Water and salt dynamics in the Clare Valley

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CONTENTS

FIGURES

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WATER AND SALT DYNAMICS IN THE CLARE VALLEY

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A water budget for two sub-catchments of the Clare Valley indicates that inputs of water from rainfall are at least matching outputs via stream flow, groundwater pumping and lateral groundwater flow out of the aquifer. Preliminary results from a first-order salt balance suggest that salt is probably being exported from the catchments, and that the rate of exportation may be up to 25 times the rate of importation. This is most likely the result of clearing of native vegetation (80–100 years ago) which has led to increased recharge and flushing of salt from the aquifer. Preliminary calculations based on a groundwater – surface-water chloride mass balance and bore hydrographs also reveal that, of the total annual stream flow in the Eyre Creek catchment, <3 mm/yr is derived from groundwater discharge.

INTRODUCTION

The Clare Valley is one of South Australia's premium wine grape growing districts. The majority of vineyards in the valley are irrigated with water that is pumped from surface storages (dams and creeks) and/or the underlying fractured rock aquifers. Total annual groundwater extraction from metered production wells is currently on the order of 1600 ML/yr. However, little is known about the size of the groundwater resource and the rate at which it is being replenished by rainfall.

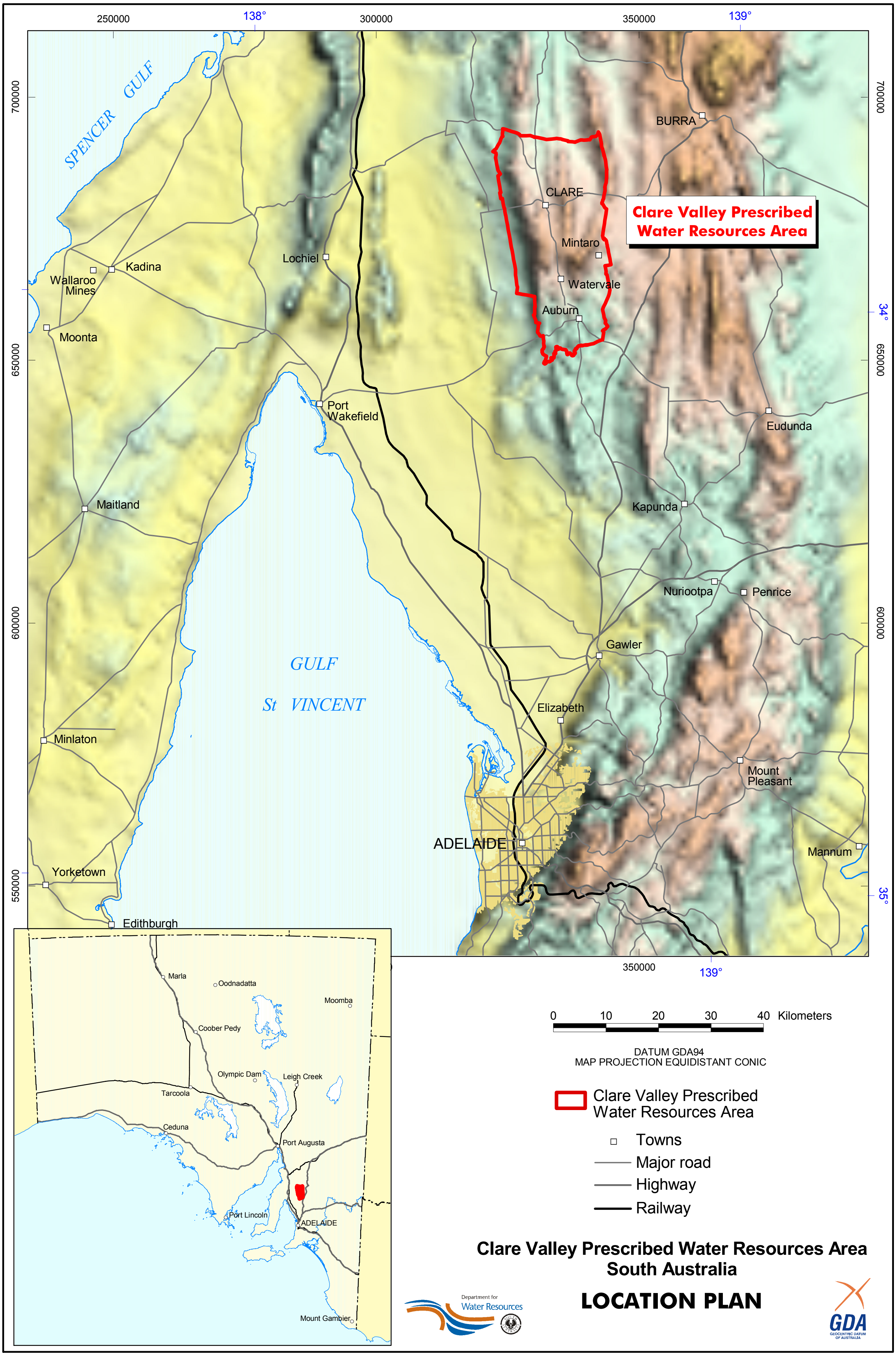
This report forms part of a comprehensive investigation into the hydrogeology and groundwater resources of the Clare Valley. This study was undertaken to determine if the groundwater system is in steady-state with respect to either water or salt fluxes. Water and salt balances are classical techniques for determining whether a groundwater system is in a steady- or transient state. Under ideal conditions, where all components of the water and salt balance are known, it may be possible to calculate aquifer recharge rates using this approach. However, these conditions are rarely satisfied due to difficulties in obtaining reliable estimates of each component. In particular, water and salt balances in fractured rock aquifers are especially difficult because groundwater flow is restricted to a small proportion of the geological formation and not through the entire rock.

Also yet to be quantified is the annual flow of groundwater into streams. For example, suppose an aquifer receives recharge at an average rate of 100 mm/yr. This value can only be used for managing the resource if all of the water enters a regional flow regime and is not lost from the aquifer via groundwater discharge to streams. This is of particular concern in fractured rock aquifers where groundwater can travel relatively large distances over short time scales (10's m/d is common). To address this issue, we have used a groundwater – surface-water chloride mass balance and a simple new approach using bore hydrographs to estimate the proportion of annual stream flow that comes from groundwater discharge.

SITE DESCRIPTION

The Clare Valley, as defined for the purpose of water resources management, is located ~100 km north of Adelaide and covers an area of ~700 km^2 (~17.5 x 40 km; Fig. 1). The region incorporates the townships of Clare, Sevenhill, Penwortham, Watervale, Mintaro and Auburn; all of which service the surrounding agriculture and horticulture industries. Water is imported to Clare and Auburn from the Murray River for domestic and municipal supplies, while all other towns rely on either local surface-water or groundwater resources.

Mean annual rainfall over the Clare Valley is in the range 550 to 650 mm/yr, with a strong positive correlation between rainfall amount and surface elevation. Whilst the majority of rainfall occurs during the winter months, thunderstorms also account for short-term heavy falls during the summer. Non-irrigated pasture is the main land



Clare Valley Prescribed Water Resources Area
South Australia

LOCATION PLAN

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Figure 1

use on an area basis, however the viticulture and wine making industries account for the majority of income and water use throughout the region.

There are a number of sub-catchments in the Clare Valley (Fig. 2). The surface-water flow regime can be broadly divided into two large river catchments; the Wakefield River which flows to the south, and the Broughton River which flows to the north. The surface-water divide between these two catchments occurs ~2 km north of Penwortham. We are only studying one sub-catchment in the headwaters of the Wakefield catchment (Eyre Creek) and a small cluster of adjoining sub-catchments in the Broughton catchment (Hutt River, Armagh Creek, Stanley Flat). The lack of stream flow gauging stations prevented analysis of other sub-catchments.

