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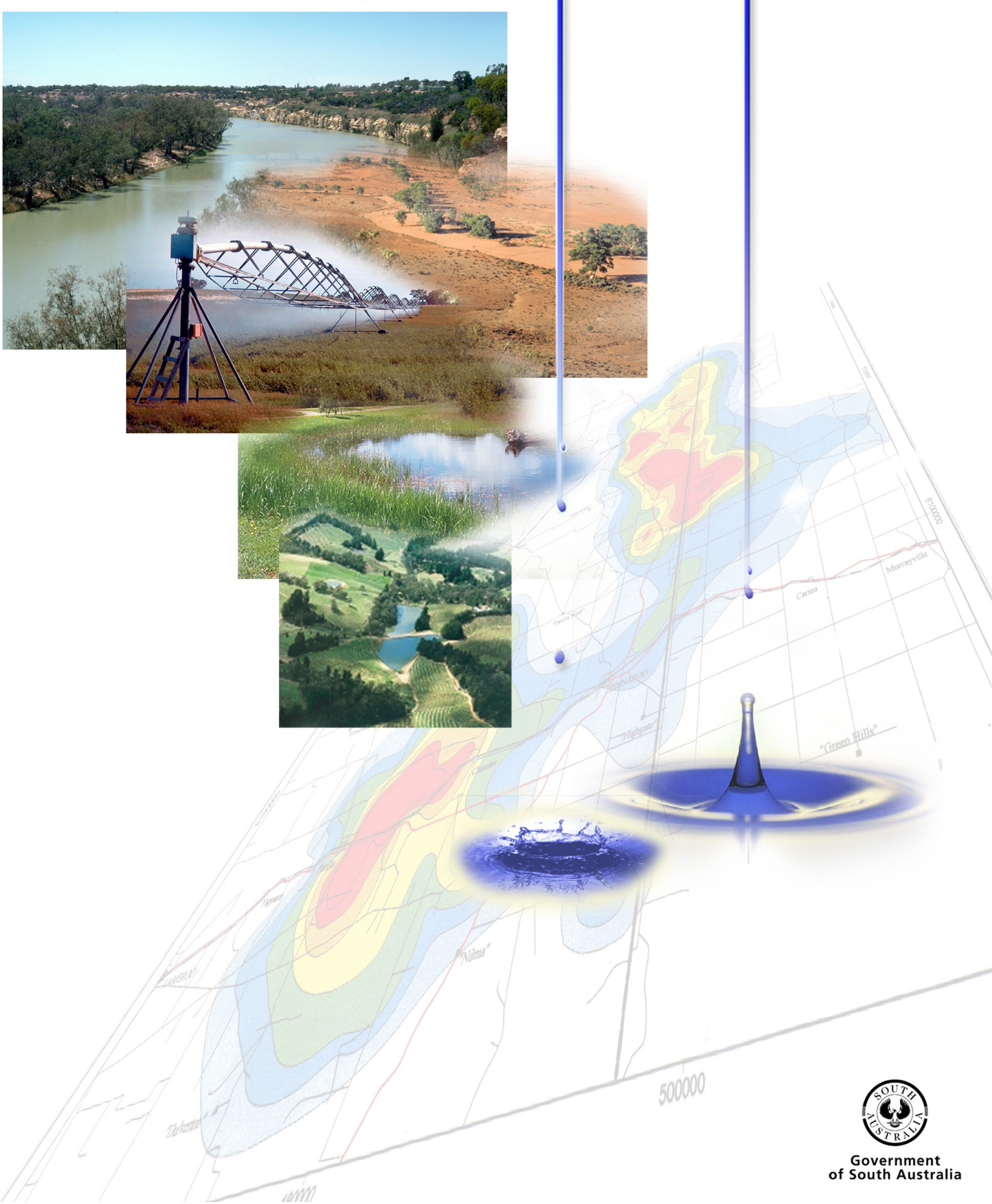
Aquifer storage and recovery in fractured rock aquifers of the Clare Valley, South Australia

Report DWR 2001/011



Government of South Australia

Aquifer storage and recovery in fractured rock aquifers of the Clare Valley, South Australia

Glenn A. Harrington and Andrew J. Love

Groundwater Assessment Research & Development Group
Resource Assessment Division

August 2001

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Department for Water Resources

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Preferred way to cite this publication
Harrington, G.A. and Love, A.J., 2001. Aquifer storage and recovery in fractured rock aquifers of the Clare Valley, South Australia. *South Australia. Department for Water Resources. Report,* DWR 2001/011.

Cover — PIRSA photo numbers 045201, T024975, 045226, 047612, 047855,. Water droplet is courtesy of Adam Hart-Davis / DHD Photo Gallery.

FOREWORD

South Australia's water resources are fundamental to the economic and social wellbeing of the State. Water resources are an integral part of our natural resources. In pristine or undeveloped situations, the condition of water resources reflects the equilibrium between rainfall, vegetation and other physical parameters. Development of surface and groundwater resources changes the natural balance and causes degradation. If degradation is small, and the resource retains its utility, the community may assess these changes as being acceptable. However, significant stress will impact on the ability of a resource to continue to meet the needs of users and the environment. Degradation may also be very gradual and take some years to become apparent, imparting a false sense of security.

Management of water resources requires a sound understanding of key factors such as physical extent (quantity), quality, availability, and constraints to development. The role of the Resource Assessment Division of the Department for Water Resources is to maintain an effective knowledge base on the State's water resources, including environmental and other factors likely to influence sustainable use and development, and to provide timely and relevant management advice.

Bryan Harris
Director, Resource Assessment Division
Department for Water Resources

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ABSTRACT

Small-scale tracer tests were conducted at two sites in the Clare Valley (Watervale Oval and Wendouree Winery) to investigate the potential for aquifer storage and recovery (ASR) into fractured rock aquifers. At both sites water tagged with known concentrations of tracers was injected into small (up to 5 m), isolated sections of the aquifer and allowed to reside there for a period of time before extraction. At the end of each test, when three to four times the injected volume had been extracted, between 50–80% of the injected tracer mass was recovered from the aquifer.

Of the two sites, a higher recovery was achieved at Watervale Oval, due to the relatively lower hydraulic conductivity at that site. High rates of natural groundwater flow in these and other fractured rock systems means that recovery efficiencies may be low, particularly at much larger scale developments. The most suitable sites for ASR in the Clare Valley are likely to be in areas of high quality groundwater and not adjacent to discharge features such as creeks.

