SUMMARY REPORT

Department for Water

IMPROVE THE KNOWLEDGE OF GROUNDWATER FLOW MECHANISMS IN FRACTURED ROCK AQUIFERS IN THE MOUNT LOFTY RANGES, NORTHERN ADELAIDE PLAINS AND KANGAROO ISLAND

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INTRODUCTION

The Mount Lofty Ranges (MLR) provides important surface water and groundwater resources for domestic, industrial and agricultural purposes locally, as well as metropolitan Adelaide's reticulated water supply. As such, water allocation in these areas needs to be actively managed to ensure that current and future uses of these resources are sustainable and that the environment is also recognised as a user of the resource.

To improve the management of groundwater resources in fractured rock aquifers (FRA), the understanding of groundwater flow mechanisms occurring in these systems needs to be enhanced. This project consists of four programs – key activities which address areas with significant knowledge gaps:

1. Surface water – groundwater interaction and implications for conjunctive use
2. Spatial extent and distribution of zones of influence from pumped wells in FRAs
3. Groundwater movement across regional scale faults and the implication for recharge to adjacent sedimentary aquifers
4. Predicting catchment scale processes in a fractured rock environment.

The primary outcome from this project contributes to knowledge and capacity building, as well as water access entitlements and planning framework, integrated management of environmental water, water resource accounting, community partnerships and development of new technology and non-traditional approaches.

1. SURFACE WATER – GROUNDWATER INTERACTION AND IMPLICATIONS FOR CONJUNCTIVE USE

Groundwater is an integral component of the water budget and contributes baseflow to surface water resources and ecological flow requirements. Groundwater contributes baseflow to the majority of streams throughout the MLR and Kangaroo Island (KI) regions and, during many summer months, is the only contributor to streamflow.

1.1. THE DEVELOPMENT OF A PROCESS BASED CONCEPTUAL MODEL OF FRACTURED AQUIFER FLOW AND INTERACTIONS USING ISOTOPES AND TRACERS, WITH AN EMPHASIS ON SURFACE WATER – GROUNDWATER INTERACTIONS IN PRISTINE AND CLEARED CATCHMENTS

Project outline

Between 2007 and 2010, a catchment study was conducted in the Rocky River Catchment on Kangaroo Island. The Rocky River Catchment represents a pristine catchment which has not undergone any major development for water resources activities.

The specific aims of the catchment study were to:

- Identify stream reaches where there is evidence of exchange between surface water and groundwater systems and whether it is gaining, losing or losing and disconnected
- Identify the locations of wetlands and permanent pools, whose permanency depends on groundwater inflows

- Understand the hydrogeological and climatic controls (i.e. evaporation and transpiration) on surface water-groundwater connectivity
- Determine the contributing sources of groundwater which maintain a fresh river system.

Hydrochemical methods, including analyses of the stable isotopes of water, major and trace ions, radon and strontium isotopes, were used to investigate the spatial and temporal variations in connections between surface water and groundwater systems in the Rocky River Catchment. The hydrochemical methods were used in conjunction with streamflow measurements and water level data from monitoring piezometers that were installed as part of this project.

Results and Conclusions

Applying an entire river system assessment, it has been demonstrated that the surface water – groundwater system types (or connectivity conditions) can change along stream reaches, as well as take place concurrently at the same location and time. Water level data, together with salinity and stable isotope results, showed that the relatively low salinity of the fresh water river system can be maintained in an otherwise saline regional fractured rock groundwater system, by virtue of the dominantly losing connectivity state (i.e. there is little to no groundwater discharge from the deeper regional system to the river as baseflow). The hydrochemistry showed that the dominant groundwater source to the river system was from the shallow sedimentary deposits in the catchment headwaters and not from the regional fractured rock aquifer system.

The emerging conceptual model of this system is that winter rainfall replenishes the shallow sedimentary perched aquifers located in the catchment headwaters which gradually drain and discharge into the tributaries of Rocky River. Groundwater discharge occurring in the catchment headwaters, provided small, but in some cases, continuous flow to the tributaries of the river. Winter rainfall must also be recharging the underlying fractured rock aquifer system, however, the consistently low salinity of Rocky River indicates that there is minimal input from this system to the river.

There has been little documentation on the importance of these shallow sedimentary systems and the role that they play in streamflow generation. Other key findings were the presence of groundwater-fed permanent pools along some river reaches, which provide important refuges for aquatic habitat. By understanding the variable nature of connectivity of an entire river system and the importance of vegetation (evapotranspiration) controls on the surface water – groundwater connectivity, more appropriate management practices can be employed.

Recommendations for management

The strong hydraulic connections between the surface water and groundwater imply that groundwater development in these types of catchments is likely to have an impact on both the surface water and groundwater resources. The impact on the different system types (i.e. gaining, losing and losing disconnected) will vary depending on the connectivity state. In gaining stream systems such as in the catchment headwaters, increased groundwater extraction may impact on the connectivity state between surface and groundwater systems, potentially causing a reduction in streamflow and duration. Significant reductions in groundwater table elevation may ultimately cause groundwater levels to drop below the elevation of the surface water system such that it becomes a losing-type system, eliminating baseflows and posing a threat to the sustenance of permanent pools. In a losing and disconnected surface water system groundwater extraction is less likely to cause any further impact to streamflow conditions. It is therefore important that quantitative estimates of the groundwater contribution to the surface water system are understood to ensure extraction volumes do not exceed the volume required to sustain streamflow.