Groundwater occurs in fractured rock aquifers of varying lithology (quartzite, sandstone, siltstone, dolomite, shale) in the Clare Valley. Very little is known about recharge mechanisms and groundwater flow in these systems. In fact no reliable methods exist for estimating these parameters in fractured rock aquifers. The watertable follows a subdued form of the topography and hence surface-water catchments. A flow divide occurs in the watertable ~2 km north of Penwortham juxtaposed to the surface-water divide. Groundwater flows from this divide to the north towards Clare and to the south towards Auburn (Fig. 2). Groundwater salinity and yield vary considerably throughout the valley, however neither parameter exhibits any distinct spatial trends. Salinity ranges from <500 mg/L to >7000 mg/L, while bore yield ranges from 0.1 to 25 L/s (Morton et al., 1998).

METHODS

THEORY

Water and salt balance calculations

The general expression for a water balance is:

$$\text{water in} - \text{water out} = \Delta S \qquad (1)$$

where ΔS = change in groundwater storage.

Thus, when ‘water in’ does not equal ‘water out’, the excess or deficit of water goes into or out of storage, respectively. Equation (1) can be written more specifically in terms of the water in and water out terms as:

$$P - (ET + \text{runoff} + \text{groundwater outflow}) = \Delta S \qquad (2)$$

where P = precipitation (m^3/yr)

ET = evapotranspiration (m^3/yr)

Runoff = surface runoff, which incorporates loss of water to dams and surface water plus groundwater discharge from the catchment in streams (m^3/yr)

groundwater outflow = lateral outflow from the catchment (m^3/yr).

In this report, the results of the water balance are expressed as water in, water out and in/out ratio:

$$\text{water I/O} = \text{water in/water out} \qquad (3)$$

Similarly, the general expression for a catchment scale salt balance is:

$$\text{salt in} - \text{salt out} = \Delta S_{SALT} \qquad (4)$$

where S_{SALT} = change in mass of salt stored in the catchment; and in most field settings equation (4) can be simplified to:

$$P.C_P - [(\text{stream flow} \times C_S) + (\text{groundwater outflow} \times C_G)] = \Delta S_{SALT} \qquad (5)$$

where C_P = mean annual salt concentration in precipitation (mg/L)

stream flow = mean annual volumetric stream flow (m^3/yr)

C_S = flow-weighted mean salt concentration in stream water (mg/L)

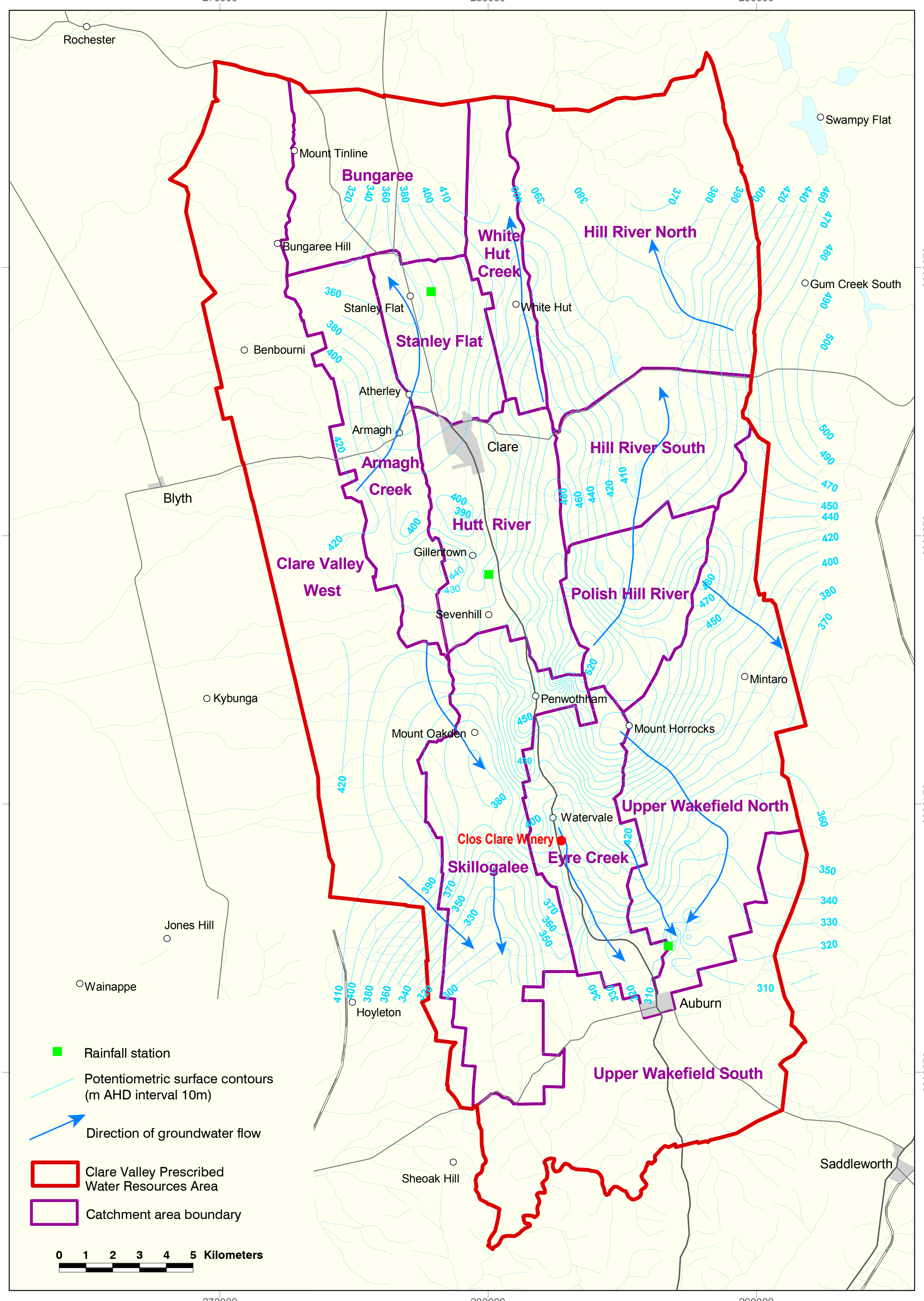
C_G = mean salt concentration of groundwater leaving catchment (mg/L).

Again, we present results of salt balance calculations in this report as salt in, salt out and in/out ratio:

$$\text{salt I/O} = \text{salt in/salt out} \qquad (6)$$

Groundwater discharge to streams

Two different approaches have been adopted for estimating the annual loss of groundwater to streams. The first relates the hydrographic response of watertables near streams to the volume of groundwater discharging into the stream. Figure 3 shows an idealised scenario of monthly stream flow and groundwater hydraulic head distributions as may be found at sites like



Clare Valley Prescribed Water Resources Area
South Australia
POTENTIOMETRIC SURFACE CONTOURS