INTRODUCTION

The aim of this study was to test the feasibility of aquifer storage and recovery (ASR) in a fractured rock aquifer in the Clare Valley, South Australia. ASR is a promising tool that can provide increased flexibility for water resource managers. Under ideal conditions ASR can increase groundwater allocations, improve the quality of saline groundwater resources and provide alternatives for town water supplies (Barnett et al., 2000; Howles, 2000).

AQUIFER STORAGE RECOVERY AND ITS EVALUATION

Aquifer storage and recovery is the process of storing excess surface water in an aquifer to be recovered at a later time for beneficial use. One way of measuring the degree of success of an ASR scheme is to calculate the recovery efficiency (RE) for individual storage-recovery cycles. Recovery efficiency can be defined as the ratio of the volume of injected water that is recovered to the volume of water injected shown in Equation (1):

$$\mathrm{RE} = \frac{\text{Volume of Injected Water Recovered}}{\text{Volume of Water Injected}} = \frac{V_{IR}}{V_I} \qquad (1)$$

However, measuring the proportion of injectant that is recovered can be difficult unless there is a clear distinction between the concentration of a particular solute (or salinity) in the injected water and the ambient groundwater. Where this difference can be measured, the recovery efficiency is more correctly termed the recovered mass (RM) shown in Equation (2):

$$\mathrm{RM} = \frac{\text{Mass of Solute Recovered}}{\text{Mass of Solute Injected}} = \frac{\int_{t_{R0}}^{t_R} (C_R(t) - C_{GW}).q_R(t)dt}{(C_I - C_{GW}).\int_{t_{I0}}^{t_I} q_I(t)dt} \qquad (2)$$

where C is solute concentration; q is pump-in (or pump-out) rate; and subscripts R, GW and I denote Recovery, Groundwater and Injection respectively. In practice however, concentrations of solutes (or salinity) in recovered water and the ambient groundwater are rarely measured at the frequency desirable for determining RM from Equation (2). Therefore, recovery efficiency is more commonly used in ASR trials, and is calculated by choosing an arbitrary upper limit for the salinity of the recovered water. For example, when using artificially recharged groundwater to irrigate salt-sensitive crops, such as stone fruits and common garden vegetables, one may wish to limit recovery to only that volume of water which will have a salinity of less than 1000 or 1500 mg/L. Using this approach to determine recovery efficiency means that real ASR schemes conducted in areas where the ambient groundwater is already of a very good quality, can result in values of recovery efficiency greater than 100%.

To date, most successful ASR schemes in South Australia have been conducted in single-porosity media, such as sand and limestone aquifers (for example in Gerges et al., 1997; Howles et al., 1999). Providing head gradients are not significantly higher than ~1:100, natural groundwater flow velocities in this type of aquifer are typically of the order 1–100 m/y, and therefore dispersive mixing is low and recovery efficiency can be high (> 50%). By contrast, natural groundwater flow in dual-porosity media (fractured rock aquifers) is characterised by very rapid flow through the fractures (1–100 m/d) and relatively little movement through the matrix. Recovery efficiency in these systems may therefore be much lower than for single-porosity media. This factor may or may not preclude the use of ASR to augment groundwater resources in fractured rock environments, depending on the salinity and volumes of water intended to be injected and recovered, and the salinity of the ambient groundwater.

WATER RESOURCES IN THE CLARE VALLEY

The Clare Valley is located within the Northern Mount Lofty Ranges ~100 km north of Adelaide (Fig. 1). Both surface water and groundwater resources are used for a wide array of domestic, municipal, industrial and agricultural purposes throughout the Valley, including the well-established wine grape industry. Current annual water use for irrigation is ~3500 $\mathrm{ML.y^{-1}}$ with ~52% derived from surface water and 48% from groundwater (Resource Assessment Division, DWR, unpublished data, 2001).

The principal aquifers in the region are fractured meta-sediments from the Torrensian Epoch of the Adelaidean Period (700–780 Ma). Major lithologies include dolomitic meta-siltstones, sandstones and quartzite. Groundwater salinity is highly variable and ranges from 500–3000 mg/L in the irrigated portion of the Valley. Surface water resources (creeks) are ephemeral and only flow for three or four months each year. Creek water salinity varies from 50–3000 mg/L with the lowest concentrations