The following recommendations primarily relate to the protection of the sedimentary perched aquifer systems to sustain the continual baseflow conditions required by some aquatic biota as refuges, and would involve:

1. Catchments in fractured rock environments tend to have strong hydraulic connections between the surface water and groundwater systems. Groundwater development in these types of catchments is likely to have an impact on the surface water and groundwater resources and implications for groundwater-dependent ecosystems.
2. The impact on the different system types (i.e. gaining, losing and losing disconnected) will vary depending on the connectivity state. In gaining stream systems such as in the catchment headwaters, increased groundwater extraction may impact on the connectivity state, potentially causing a reduction in streamflow and duration. Significant groundwater extraction may ultimately cause groundwater levels to drop below the elevation of the surface water system such that it becomes a losing-type system, eliminating baseflow and posing a threat to the sustenance of permanent pools.
3. In a losing and disconnected surface water system, groundwater extraction is less likely to cause any further impact to streamflow conditions. In this environment, groundwater extraction limits may be more generous and buffer zones around surface water systems may be more limited. However, due to the limited understanding of disconnected conditions, it is strongly recommended that a detailed investigation be undertaken in such environments.
4. Land clearance should be limited in areas of wooded swamps with thick organic sediments. These areas act as a sink for winter recharge. If vegetation is cleared the water holding capacity of these systems is largely diminished and streamflow duration may be markedly reduced. In cases such as the catchment headwaters of the Rocky River catchment, clearance of vegetation may over time cause erosion of Quaternary sedimentary deposits which provide much of the water-buffering capacity of the catchment and act as the primary source of streamflow between rain events.
5. Groundwater extraction limits and buffer zones to shallow quaternary sedimentary aquifers in close proximity to surface water systems are recommended to allow protection of the sedimentary perched aquifer systems that sustain continual flow conditions, required by some aquatic biota as refuges.
6. Any widespread clearance of vegetation may result in rising watertables within the saline regional fractured rock aquifer system leading to saline groundwater discharge into the low salinity surface water system which could be hazardous to aquatic biota.
7. In many cases, the health of aquatic ecosystems are predicated on a continuation of typical levels of stream baseflow and adequate water residence time. In the pristine Rocky River Catchment, groundwater discharge is essential in providing a residual water supply to in-stream pools that act as ecosystem refuges through summer. Extended riparian zones, sufficient to allow natural dams and swamp systems to form, can be effective in increasing the residence time of water in a watercourse. This is particularly important in extending streamflow duration in ephemeral surface water systems.

1.2. DEVELOPMENT OF ANALYTICAL AND NUMERICAL MODEL FOR PRISTINE AND CLEARED CATCHMENTS

Project Outline

The development of an analytical and numerical model supports and quantifies the isotopic and hydrochemical-process based model and enables predictive modelling of future scenarios, such as land use and climate change.

The way in which cleared and pristine catchments behave in response to similar climatic and geologic conditions is not well understood. One component of this project will compare the outcomes of modelling a pristine catchment scenario versus a cleared catchment scenario.

The outcomes of modelling scenarios can be used in assessing the response of the FRA to various climatic-induced stresses, to enable more robust management practices, which promote the protection of the FRA resource and any dependant ecosystems.

The objective of the study was to develop a groundwater model of the FRA of Cox Creek Catchment (CCC), Mount Lofty Ranges, to address the following requirements:

1. To provide a model which can be used to determine regional-scale impacts of increased licensed groundwater use from the FRA. *Predictive model runs will be undertaken to assess what impact an increase of existing water user allocations will have on the current groundwater system.*

2. To provide a model which can be used to assess the regional-impact climate change (decreased recharge) may have on the groundwater resource of the FRA. *Predictive model runs with reduced recharge rates will be undertaken to examine the impacts on the groundwater resource.*

3. To provide a model which can determine regional scale impacts of changed land use conditions. *A predictive model run, which simulates pristine conditions, will be undertaken to examine the different response the system has to cleared and pristine conditions.*

Cox Creek Catchment was chosen as the study site not only due to its good monitoring record, which is required for the purpose of confirmation and calibration of the model, but more importantly because groundwater has been extracted for the irrigation of vegetables and orchards in the area, for over 40 years. Due to this extended period of extraction the system has had sufficient time to reach equilibrium after the clearing which occurred in the 1960s.

This has resulted in an aquifer system which has changed very little over the past ten years (1998 – 2008). As a result of this equilibration, the potentiometric surfaces for both 1998 and 2008 are alike; the system has proved to be in post clearing equilibration.

The model was constructed with a 10 year calibration period 1998–2008 and a 20 year predictive period 2008–2028. The model was run via the Modflow three-dimensional finite-difference mathematical code, where the Visual Modflow 2009 graphic user interface was used for pre and post processing of Modflow files. In view of the size of the catchment (16.4 km^2), 50 m x 50 m model cells were used to simulate that area, with a view to understanding regional scale trends. Hydraulic variables such as storage coefficients, hydraulic conductivity and aquifer recharge were derived from previous studies conducted by DWLBC. Groundwater extraction rates were sourced from land and water use surveys conducted within the catchment. The model was constructed with two layers, the first simulating the active fracture zone with the second deeper layer simulating the fracture extinction zone, where conductivity values are significantly lower. The model was constructed with numerous boundary conditions including; no flow boundaries where groundwater flow is parallel to the model edge, general head boundaries were groundwater flow is perpendicular to the model edge (flow into the model domain), river cells to simulate the middle to lower reaches of Cox Creek, and drainage cells to simulate the upper reaches of Cox Creek.

Steady state model calibration was carried out and followed by a sensitivity analysis and transient calibration. Several observation well hydrographs, and streamflow data from a gauging station on Cox Creek, provided calibration data.

Results and Conclusions

Transient calibration resulted in a well matched qualitative comparison between the modelled and observed potentiometric head contours, which indicated that the modelled groundwater head distribution closely represented the regional gradient of the observed distribution. This was further confirmed by the quantitative analysis of hydrographs for all observation wells in the model domain. Transient calibration, comparing modelled groundwater heads with observation well hydrographs, resulted in a normalised root mean square error for the domain of 1.7% for 2008. This value is less than the 5% recommended by the Groundwater Flow Modelling Guideline (MDBC, 2001) and indicates a very good fit between modelled and observed data over the time period considered in the analyses.

Once satisfactorily calibrated the model was used to run scenarios simulating decreases in recharge and increases in extraction from wells. Seven different scenarios were run, as presented in Table 1.

Table 1. Summary of Modelled Scenarios and Conditions

Scenario	Name	Model Run	Recharge	Extraction
S-1	Current Conditions Continued	1998–2028	No change	No change
S-2	Increased Extraction	2008–2028	No change	**20% increase**
S-3	Decreased Recharge	2008–2028	**20% reduction**	No change
S-4	Decreased Recharge, Increased Extraction	2008–2028	**20% reduction**	**20% increase**
S-5	Decreased Extraction	2008–2028	No change	**20% reduction**
S-6	Decreased Recharge, Decreased Extraction	2008–2028	**20% reduction**	**20% reduction**
S-7	Pristine Conditions	2008–2028	**85% reduction**	**No extraction**

Modelling results

Predictive modelling results indicate that the system is highly responsive to changes in both recharge and extraction and as such the system should be managed to reflect these findings.