Department for Water Resources

GDA

Figure 2

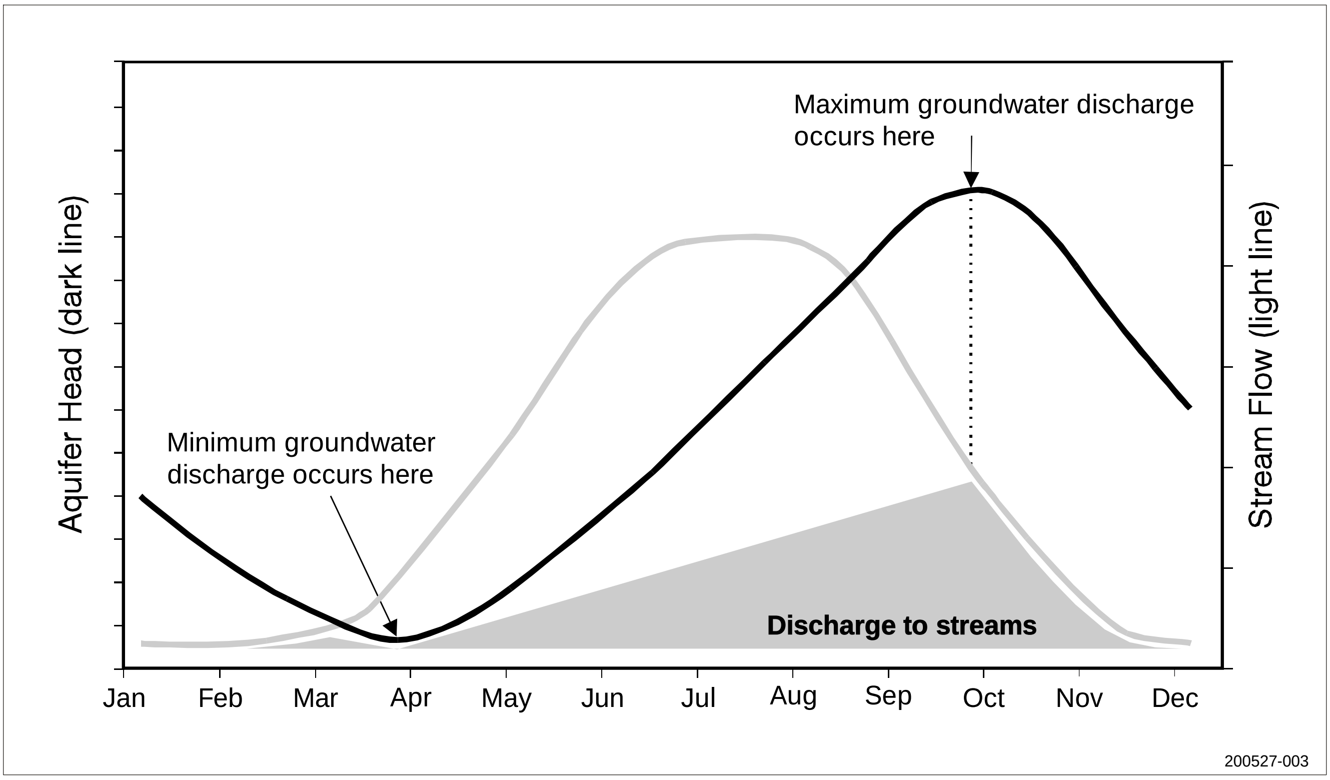


Figure 3 Schematic representation of the model used to determine annual groundwater discharge to streams. In this example, at the time of minimum and maximum groundwater discharge rates, there is 0% and 100% groundwater in the stream respectively.

those in the Clare Valley. We assume that when the hydraulic head in the aquifer is at a maximum (October in this case), the groundwater discharge rate into the stream is also at a maximum. Conversely, when the hydraulic head is at a minimum (April in this case), so too is the volumetric groundwater discharge rate. It is highly probable in situations such as those depicted in Figure 3 that at the time of maximum groundwater discharge, the total stream flow is derived from groundwater (i.e. base flow).

Therefore, providing the stream flow record from which mean monthly flows are calculated is long enough to smooth any rare, extreme rainfall (and hence flow) events, the maximum groundwater discharge rate is simply equal to the stream flow rate at the time of peak hydraulic head.

Unfortunately, it is more difficult to estimate what fraction of the total stream flow rate is derived from groundwater discharge when the hydraulic head in the aquifer is at a minimum. Hence we have chosen to leave this parameter as a variable that can range between 0 and 100% in the annual discharge calculations. Once the minimum fraction of stream flow that can be derived from groundwater has been set, a linear trend is used to estimate the proportion of total stream flow that is baseflow at any other time of the year, which can then be converted into a volumetric discharge rate using the peak groundwater discharge. That is, the percentage of stream flow that is groundwater at any time of the year can be determined using:

$$\text{\% groundwater} = \min\% + \frac{(\max\% - \min\%).t}{t^*} \qquad (7)$$

and hence, the volumetric groundwater discharge rate at that time is:

discharge = (% groundwater) x (maximum groundwater discharge) (8)

where min.% = the minimum percentage of stream flow that is derived from groundwater

max.% = the maximum percentage of stream flow that is derived from groundwater

t = the time since the minimum or maximum discharge rate occurred (which-ever is lower)

t* = the total time between minimum and maximum discharge rates or maximum and minimum discharge rates, depending on where t is in Figure 3.

A steady-state chloride mass balance between groundwater and surface water was also used to estimate the mean annual volume of groundwater discharge to streams. Assuming conservative behaviour of Cl, the following expression states that the total mass of chloride in the stream is equal to the mass of Cl introduced from run-off plus the mass of Cl added by groundwater discharge:

$$Cl_S.Q_S = Cl_R.Q_R + Cl_{GW}.Q_{GW} \qquad (9)$$

where Cl is the chloride concentration;

Q is the volumetric flow rate, and

subscripts S, R and GW represent stream flow, run-off and groundwater.

Thus, the total annual groundwater discharge to streams can be determined from daily stream flow and salinity data, and a re-arrangement of Equation (9):

$$Q_{GW} = \frac{Q_S.(C_S - C_R)}{(C_{GW} - C_R)} \qquad (10)$$

INPUT DATA

This section presents the necessary input data for both the water and salt budgets for each sub-catchment. Data is also supplied for the baseflow calculations for the Eyre Creek catchment. Chloride ion concentration was used as a proxy for total salinity in this study, due to its conservative behaviour in most groundwater systems.

Eyre Creek catchment

Area

The area of the Eyre Creek catchment is 3570 ha (Department for Environment, Heritage and Aboriginal Affairs, 1999).

Rainfall

There are at least two reliable long-term rainfall records for the Eyre Creek catchment, one from Watervale and the other from Auburn. Both gauges have monthly rainfall records from 1880 until present. The mean annual rainfall at Watervale over this period is 656 mm/yr, while the average at Auburn is 596 mm/yr. The Watervale value was assumed to be most representative of the average rainfall over the Eyre Creek catchment. For the years in which individual water and salt balances were constructed for this catchment, the annual rainfall at Watervale was 615 mm (5.95–4.96) and 629 mm (2.98–1.99). Because the mean annual rainfall is determined from historical records, the error in using this figure for a long-term water balance is likely to be less than ± 5%.

Surface-water discharge from the catchment

There are two equipped stream flow gauging stations situated on the Eyre Creek, one at Watervale Oval and the other just north of Auburn prior to its confluence with the Wakefield River. Both stations measure flow rate and salinity on a daily basis. The average annual flow at the bottom end of the catchment (Auburn) is 345.9 ML/yr, although it should be noted that since this gauge was installed almost four years ago, it has intermittently been out of operation. Nevertheless, the flow data set from this gauging station is the most complete of any collected throughout the Clare Valley to date, and was therefore used for the groundwater discharge to streams calculation. The error associated with this figure is likely to be of the order ± 10%. Mean and median monthly and annual stream flow rates are shown in Table 1, and the full data set is presented graphically in Appendix A.

Near-stream groundwater hydrograph

The hydrograph used to estimate the annual volume of groundwater lost to streams was obtained from a well located ~100 m from Eyre Creek in Clos Clare Winery (Fig. 2). The sinusoidal nature of this hydrograph (Fig. 4) allows the timing of both minimum and maximum groundwater discharge to be clearly identified as May and October, respectively.

