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# Characterisation of the hydrogeology of the Augustus River catchment, Western Australia

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**Abstract** Understanding the hydrogeology of weathered rock catchments is integral for the management of various problems related to increased salinity within the many towns of Western Australia. This paper presents the results of site characterisation investigations aimed at improving the overall understanding of the hydrogeology of the southern portion of the Augustus River catchment, an example of a weathered rock catchment. Site data have highlighted the presence of both porous media aquifers within the weathered profile and fractured rock aquifers within the basement rocks. Geophysical airborne surveys and other drilling data have identified a large number of dolerite dykes which crosscut the site. Fractured quartz veins have been found along the margins of these dolerite dykes. Detailed groundwater-level measurements and barometric efficiency estimates indicate that these dolerite dykes and fractured quartz veins are affecting groundwater flow directions, promoting a strong hydraulic connection between all aquifers, and also influencing recharge mechanisms. The hydrogeological significance of the dolerite dykes and fractured quartz veins has been assessed using a combination of high-frequency groundwater-level measurements (30-min sampling interval), rainfall measurements (5-min sampling interval) and barometric pressure fluctuations (30-min sampling interval). A conceptual model was developed for describing various hydrogeological features of the study area. The model indicates that fractured quartz

veins along the margins of dolerite dykes are an important component of the hydrogeology of the weathered rock catchments.

**Résumé** Comprendre l'hydrogéologie des bassins en roches altérées est essentiel pour la gestion de différents problèmes liés à l'augmentation de la salinité dans de nombreuses villes d'Australie occidentale. Cet article présente les résultats d'études de caractérisation de sites conduites pour améliorer la compréhension de l'hydrogéologie de la partie sud du bassin de la rivière Augustus, exemple de bassin en roches altérées. Les données concernant le site ont mis en évidence la présence simultanée d'aquifères poreux dans le profil d'altération et d'aquifères de roches fracturées dans le socle. Des campagnes de géophysique aéroportée et d'autres données de forages ont identifié de très nombreux dykes de dolérite traversant le site. Des veines de quartz fracturées ont été trouvées aux marges de ces dykes de dolérite. Des mesures détaillées de niveau des nappes et des estimations des effets barométriques indiquent que ces dykes de dolérite et les veines de quartz fracturées affectent les directions d'écoulement souterrain, favorisant une forte connexion hydraulique entre tous ces aquifères, et influençant également les mécanismes de recharge. La signification hydrogéologique des dykes de dolérite et des veines de quartz fracturées a été analysée en combinant des mesures à haute fréquence du niveau des nappes (toutes les 30 min), de la pluie (toutes les 5 min) et des variations de la pression barométrique (toutes les 30 min). Un modèle conceptuel a été établi pour décrire les différents phénomènes hydrogéologiques de la région étudiée. Ce modèle indique que les veines de quartz aux marges des dykes de dolérite sont une importante composante de l'hydrogéologie des bassins en roches altérées.

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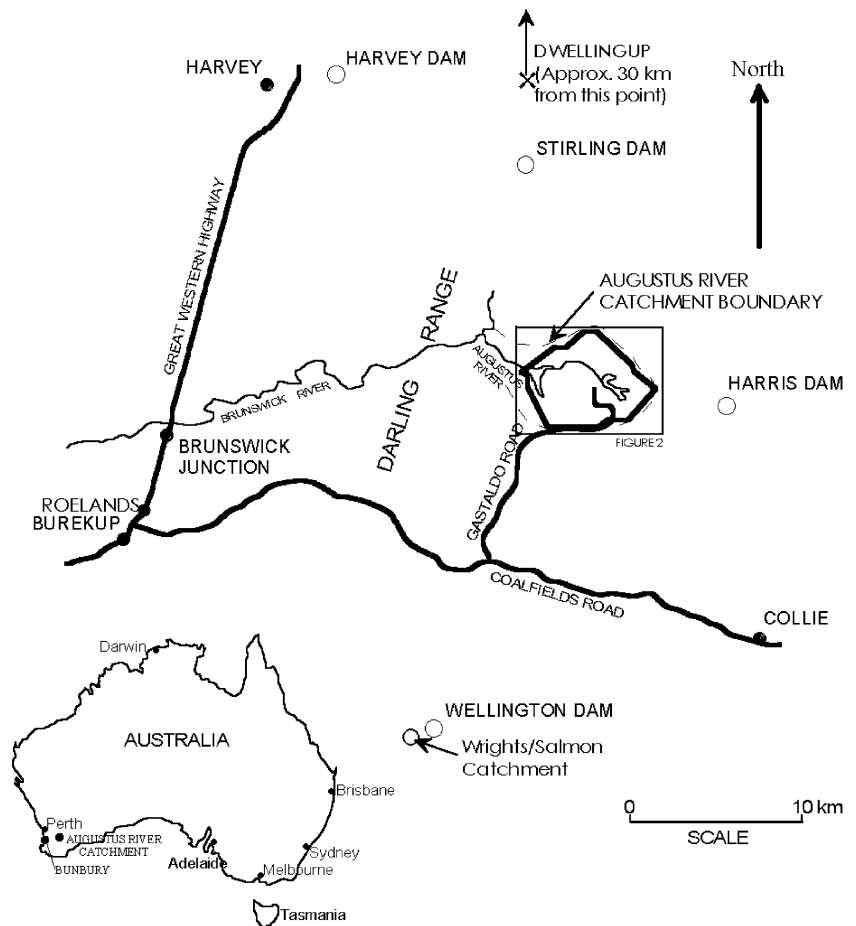
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**Resumen** Entender la hidrogeología de cuencas con rocas meteorizadas es esencial para gestionar diversos problemas relacionados con el incremento de salinidad en muchas ciudades de Australia Occidental. Este artículo presenta los resultados obtenidos en la caracterización de varios emplazamientos con el fin de mejorar el conocimiento general de la hidrogeología en la zona sur de la cuenca del Río Augustus, que sirve como ejemplo de cuenca en rocas meteorizadas. Los datos de campo