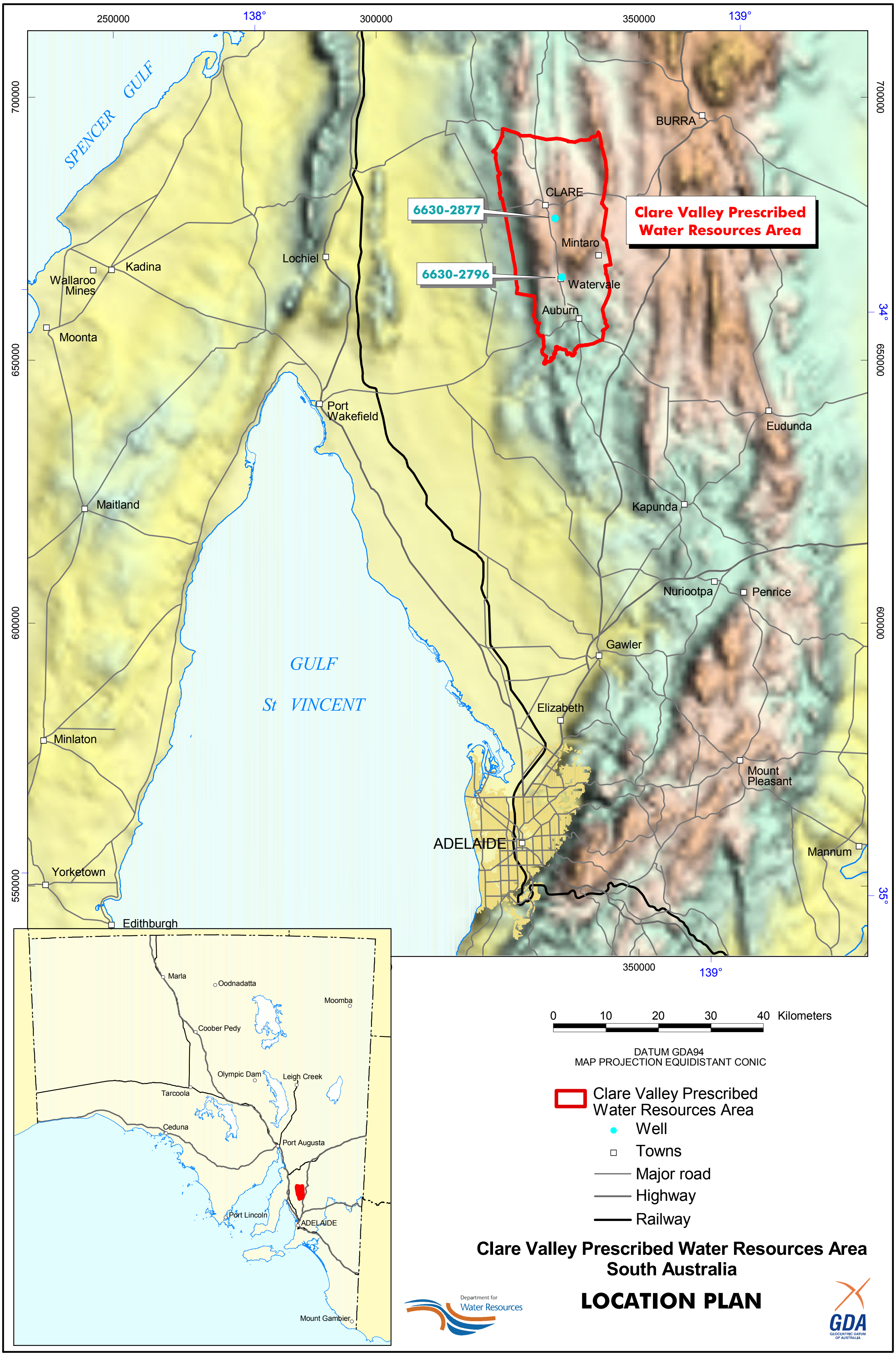

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Figure 1

occurring during high flows after intense rainfall events. This high-flow, low-salinity creek water, which until now has flowed out of the region without being used for irrigation, provides an opportunity for enhancing the groundwater resources of the Clare Valley through artificial recharge. However, the location of these creeks may also limit the feasibility of ASR if the artificially recharged groundwater discharges before it can be extracted for irrigation.

WENDOUREE WINERY

SITE DESCRIPTION

Wendouree Winery is situated ~2 km southeast of the township of Clare (Fig. 1). Mean annual rainfall determined from a 133-year record (1862-1994) of monthly rainfall amounts collected at the Clare Post Office is 632 mm/y. The Wendouree site has been used for numerous hydrogeological investigations over the past three years and provides an ideal site to perform an ASR trial since the local hydrogeology is well known.

The geology at Wendouree is primarily the dark-grey Auburn Dolomite member of the Saddleworth Formation. Groundwater salinity increases in a step-like fashion from ~1500 mg/L near the water table to ~6000 mg/L at 100 m depth (Love et al., 1999). Well yields are generally in the range of 0.5–2.0 L/s (Morton et al., 1998). Well dilution tests conducted previously at the site indicate that groundwater flow can be up to 10 m/d from large fracture zones (Love et al., 2001).

TESTING METHODS

Aquifer Test

A 200 mm well was drilled to a depth of 200 m and completed as an open hole with 6 m surface casing (unit number 6630-2877). Prior to the ASR trail a small-scale pumping test was performed to determine suitable injection and recovery rates for the trial. A dual packer system isolated a section of the aquifer between 13.5–15.1 m. The pumping test was performed using a Grundfos® MP1 submersible pump for 120 minutes and analysed using the Jacob straight-line method.

Tracer Test

Bromide (Br) and helium (He) were chosen as tracers for the ASR trials as they are chemically conservative species, which have different aqueous diffusion coefficients (7.22×10^{-5} cm^2/s for He and 2.01×10^{-5} cm^2/s for Br), and therefore will diffuse into the unfractured rock at different rates. A solution of bromide measuring 1125 mg/L was made by dissolving 750 g of potassium bromide (KBr) in a 500 L rainwater tank filled with bore water from the aquifer test. Helium was infused into the same injection tank by a gas sparging system for three days before the ASR test. Whaler pumps were used to ensure complete mixing of the tracers in the injection tank.

Injection system

The injection system consisted of two 500 L sealed rainwater tanks (Plate 1). One tank contained local groundwater from the aquifer test doped with bromide and helium. The other tank contained local groundwater to be used as a chaser after injection of the tracer. The outlets of both tanks met at a ‘T-piece’ constructed with copper tubing. After the T-piece, a short copper tube was connected to a septum port for sampling the injected water and an in-line flow meter was used to ensure a constant injection rate. The copper tubing was fed down the well to a depth of 14.65 m in the middle of the packers (Plate 2). Copper tubing was chosen to prevent

Plate 1 Two rainwater tanks, copper tube, T-piece and flow meter used for the injection phase, ASR trial at Wendouree Winery. (photo 047939)

Plate 2 Installation of inflatable packers with pole truck and two rainwater tanks; one containing tracer solution (He and Br) and the other being chaser (bore) water, field site for ASR trial at Wendouree Winery. (photo 047938)

any degassing of helium from the water. The injection of both tracer and chaser was done under gravity at a constant rate of 4.7 L/min. The total injection time for both tanks was 140 minutes.

Pumping/residence time

After injection of both the tracer solution and chaser water the site was left undisturbed for a period of 300 minutes. During this phase the injected water was expected to move and mix with the ambient groundwater. Recovery was carried out using the Grundfos® MP1 pump centred at the mid point of the packers. Attached to the pump was copper tubing that went to the surface, where it discharged upwards to prevent air from entering the tubing and altering the helium concentration of the recovered water. The recovery rate was 4.7 L/min, which is the same as the injection rate. The packed interval was pumped for 560 minutes; four times the injected time. A further residence time of 340 minutes was followed by 90 minutes of pumping. No samples for helium were analysed during the second pumping phase.

SAMPLING AND ANALYSIS

Water samples were collected every 15 minutes from the outlet of the copper tube for bromide and helium analysis. Bromide was collected in 50 mL plastic bottles and helium was collected by slowly drawing water from the septum into a glass syringe. Once 10 mL of water was collected, the needle was replaced with a small rubber vial cap.