Table 1 *Mean and median monthly and annual stream flows for the Eyre Creek near Auburn, 1995–99*

Month	**Mean** (ML/month)	**Median** (ML/month)
January	0.16	0.07
February	0.30	0.24
March	0.15	0.17
April	0.25	0.30
May	0.10	0.05
June	1.74	0.41
July	34.73	23.32
August	61.88	17.76
September	17.96	3.79
October	3.09	2.05
November	166.89	0.55
December	0.42	0.21
ANNUAL	345.9	182.5

Evapotranspiration

Estimating total water loss by evaporation and transpiration from the catchment is likely to be the most erroneous component of the water balance (possibly up to ± 40%). The total water use (evapotranspiration) by wine grapes in the Clare Valley is estimated to be ~700 mm/yr (T. Thomson, Primary Industries and Resources SA, pers. comm., 2000). If non-irrigated pasture uses half this amount of water annually (i.e. ~350 mm/yr), then the total evapotranspiration from the catchment would amount to 15 753 ML/yr given that 768 ha is covered by grapes and the remainder is non-irrigated pasture (D. Cresswell, Department for Water Resources, pers. comm., 2000).

Surface storages

The total volume of surface-water storages in the Eyre Creek sub-catchment is 967 ML (Department of Environment, Heritage and Aboriginal Affairs, 1999). On-stream and off-stream dam development in this region has been closed as the surface water in the catchment is already over allocated. We have assumed that the dams are completely filled and emptied each year, so that the value of 967 ML/yr can be used to represent the annual loss of rainfall to dams (and subsequently to stock water, domestic supplies and irrigation). Hence, the estimate of 967 ML/yr for the total volume of surface water lost annually to dams has an error associated with it, which we assume is ± 25%.

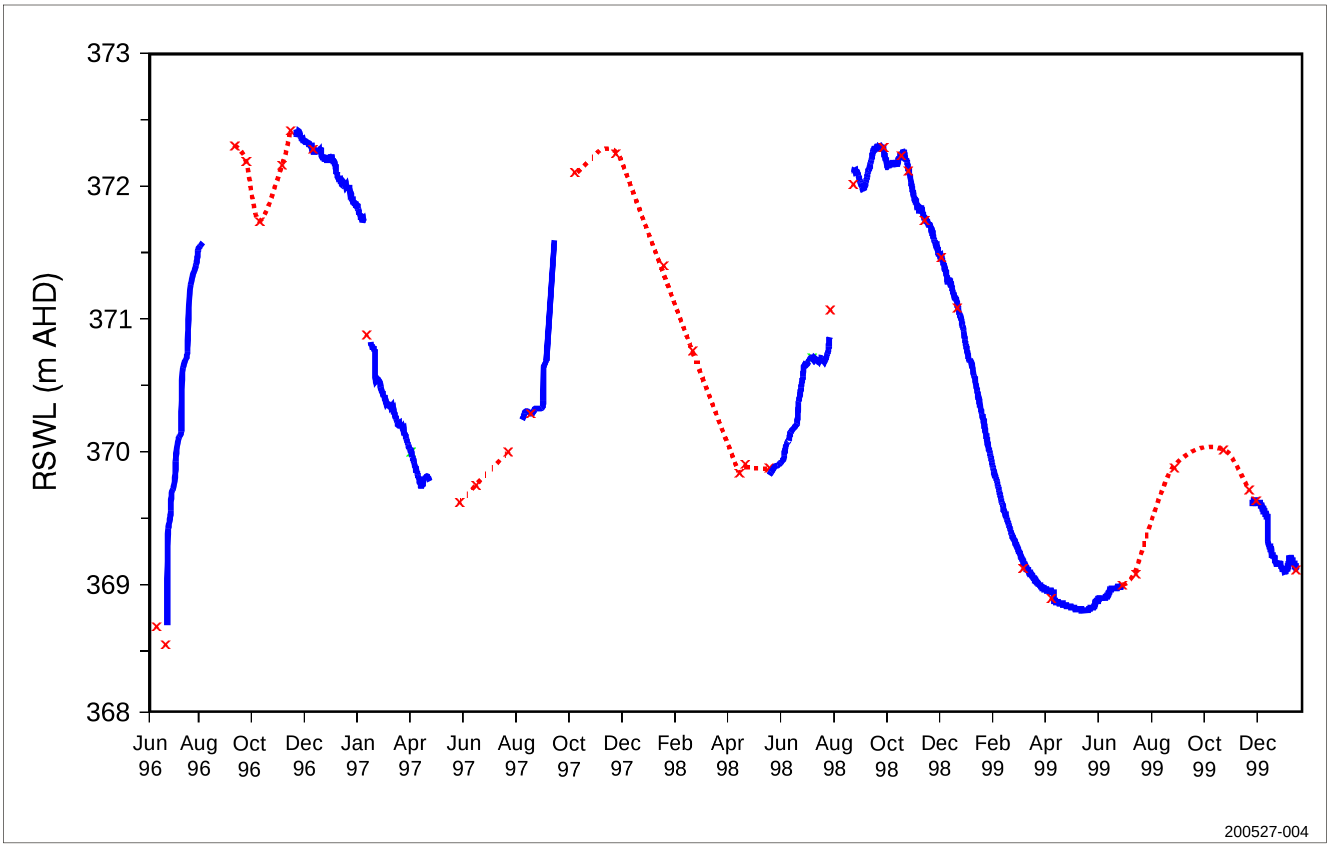


Figure 4 Hydrograph showing seasonal variations in water table elevation at Clos Clare Winery. The water table is generally highest in October and lowest in April.

Groundwater extraction

Although most of the production wells in the Eyre Creek catchment are metered, comprehensive monitoring of groundwater extraction has only been undertaken over the last one to two years. From this short record, the mean annual volume of groundwater used for irrigation is 187 ML/yr. Using this estimate as the long-term groundwater usage introduces an error of the order ± 20%.

Natural groundwater outflow

In order to estimate the total volume of groundwater that naturally flows out of the Eyre Creek catchment each year, the aquifer is assumed to behave as a single porosity media (cf. fractured rock aquifer). This approach enables the use of Darcy's Law to estimate the volumetric outflow (Q) from the system:

$$Q = T.i.w \tag{11}$$

where T = the average transmissivity of the aquifer
i = the hydraulic gradient
w is the width of the aquifer.

Using conventional flow-net analysis with a value of 6.8×10^{-5} m^2/s for T, and a range of values for i (0.025–0.05) and w (1–2.5 km), we have determined Q to be ~373 ML/yr.

Whilst the assumption that this aquifer behaves as a single porosity media is theoretically incorrect, Darcy's Law may be used to obtain first order estimates of Q if T can be estimated with a reasonable degree of confidence. Ideally one should determine the average T by calibrating a groundwater flow model to observed head distributions using only T as the fitting parameter. The value of T used above (6.8×10^{-5} m^2/s) was the mean value obtained from consecutive 5 m pump-packer aquifer tests down a 100 m well at Watervale (Fig. 5). Further evidence that this value is a reasonable estimate of the true mean value is that it compares well to a mean value of 4.6×10^{-4} m^2/s determined from 31 aquifer tests throughout the Clare district (D. Clarke, DWR, pers. comm., 2000). We attribute the factor of ~7 difference between the mean Watervale transmissivity value and that determined by D. Clarke to the fact that the majority of aquifer tests used to obtain the latter estimate were conducted in relatively shallow wells, where average transmissivities are obviously higher than for deeper wells (Fig. 5). Results from a similar series of pump-packer aquifer tests at Wendouree Winery (~10 km N of the Eyre Creek catchment) suggest the mean aquifer transmissivity is more in the order 6.6×10^{-4} m^2/s. Thus, we shall test the effect of using this value instead of the Watervale estimate on the water and salt balance calculations.

Chloride in rainfall

The chloride concentration in rainfall is measured using specially constructed rain gauges that are sampled approximately once per month. The amount-weighted mean Cl concentrations of rainfall at Auburn and Sevenhill are 5.2 mg/L and 3.7 mg/L respectively. We use the average of these two values (i.e. 4.5 mg/L) as the mean Cl concentration of rainfall throughout the catchment, and assume an error of ± 10% for this value.