**Fig. 1** Location of the study area in the south-west of Western Australia



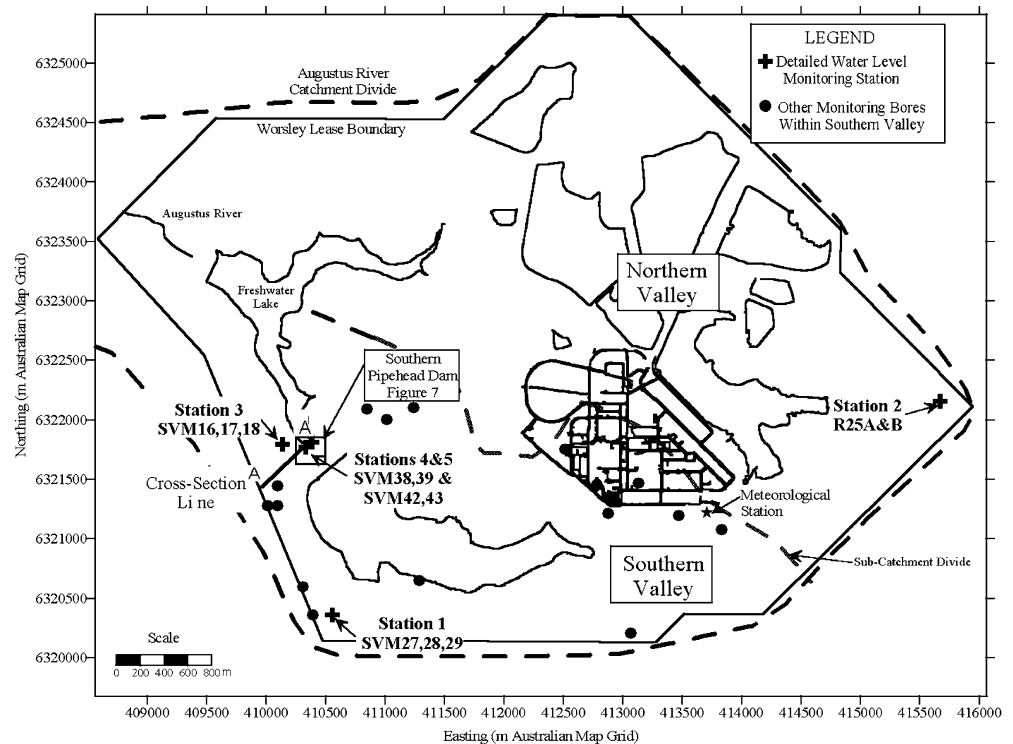
resaltan la presencia tanto de medios acuíferos porosos dentro del perfil meteorizado como de acuíferos en rocas fracturadas dentro de la roca fresca. Los registros geofísicos aéreos y datos de las perforaciones han identificado un gran número de diques de dolerita que intersectan el emplazamiento. Se ha hallado venas de cuarzo fracturado a lo largo de los márgenes de los diques de dolerita. Medidas detalladas del nivel piezométrico y estimaciones de la eficiencia barométrica indican que los diques de dolerita y las venas de cuarzo fracturado afectan las direcciones del flujo de las aguas subterráneas, originando una fuerte conexión hidráulica entre todos los acuíferos e influenciando también a los mecanismos de recarga. Se ha establecido la importancia hidrogeológica de los diques de dolerita y de las venas de cuarzo fracturado mediante una combinación de medidas muy frecuentes del nivel piezométrico (cada 30 min), de la precipitación (cada 5 min) y de las fluctuaciones de la presión barométrica (cada 30 min). Se ha desarrollado un modelo conceptual para describir varias características hidrogeológicas del área de estudio. El modelo indica que las venas de cuarzo fracturado en los márgenes de los diques de dolerita constituyen un componente importante de la hidrogeología de cuencas con rocas meteorizadas.

## Introduction

The study area is the southern portion of the Augustus River catchment, located approximately 42 km east of Bunbury, Western Australia (Fig. 1). Within the catchment is an alumina refinery currently operated by Worsley Alumina Pty Ltd (Worsley). The refinery lease area is approximately 21 km<sup>2</sup> in size, with the lease boundaries approximating the catchment divides. The Augustus River is a tributary of the Brunswick River, which provides agricultural and drinking water to the surrounding towns of Roelands, Burekup and Brunswick Junction. Important neighbouring reservoirs include the Wellington Dam (south), Stirling Dam (north), and Harris Dam (east), all of which provide drinking water to many south-western towns of Western Australia. Figure 1 shows the study area in relation to these surrounding reservoirs. Figure 2 shows the monitoring bores and the major operational facilities located within the study area.

The objective of the study was to characterise the overall hydrogeology of the Augustus River catchment with particular reference to the hydrogeological significance of dolerite dykes. In the literature, conflicting statements have been made regarding the influence of dolerite dykes on groundwater flow. For example, Engel et al. (1987) and Lewis (1991) state that dolerite dykes

**Fig. 2** Site plan showing detailed groundwater monitoring stations and cross-section line



form barriers to groundwater flow while Ventriss et al. (1982) indicate the margins of the dykes are zones of high hydraulic conductivity. Clark et al. (2000) observed higher hydraulic conductivities of the pallid zone over the dolerite dykes. In this study drilling data and groundwater-level response data were used to develop a more comprehensive model for representing the hydrogeological significance of dolerite dykes within the Augustus River catchment.

## Data Collection

### Existing Data

Drilling investigations within the study area began in early 1980. Since then, several drilling programs have been completed. The geological data obtained during the drilling investigations were reviewed in this study. The data included details of important geological and hydrogeological information such as depth to bedrock, rock types, aquifer intervals, and airlift yields. These data helped construct a conceptual hydrogeological framework for the study area.

Since the first monitoring bores were installed in 1980, groundwater-level monitoring and sampling have been undertaken at a variety of locations within the study area and at various frequencies ranging from annual to quarterly cycles. These data were made available for this study and included historical water-quality parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS) and major ions.

Investigations were concentrated within the southern portion of the Augustus River catchment (designated as the Southern Valley in Fig. 2) where monitoring bores have been designed to measure groundwater-level responses and chemistry within discrete aquifers. The monitoring bores were constructed using 50-mm nominal diameter (ND) class 9 UPVC slotted adjacent to individual aquifers, with slotted intervals ranging from less than 2 to 6 m in length. Over the slotted interval, the annulus has been filled with graded filter pack, and sealed above with bentonite grout. At each location, three separate bores (arranged in a triangle and separated by about 1 m) were constructed in this manner to monitor the three aquifers (when present). All monitoring bores were airlift developed for a minimum of 2 h after completion.

### Detailed Monitoring

In addition to the assessment of over 20 years of existing drilling and monitoring data, 12 capacitance water-level probes and loggers were installed to measure and record groundwater levels across the study area, as shown in Fig. 2. The aim was to provide coverage across the Southern Valley. The loggers were programmed to record the groundwater level at 30-min intervals. The construction details of each of the monitoring stations are summarised in Table 1.

Barometric pressure was not measured within the study area. However, for a given time, the difference between the measured barometric pressures at different stations within the south-west of Western Australia do not vary by more than 3 hPa (Bureau of Meteorology, WA, personal communication). Dwellingup, located about

**Table 1** Summary of groundwater monitoring locations

Transducer monitoring station	Monitoring bore	Distance from discharge area (m)	Depth (m bgl) <sup>a</sup>	Slotted interval (m bgl)	Aquifer monitored	Average hydraulic conductivity <sup>b</sup> (m/day)
1	SVM27	650	31.1	25.3–31.1	Bedrock	3.1E–01
	SVM28	650	23.9	18.0–23.9	Zersatz	9.1E–01
	SVM29	650	13.0	7.0–13.0	Shallow	1.1E–02
2	SVM16	200	24.3	20.3–24.3	Bedrock	3.0E–01
	SVM17	200	17.4	14.0–17.4	Zersatz	1.6E+01
	SVM18	200	9.5	4.5–9.5	Shallow	2.3E–02
3	SVM38	70	25.7	19.7–25.7	Bedrock	3.1E–01
	SVM39	70	17.1	11.4–17.0	Zersatz	1.0E+00
4	SVM42	20	15.4	9.4–15.4	Bedrock	5.1E–02
	SVM43	20	6.7	5.0–6.6	Zersatz	3.1E–01

<sup>a</sup> m bgl, metres below ground level

<sup>b</sup> Estimated by analysing six slug tests using the Bower and Rice (1976) method

50 km north of Worsley and at a similar distance from the coastline, is the closest meteorological station which recorded barometric pressure at a frequency consistent with the groundwater-level measurements made during this study. Therefore, the barometric pressure data measured at Dwellingup were used in this study. Rainfall and evaporation were computed every 5 min from data collected at a meteorological station located within the study area (refer Fig. 2).