The samples were analysed at a temporary laboratory near the field site. Bromide concentration was determined using an ion-selective electrode. For helium analysis, 2 mL of water was removed from the syringe and 2 cm^3 of high purity nitrogen gas was added to the sample. After shaking the sample for 60 seconds, 1 cm^3 of gas was extracted from the headspace and analysed for helium concentration using gas chromatography (Sanford et al., 1996).

RESULTS AND DISCUSSION

Helium and bromide concentrations in the recovered water are expressed as a ratio of recovered concentration (C) to initial concentration (C_0) (Fig. 2). Both the helium and bromide curves have a similar shape; starting with a ratio of 0.25 and trailing down to a ratio of 0.01 by the end of recovery. Since the two tracers have different aqueous diffusion coefficients, the similarity of the two curves in Figure 2 suggests that any loss of tracer mass to the system via adsorption or diffusion into the matrix is not important in the time frame of the ASR trial.

A plot of the cumulative mass recovery for both tracers is shown in Figure 3. The total mass recovery at the end of pumping is 46% for He and 48% for Br (despite pumping four times longer than the injection period, only ~50% of the tracers were recovered). The remaining tracers were probably removed from the zone of influence of the well by rapid groundwater flow through the fractures. This highlights potential problems with ASR in highly fractured formations, since natural groundwater flow could disperse the injected water long distances away from the pumping well. In addition, injection of fresh water into a fractured aquifer containing brackish or saline groundwater will most likely lead to very low recovery efficiencies.

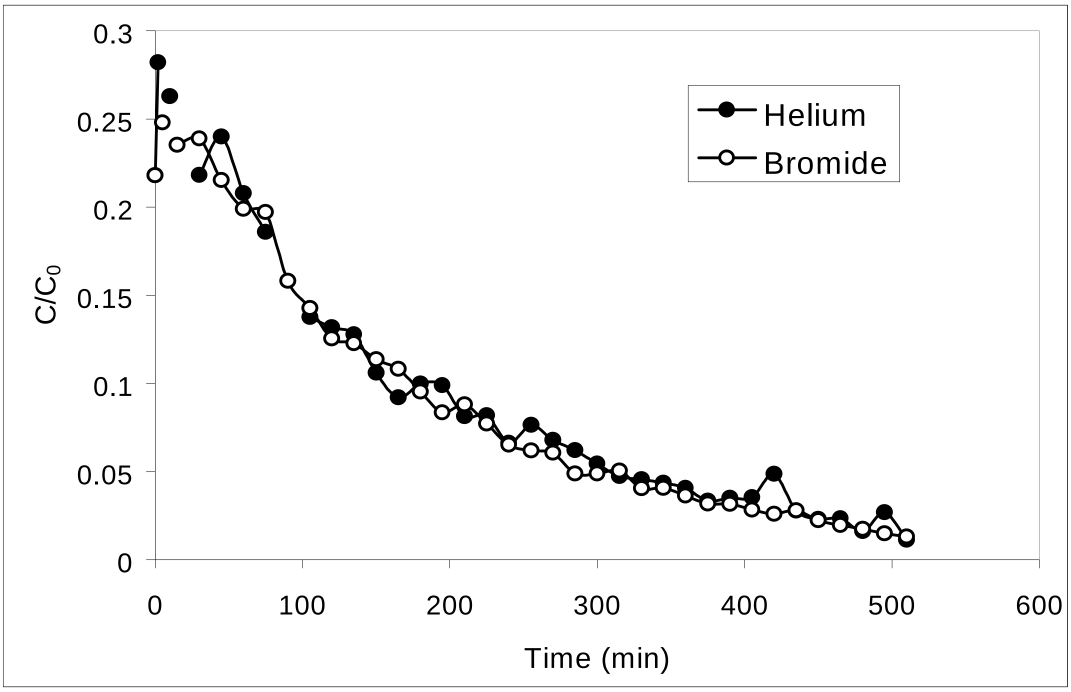

Figure 2 Relative concentrations of helium and bromide during the recovery phase of the ASR trial at Wendouree Winery

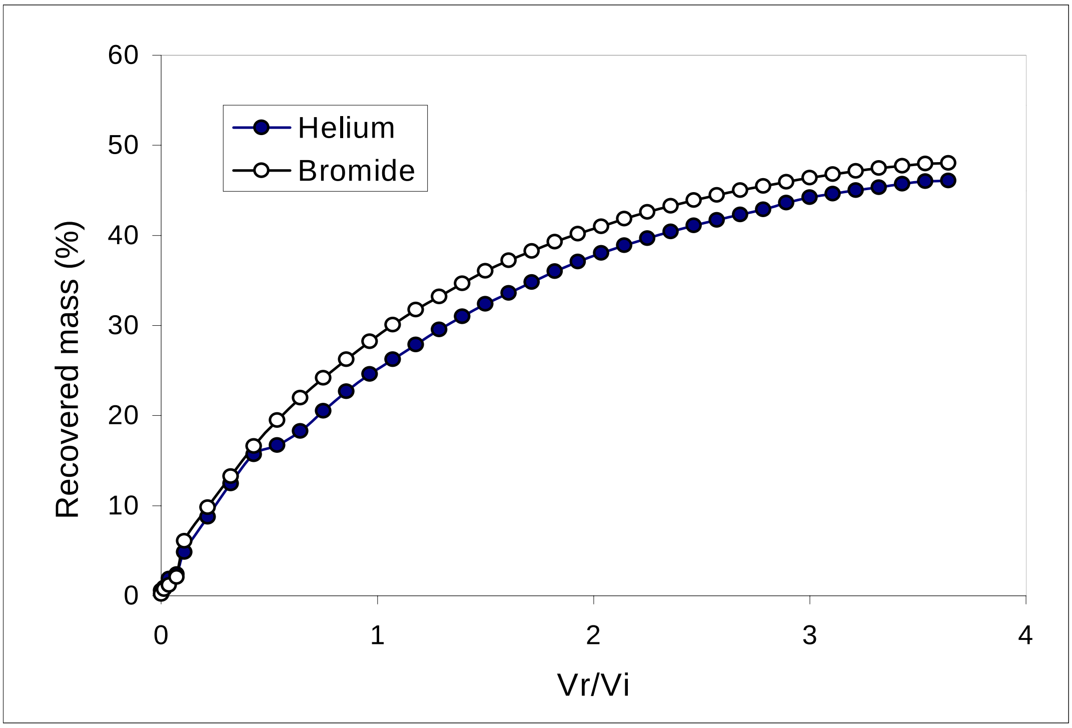

Figure 3 Tracer mass recovery (as a percentage of total injected tracer mass) as a function of the ratio of volume water recovered to volume water injected (Vr/Vi) at Wendouree Winery

