitriou and Vardavas, in preparation]. This model requires daily mean temperature, relative humidity and cloud cover (derived from sunshine hours). The IHACRES parameters were then estimated using the surface runoff, rainfall and potential evaporation data.

The period over which the IHACRES_GW model was applied was defined by the availability of the climate data needed to calculate the daily PET, and streamflow. The resulting period was from February 1, 1978 to April 1, 1997. The mean rainfall for the period was 633 mm/yr, PET was 1214 mm/yr, with the model estimating actual ET at 536 mm/yr. The estimated streamflow volume was 4055 ML/yr, or 100 mm (for an area of 40.35 km^2). The average recharge (and hence baseflow volume) given by the model was 39 mm/yr.

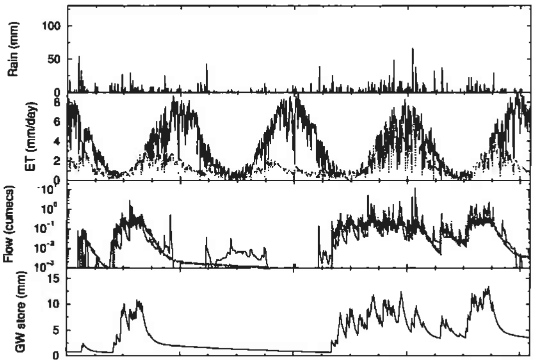

Figure 2. Results from IHACRES_GW model. The second panel shows potential ET (black line) and actual ET (grey line), while the third panel shows observed flow (black line) and modelled baseflow (grey line).

6. DARCY'S LAW

Recharge volumes can also be estimated from an analysis of groundwater movement using Darcy's Law;

$$Q = KIA \tag{4}$$

where Q is the volume of groundwater flowing through a cross-sectional area A, under a hydraulic gradient I, with a hydraulic conductivity of K. Data describing the hydraulic conditions for the fractured rock aquifer are unknown at this stage. However, an instructive example can be used to provide some independent estimates on recharge.

The following example is based on a conceptualisation of the groundwater flow system operating within the area of the Capital Golf Course. It is assumed that the flow is predominantly down slope, with some convergence towards the break of slope located near the eastern boundary of the Capital Golf Course. The width of the downslope end of the flow section is set at 400 m – this is chosen to be consistent with an approximate radius of influence of 100 m for the two operating bores on the Golf Course. The width of the upslope end of the flow region is set at 1,500 m, with a flow length of 1,800 m.

A range of values for both hydraulic conductivity and hydraulic gradient were estimated as providing bounding values that reflected expected conditions. The values of hydraulic conductivity and specific capacity that were found to provide a best fit for the groundwater component of the IHACRES_GW model were 5 m/day and 0.5%, respectively.

Table 4. Estimated parameter values.

Parameter	Value
Aquifer thickness	60 m
Width of flow section	400 m
Hydraulic Conductivity	1 – 5 m/day
Hydraulic Gradient	0.005 – 0.025
Specific capacity	0.5%
Radius of bore influence	100 m
Contributing area for groundwater flow	171 ha
Average Daily pump rate	0.75 ML

Table 5. Darcy throughflow volumes (ML).

Hydraulic gradient	Hydraulic Conductivity			
	1 m/day		5 m/day	
	Year	Day	Year	Day
0.025	219	0.60	1095	3.0
0.005	43.8	0.12	219	0.60

Table 6. Recharge rate in mm/yr (based on Darcy throughflow volumes from Table 5 and a contributing area of 171 ha).

Hydraulic gradient	Hydraulic conductivity	
	1 m/day	5 m/day
0.025	128	640
0.005	26	128

The values for throughflow and recharge given above show a broad range. The value for a combination of hydraulic gradient and conductivity of 0.025 and 5 m/day is discounted as being physically unobtainable (recharge will never be equal to rainfall). However, the remaining values range across the same breadth of values as the recharge estimates obtained from the mass balance/modelling approaches. If it is assumed that the hydraulic conductivity is more likely to be 5 m/day, then the calculations suggest that the hydraulic gradient is low.

For a radius of bore influence of 100 m and the aquifer property estimates in Table 4, it can be shown that there is a volume of aquifer storage of 19ML within the zone of influence of the two pumping bores on the Golf Course. The average daily pumping rate for these bores is 0.75 ML, and, from Table 4, it is likely that there is a daily throughflow of up to 0.60 ML. From these volumes it can be seen that the pumping rate is slightly in excess of the estimated daily throughflow, with the balance of water being drawn from aquifer storage during pumping periods. The reduction in aquifer storage would be replenished during periods of no pumping. During periods of very low recharge (as can be seen during 1994 from the modelling above) almost all water would come from aquifer storage. This volume, though, is a finite amount, and continued pumping over long periods of low recharge/throughflow would result in depleted storage volumes. Anecdotal evidence from the Golf Course suggested that the pumps did de-water during the 1994 dry spell.

The ratio of daily pumping rate to aquifer storage is very high at about 4%. The more informative measure here though is the ratio of the difference between daily pump rate and daily throughflow rate to aquifer storage. At recharge rates of 128 mm/yr, the ratio would be about 0.8%, and at recharge rates of 26 mm/yr the ratio would be about 3%.

The mitigating circumstance that might allow the current pumping regime to be continued lies in the large variability of recharge rate as expressed above by all the timestep methods. Within the last 20 years of data there has only been two consecutive years of low recharge and these are generally followed by a recharge year that is 5 to 6 times greater than the preceding. This has the effect of topping up the aquifer storage depletion. However, this practice is only supportable when the aquifer depletion levels are the same order of magnitude as the difference between annual recharge events. The decision to allow pumping to deplete aquifer storage during dry periods with the knowledge that wet years will replenish the overdraft is a common approach in these types of aquifers. The practice is equivalent to averaging recharge for wet and dry periods over a short time. It can, however, sometimes be misconstrued and used as a justification to allow much longer term depletion of storage as a means of allowing a higher sustainable yield than is justified. This latter case is unsustainable.

7. CONCLUSIONS

The mass balance approach can give an estimate of the recharge providing that there is no significant change in the initial and final catchment water storage. Using a suitable rainfall-runoff model, such as IHACRES_GW, reduces the influence of such changes, enabling more accurate estimates of recharge in highly variable climates. The inclusion of the physics-based groundwater model Sloan [2000] enables use of the IHACRES model in investigations of groundwater storages.

The estimated recharge rate for the ACT portion of the Jerrabomberra Creek catchment ranges between 50mm/yr and 100mm/yr depending on the method used. The errors in the input data (rainfall, evapotranspiration) result in large uncertainty in estimated recharge. For management purposes, it is recommended that a recharge rate of 60mm/yr be adopted, with the ACT portion sub-divided into 3 groundwater zones: Narrabundah-Symonston, Woden Creek and Eastern Catchment zones.

8. ACKNOWLEDGEMENTS

The authors wish to thank Dan Diaconu (Environment ACT, Canberra, Australia) for providing us with all available data, and Lachlan Newham for assistance with GIS processing. This project was funded by Environment ACT.

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