### Physiography and Climate

The study area lies on the Darling Plateau, an ancient erosion surface which forms part of the Great Plateau of Western Australia (Wilde and Walker 1982). The highest remnants of the plateau reach almost 400 m Australian Height Datum (AHD; Worsley Alumina 1998). The undulating plateau surface is underlain by a lateritic weathered profile which is dissected by numerous drainage systems, one of which includes the Augustus River.

The area experiences Mediterranean-type climate with cool, wet winters and hot, dry summers. Approximately 80% of annual rainfall is received during the six-month period between April and October. Mean monthly maximum temperatures range from 15 °C in July to 33 °C in February. Mean monthly minimum temperatures range from 6 °C in July to 19 °C in February.

The average annual rainfall measured within the study area is 1,138 mm (record dates back to 1980). Evaporation exceeds rainfall in the months between October and April and on an annual basis. During the year of this study (2001), the annual rainfall was the lowest recorded for the study area. The rainfall measured in 2001 totalled 637 mm, which is about 56% of the long-term average rainfall.

### Geology

The study area is located within the south-western portion of the Archaean age Yilgarn Craton. The south-western

portion of the Yilgarn Craton has been sub-divided into the Balingup, Boddington and Lake Grace terranes (Wilde et al. 1996). The study area lies within the Balingup Terrane, but very close to the inferred contact with the more easterly Boddington Terrane. Regional studies indicate a high number of dolerite intrusions occur along or near terrane boundaries (Myers 1990).

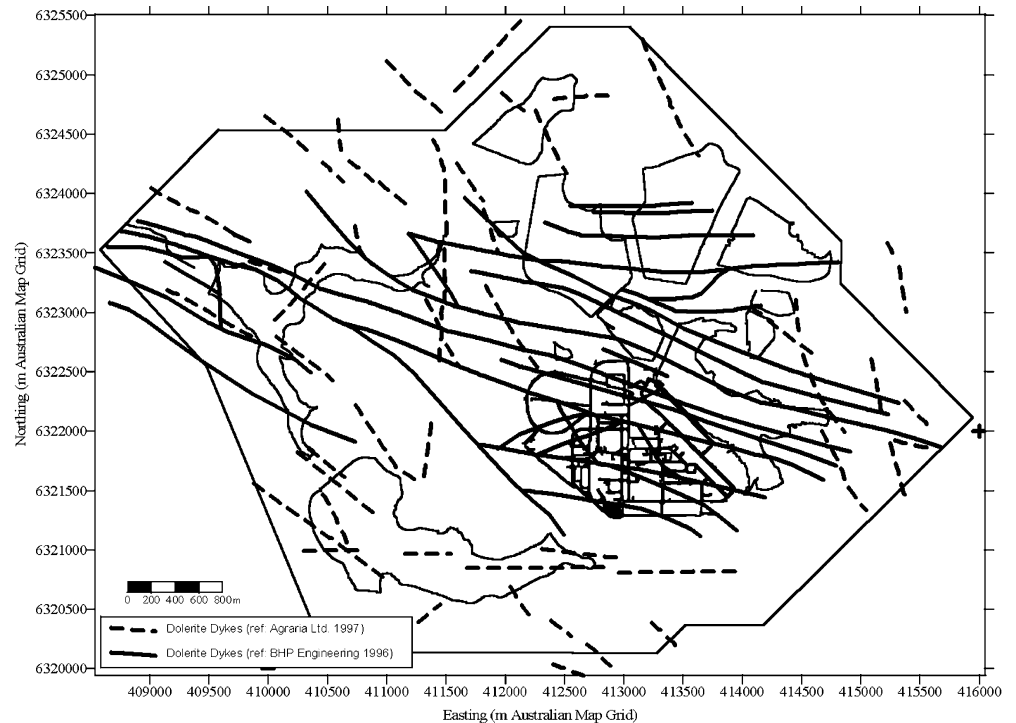
Intruded within the Balingup Terrane is a large granitic batholith identified as the Darling Range Batholith (Wilde and Walker 1982). The granites within this batholith are diverse, showing considerable textural variation and range in composition from granodiorite through adamellite to granite (Wilde et al. 1996). There appears to be little regular pattern in the distribution of the different granitic rocks, but the complex crosscutting relationships suggest phases of a single magmatic event which occurred at about 2.66 Ga (Arriens 1971). The predominant rock type intersected during drilling within the Southern Valley is porphyritic granite, which regionally forms part of the Darling Range Batholith.

Crosscutting the granitic rocks are numerous dolerite dykes. The dykes generally strike in two major directions, approximately along the east–west and north–south directions. The east–west dykes are regionally referred to as the Widgiemooltha Dyke Suite (GSWA 1990) and the more north-oriented dykes are referred to as the Boyagin Dyke Suite (GSWA 1990). Various dykes of the Widgiemooltha Dyke Suite have been dated at about 2.42 Ga (Turek 1966; Nemchin and Pidgeon 1998), which is of Proterozoic age.

### Dolerite Dykes

The results of airborne geophysical surveys (magnetic and radiometric methods), drilling, and field mapping of rock exposure have identified a large number of dolerite dykes which crosscut the site. Figure 3 shows the inferred locations of dolerite dykes (BHP Engineering Pty Ltd 1996; Agraria Ltd 1997). The dolerite dykes are of Proterozoic age and crosscut the granitic rocks. The dykes generally strike east to south-east with a dip of about 65° to the north and north-east (Gordon 1984a).

**Fig. 3** Mapped (*solid lines*) and interpreted (*dashed lines*) location of dolerite dykes within study area



The anastomosing nature and numerous crosscutting features associated with the dyke suites suggest more than one intrusive event. The dykes are 1–65 m wide, based on the results of mapping and interpretation of the geophysical data.

Common features associated with the dolerite dykes are an increased depth of weathering of the granitic rocks on either side of the dykes, and increased fracturing both on the margins of the dykes and within the surrounding bedrock. The influence of dolerite dykes on the hydrogeology of catchments has yet to be definitively outlined. It is plausible that dolerite dykes may form either barriers or conduits for groundwater movement, depending on the degree of weathering, the degree of fracturing and the orientation with respect to the regional groundwater flow.

The airborne geophysical datasets were acquired primarily from east–west flight lines, thus promoting the detection of the north–south-trending dykes. In addition, the noise attributed to the plant site and other cultural features make delineation of the east–west dykes (primarily mapped within the magnetic ‘noisy’ areas) very difficult using the geophysical datasets. Hence, there is little overlap between the two sources which show the locations of dolerite dykes. Subsequent drilling investigations have, however, confirmed the location of many of the dolerite dykes shown in Fig. 3.

### Quartz Veins

Quartz veins are inferred to be the youngest rocks in the area. They are normally closely associated with dolerite dykes, but sometimes crosscut the dykes. Highly fractured quartz veins are commonly noted throughout the weathered horizon and extend to the near-surface. The width of

these features varies from a few centimetres to greater than 5 m.

### Regolith

Overlying the bedrock is, in many locations, a well-preserved regolith (weathered) profile. It is thought that during the Triassic Period to the Pliocene Epoch the climate across many parts of Australia was humid and tropical (Butt 1983). Within this period, a characteristic laterite weathering profile developed and it is preserved in many places beneath the Worsley site. The formation of the laterite horizons within the south-western areas of Australia is generally regarded to have occurred within the Pliocene (Playford 1954).