Under an extension of current recharge and extraction conditions (scenario S-1), head levels are maintained and no new cones of depression are created. Cones of depression present in the model domain are actually slightly minimised. Water levels across the catchment rise slightly and river outflow (loss from the aquifer to the rivers and drains) volume remains somewhat constant to that of the ten year calibration period.

Increasing extraction in the project area causes declines in head levels across the catchment and reduces river outflow, whilst decreases in extraction result in recovered head levels and increased groundwater flux into Cox Creek.

Reductions in recharge result in head level reductions across the whole project area, in turn significantly diminishing flow to Cox Creek. It should be noted that the model responds similarly to reductions in recharge as it does to increases in extraction.

Predictive modelling indicates that the worst case scenario, in which recharge is decreased and extraction is increased, results in significant declines in groundwater flow to Cox Creek and drastic drops in head levels. In some cases winter highs in groundwater head are nearly equivalent to summer lows of the baseline (S-1) scenario.

Predictive modelling indicates that decreased recharge in conjunction with decreased extraction results in very similar, but slightly lower, head levels to those produced in the S-1 scenario. It should be noted that 20% of recharge does not equate volumetrically to 20% of extraction therefore there is diminished flow of groundwater to Cox Creek compared to the S-1 scenario results.

In pristine conditions the model indicates that with reduced recharge due to evapotranspiration and interception, and no extraction, the seasonal variability of groundwater head levels is minimised. The summer head levels are consistently higher than those of scenario S-1, whilst the winter head levels are slightly lower than those of scenario S-1. The potentiometric surface contains no cones of depression but is slightly lower on average than that of scenario S-1. River outflow volume is the lowest of all scenarios, however it is also more consistent, with less polarity between seasonal highs and lows. Stream flows are lower in this scenario because of a widespread interception of recharge by pristine native vegetation, resulting in a small but widespread decline in groundwater levels. However, it is possible that in reality, pristine vegetation causes increases to the residence time of water in the surface system, thereby increasing streamflow duration. However, this effect is not simulated in the model or reflected in the results of this scenario.

Recommendations for Management

Decreases to recharge and increases to extraction both result in the reduction of groundwater flow to Cox Creek. This is likely to have an adverse effect on macroinvertebrates and fish species present in Cox Creek. There are also a number of permanent pools (>15 m in length) located within Cox Creek which may act as ecological refuges during summer months or periods of extended drought. It should also be considered that diminished flow to Cox Creek in turn results in diminished flow within the Onkaparinga River which also acts as a refuge for many species.

The model indicates groundwater and surface water systems in Cox Creek Catchment are highly responsive to changes in both groundwater recharge and extraction. Management strategies should be employed to reflect these findings. Management strategies should be implemented which protect the permanent pools, current flow regime, and water levels of the Cox Creek Catchment, and also take into account the high dependence of the catchment on recharge and extraction. Such strategies include:

1. The application of buffer zones between Cox Creek and groundwater extraction points is essential to prevent direct impacts on stream flow.
2. Applying restrictions on extraction in the modelled portion of Cox Creek Catchment such that it does not exceed current extraction levels.
3. Recharge decreases of 20% or more, due to drought or climate variability, should ideally be offset by decreases in groundwater extraction to maintain water levels and the Cox Creek flow regime.

1.3. INVESTIGATION OF SPATIAL EXTENT OF SURFACE WATER – GROUNDWATER INTERCONNECTIVITY IN PRISTINE AND CLEARED CATCHMENTS, AND RECOMMENDATION OF APPROPRIATE MANAGEMENT STRATEGIES TO ADDRESS CONJUNCTIVE USE SCENARIOS

Project outline

Between 2006 and 2010, surface water – groundwater interactions were studied in a number of contrasting hydrologic environments in the Mount Lofty Ranges (MLR) and Kangaroo Island (KI). These were primarily areas of fractured rock hydrogeology, with some sedimentary groundwater systems. The areas studied were:

1. The catchment of Rocky River, Kangaroo Island, which has undisturbed, 'pristine' native vegetation

2. The catchments of Cox, Lenswood and Kersbrook Creeks, three fractured rock catchments in the Western MLR, largely cleared of native vegetation

3. The whole of the Eastern MLR Prescribed Water Resources Area (PWRA), which includes both fractured rock and sedimentary aquifers and is also largely cleared.

Hydrochemical methods, including analyses of the stable isotopes of water, major and trace ions, radon and strontium isotopes, together with measurements of streamflow and groundwater levels, were used to reveal the spatial and temporal variations in connections between groundwater and surface watercourses.

Results and Conclusions

In the fractured rock catchments of Eastern and Western MLR, our investigation showed surface – groundwater interactions to be widespread. Throughout many of the catchments studied, surface watercourses either gain from, or lose water to the underlying fractured rock system. Creek lines in these catchments are incised into fractured rock landscapes, creating abundant conduits for water to transfer between the two systems. However, the flux of water between systems is highly spatially and temporally variable. There is a high temporal variation in flow between summer and winter. Widespread cessation of flow occurs during the summer, indicating that groundwater levels drop to an extent at which they no longer discharge to watercourses.

In most places, there is not an obvious point of discharge from the groundwater system into surface watercourses. 'Gaining stream' interaction is evidenced by a progressive down-stream increase in streamflow rate and presence of water with hydrochemical characteristics that indicate its groundwater origin. 'Losing stream' interaction is evidenced only by a progressive down-stream reduction in flow. There are however a few points of major gain or loss between the surface and groundwater systems in the MLR, where volumes of water in the order of megalitres per day transfer between surface and groundwater systems. These locations require particular attention for conjunctive resource management. While they are few in number, imprudent management of the surface or groundwater resource in the vicinity of these locations could lead to significant impacts on the linked water resource.