Chloride in surface (creek) water

Creek water has only been sampled for Cl analysis on rare occasions over the last decade, which means this parameter had to be estimated from stream salinity records. The flow-weighted mean salinity of creek water sampled at the Eyre Creek gauging station near Auburn is 430.4 S/cm. If the total dissolved solids (TDS) concentration of creek water is 60% of the EC value (i.e. TDS = 0.6 x EC), and Cl is assumed to constitute 25% of the TDS concentration, then the flow-weighted mean Cl concentration of creek water is likely to be ~65 mg/L. Complete records of stream flow and salinity from the Auburn Gauging Station are provided in Appendix A.

Estimating the flow-weighted mean Cl concentration of stream flow using this approach introduces a significant error, possibly in the range ± 20%.

Chloride in groundwater outflow

The mean Cl concentration of groundwater in the Eyre Creek catchment is 584 mg/L. As we do not know the actual volume nor salinity of groundwater flowing laterally out of the aquifer, this estimate of outflow Cl is expected to have an error of ± 20%.

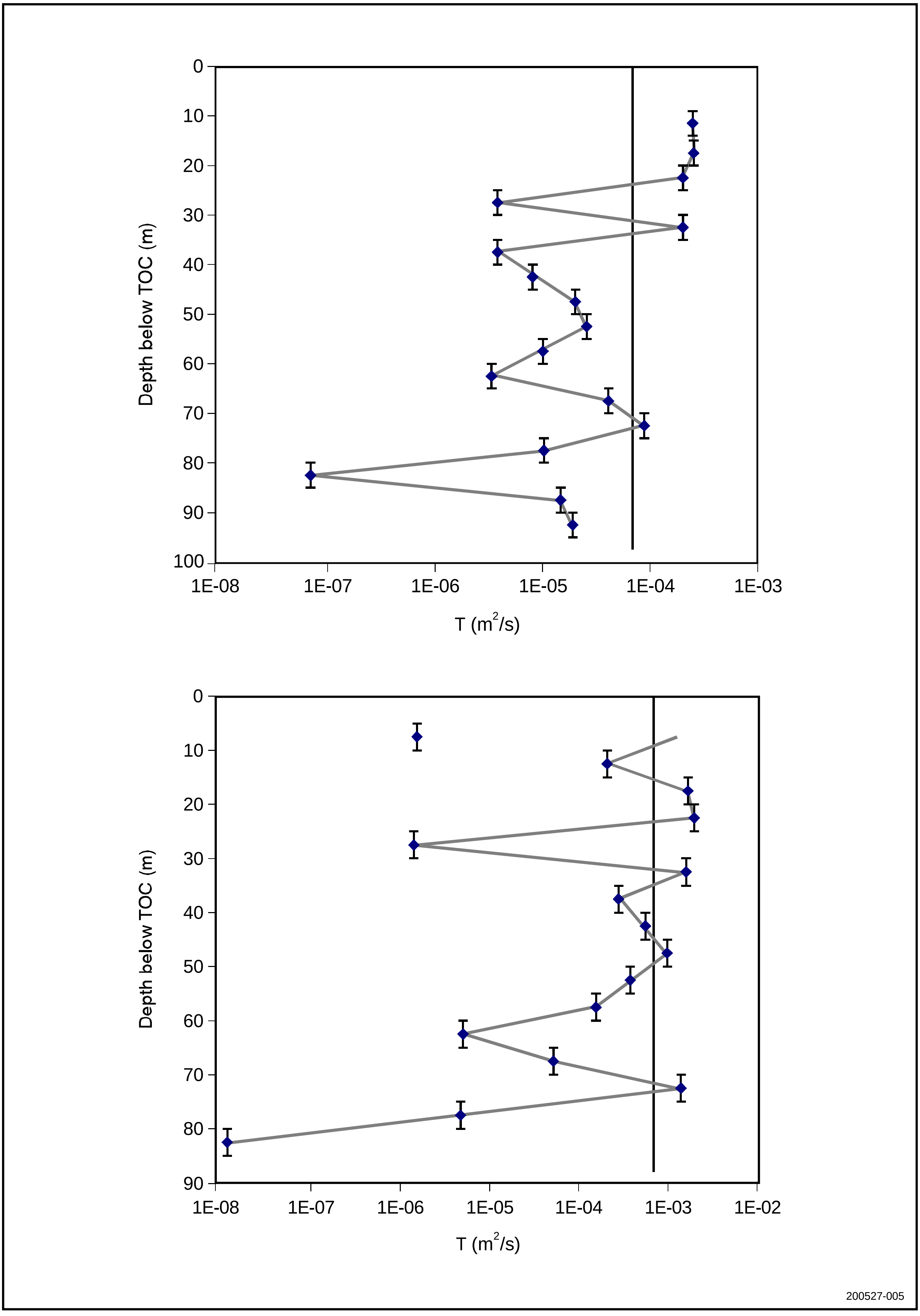


Figure 5 Transmissivity values determined from pump-packer aquifer tests at (a) Watervale Hill and (b) Wendouree Winery. The solid line represents the mean transmissivity at each site

Northern catchments (Hutt River, Armagh Creek, Stanley Flat)

Area

The areas of the Hutt River, Armagh Creek and Stanley Flat sub-catchments are 4299, 3733 and 2267 ha respectively; giving a combined total of 10 299 ha.

Rainfall

Monthly rainfall data was recorded at the Clare Post Office between 1862 and 1994 (133 years). The mean annual rainfall over this period is 632 mm/yr (Bureau of Meteorology, 2000). Using this value for the water balance of the northern sub-catchments introduces an error of less than ± 5%.

Surface-water discharge from the catchment

There are no stream flow gauging stations on any of the creeks in the Hutt River, Armagh Creek or Stanley Flat sub-catchments of the Clare Valley. Thus, surface-water discharge from this northern region was estimated by multiplying the mean annual runoff value for each sub-catchment (52 mm/yr, 39 mm/yr and 37 mm/yr respectively; Department of Environment, Heritage and Aboriginal Affairs, 1999) by its respective area, and subtracting the total surface storages (below). Using this approach, we obtained a value of ~2773 ML/yr for the mean annual surface-water discharge from the area. This value is obviously only a rough estimate and hence carries with it an error of approximately ± 20%.

Evapotranspiration

Total annual evapotranspiration from the northern catchments was estimated using the same approach adopted for the Eyre Creek catchment (i.e. 700 mm/yr for grapes and 350 mm/yr for non-irrigated pasture). A value of ~42 489 ML/yr was obtained for the total annual ET by assuming 1402 ha of the total 10 299 ha (i.e. 13.6%) is covered by grapes, and the remainder is non-irrigated pasture (D. Cresswell, DWR, pers. comm., 2000). As for the Eyre Creek sub-catchment, there are potentially very large errors associated with these estimates of evapotranspiration, possibly up to 40%.

Surface storages

The total volume of surface-water storages in the Hutt River, Armagh Creek and Stanley Flat catchments are 1032 ML, 473 ML and 252 ML respectively (Department Of Environment, Heritage and Aboriginal Affairs, 1999). Again, we assumed that the dams are completely filled and emptied each year, so that the total value (1757 ML/yr) could be used to represent the annual loss of rainfall to dams. The error in using this assumption is likely to be ± 25%.

Groundwater extraction

The combined total volume of groundwater extracted each year for irrigation in the three northern sub-catchments is on the order of 811 ML/yr, although as mentioned in the Eyre Creek section, this value has only been determined from approximately two years of monitoring data and hence has a large uncertainty (± 20%).

Natural groundwater outflow

Mean annual groundwater flow out of the northern catchments was estimated using the same approach that was applied to the Eyre Creek catchment (i.e. flow net analysis with Darcy's Law, Equation 11). A value for Q of 5676 ML/yr was determined using a mean aquifer transmissivity (T) of 6.6×10^{-4} m^2/s and a range of values for i (0.012–0.023) and w (1.4–5.6 km). The transmissivity value was obtained from consecutive 5 m pump-packer aquifer tests at Wendouree Winery, which is closer to the 'northern catchments' than Watervale, and therefore more representative of the local hydrogeology than the latter site.