The thickness of the regolith beneath the study area is highly variable but is broadly dependent on the topographic location within the catchment (i.e. high and low areas of the catchment), the parent rock type, and on the presence or absence of structural features. Generally, the topographic high areas have the greatest depth of weathering, and the low areas have the least. The depth of weathering is shallower over the dolerite dykes than over the granitic rocks, and geological structures tend to enhance the permeability of the rock mass and hence promote weathering, resulting in a greater depth of weathering in these areas. The depth to bedrock ranges from less than 5 m to more than 50 m, with variations of more than 40 m over distances of less than 50 m in some places.

Despite the variability in the weathered zone, it is possible to define a characteristic profile which is generally applicable for the site. A typical regolith profile for the site is summarised in Table 2 (adapted from



**Table 2** Generalised regolith profile within the Worsley lease area

Geological zone	Approximate depth to top of units (m bgl) <sup>a</sup>	General lithology
Laterite, ironstone	0–1	Soil/pisolitic laterite: grey sands and organic mater grading to pisolitic laterite
	1–4	Gibbsite laterite: mottled ferruginous clays, lightly cemented, minor quartz grits
Mottled zone	4–8	Mottled zone: ferruginous clay and quartz grits, containing partially iron-cemented pisolite
Plasmic zone	8–12	Plasmic zone: white to off-white clays having variable quartz content, with large variations in the thickness, no original rock fabric preserved
Upper saprolite	12–60	Saprolite: white to off-white clays which contain <20% original rock fabric, variable quartz content, and possibly minor iron-cemented zones
Lower saprolite (Zersatz aquifer)	15–60	Quartz residual: pale yellow brown sand with variable proportions of clay and some mica, typically 1–10 m thick
Saprock/bedrock	>40	Slightly weathered bedrock (saprock): fractured and jointed, minor clay weathering, grading into fresh bedrock

<sup>a</sup> m bgl, metres below ground level

Gordon 1984b). As indicated, the depths to various zones may vary between locations and, in some areas, part or all of the profile may be absent. In this paper, the depth to bedrock (or depth of weathering) represents the depth to the top of the saprock horizon.

## General Site Hydrogeology

### Aquifer Description and Distribution

Based on the drilling data, three main aquifer formations were identified at the site:

- a shallow weathered zone (designated as the shallow aquifer)
- a deep weathered zone (designated as the Zersatz aquifer)
- fracturing within the bedrock (designated as the fractured bedrock aquifer).

Separating the shallow and Zersatz aquifers is a low-permeability saprolite clay zone, which forms an aquitard. In those areas where the shallow aquifer is absent, saprolite clay overlies the Zersatz aquifer. The thickness of the aquitard varies from 5 to over 25 m.

#### Shallow aquifer

The shallow sandy aquifer consists of clayey sand to sand with varying proportions of silt. The aquifer is found within the saprolite zone and ranges in thickness from 1 to 4 m but does not form a continuous aquifer within the study area. This aquifer is predominantly found in areas underlain by granitic basement rocks.

#### Zersatz aquifer

The principal aquifer within the study area is the Zersatz aquifer. This aquifer rests immediately above the bedrock, at depths normally varying in the range 15–40 m. The

thickness is within the range of 1–10 m. The aquifer is characterised by fine to gravel-sized granite or quartz sand with varying proportions of silt and clay. This aquifer also appears to be predominantly located within areas underlain by granitic basement rocks.

#### Fractured bedrock aquifers

The fractured bedrock aquifer within the Augustus River catchment consists of both joint sets within the saprock, fault zones and fractures within the granitic and dolerite rock types. Sub-horizontal joint sets have been observed within the granitic rocks to depths of 30 m below the base of the Zersatz aquifer, and sub-vertical fracture and fault zones have also been intersected by various drill holes. These joints, faults and fractures are identified as the fractured bedrock aquifer system.

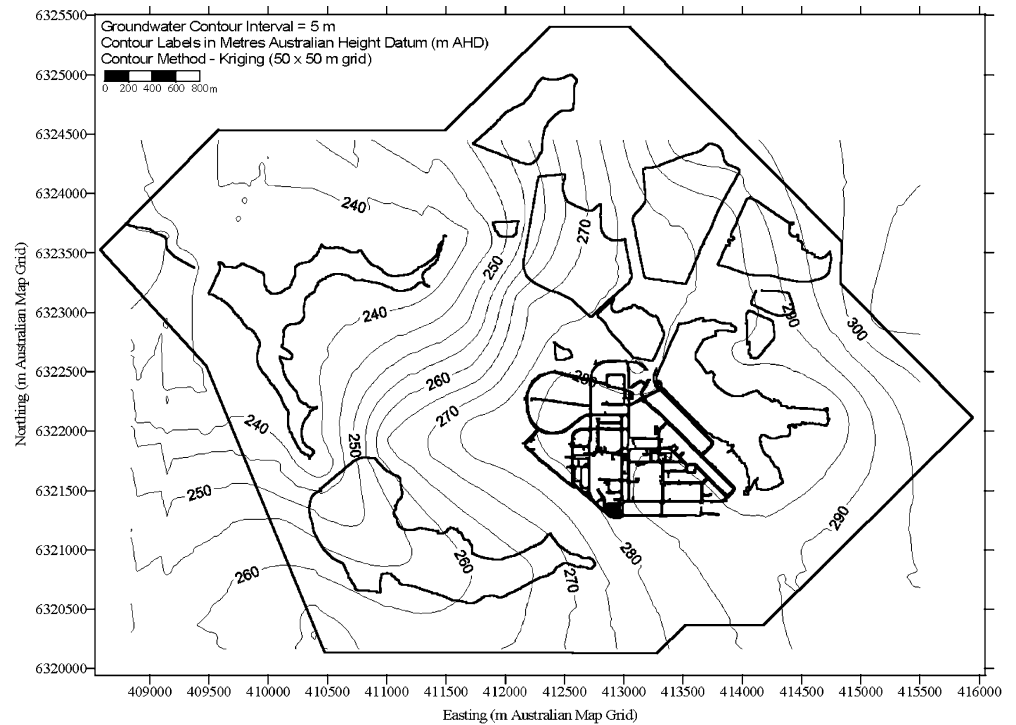
In nearly all cases, the margins of the dolerite dykes are fractured. Gordon (1984a) has noted the presence of iron staining along the margins of dolerite dykes, which could indicate preferential movement of groundwater. Quartz veins are also commonly found along the margins of the dolerite dykes. These quartz veins are often highly fractured, iron stained and yield relatively high volumes of groundwater during drilling. These veins have also been identified extending throughout the weathered profile, providing a possible link between each of the aquifers.

## Aquifer Hydraulic Parameters

### Previous studies

There are relatively few data available regarding the hydraulic properties of the aquifers and aquitards within the study area. Soil & Rock Engineering (1980) conducted falling head laboratory permeability tests on various samples of the saprolite (aquitard), shallow aquifer and Zersatz aquifer. The hydraulic conductivity of the saprolite was estimated to be  $6 \times 10^{-4}$  m/day, while the hydraulic conductivity of the shallow and Zersatz aquifers

**Fig. 4** Groundwater contour plan within study area (shallow aquifer)



was 0.001–0.4 m/day. Short-term (less than 6 h pumping) test pumping was also completed at a number of locations with monitoring bores screening the entire weathered profile. Analysis of these data indicated that the hydraulic conductivity of the entire weathered profile was 0.01–1 m/day.