A few catchments in the Eastern MLR PWRA have largely sedimentary groundwater systems, particularly in areas of Permian Cape Jervis Formation sand and gravel deposits. These catchments are mostly cleared of native vegetation and in many cases turned over to dairy pasture. Aquifers here are mostly unconfined and diffuse recharge occurs through a fairly permeable vadose zone. Removal of vegetation has had more effect in reducing transpiration than enhancing runoff. Hence, recharge is high and groundwater flows freely into watercourses. The clearance of vegetation in these areas has enhanced recharge, reduced direct uptake from shallow groundwater, and resulted in increased streamflow. Conversely, surface streamflow in this environment can be severely impacted by high levels of groundwater extraction, including root water uptake by plantation forestry.

The largely undisturbed catchment of Rocky River was selected as a study catchment intended to provide a comparison with cleared fractured rock catchments in the MLR. As well as having almost pristine native vegetation cover, Rocky River is known to flow year-round in most years, suggesting flow sustained by groundwater through the summer. Regional basement rock in this area is mostly covered by a deep layer of weathered basement material, which is largely impermeable. However, the steep topography with deep valleys in the upper catchment and the perennial nature of surface flow here suggested that conduits must exist between the underlying fractured rock groundwater system and the surface streams.

Contrary to these expectations, extensive hydrochemical sampling in the lower Rocky River Catchment, showed that there were minimal, if any, interactions between the surface water system and the deeper underlying fractured rock groundwater. It is apparent that this is essentially a 'disconnected' catchment, in which there are no significant connections between the surface water system and the underlying fractured rock aquifer system. While there was scope for creeks to be fed by groundwater slowly seeping from the deep weathered basement, samples of groundwater taken from this were significantly more saline than the water in Rocky River.

This presents a counter-intuitive finding, in which Rocky River has no connections with regional groundwater and yet flows perennially, while many of the streams in cleared fractured rock catchments in the MLR are shown to have strong surface – groundwater connections but do not flow perennially.

Further hydrochemical sampling and piezometric measurements showed that the perched shallow groundwater in a thin (<3 m) quaternary surface layer overlying the weathered basement layer was of the same water quality as the surface stream water and may provide a source of the summer flow in Rocky River. However, this layer represents a much smaller water storage capacity than the fractured rock aquifers that discharge to streams in the MLR. Furthermore, the extensive native vegetation is expected to transpire a large proportion of the shallow groundwater stored in the thin surface layer, leaving even less capacity for this layer to sustain streamflow.

Further investigation was enabled by extensive bush fire in the Rocky River Catchment in December 2007. This allowed access through the previously impenetrable bush of the upper catchment, enabling observations that were critical to the understanding of water dynamics in this catchment.

The creek lines the upper Rocky River Catchment are punctuated by large areas of wooded swamps with thick organic sediments of peat and woody detritus. In these environments, which were extensive along creek lines in the upper catchment, fallen trees and large amounts of organic detritus effectively dam the creeks, causing water to spread out laterally. This results in a marked increase in the residence time of the water in the surface system compared with the open channels observed in cleared catchments. Water sourced from winter rain, occasional summer rain, and the slow discharge from the thin perched quaternary groundwater layer is buffered in these swamp systems, facilitating year-round flow of the surface water system without the need for connection to the regional groundwater system.

In marked contrast, watercourses in cleared catchments are often incised into the landscape due to the rapid, erosive flow that occurs through them in the absence of vegetation, resulting in a single narrow stream channel which rapidly drains the catchment of surface runoff and groundwater-derived baseflow. Much of the rain falling during winter runs off rapidly and groundwater discharging into gaining stream reaches flows largely unimpeded through the system. Water is thus retained in cleared catchment watercourses for a much shorter time than in catchments with pristine vegetation.

These findings explain why streamflow duration is often greater in Rocky River Catchment, with apparently low groundwater storage capacity, than in the cleared fractured rock MLR catchments, where there is relatively high groundwater storage capacity. Perennial surface streamflow is due to extensive water storage capacity in the surface system rather than the subsurface groundwater system. In disconnected catchments such as this, groundwater extractions from the regional fractured rock system will not have a significant impact on flows in surface watercourses.

The investigations and observations made here present us with some contrasting findings:

1. In a catchment where there is no significant connection with the regional groundwater system and the only surface – groundwater interaction is with water in shallow (<3 m deep) surface deposits close to creek lines, there is perennial flow. Here, summer flow is sustained by water stored mainly in the surface water system and extensive fringing swamp zones.

2. In a similar climatic environment, but with strong connections to extensive fractured rock groundwater system, flow continues through summer in some creeks due only to discharge from the regional fractured rock system.

3. A key impact of the undisturbed native vegetation cover in the Rocky River Catchment is to retain water in the landscape, resulting in a more sustained flow in the river system. While the amount of water transpired by vegetation in the catchment must be greater that that in an otherwise identical cleared catchment, the loss is offset by the much lower end-of-system runoff in the undisturbed catchment compared to the cleared catchment.

Evidently, surface flows may persist though summer in creek systems without connection to deeper groundwater systems, even in the semi-arid environments of southern South Australia. In most cases, and particularly in fractured rock environments, there are significant connections between surface and groundwater systems. However, the flux of water between systems is dependent on groundwater levels, which may vary significantly between summer and winter. The clearance of native vegetation appears to further polarise this variation between summer and winter flows, by reducing the capacity for water to be stored in surface-water features of the landscape.

Recommendations for management

The recommendations for appropriate management strategies that can be drawn from these findings are summarised in the following points:

1. In catchments with fractured rock groundwater environments there are likely to be many connections between surface and groundwater systems. Any impact on groundwater levels, due for example to groundwater extraction, will have an immediate impact on streamflow, with implications for downstream water users and water dependent ecosystems. If streamflow rates are to be preserved, conjunctive resource management strategies for these systems should include a limiting of groundwater allocations to a maximum of the annual catchment recharge volume minus the annual total groundwater-derived baseflow volume in all significant streams. In addition, the application of buffer zones between streams and groundwater extraction points is essential to prevent direct impacts on streamflow.

2. A groundwater management framework that does not seek to maintain flows to surface watercourses remains an option in these connected environments. However, where the surface water system is also exploited as a resource for human uses, the management framework for the surface water resource must then take account of the reduction in baseflow that may occur due to the proposed groundwater extraction, rather than (as is often the case) be based on an assumption that historic baseflow rates will continue. In many cases, the health of aquatic ecosystems is predicated on a continuation of typical levels of stream baseflow. In the context of the MLR, groundwater discharge is essential in many streams to provide at least a residual water supply to in-stream pools that act as ecosystem refuges through summer.