WATERVALE OVAL

SITE DESCRIPTION

Watervale Oval is situated on the northern outskirts of the township of Watervale (Fig. 1) where mean annual rainfall is ~655 mm/y. Watervale has no reticulated mains water and relies on groundwater and harvested surface water for its domestic and municipal needs. The proximity of the oval to Eyre Creek and the township makes this site an ideal demonstration site for ASR in the Clare Valley. The study also investigated the effect of hydraulic fracturing on well yield and recovery efficiency of ASR trials.

While the geology at this site is similar to that at Wendouree Winery (Auburn Dolomite), the local hydrogeology is far more variable and therefore not as well understood. Groundwater salinity is generally ~1700 mg/L, however well yields are highly variable between 0.1 and 3.0 L/s.

TESTING METHODS

A 200 mm diameter well was drilled to 100 m depth and completed as an open hole with 6 m of surface casing. Inflatable packers were then installed over consecutive 5 m intervals for the entire open section of the well. Standard constant discharge tests were completed over each interval for ~100 minutes and analysed using Jacob's straight-line method. Several months after drilling, the well (unit number 6630-2796) was logged for salinity, temperature and pH using a YSI® sonde. After selecting the most suitable interval for the ASR trial from the pump-packer test (52.5–57.5 m) an injection rate of 0.1 L/s was chosen to ensure minimal build-up of head in the well. The drawdown versus time plot obtained from the 52.5–57.5 m of the pump-packer aquifer test is presented in Figure 4.

Pre-fracturing ASR trial

Two tanks were used for the ASR trial, one containing tracer solution and the other containing chaser water. Potassium bromide (4 kg KBr) and fluorescein (5 kg) were mixed into tank 1 (2590 L) which initially contained rainwater of salinity 90 $\mu S.cm^{-1}$. Samples were collected from the mixed tank for bromide and fluorescein analysis of the injectant water. Fluorescein is a non-toxic fluorescent green dye that is commonly used in surface water tracing experiments (Smart et al., 1977; Davis et al., 1985). Tank 2 contained 1730 L of rainwater of the same salinity as tank 1. The two tanks were connected with 1" ID polypropylene pipe before a MAGFLO centrifugal flow meter and gate valve for flow regulation. The injection pipe was then fed to 55 m below ground level, which corresponded to the mid-point of the packed-off interval. Tank 1 was gravity fed at a rate of 0.1 L/s for a total injection time of 345 minutes (total volume 2070 L). Chaser water from tank 2 was then introduced to the packed interval by gravity feed for 55 minutes at 0.1 L/s (total volume 1500 L).

Following injection, the total injected volume (tracer + chaser) was allowed to reside in the aquifer for 325 minutes. Recovery of the injectant was then performed by pumping at a constant rate of 0.1 L/s for 825 minutes (10 950 L) and a further 0.18 L/s for 105 minutes (630 L) using a Grundfos® MP1 submersible pump (Plates 3 and 4). A summary of the timing of injection, residence and recovery phases is presented in Figure 5. Samples were initially taken for bromide and fluorescein analysis at intervals of 15 minutes with the sampling frequency decreasing gradually to one per hour by the end of the recovery.

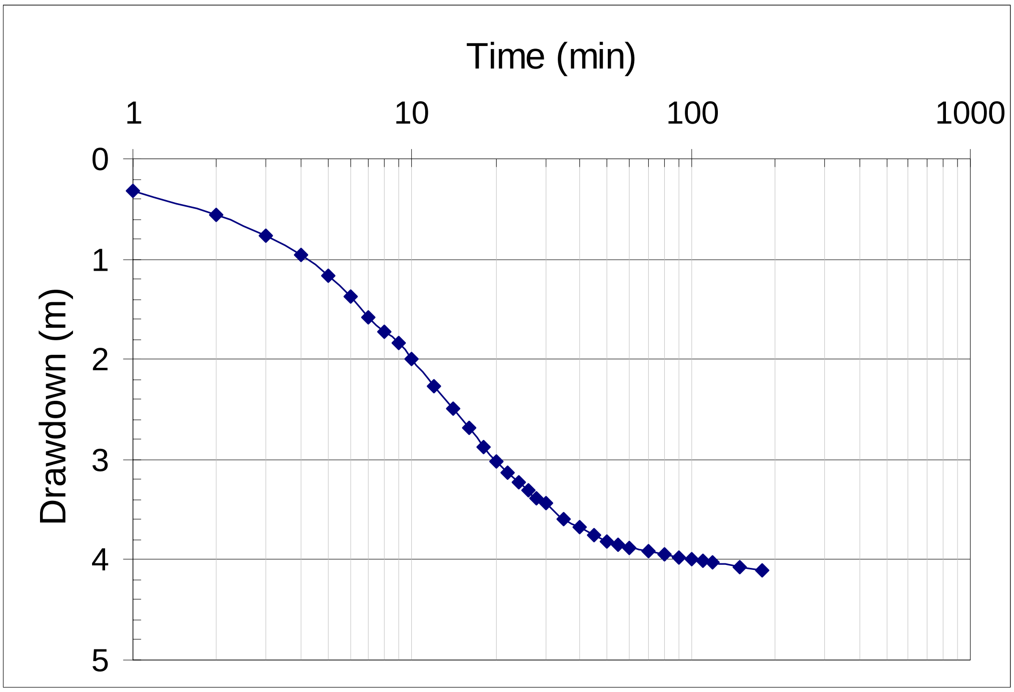

Figure 4 Drawdown response of pump-packer aquifer test conducted over interval 52.5–57.5 m prior to hydraulic fracturing, Watervale Oval