#### *Slug tests*

During the course of this investigation, 108 slug tests were undertaken in 18 monitoring bores which screened individual aquifers. A Mini Troll pressure transducer and data logger were used to measure groundwater levels during the slug tests. Slugs were constructed of soil-filled PVC tubes of various lengths (1-, 2- and 3-m lengths). Each slug was initially inserted into the monitoring bore (falling head test) and then, once the groundwater levels had returned to within 5% of the initial groundwater level, the slug was rapidly removed (rising head test). A total of six tests were performed within each monitoring bore. Each test was analysed using the Bower and Rice (1976) method and the average of the hydraulic conductivity for each of the aquifers estimated.

Based on the slug test results, the average hydraulic conductivity values for the aquifers are:

- shallow aquifer—0.06 m/day
- Zersatz aquifer—1.3 m/day
- fractured bedrock—0.07 m/day
- fractured quartz veins—4.1 m/day

The hydraulic conductivity estimated from slug tests performed within those bores assigned for detailed groundwater-level measurements is summarised in Table 1.

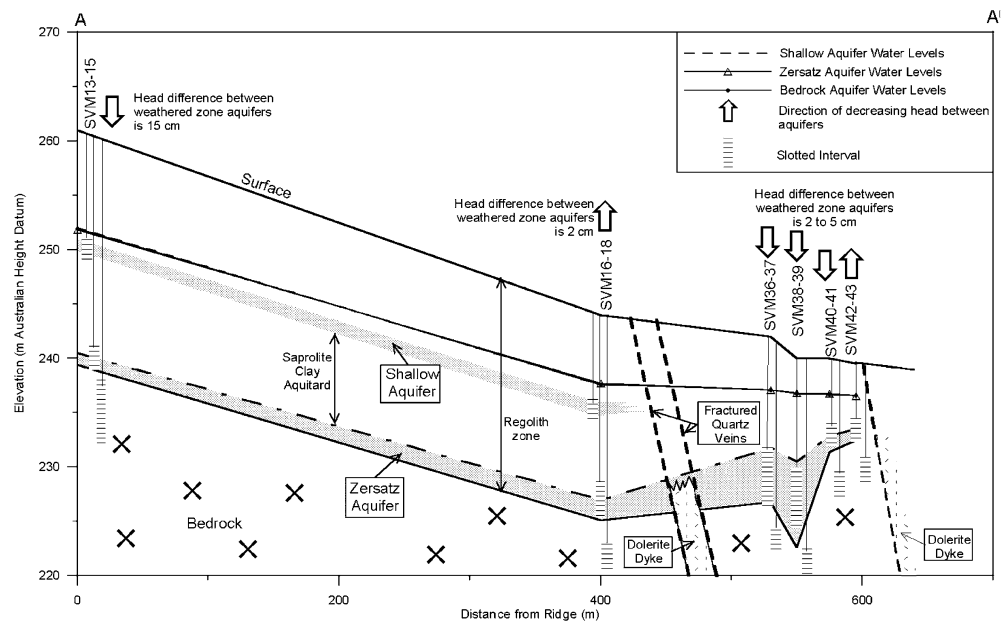
#### **Groundwater Flow Patterns**

Generally, groundwater levels within all aquifers appear to follow the topography (i.e. groundwater level is highest in areas of highest topography and lowest in areas of lowest topography). Figure 4 is a contour map of the measured groundwater levels within the shallow aquifer of the study area. The measurements show that groundwater flows from the topographic high areas towards the topographic lower areas where the discharge sites are located. There are some subtle variations in the groundwater flow pattern due to the presence of dolerite dykes and associated fracturing. These features will be discussed in the section regarding the hydrogeological significance of dolerite dykes.

The groundwater flow direction also has a vertical component. The vertical component of groundwater flow is shown in Fig. 5, which is a cross section approximately following a groundwater flow line. The location of this cross section A–A' is shown in Fig. 2.

Figure 5 indicates that there is generally a reduction in the total head measured with increasing depth within each of the aquifers in the topographic higher areas (i.e. downward heads). Near the main discharge areas (topographic low areas), the total heads measured within the deeper aquifers is greater than that measured in the shallowest aquifer (i.e. upward heads). However, there are also additional variations in the direction of vertical flow of groundwater on either side of dolerite dykes, as indicated in Fig. 5. On the up-gradient side of the dolerite dykes, the direction of vertical groundwater flow is upwards, which is similar to that observed within the primary discharge zones in the topographic low areas. On the down-gradient side of the dykes, the vertical compo-

**Fig. 5** Cross section along flow line within the Southern Valley



ment of groundwater flow reverses and is once again downwards.

### Groundwater Recharge

Recently, Herczeg and Edmunds (2000) demonstrated the use of a chloride mass-balance technique for estimating recharge, which was first developed by Anderson (1945). Many others have utilised the technique to estimate recharge (Kitching et al. 1980, Sharma and Hughes 1985 and Cook and Herczeg 1998).

In this technique, firstly a steady-state water balance for a catchment is written as:

$$P = E + R + Q \quad (1)$$

where  $P$  is precipitation,  $E$  is evapo-transpiration,  $R$  is recharge and  $Q$  is discharge to surface water bodies and runoff.

If we assume that the chloride within the groundwater is only deposited by precipitation or dust particles within the precipitation then, under steady-state conditions, the chloride mass balance can be included in Eq. (1) as:

$$P[Cl]_p = E[Cl]_e + R[Cl]_r + Q[Cl]_q \quad (2)$$

where  $[Cl]_p$ ,  $[Cl]_e$ ,  $[Cl]_r$  and  $[Cl]_q$  are the concentrations of chloride within the precipitation, water removed via evapo-transpiration, recharge water (i.e. quality of the groundwater) and water removed via surface runoff respectively.

If significant quantities of chloride are not removed by evapo-transpiration (i.e. this term tends to zero) and sites are selected such that surface runoff is minimal (i.e. areas of low surface gradients much like the topographic divides within the study area), Eq. (2) can be simplified and rearranged to solve for recharge as:

$$R = P[Cl]_p / [Cl]_r \quad (3)$$

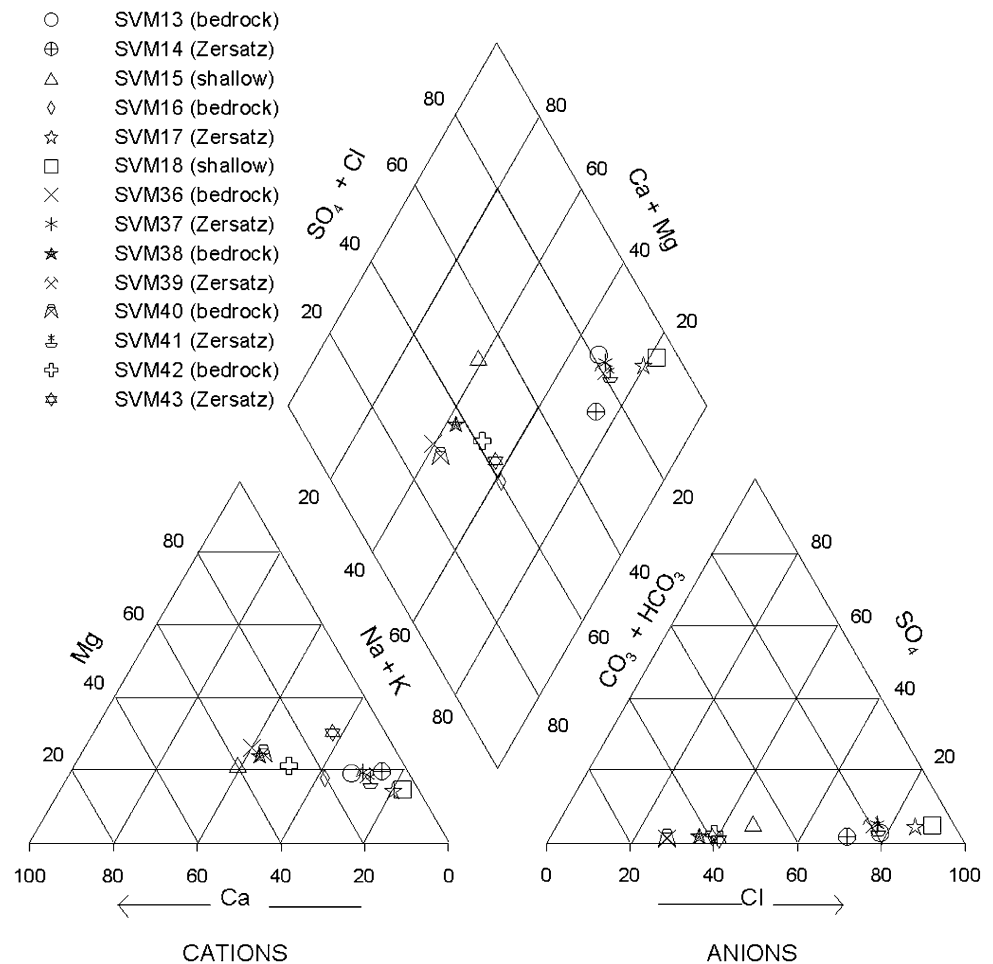
By selecting bores monitoring the shallow aquifer which are located in the upper parts of the Southern Valley and using the simple relationship outlined by Eq. (3), the annual recharge rate for the study area has been estimated to be about 7% of incident annual rainfall. Sukhija et al. (2003) indicates that the error attributed to this method could be as high as 25% of the true value.