3. In areas with unconfined sedimentary aquifer systems, groundwater extraction limits and buffer zones around connected watercourses are similarly important.

4. Where points of major flow between surface and groundwater systems exist, an understanding of the importance of this flow to the receiving system is required. The amount of flow that is considered to be ‘major’ is subjective, and depends on the scale of the surface and groundwater resources in comparison to the rate of the flow between systems. Additional restrictions on resource exploitation may need to be tailored for these locations, according to the significance of the flow volume, the human demands and the dependence of ecosystems on the linked resources.

5. In disconnected catchments, where a substantial weathered layer separates the surface and groundwater water systems, impacts of groundwater extraction on surface watercourses are less likely. In this environment, extraction limits and buffer zones may be more liberal. However, care must be taken to confirm disconnected conditions, which are not common in fractured rock environments.

6. In catchments where undisturbed native vegetation exists, removal of this vegetation creates a severe risk of causing erosion to shallow surface sediments that may provide much of the water buffering capacity of the catchment and act as the primary source of stream base flow between rain events.

7. Extended conserved riparian zones, sufficient to allow natural dams and swamp systems to form, can be effective in increasing the residence time of water in a watercourse. This is particularly valuable in extending streamflow duration in ephemeral creek systems.

2. SPATIAL EXTENT AND DISTRIBUTION OF ZONES OF INFLUENCE FROM PUMPED WELLS IN FRACTURED ROCK AQUIFERS

Project Outline

Fractured rock aquifers are becoming increasingly important water supplies as traditional sedimentary aquifers become more fully utilised. Characterisation of groundwater flow in fractured rocks is difficult as hydraulically-conductive fractures are inherently complex and often unpredictable. As fractures act as conduits for flow of both groundwater and electrical charge, methods that can efficiently detect the distribution of electrical pathways may be used to infer characteristics of significant hydrological parameters.

Electrical data from direct current (DC) borehole–to–surface resistivity and self–potential (SP) measurements were used for the interpretation of major hydrological structures at 21 sites in the Eastern Mount Lofty Ranges (EMLR) and 18 sites in the Western Mount Lofty Ranges (WMLR), South Australia. Application of borehole–to–surface methods generated an interpretation of sub-vertical fracture strike and dip. The natural-voltage SP signals generated during pumping tests are of a complex nature, but, the magnitude of changes in the electrokinetic measurement can be attributed to fluid flow rates and determine the dominant direction of groundwater flow.

Results and Conclusions

Borehole–to–surface measurements at numerous sites have confirmed that dominant fracture sets in the Adelaidean metasediments and Kanmantoo Group are controlled by the major north of north-east structural trends in the EMLR and north – north-west to north – north-east structural trends in the WMLR.

Deviations from this dominant strike pattern are seen around a few sites in the Mount Barker area most likely because they are located within the hinge of major regional synclines and anticlines. Although the borehole–to–surface technique shows localised results, it is evident from the consistent interpretations throughout the field area that orientations of the dominant hydraulically conductive sub-vertical fractures are consistent with regional trends.

Borehole–to–surface electrical measurements exhibited significant variations in magnitude, which are indicative of different porosities and saturations within the area. Bulk electrical resistivity could be estimated and, at sites for which electrical conductivity was measured, porosity could also be estimated. The ratio of maximum to minimum apparent resistivity could be attributed to the hydrogeology and used to characterise areas exhibiting substantial differences in fluid flow. Due to the linear vs. cubic nature of electric vs. hydraulic conductivity, a doubling of electrical conductivity could potentially correspond to an eight–fold increase in fluid flow in the dominant fracture orientation. The bulk resistivity is also linked to the salinity of the groundwater and variations are partially attributed to this.

These two electrical methods are sampling the top 20 metres at most, however this is a depth range from which the majority of groundwater is sourced from in the EMLR and WMLR. Much of what is being imaged is the water in fractures parallel to bedding planes and these are likely to be open due to uplift and stress relief.

Due to the complex distribution of fractures in almost every type of rock, no single method can unambiguously map fractures and their capacity for fluid movement. Although SP is a relatively new technique, using interpretations from these two methods will lead to a greater understanding of characterisation subsurface flow in recharge zones and can be used to define orientation of fractures in terms of strike and dip, as well as broadly defining bulk electric resistivity, bulk porosity and hydraulic conductivity. By using a combination of the methods described it could be possible to determine zones of influence around pumping wells in the future, primarily inferring dominant orientation of strike and an estimate of the elliptical radius from the magnitude measurements.

Hydraulic anisotropy may be applied to (or refine) existing extraction well buffer guidelines in line with the following example. A nominal buffer for a particular area depending on geology, geological structure and rate of and volume of extraction, may typically have a radius of 200 metres. Current guidelines assume equal drawdown in each direction from the extraction well and hence a circular buffer (with this radius) is applied. However in a fractured rock environment there will be preferential fracturing in a particular direction. Consider a site which exhibits preferential fracturing in the north-west to south-east direction (direction of strike and anisotropy). Say the hydraulic anisotropic ratio was calculated to be 3. Therefore the radius of the maximum axis (in the north-west to south-east direction) would be three times that of the minimum axis (in the north-east to south-west direction).

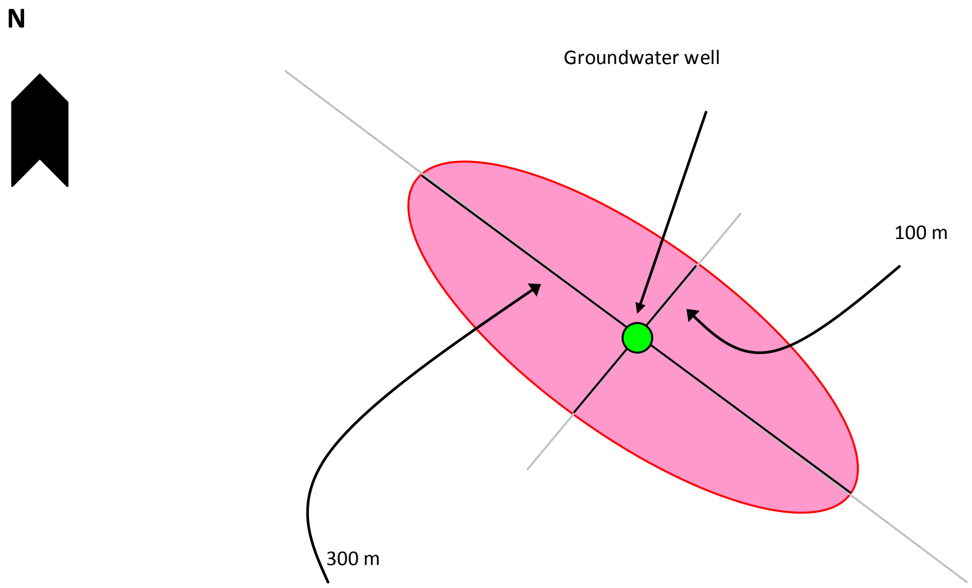

Figure 1. **Hypothetical example of anisotropic direction and ratio as applied to circular buffering system**