Chloride in rainfall

The amount-weighted mean chloride concentration of rainfall collected at Stanley Flat is 4.7 mg/L, and an error of ± 10% is assumed for this figure in the salt balance.

Chloride in surface (creek) water

As there are no stream flow gauging stations in any of the northern catchments, there are also no records of creek salinity. From observations in the Eyre Creek catchment, we have assumed a value of 75 mg/L for the mean Cl concentration of creek water leaving the northern region, although this value could easily be ± 30%.

Chloride in groundwater outflow

The mean Cl concentration of groundwater in the Bungaree sub-catchment, immediately to the north (down-gradient) of the Armagh Creek and Stanley Flat catchments, is 1139 mg/L. We assume this value to be most representative of groundwater leaving the 'northern' catchments, and hence a relatively small error (cf. Eyre Creek) of ± 10% is introduced to the salt balance.

All of the input data used in the Clare Valley water and salt budget calculations is presented in Table 2.

RESULTS

WATER AND SALT BUDGETS

The results of both the water and salt budgets for the Eyre Creek and northern catchments (Hutt River/Armagh Creek/Stanley Flat) are presented in Table 3. Two interesting observations can be made from this table.

Firstly, both the water in/out and salt in/out ratios for the Eyre Creek catchment are essentially the same for each period of investigation. This most likely reflects the very small deviations in annual rainfall (-6.3% for 1995/1996 and -4.1% for 1998/1999) from the mean value of 656 mm/yr (1995–1999). Furthermore, the water in/out ratios of the Eyre Creek catchment are the same as those determined for the northern catchments, albeit the magnitude of the in and out components are significantly different between catchments. The range of salt in/out ratios calculated for the northern catchments (0.004–0.47) is significantly lower than that determined for the Eyre Creek catchment (0.04–3.0); this is most likely due to the higher value of aquifer transmissivity adopted for the northern catchments.

GROUNDWATER DISCHARGE TO STREAMS

Results to the calculations of mean annual groundwater loss to streams in the Eyre Creek catchment are presented for both the hydrographic (Fig. 6a) and chloride mass-balance approaches (Fig. 6b). In the case of the hydrographic method, the minimum fraction of stream flow that can be derived from groundwater (which was allowed to vary) was set to occur in May, while the maximum fraction (100%) was set to occur in October. The fraction of mean and median monthly stream flows for all other months were then determined using the approach outlined in the methods section. Figure 6a shows the total annual volume of groundwater lost to streams as a function of the minimum fraction of groundwater in stream flow, determined using both mean and median monthly flow data. Because the minimum percentage of groundwater in stream flow occurs in May (before the region's wettest months) it is likely that some groundwater is present in the stream at this time. Supposing this fraction is 20 to 40%, we obtain an annual groundwater discharge volume of between 15 and 25 ML/yr or just 4.3 to 7.2% of the mean annual stream flow. These values correspond to a mean areal groundwater discharge of 0.4 to 0.7 mm/yr.

Estimates of groundwater discharge determined using the chloride mass balance method were performed using both mean and median annual salt loads through the Eyre Creek. It was assumed that the concentration of chloride in surface run-off (C_R in Equation 10) is negligible compared with the chloride concentration in both stream flow (C_S) and groundwater (C_{GW}). This assumption is likely to be valid most of the year; the only time C_R will approach C_S is after very heavy rainfall events when the majority of stream flow is derived from surface run-off. Most of the groundwater in the vicinity of the Eyre Creek has a salinity in the range 1000–1500 mg/L (Morton *et al.*, 1998) which equates to chloride concentrations of the order 500 mg/L. Figure 6b indicates that a groundwater chloride concentration of 500 mg/L corresponds to an annual groundwater discharge of 96 ML/yr using the mean annual salt load or 44 ML/yr using the median data. These estimates are a factor of three to four larger than those obtained using the hydrographic method, and hence correspond to between 12.7% and 27.8% of the mean annual stream flow. Furthermore, they relate to mean areal groundwater losses of between 1.2 mm/yr and 2.7 mm/yr.

One limitation of the hydrographic and chloride mass-balance approaches presented herein is that they both neglect the volume (and chloride concentration) of water removed from the Eyre Creek daily for irrigation. Once this information becomes available, through installation and monitoring of metering devices, the above estimates of mean annual groundwater discharge to streams should be refined. However, because most of the creek water that is used for irrigation is pumped out during times of high flow (to supplement existing supplies such as dams) when the groundwater component is likely to be minimal, the actual volume of groundwater lost to streams is not likely to be significantly different from that calculated above.

Table 2 Input data for the Clare Valley water and salt budget calculations

Catchment	Eyre Creek			Hutt River/Armagh Creek/Stanley Flat
Period	5/95–2/99	5/95–4/96	2/98–1/99	NA
Area (ha)	3570	3570	3570	10299
% vineyard	21.5	21.5	21.5	13.6
Rainfall (mm/yr)	656 [1]	615 [1]	629 [1]	632 [4]
Cl (rain) (mg/L)	4.5 [2,3]	4.5 [2,3]	4.5 [2,3]	4.7 [5]
Creek flow (ML/yr)	345.9 [3]	122.3 [3]	46.7 [3]	2773.1
Cl (creek) (mg/L)	65 [3]	79 [3]	212 [3]	75
Dam storage (ML)	967	967	967	1757
ET (ML/yr)	15753	15753	15753	42489
G/water pumping (ML/yr)	187	187	202	811
G/water discharge (ML/yr)	373	373	373	5676

1 Watervale 4 Clare
2 Sevenhill 5 Stanley Flat
3 Auburn

Table 3 Results of the Clare Valley water and salt budgets; expressed as water in, water out, salt (Cl^-) in, salt (Cl^-) out and water and salt in/out ratios

Catchment	Eyre Creek			Hutt River/Armagh Creek/Stanley Flat
Period	5/95–2/99	5/95–4/96	2/98–1/99	NA
Water in (ML/yr)				
Rainfall	23419 ± 5%	21956 ± 5%	22455 ± 5%	65090 ± 5%
Total	22250–24600	20900–23000	21350–23600	61850–68350
Water out (ML/yr)				
Surface discharge	346 ± 10%	123 ± 10%	47 ± 10%	2773 ± 20%
Evapotranspiration	15755 ± 40%	15755 ± 40%	15755 ± 40%	42489 ± 40%
Dam storage	967 ± 25%	967 ± 25%	967 ± 25%	1757 ± 25%
G/water pumping	187 ± 20%	187 ± 20%	202 ± 20%	811 ± 20%
G/water discharge	373 ± 1000%	373 ± 1000%	373 ± 1000%	5676 ± 1000%
Total	10700–27950	10500–27750	10450–27650	30250–128400
Water in/out	0.80–2.30	0.75–2.20	0.77–2.26	0.48–2.26
Salt in (tonnes/yr)				
Rainfall + dryfall	104 ± 15%	98 ± 15%	100 ± 15%	306 ± 15%
Total	89–120	83–112	85–115	260–352
Salt out (tonnes/yr)				
Surface discharge	22 ± 20%	10 ± 20%	10 ± 20%	208 ± 50%
G/water discharge	218 ± 1000%	218 ± 1000%	218 ± 1000%	6465 ± 1000%
Total	40–2423	30–2408	30–2408	750–71427
Salt in/out	0.04–3.0	0.03–3.7	0.04–3.8	0.004–0.47