Kitching et al. (1980) suggested that a major source of error in estimating recharge using this technique is due to the inaccuracies in the estimation of chloride concentration within the rainfall,  $[Cl]_p$ . Our calculations were based on an average concentration of chloride within the rainwater of 8.5 mg/l, which is consistent with values presented by Turner (1984). The average concentration of chloride within rainfall presented by Turner was based on 130 measurements made between 1974 and 1981 within a catchment located about 15 km south of the study area, but a similar distance from the coastline. A sample of rainwater was collected from the study area and analysed for comparison with Turner's data. The concentration of chloride within the sample collected from within the study area was 10 mg/l, which is consistent with the variation in measured values of chloride concentrations presented by Turner (1984).

Johnston (1987a) estimated the recharge in a nearby catchment by modelling observed chloride concentration profiles within the unsaturated zone using a one-dimensional convective-diffusive model. Using this technique, Johnston estimated the average recharge rate across the basin was about 1% of incident rainfall below 5 m. However, the presence of preferential pathways could increase the estimated recharge by up to an order of magnitude. Preferential pathways noted by Johnston were either root systems or weathered quartz veins along the margins of dolerite dykes. The hydrogeological significance of preferential pathways will be examined in the



**Fig. 6** Piper plot from analyses of bores along the cross section shown in Fig. 5



section regarding the hydrogeological significance of dolerite dykes.

Johnston also used the same chloride tracer technique used in this study to estimate the recharge to the shallow groundwater system in his study area. Using this technique, Johnston estimated the recharge to be about 8% of incident rainfall, which is similar to that estimated for the Augustus River catchment.

### Groundwater Quality

The groundwater within the Southern Valley is fresh. The total dissolved salts concentrations vary in the range 70–600 mg/l, with no identifiable trends in the time series data. Figure 6 is a Piper plot of chemical analyses of groundwater from bores along a cross section within the Southern Valley (cross-section line shown in Fig. 2). Figure 6 shows that there are principally two distinct groupings of groundwater chemistry, one with proportionately more bicarbonate than the other group. It is generally accepted that groundwater evolves from proportionately higher concentrations of bicarbonate, through to sulphate and then finally to chloride along a groundwater flow path from the recharge to the discharge zone (Toth 1999). Or, put another way, the longer groundwater remains within the subsurface system, the more the

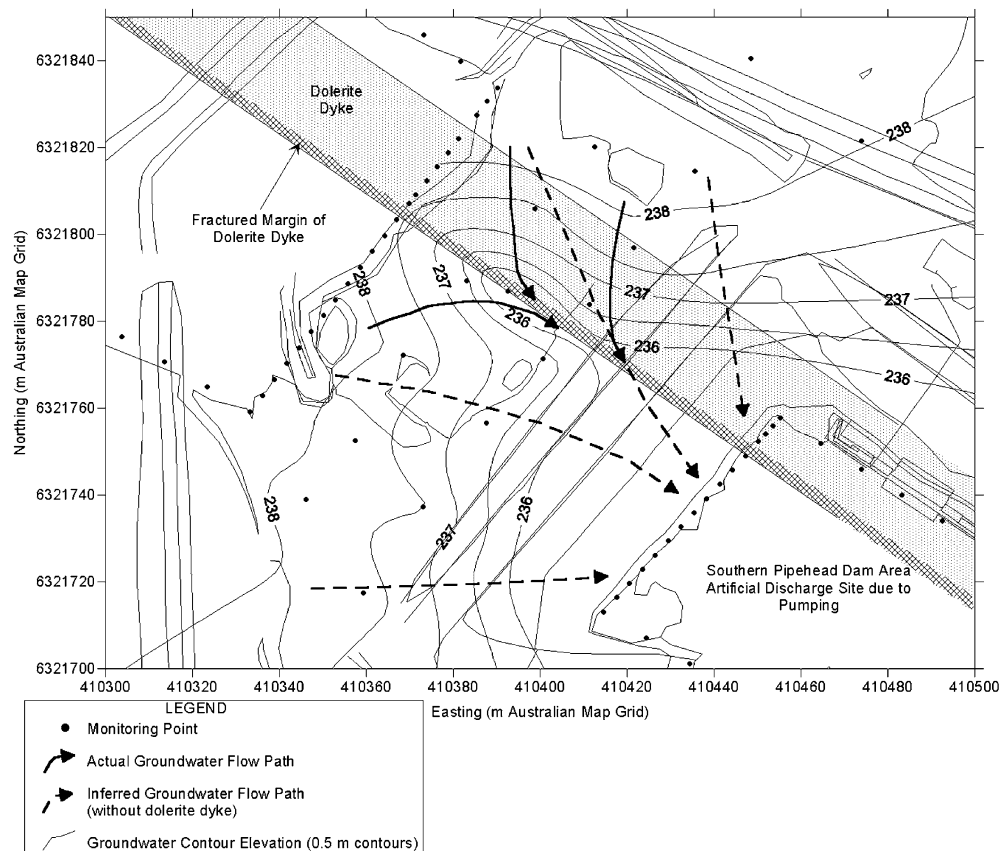
groundwater will evolve from predominantly bicarbonate water to more mature, chloride-rich water.

The bores which show proportionately greater concentrations of bicarbonate in Fig. 6 are predominantly bores screened in the bedrock and the shallow monitoring bore in the topographic high area (SVM15). This result indicates that the residence time of the groundwater within the bedrock aquifer is less than the residence time of groundwater within the Zersatz aquifer, despite the Zersatz aquifer having a greater average hydraulic conductivity than the bedrock aquifer. It has been noted by others that the velocity of groundwater flow within fractures may be orders of magnitude higher than groundwater velocities within porous media aquifers (Cook 2003). A greater groundwater flow velocity within the bedrock aquifer would explain the low maturity of groundwater within the bedrock aquifer as compared to the Zersatz aquifer.