In order to maintain an area size similar to the current (circular) buffer guidelines, the radius would be reduced by 50%, this becomes the radius of the minimum axis. The anisotropic ratio is then applied to this minimum axis to generate a radius for the maximum axis. Using the example and an original (circular) buffer of 200 m, an ellipse with the following specifications would apply (Fig. 3):

- Minimum radius in the NE/SW direction = 100 m
- Maximum radius in the NW/SE direction = 300 m

Recommendations for management

The investigation showed that the borehole–to–surface DC resistivity proved to be effective in determining preferential fracture orientation as defined by both strike and dip. It compares well with the known structure in the WMLR.

The SP data proved to be a little more challenging than first thought. The results suggest that there are more chemical processes at work that are not fully understood at this early stage. It is recommended, as expressed in earlier chapters, that the ability of these techniques be further investigated.

Based upon these geophysical findings, the extents of the zones of influence around a number of extraction wells in the EMLR and WMLR have been identified. These buffer distances can be recommended for these specific sites and provide a guide to the method by which buffer distances can be determined in water management plans. The direction and range of magnitudes of the hydraulic anisotropy identified at the locations assessed provides a guide to the specification of buffers for wells in similar geological settings.

It is recommended that these guidelines are used when reviewing buffer zones in current and future groundwater resource management plans.

3. GROUNDWATER MOVEMENT ACROSS REGIONAL SCALE FAULTS AND THE IMPLICATION FOR RECHARGE TO ADJACENT SEDIMENTARY AQUIFERS

Project outline

This investigation comprised a case study of the Eden-Burnside Fault and Western Mount Lofty Ranges, investigating mechanisms by which groundwater flow traverses this regional-scale fault. Furthermore, the spatial extent of recharge zones proximal to the fault zone was delineated, and the importance of catchments of the Western Mount Lofty Ranges as areas of potential recharge was examined. Various complementary hydrogeological and hydrochemical methodologies were employed, such as downhole geophysics, fracture mapping, hydraulics, strontium tracers, analysis of stable isotopes of water, and interpretation of hydrochemical evolution to infer groundwater flow paths and potential recharge mechanisms. Estimates of the volume or rate of flow across the fault were not within the scope of this study.

Results and Conclusions

Groundwater may flow directly across a fault boundary between the two aquifer types or may be inhibited by low-permeability layers and flow parallel to the plane of the fault, emerging elsewhere in the lower fault zone. Groundwater will preferentially flow across the boundary in areas where more conductive zones of fractured rock on one side of the boundary coincide with more conductive zones of sedimentary aquifers on the other side.

Flow across regional-scale faults is enhanced or inhibited depending on orientation of fractures with respect to the cross-fault hydraulic gradient. Observations of structural geological features in the vicinity of the Eden-Burnside Fault indicate that (a) there are fractures of a variety of aperture sizes and orientations that collectively allow flow of groundwater in the direction of the regional hydraulic gradient along the whole of the 13 km section of the Eden-Burnside Fault identified as the primary mountain-front recharge zone, and (b) the spatial variation in fracture orientation results in zones of preferential flow and zones of restricted flow.

The active stresses within the Eden-Burnside Fault appear to result in a highly fractured ‘zone of breakage’, creating exceptional conditions for groundwater flow, both across and along the fault. The existence of this zone and its degree of hydraulic conductivity must be largely affected by the contemporary activity of the fault and the direction of stresses. In the Eden-Burnside Fault non-compressive shear stresses and unloading effects are biased toward further opening of fractures. Furthermore, the contemporary activity of the fault inhibits the infilling of fractures in the breakage zone with diagenic products as may occur in older, non-active faults.

On a regional scale, flow of groundwater across the fault may be considered to follow Darcian flow principles, being proportional to the hydraulic gradient existing between groundwater systems above and below the fault. However, on all sub-regional scales, flow across the fault is highly spatially variable, due to the high degree of variability in rock types, geological structures, fracture aperture sizes and fracture density. Furthermore, the nature of the flow across the fault is made more unpredictable by the highly conductive nature of the fault line and its associated ‘zone of breakage’. Hydrochemical tracer results show no clear evidence of groundwater following a particular preferential pathway across the fault zone, suggesting that water flowing to the fault on the fractured rock side can then flow in several directions due to the local variations in fracture plane orientations and the highly anisotropic conductivity of the fault zone.

An east–west groundwater flow transect through the Mount Lofty Ranges indicates that flow from the fractured rock aquifer system in the Western MLR travels toward the west/north-west from the high topographic ridge on the western side of the Onkaparinga River catchment. To the east of this ridge, all groundwater flow is toward the east and south-east. This implies that only the catchments on the eastern side of the Central Adelaide Groundwater Area and on the western side of the Western MLR prescribed area act as recharge areas to groundwater systems that recharge the Adelaide Plains sedimentary aquifers across the Eden-Burnside Fault.

Recharge into the Quaternary aquifers close to the fault zone (hydrogeological zones 2 and 4A) is shown to be relatively recent (generally less than 44 years, according to groundwater-age dating results (CFCs)), implying that where flow to these occurs from the fractured rock system, it is laterally across the fault from the fractured rock aquifer at a similar or greater elevation to the receiving quaternary aquifers. However, analyses of hydrochemical and stable isotope data show that the recharge of the overlying Quaternary sedimentary aquifers is largely due to diffuse local recharge. In addition, stream bed recharge from the watercourses crossing the plains is a significant contribution. A proportion of the water in these watercourses is discharged from fractured rock aquifers in the Western MLR.