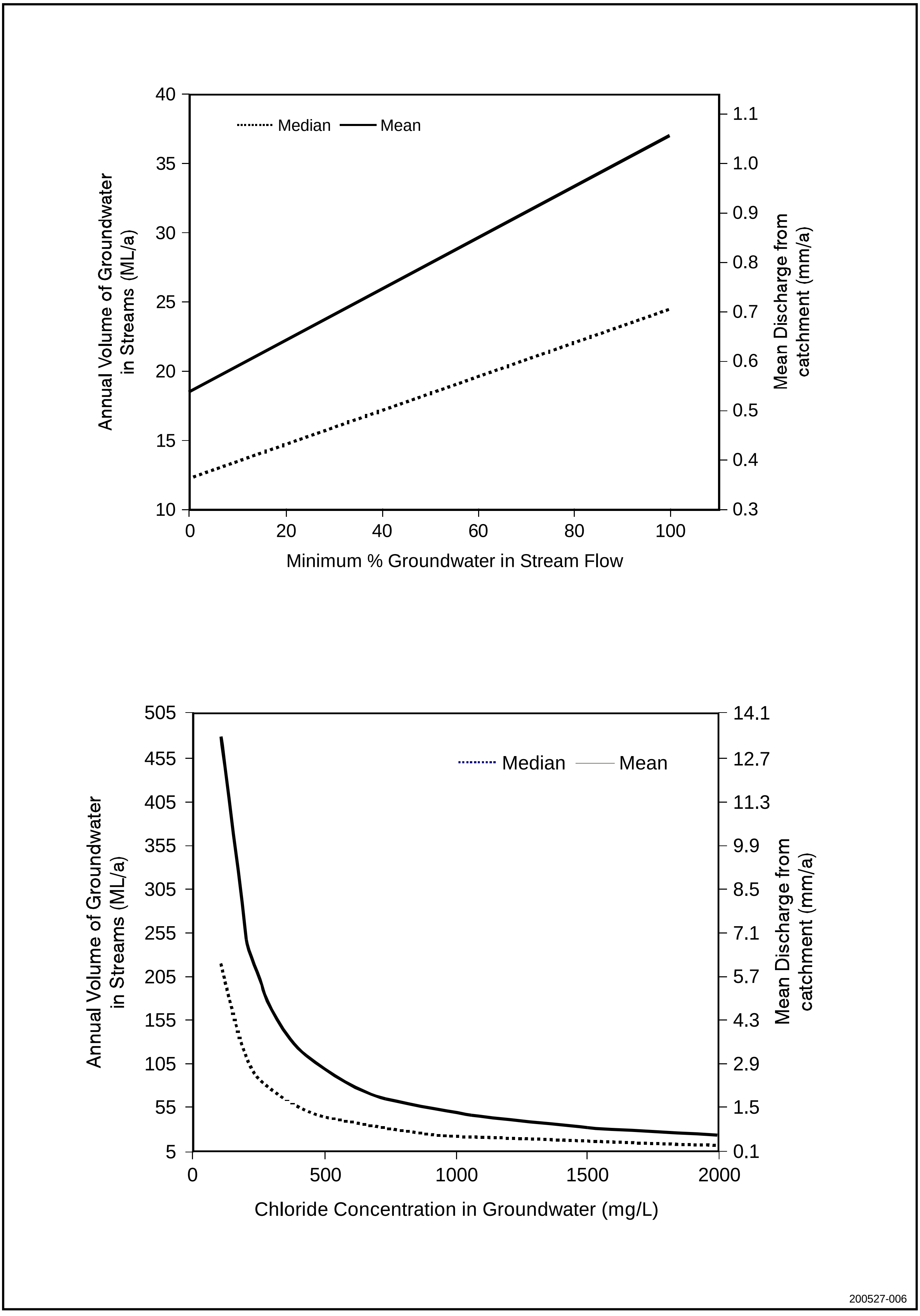


Figure 6 Estimates of the annual volume and mean areal rate of groundwater discharge from the Eyre Creek catchment, determined using (a) the hydrographic approach, and (b) a groundwater-surface water chloride mass balance. Given that the mean chloride concentration of groundwater discharging into the Eyre Creek is likely to be ~500 mg/L, the annual discharge rate is likely to be less than 3 mm/a.

ERROR ANALYSIS

The water and salt balances presented above have significant errors due to large uncertainties in the input data. A root mean square error has been calculated for each water and salt budget:

$$\text{Error} = \sqrt{\frac{\sum(\textit{individual errors})^2}{n}}$$

where *individual errors* is the percentage error associated with each of the *n* parameters used in the calculation. A summary of the anticipated errors associated with each input parameter for the water and salt budgets of each catchment (excluding the groundwater outflow component, see below) is presented in Table 4. Using these values we obtain a root mean square error of 23 to 25% for each water balance. These errors highlight the inappropriateness of conventional water balances for estimating fluxes in the hydrologic cycle such as recharge rates.

By applying the same analysis to the salt balance calculations, we obtain root mean square errors of 20% and 23% for the Eyre Creek and northern catchments respectively. The slightly higher error for the northern catchments reflects the rough estimates of chloride concentration in surface-water discharge. The errors presented in Table 4 do not account for uncertainty in the estimate of mean aquifer transmissivity and hence groundwater flow out of the catchment, which is arguably the most difficult component of these water and salt balances to estimate. Whilst the choice of mean T for the Eyre Creek catchment has already been justified, we also applied the higher estimate of T obtained from the Wendouree site (6.6 x 10^{-4} m^2/s) to test the effect of using this value on the water and salt balances. Use of the Wendouree mean T value yielded water in/out ratios of ~1.08 (average) and salt in/out ratios of 0.05 (average) for each period of investigation. Therefore, if the most uncertain parameter for the water and salt balances (mean aquifer transmissivity) is increased by an order of magnitude, it does not alter the general results of the investigation; i.e. water in/out ratios are ~1 and salt in/out ratios are generally << 1.

The distribution of hydraulic conductivity (transmissivity) at the Watervale and Wendouree sites (Fig. 5) indicates that the majority of groundwater flow occurs in the upper 30–50 m of the aquifer. This being the case, we would expect greater flushing of salt to occur in the upper portion of the system rather than deeper in the system where the hydraulic conductivity decreases.

Table 4 *Individual and cumulative errors associated with water and salt budgets*

Parameter	Eyre Creek catchment	Northern catchments
Mean annual rainfall	< 5%	< 5%
Surface-water discharge	10%	20%
Evapotranspiration	40%	40%
Surface (dam) storages	25%	25%
Groundwater extraction	20%	20%
Chloride in rainfall	10%	10%
Chloride in creek water	10%	30%
Chloride in groundwater	20%	10%
Total error (water balance)	23%	25%
Total error (salt balance)	20%	23%

RESOURCE IMPLICATIONS

Results of the sub-catchment scale water and salt balances are inconclusive due to the large ranges in water and salt in/out ratios that were brought about by significant uncertainties in the input data. Due to large errors in the water budgets (Table 4), any water I/O ratio between 0.75 and 1.25 is considered not statistically different from 1.0. Therefore, ranges of water in/out ratios between 0.75 and 2.3 for each area of investigation indicate that inputs of water from rainfall are possibly matching (and may even be exceeding) outputs via stream flow, irrigation and lateral groundwater flow out of the aquifers.

Whilst water in/out ratios vary over almost and order of magnitude, the range of calculated salt in/out ratios are over three orders of magnitude (0.004–4.0). However, these ranges are certainly biased towards ratios of < 1.0, indicating that salt is most likely being exported from the catchments. A possible scenario why water is in steady state but salt is not maybe due to a change in recharge rates brought about by the clearing of native vegetation for improved agriculture. The clearing of native vegetation in many parts of southern Australia has resulted in order of magnitude increases in recharge rates (e.g. Allison and Hughes, 1983; Walker et al, 1991). The time to reach a new state of equilibrium is dependent upon the size and hydraulic properties of the aquifer. In the Clare Valley it appears that water has reached a new state of equilibrium but salt has not. These differences are due to the varying properties of the fractured rock aquifer that transport water and salt. Water is transported by hydraulic properties only, while salt is transported by hydraulic and diffusive processes. Salt is slowly moving out of the rock matrix into the fractures where the majority of groundwater flow is occurring. Because of the low porosity of these rocks, it takes a much longer time for the salt to reach a new equilibrium compared with water.