### Significance of Dolerite Dykes

During the process of hydrogeological characterisation, it was clear that the presence of dolerite dykes was integral to defining the hydrogeology of the catchment. The

**Fig. 7** Groundwater contours around a dolerite dyke showing groundwater flow lines (*solid lines*) and inferred groundwater flow lines (*dashed lines*) without the dolerite dyke



hydrogeological significance of these dolerite dykes and associated fractured quartz veins, discussed below, forms an important component of the conceptual hydrogeological model. As stated in the Introduction, in the published literature considerable controversy exists regarding the influence of dolerite dykes on groundwater flow. In the following sections we identify the hydrogeological significance of dolerite dykes and its impacts on regional groundwater flow within the Augustus River catchment. The analysis is based on detailed groundwater, rainfall and barometric pressure datasets.

### **Impact of Dolerite Dykes on Groundwater Flow Direction**

Previous studies have indicated that dolerite dykes may form either barriers or conduits to groundwater movement, depending upon the nature of the fracturing (e.g. Engel et al. 1987). However, few have presented groundwater-level data at a suitable spatial scale to identify the effect the dolerite dykes have on the movement of groundwater. Figure 7 is a groundwater contour plan of groundwater levels measured near the topographically lower area of the Southern Valley (area shown in Fig. 2). The close spatial scale of monitoring bores (spacing of 25 m) and the presence of a monitoring bore where groundwater levels can be measured within a known fracture zone along the margin of a dolerite dyke allow assessment of the effects of the dolerite dyke on the lateral movement of groundwater. Figure 7 shows that

groundwater flow is preferentially directed to the highly permeable margin of the dyke. Figure 7 also shows the inferred groundwater flow paths which may exist if the dolerite dyke were not present, and this highlights the hydrogeological significance the dolerite has on the lateral movement of groundwater towards a discharge point. Without the presence of the fractured margins of the dolerite dyke, the groundwater flow path will not preferentially converge towards the fractured margins.

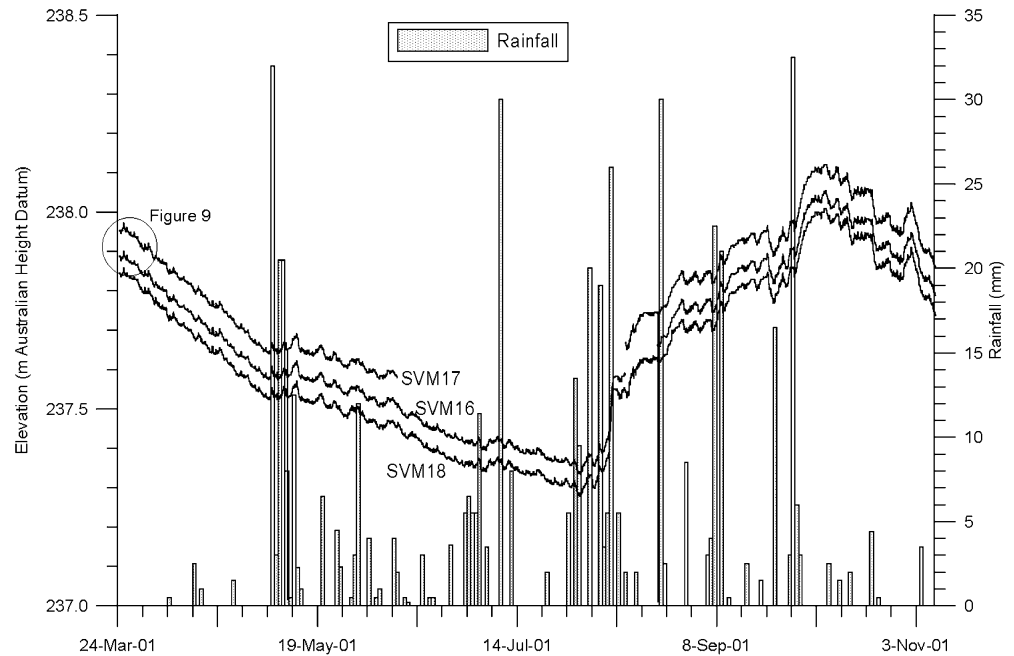
### **Impact of Dolerite Dykes on Aquifer Connectivity**

The detailed water-level measurements made during this study have also provided a method for qualitatively assessing the hydraulic connection between the aquifers due to the preferential pathways along the margins of the dolerite dykes. The simultaneous response measured in all aquifers due to various rainfall events provides a clue to the strong vertical connection between the aquifers. In addition, the barometric efficiency of the deeper aquifers has been identified to be low, despite the presence of a confining saprolite clay aquitard. The preferential pathways along the margins of dolerite dykes result in the deeper aquifers responding as unconfined aquifers.

#### *Analysis of rainfall response data*

Despite the differences in head measured in the various aquifers at different distances from the ridges, it is noted that all of the aquifers at all of the monitoring stations responded similarly to the various rainfall events (i.e.

**Fig. 8** Detailed groundwater-level and rainfall measurements. Monitoring station 2: SVM16, SVM17 and SVM18



patterns of response in the shallow aquifer are repeated in the Zersatz and bedrock aquifers with less than a 30-min lag). The shallow and Zersatz aquifers are separated by at least 9 m of saprolite clay, which has a low hydraulic conductivity (average is  $6 \times 10^{-4}$  m/day). Aquifers separated by 9 m of low-permeability clay should transmit changes in pressure with a lag greater than 30 min and also show some attenuation of the amplitude. The site data did not show this attenuation or lag. Figure 8 is the hydrograph of groundwater levels measured at 30-min intervals in monitoring bores SVM16, SVM17 and SVM18 (monitoring station 2), which is located within the mid-slope regions of the Southern Valley. Figure 8 shows that the response of groundwater levels measured in all aquifers to various rainfall events is almost identical. This type of response can only be described if the aquifers are well connected.

If we assume that the bores are not providing the connection between the aquifers (validity of this assumption will be discussed below), a natural mechanism is needed to provide this connection. The cross section shown in Fig. 5 indicates that a dolerite dyke is located less than 50 m from monitoring station 2. The fractured quartz veins existing along the margins of the dolerite dykes and found to extend throughout the weathered profile provide a suitable natural mechanism to promote the connection between aquifers inferred by visual examination of the groundwater-level responses measured in each of the aquifers.