Transfer of water between groundwater systems on opposing sides of the fault occurs not only via the groundwater system. Groundwater also discharges from fractured rock aquifers into surface watercourses above the fault, then traverses the fault zone via the surface water system before recharging sedimentary aquifers below the fault zone. This is a significant pathway for groundwater traversing the Eden-Burnside Fault. The volume of water transported via this pathway is up to 13% of the volume of groundwater flow across the fault (~8000 ML estimated by Gerges (1999)), and represents some of the lowest-salinity recharge to the shallow aquifers of the plains. If surface and groundwater resources are not managed conjunctively in this setting, there is a high risk of unexpected impacts on surface watercourses in the mountain-front zone and recharge to sedimentary aquifers of the plains.

The potentiometric surface analysis of the Tertiary and Quaternary aquifers in the study area shows that there is a downward hydraulic gradient from Quaternary to Tertiary, implying that the latter may be at least partially recharged by downward leakage from the Quaternary aquifers. This is contrary to previous understanding of the direction of hydraulic gradient between Quaternary and Tertiary aquifers in the Adelaide metropolitan area.

The results of stable isotope analyses suggest that water in the Tertiary sedimentary aquifer in hydrogeological zones 2 and 4A is an approximately equal mix of water flowing from the mountain-front fractured rock aquifers and downward leakage from the overlying Quaternary aquifers. This finding highlights the importance of managing both the Quaternary aquifer and the mountain-front fractured rock aquifers with a view to preserving recharge to the important Tertiary aquifer resource.

This finding of approximately equal recharge from the two contributing recharge sources presents an opportunity to quantify the recharge across the fault to the Tertiary aquifer from the fractured rock system. While this is extremely difficult to determine directly, due to the extreme spatial variability of flow through the fault, the downward leakage from the Quaternary aquifers to the Tertiary system may be an easier approximation to make, given sufficient empirical data. The contribution flowing from the fractured rock aquifer system could then be approximated by equating it to the downward leakage. Generating data necessary for this approximation was, however, beyond the scope of this investigation.

Recommendations for management

The following recommendations are made with a view to managing the groundwater resources existing on either side of the Eden-Burnside Fault in light of the findings of this study. However, the these recommendations also represent a guide to the management of groundwater in any regional fault zone where fractured rock systems are recharged in an up-thrown fault block and discharge to confined sedimentary aquifers on the adjacent down-thrown block.

1. Groundwater extraction and allocation policies should take account of the anisotropic nature of flow in the Eden-Burnside fault zone. The delineation of groundwater management areas in this

area should allow for unpredictable impacts of groundwater extraction on neighbouring water resources. Groundwater and surface water protection zones should be more generous than may be applied in fractured rock groundwater areas away from regional fault zones.

2. The application of groundwater-age dating techniques, using environmental hydrochemical tracers such as CFCs and ^{14}C, in combination with stable isotope analyses of samples from mountain-front fractured rock aquifers and their associated sedimentary aquifers is recommended as an effective method to reveal the degree of connection between aquifers linked by a regional fault system.

3. Recharge of the confined Tertiary sedimentary aquifers of Adelaide Plains hydrogeological zones 2 and 4A is due, in approximately equal proportions, to 1) downward leakage from the overlying quaternary sedimentary aquifers and 2) groundwater flow through the Eden-Burnside fault from the fractured rock aquifers of the Western MLR. Groundwater management policies for the Central Adelaide Groundwater Area should take account of this dependence of the important Tertiary confined aquifer on its two primary recharge sources. Extractions from the Quaternary aquifer have historically been largely uncontrolled. Allocation policies applied to this aquifer should consider the implementation of pressure reduction limits in both the Adelaide Plains Quaternary aquifers and the fractured rock aquifers in the Western MLR mountain-front zone to preserve recharge to the deeper Tertiary aquifers.

4. Water transported via surface watercourses from fractured rock to sedimentary systems is a component of the flow across the fault that is particularly prone to the management of the groundwater resource in catchments above the fault. A reduction of groundwater head by perhaps 10 m in the upper catchments, over a total hydraulic head difference of perhaps 300–400 m between the upper fractured rock aquifers and the sedimentary aquifers below the fault results in a small percentage change in the hydraulic gradient and correspondingly small change in the recharge of the sedimentary aquifer from the flow of groundwater across the fault. However, in the upper catchments above the fault, relatively small reductions in head potential in the fractured rock aquifers may result in a major decline in surface watercourse flows across the fault zone, thus significantly reducing the recharge that occurs to the plains sedimentary aquifers via the surface watercourse pathway. In view of this, surface and groundwater resources in this setting must be managed conjunctively. Imprudent allocation of the mountain-front fractured rock groundwater resource may result in unexpected impacts, both on surface watercourses in the mountain-front zone and on recharge to sedimentary aquifers of the neighbouring plains.

4. PREDICTING CATCHMENT-SCALE PROCESSES IN A FRACTURED ROCK ENVIRONMENT

Project Outline

The fractured rock aquifer systems are characterised by high spatial variability in hydraulic conductivity, making traditional hydraulic methods for estimating groundwater flow difficult to apply. Due to the heterogeneous nature of these systems, there is a lack of predictive capability at regional scales.

Conceptualisation of groundwater flow in a fractured rock environment requires several assumptions regarding fracture network development and the structural geology at a regional or catchment scale. Studies of contaminant transport in fractured rock aquifers have highlighted groundwater flow is focused along major fracture sets with a preferred orientation. Additionally, potentiometric surfaces of fractured rock aquifers at a catchment scale have long been recognised as not accurately reflecting groundwater flow directions at a local scale. Given this, a reasonable assumption regarding fractured rock aquifer systems is that groundwater flow directions are preferentially controlled by one or more dominant fracture sets. Furthermore, the development of these dominant fracture sets, their orientation, spacing and interconnectivity will be largely controlled by the deformation history, lithology and competency variations of the rocks throughout the catchment.

This program included detailed structural mapping at the catchment scale, and the analysis of obtained information on fracture orientations, spacing and connectivity. The purpose of this project was to determine consistent geological and structural characteristics within a catchment and determine which regions in the Mount Lofty Ranges are favourable for groundwater flow based on these measured fracture set orientations. The concept that past and present stress regimes play a controlling role in the development of fractured rock aquifers has been established for many years and was considered in the structural analysis. The final element of the project was to analyse the relationship between yield and lithology in order to qualitatively estimate fracture density.