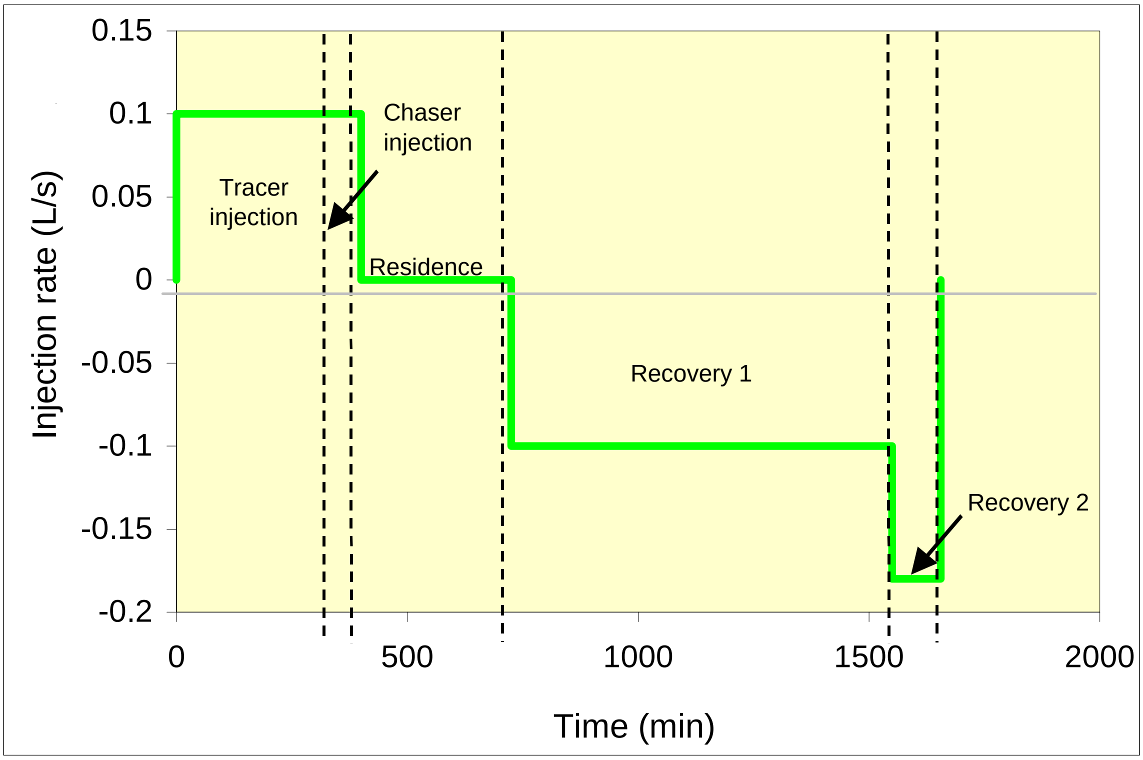

Figure 5 Injection, residence and recovery phases, Watervale Oval

Plate 3 Pole truck and air tanks used to install inflatable packers into the well and green (Fluorescein) discharge water. (photo 047940)

Plate 4 Fluorescein in groundwater discharge during first recovery cycle. (photo 047941)

Sample bromide concentrations were determined using an Orion® *ionplus* Ion Selective Electrode (ISE) coupled to an Orion® 520A electronic meter. Actual concentrations were calculated from voltage readings using a calibration curve that was constructed using five standards of known concentration. Sample reproducibility was generally in the range ±3 mg/L. Fluorescein concentrations were determined using a Turner Designs® TD-700 Laboratory Fluorometer which was borrowed from CSIRO Land and Water, Canberra. Samples initially had to be diluted 250 to 1500 times using micro-pipettes before analysis. Such high-dilution factors introduced a relatively high degree of uncertainty in the measured concentrations of ~20 mg/L.

RESULTS AND DISCUSSION

Bromide and fluorescein concentrations in the recovered water (C), expressed as a ratio to initial (pump-in) concentrations (C_0), are presented in Figure 6. Both tracers exhibit classic break-through type curves, although the bromide peak (0.35) is clearly much higher than the fluorescein peak (0.19). This data suggests that fluorescein has been removed from the groundwater in the fractures, possibly via adsorption onto minerals or diffusion into the rock matrix, at a greater rate than bromide. Such adsorption and forward-diffusion processes are reversible, which means that both fluorescein and bromide will eventually desorb or diffuse back into the fractures and could therefore be completely recovered if pumping was carried out for enough time. A plot of cumulative tracer mass recovery versus time (Fig. 7) provides further support for this hypothesis. At the end of the recovery period, 78% of the injected Br mass was recovered, compared with only 46% of the fluorescein.

Hydraulic Fracturing

Originally developed for the oil industry, the process of hydraulic fracturing has been identified as a promising technique for improving the hydraulic conductivity of fractured rock aquifers and hence the yields of water wells in these environments (Williamson and Woolley, 1980; Smith, 1989). Although many of the early fracturing trials required elaborate and expensive apparatus, the general approach is relatively simple; water is injected to a fractured zone of the well under a sufficiently high pressure in order to propagate and increase the aperture of existing fractures and initiate new fractures. In some instances, the injection of a propping agent into the fractures has been shown to prolong the improved well yields (Stewart, 1978).

One of the aims of this study was to investigate whether hydraulic fracturing of the aquifer at Watervale Oval could improve the recovery efficiency of ASR trials. The adopted approach involved setting specially constructed, high-pressure inflatable packers over the test interval (52.5–57.5 m) and injecting water into the interval at a pressure of 300–500 kPa for up to 60 minutes. Following injection, a pump was installed into the packed interval and an aquifer test conducted to determine if the local transmissivity around the well had increased. The test results, which are presented as 'Post-fracturing H_2O' in Figure 8, reveal a 10.5% reduction in the total drawdown after 180 minutes compared with the pre-fracturing test. Furthermore, the slope of the drawdown curve over the last 100 minutes is lower than that measured pre-fracturing. These observations suggest that the well yield has improved slightly as a result of fracturing with water alone.