The salt and water balance approach adopted in this study provides a good first order approximation to whether a catchment is in hydrological equilibrium. However this approach should not be used to estimate individual parameters of the water budget. For example, this method cannot accurately estimate groundwater recharge or discharge rates.

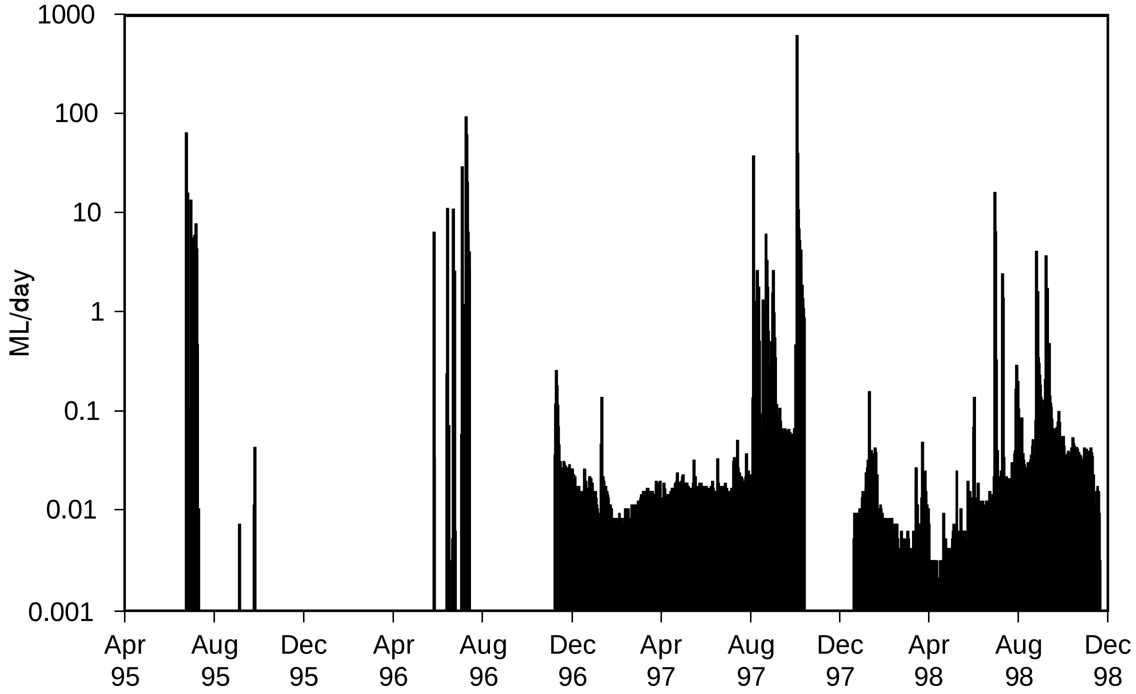
The use of a groundwater chloride mass balance to estimate recharge (Eriksson and Khunakasem, 1969) requires that the groundwater system be in steady state with respect to salt, in particular chloride. Therefore, this technique is not applicable to the Clare Valley and possibly other fractured rock aquifers of the Mount Lofty and Flinders Ranges. The only way a chloride mass balance may be applied to such systems is if detailed soil chloride profiles are obtained and it can be shown that the chloride distributions through the soil profiles are indeed in steady state.

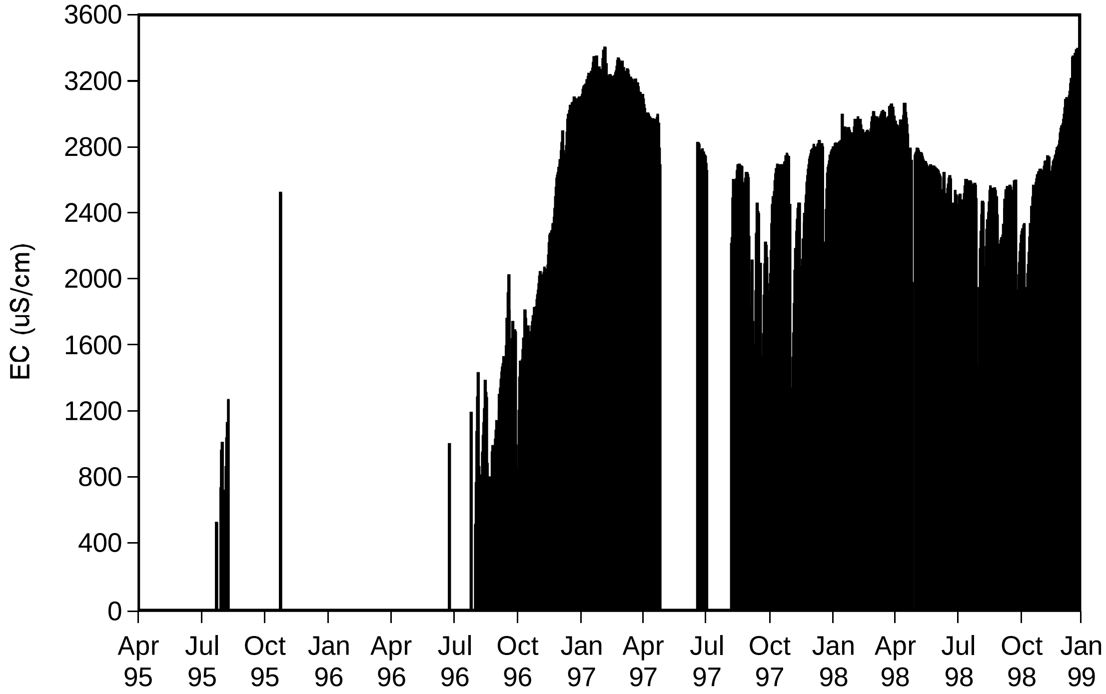
RECOMMENDATIONS

- Installation of stream flow and stream salinity gauging stations in the Northern Catchments region to provide better constraints for these parameters in the water and salt budgets.
- Soil chloride profiling to enable the use of chloride mass balance to estimate recharge rates.
- Study other catchments and fractured rock aquifers throughout the Mount Lofty Ranges.
- Develop techniques to directly measure groundwater discharge to streams, including ways of measuring the importance of peak rainfall events.
- Develop more accurate methods for estimating horizontal groundwater flow that are not dependent on aquifer transmissivity.

APPENDIXES

Appendix A Stream flow and salinity records from the Eyre Creek gauging station near Auburn


1000
100
10
1
0.1
0.01
0.001
ML/day
Apr 95
Aug 95
Dec 95
Apr 96
Aug 96
Dec 96
Apr 97
Aug 97
Dec 97
Apr 98
Aug 98
Dec 98


3600
3200
2800
2400
2000
1600
1200
800
400
0
EC (uS/cm)
Apr 95
Jul 95
Oct 95
Jan 96
Apr 96
Jul 96
Oct 96
Jan 97
Apr 97
Jul 97
Oct 97
Jan 98
Apr 98
Jul 98
Oct 98
Jan 99

200527-007

Appendix B Chloride concentrations in accumulated rainfall at three sites within the Clare Valley

Sample date	Stanley Flat	Sevenhill	Auburn
09.07.1998	3.3	2.9	3.3
13.08.1998	5.5	4.4	6.1
08.10.1998	4.9	3.9	5.3
09.11.1998	7.1	5.4	8.0
31.03.1999	3.0	2.2	5.2
28.04.1999	3.8	2.6	3.6
21.07.1999	5.3	4.4	5.2
Mean	4.7	3.7	5.2

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