Results and Conclusions

Fracture orientation, fracture spacing and bedding measured at 84 sites were plotted as poles on equal area, lower hemisphere stereonets, which highlighted the scattered and variable orientation of the dominant fracture sets. This is not necessarily unexpected given the large sampling area, variable lithologies and structural complexity throughout the MLR. It did, however, indicate a broad clustering of poles in the NW quadrant of the stereonet with an average orientation of 014/56° E.

An analysis of the parallelism between bedding and the dominant fracture set at each site was also undertaken. Of the 51 sites where bedding could be observed, 40 sites exhibited the dominant fracture set parallel to bedding; at 11 sites the dominant fracture set was not parallel to bedding. Sites where dominant fracture orientation was not parallel to bedding often exhibited fractures parallel to schistosity. For the remaining sites, bedding was not observed due to lithological type or metamorphic grade.

Overall, this has indicated a tendency for fractures to be oriented NNE with moderate to steep easterly dips where bedding exhibits a significant role in controlling the orientation of the dominant fracture sets throughout the MLR.

Studies into stress-dependent fracture permeability processes within the MLR have found that the contemporary in-situ stress field has a significant influence on the hydraulics of pre-existing fractures. In particular, within the upper ~0-1.0 km there is a pronounced anisotropic permeability orientation that favours steeply dipping to vertical fractures. Their enhanced permeability is in response to far-field, isotropic, lateral relaxation of the rock mass. As this stress field is more or less isotropic there is no preferred strike orientation. The direction of maximum hydraulic conductivity is often coincidental with the strike of bedding, as bedding planes are often steeply dipping and the densest and most extensive mechanical planes within the rock mass. The effects of uplift and unloading also results in an increase in fracture density and bulk hydraulic conductivity close to the present-day surface. At depths below the effects of uplift and unloading (>1.0 km) it is expected that fracture permeability will favour shallow dipping to horizontal fractures. The major bounding faults of the MLR are currently tectonically active and, by corollary, are also hydraulically active.

In general, the conceptual fracture network model consists of a densely fractured weathered upper zone, less fractured transitional zone and a broadly fractured lower zone. With increasing depth there is a trend of decreasing fracture density based upon a reduction in the number of joint sets and a reduction in yields is expected.

Analysis of the relationship between yield and depth at which the yield stops increasing shows that in the siltstone formations yields increase to a maximum of 80 L/s at about 120 m, with the majority of yields observed to be between 20 and 40 L/s. The transition zone is between 120–200 m and a few samples were recorded in the lower zone, between 200–300 m in depth.

Wells completed in sandstone and quartzite units show an almost identical relationship between change of yield and depth, with the upper zone being between 0–100 m and the transition zone between 100-250 and 100–200 m for sandstone and quartzite respectively. The maximum yields are very similar for both lithologies, with lower yields at greater depths being observed in quartzites. Both quartzites and sandstones have quite similar characteristics to siltstones, which only occasionally display very high yields, which can be associated with zones of major faulting.

The Barossa Complex metasediments, Cambrian turbidites, and Adelaidean limestone are lower yielding units with maximum yields of ~15 L/s and significantly smaller spatial distribution. These lithological units only have distinct upper and lower zones, the upper zone in the former being from 0–120 m, and the two latter units having a shallower upper zone between 0–100 m.

The investigations and analyses resulted in the following findings:

- The current day stress regime does not appear to exert a significant influence over preferential flow directions in shallow fractured rock aquifers. Results indicate, unloading and weathering has a much greater influence on the development of fractures and their density at shallow crustal levels.
- Dominant fracture set orientations in the study area are typically oriented north-northeast with moderate to steep easterly dips and are parallel to bedding. Deviations from this dominant strike pattern are most likely due to variations in bedding orientation associated with hinge zones of major regional synclines and anticlines.
- Bedding parallel fractures appear to be the dominant fracture set, consistent with the findings of the Zones of Influence sub-program and correlates with the preferential groundwater flow path. Orientations of the dominant hydraulically conductive sub-vertical fractures are consistent with regional trends.
- All fracture sets collectively allow the flow of groundwater in the direction of the regional hydraulic gradient. However, on a sub-regional or local scale, groundwater flow is highly variable and dependent on rock type, geological structure, fracture aperture and density.
- Fracture spacing analyses indicate increased fracture spacing with increased competency of the rock type. Competent units, such as the Barossa Complex, Adelaidean quartzites and Cambrian turbidites, typically have average fracture spacings greater than 6 cm, whilst units of lesser competency, such as siltstones, exhibit much closer fracture spacings averaging 1–3 cm.
- The conceptual fracture network model for the study area can be broadly divided into a densely fractured weathered upper zone (0–100 m), less fractured transitional zone (100–200m) and a broadly fractured lower zone (>200 m). The extreme high yielding characteristics (>60 L/s) may be associated with densely fractured fault zones.
- Consistently low yields observed in the Cambrian metasediments, compared to Adelaidean metasediments, may be a result of erosion of the upper weathered section of the sequence. This suggestion is consistent with results indicating uplift and unloading producing higher yields at shallow depths in the Adelaidean metasediments.

Recommendation for management

Data presented in this report provides a baseline data set for the fractured rock aquifers of the MLR. An increase in both structural orientation data and preferential flow direction information is recommended for future investigations. The baseline dataset requires denser data populations, addressing localised variations, to improve the confidence level in management recommendations.

Due to the complex distribution of fractures in almost every rock type, no single method can unambiguously map fractures and their capacity for fluid movement. Using integrated interpretations from a number of methods will lead to a greater understanding of the characterisation of subsurface flow in recharge zones and can be used to define orientation of fractures in terms of strike and dip, as well as broadly defining bulk electric resistivity, bulk porosity and hydraulic conductivity.

Findings of this project also lead to recommendations for cost effective drilling. Any new drilling which is to take place should consider the general observations made relating to fracture spacing and lithology as well as the results of the yield versus depth analysis. Yields should be monitored whilst drilling occurs to ensure the well is drilled to the most effective depth without entering the transitional (lower yielding) zone, to provide a more economical process of well construction.

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