In an attempt to further increase the transmissivity around the well and prevent fractures from 'closing' after injection, the hydraulic fracturing process was repeated over the same interval, but on this occasion a proppant (high-purity, fine-grade sand) suspended in a synthetic polymer solution was injected instead of water. An

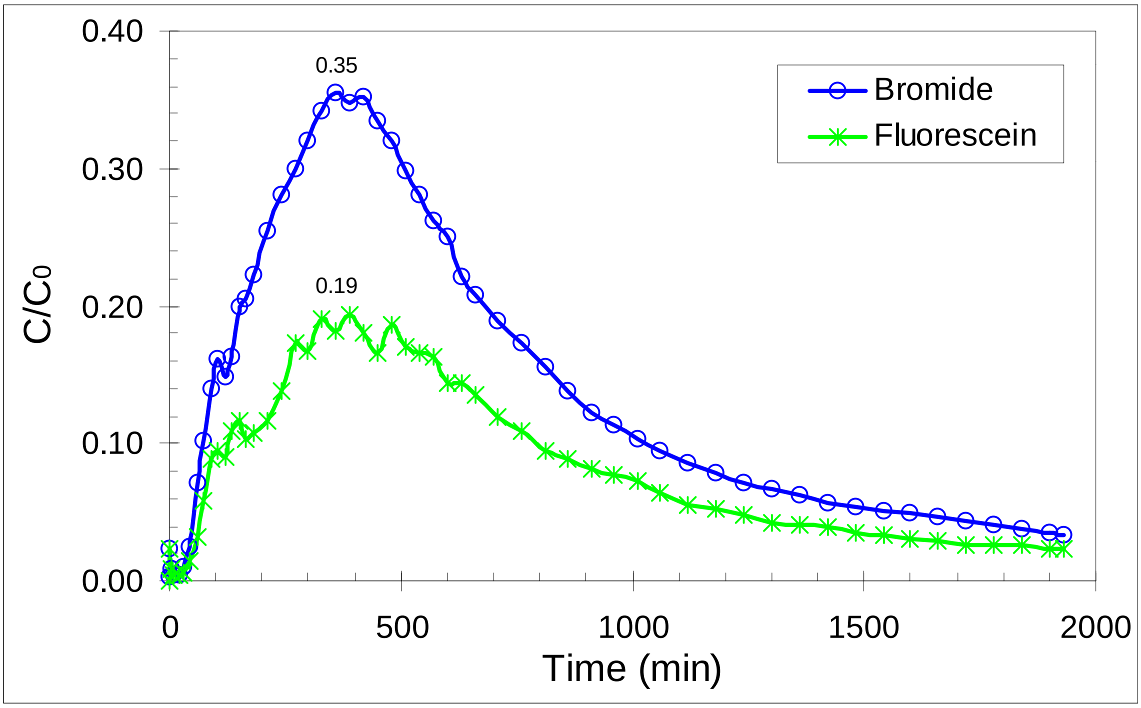

Figure 6 Relative concentrations of tracers in recovered ASR water at Watervale Oval. Bromide concentrations reach 35% of the injectant concentration, whereas Fluorescein reaches only ~ 19% of the injectant concentration.

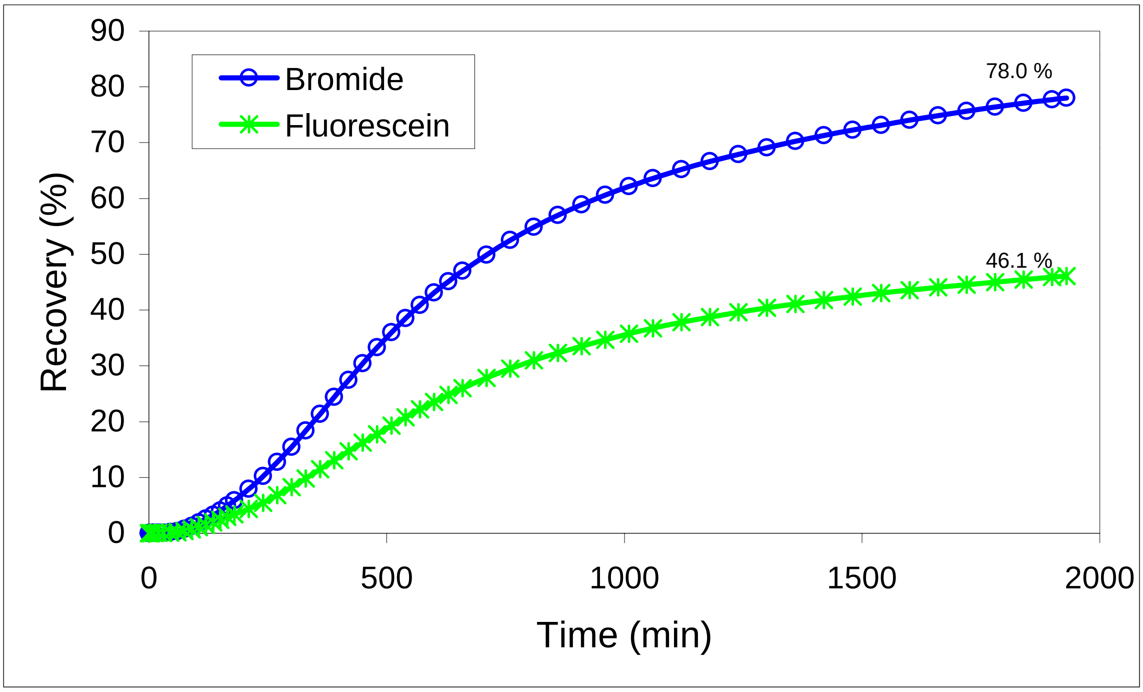

Figure 7 Tracer mass recovery as a percentage of total injected tracer mass, Watervale Oval. Bromide recovery is clearly much higher than fluorescein recovery throughout the test, indicating possible retardation of the fluorescein in the aquifer by matrix diffusion and/or adsorption onto fracture walls.

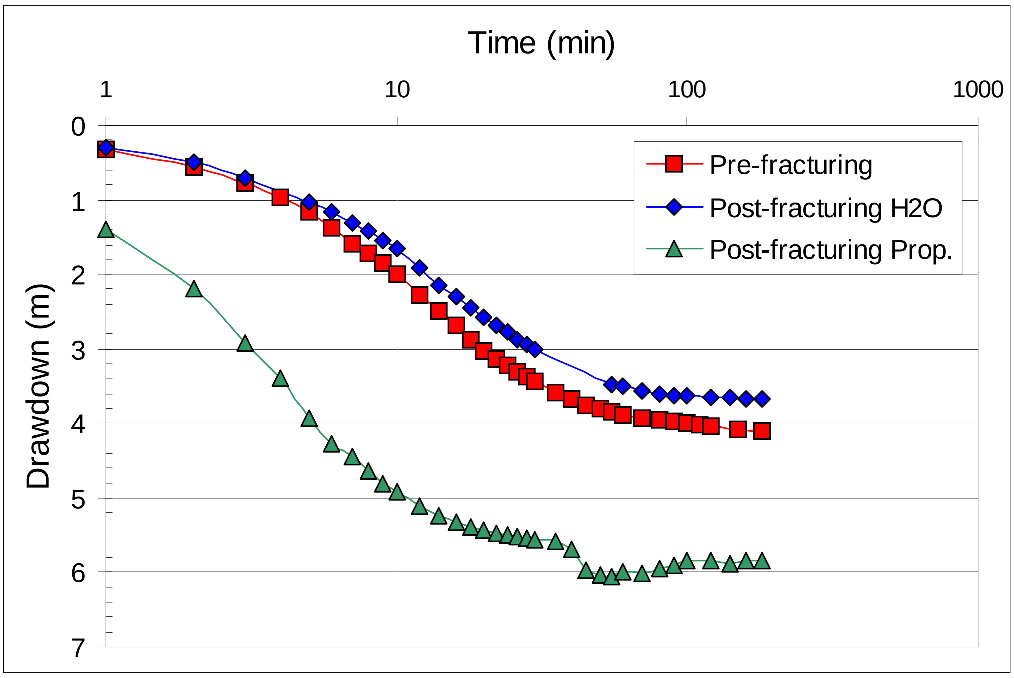

Figure 8 Drawdown response of pump-packer aquifer test conducted over interval 52.5–57.5 m after hydraulic fracturing with both water and proppant, Watervale Oval. The drawdown curve obtained prior to fracturing is also provided for comparison.

aquifer test was again carried out after injection had ceased, however the results were surprising ('Post-fracturing Prop.' in Figure 8). Drawdown in the packers was between 42% and 363% greater throughout the test compared with the pre-fracturing test. This indicates a significant reduction in aquifer transmissivity, most likely due to clogging of fractures with the polymer. Repetitive pumping of the well under high stress failed to improve subsequent aquifer tests and clear the fractures of polymer. Several treatments of the test interval with chlorine (which is known to dissolve the polymer) were unsuccessful and no further ASR trials were able to be conducted on the well to investigate the effect of hydraulic fracturing on recovery efficiencies.

PREVIOUS ASR TRIALS IN FRACTURED ROCK AQUIFERS

The majority of ASR trials conducted in South Australia, and probably Australia to date have been conducted in limestone or sand aquifers rather than fractured, crystalline-rock aquifers. Two local exceptions are;

- the artificial recharge of a deep, confined, quartzite aquifer at Regent Gardens northeast of Adelaide
- the storage of creek water, also in a deep, fractured quartzite aquifer at Scotch College to the southeast of Adelaide.

Currently at the Regent Gardens site, wetland-treated stormwater is injected into a heavily-jointed quartzite aquifer at ~70–80 m depth for subsequent irrigation of surrounding parklands. The site has been operational since 1994, with up to 50 ML (in 1996) being injected each winter (Barnett et al., 2000). Unfortunately there is insufficient volume and salinity data available for calculating the seasonal mass recovery (RM) of this ASR scheme. However in the summer of 1996–97, 20 ML of groundwater, with a salinity not exceeding 950 mg/L, was extracted from the aquifer, indicating a recovery efficiency of more than 40%.

Similarly, at the Regent Gardens site, surface water (sourced from Brownhill Creek) is injected into a deep, fractured quartzite aquifer for subsequent use in the summer. Weekly discharge volume and salinity data have been collected over most recovery seasons since the commencement of this scheme, thereby enabling calculation of the recovery efficiency for each season. Pavelic et al. 1999, report recovery efficiencies of between 7–20% for the first three years of operation, assuming a salinity threshold of 2000 mg/L. Values of recovery efficiency have increased steadily since 1992 due to the accumulation of residual injected water from each season. This trend is also reflected in the recovered mass values increasing from 9–30% between 1992–93 and 2000.

The recovered mass results obtained from the ASR trials in the Clare Valley are significantly higher than those previously obtained at Regent Gardens and Scotch College. This is most likely due to significantly smaller volumes of injected water and shorter residence times for the Clare trials. Although it may be worthwhile conducting further ASR trials with much larger injectant volumes and longer residence times in the future, it is envisaged that the results would be similar to those of existing operations in fractured rock aquifers. The only factor which could significantly reduce the recovery efficiency of such a trial in the Clare region is the loss of injected water through groundwater discharge into creeks. This problem has not been an issue for previous ASR trials in other parts of the State because they have relatively less variable topography and hence fewer active groundwater discharge features.

An earlier study by Harrington and Love (2000) has estimated the mean annual volume of groundwater that discharges naturally into the Eyre Creek. Unfortunately the methods employed in the study required comprehensive historical records of stream flow and salinity which were not available for the other catchments in the region. It is also unknown what affect the increase in recharge by ASR will have on the discharge rate to creeks. Therefore a crucial factor which could determine the success or demise of a potential ASR scheme in the Clare Valley is the siting of the injection well away from surface discharge features, such as springs and watercourses.

CONCLUSIONS AND RECOMMENDATIONS

The results of two small-scale tracer tests conducted in fractured rock aquifers of the Clare Valley indicate that recovery efficiencies of ASR schemes in these systems may be low. Any injected water will rapidly mix with native groundwater and be transported away from the injection well due to naturally high groundwater flow velocities through fractures. However, the use of ASR to augment groundwater resources in the Clare Valley is likely to be feasible because the ambient groundwater quality is already suitable for irrigation in areas where there is a demand for increased allocations. Hence, additions of relatively fresh surface water by ASR will only serve to improve the groundwater resource. The only concern however, is that surface water added to the aquifer by ASR does not discharge to creeks before it can be recovered for beneficial use. While some preliminary calculations of mean annual groundwater discharge to the Eyre Creek have been determined previously, very little is known about how natural discharge to creeks varies spatially and temporally across the region. It is proposed that further work be undertaken to investigate these factors, as well as the likely impacts of artificially increasing groundwater recharge and thereby potentially increasing groundwater discharge to creeks.

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