#### *Analysis of barometric response data*

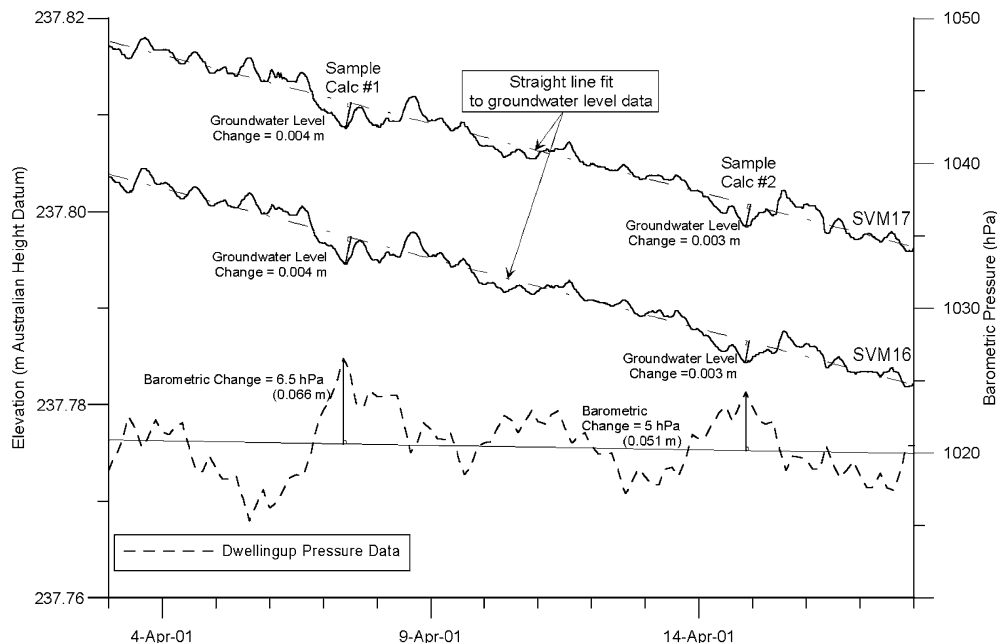
Barometric efficiency of an aquifer is a term introduced by Jacob in 1940 (Jacob 1940). It is the ratio of water-level change to the atmospheric pressure change expressed in consistent terms of water height (Bear 1972).

Care must be taken to choose periods when the aquifer is not receiving recharge from earlier rainfall events, as this moisture front can result in erroneous estimations of barometric efficiency.

Monitoring locations away from the ridges show variable response to barometric pressure fluctuations. Assuming the pressure measurements at Dwellingup are similar to that which occurs around the study area, estimations can be made as to the barometric efficiency of the various aquifers. There should be little or no response in unconfined aquifers (i.e. barometric efficiencies should be very low or zero) because pressure changes are transmitted directly to the aquifer and the monitoring bore. However, two scenarios can occur which result in barometric fluctuations measured in monitoring bores supposedly screened across unconfined aquifers. Firstly, in highly heterogeneous systems, similar to that which may occur in weathered environments, monitoring bores rarely screen a single unconfined aquifer but may screen both a very shallow, unconfined and slightly deeper, confined or semi-confined aquifer. Secondly, air entrapped in the pores below the groundwater table is also affected by changes in barometric pressure, causing barometric fluctuations of a lower magnitude than in confined aquifers (Peck 1960).

To illustrate the low barometric efficiencies measured in bores within the Augustus River catchment, the measured barometric responses of the Zersatz (SVM17) and bedrock (SVM16) aquifers at monitoring station 2 are shown in Fig. 9. The measured responses of groundwater level to barometric pressure changes are distinguishable by trend, but the magnitude of this change is very small. However, the small nature of this change gives us a measure of how poorly confined each of the aquifers is. The very low, but measurable responses to barometric

**Fig. 9** Low barometric efficiency (BE) of the Zersatz



Bore	Date	Groundwater-level change (m)	Barometric pressure change (m)	Barometric efficiency (%)
SVM16	7 April 2001	0.004	0.066	6.0
SVM16	14 April 2001	0.003	0.051	5.9
SVM17	7 April 2001	0.004	0.066	6.0
SVM17	14 April 2001	0.003	0.051	5.9

pressure indicate that the Zersatz and bedrock aquifers are not well confined by the overlying saprolite clay. Barometric efficiencies for the Zersatz and bedrock aquifers are estimated to be 1–6% (Table 3), which is consistent with an unconfined aquifer. Previous investigations have found that confined aquifers normally measure barometric efficiencies of 40–80% (e.g. Jacob 1941; Bredehoeft 1967; US Dept of Interior 1977). These data confirm the strong vertical hydraulic connection between the various aquifer formations.

### Estimate of Aquifer Leakage via Preferential Pathways

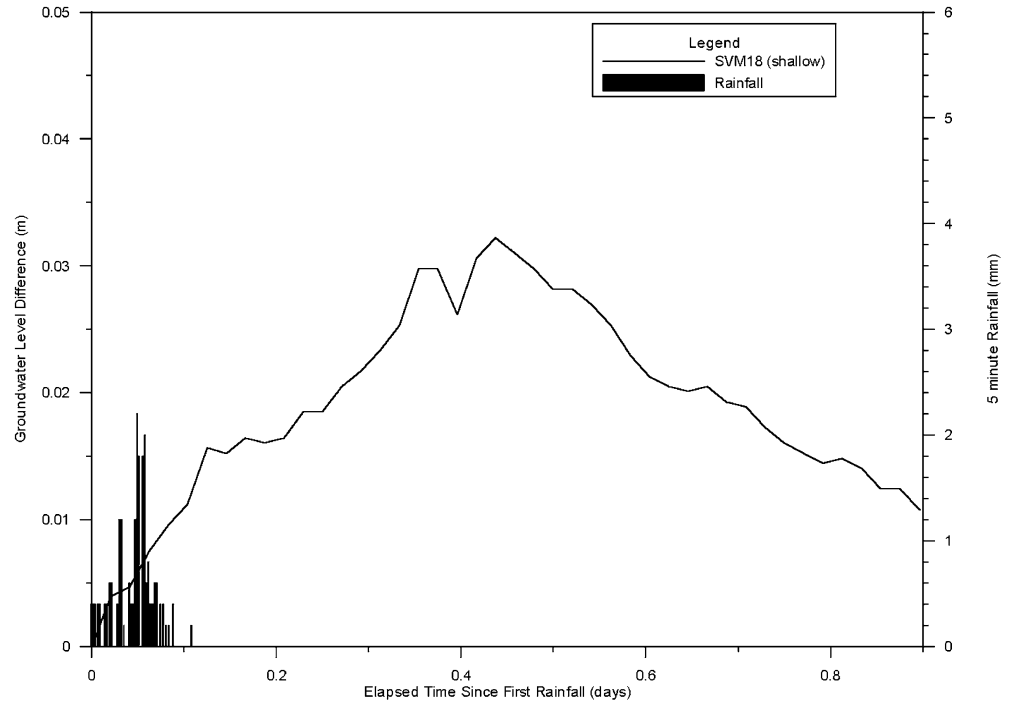
Detailed groundwater-level measurements within the shallow (SVM18) aquifer at monitoring station 2 also indicate that the velocity of infiltrating rainwater through the unsaturated zone is high. Figure 10 shows the response measured in the shallow aquifer following the first rainfall event in 2001 (rainfall measured at 5-min intervals). The groundwater measured in the shallow aquifer begins to rise almost immediately and peaks at about 0.5 days after the peak of the rainfall occurred. The shallow aquifer is overlain by about 9 m of unsaturated saprolite clay. Based on the measured responses in the shallow aquifer monitored by bore SVM18, the average velocity of the infiltrating water is about 18 m/day. This is

a very high velocity for water migrating through an unsaturated saprolite clay zone if preferential pathways do not exist. However, there is strong evidence for the presence of preferential pathways within the study area. Johnston et al. (1983), and Johnston (1987a, 1987b) observed preferential pathways through unsaturated saprolite clay overlying a dolerite dyke. Relic root channels formed these pathways but they only extend about 3 m below the surface. Johnston (1987a) also observed quartz veins at much greater depths and observed that these were also forming preferential pathways for infiltrating water. The presence of a nearby dolerite dyke with associated fractured quartz veins extending throughout the weathered profile is the most likely explanation for the rapid velocity of the infiltrating water. The measured response has highlighted that preferential pathways are a mechanism of recharge within the Augustus River catchment, and that the fractured quartz veins associated with dolerite dykes within this catchment are the most likely preferential pathway.

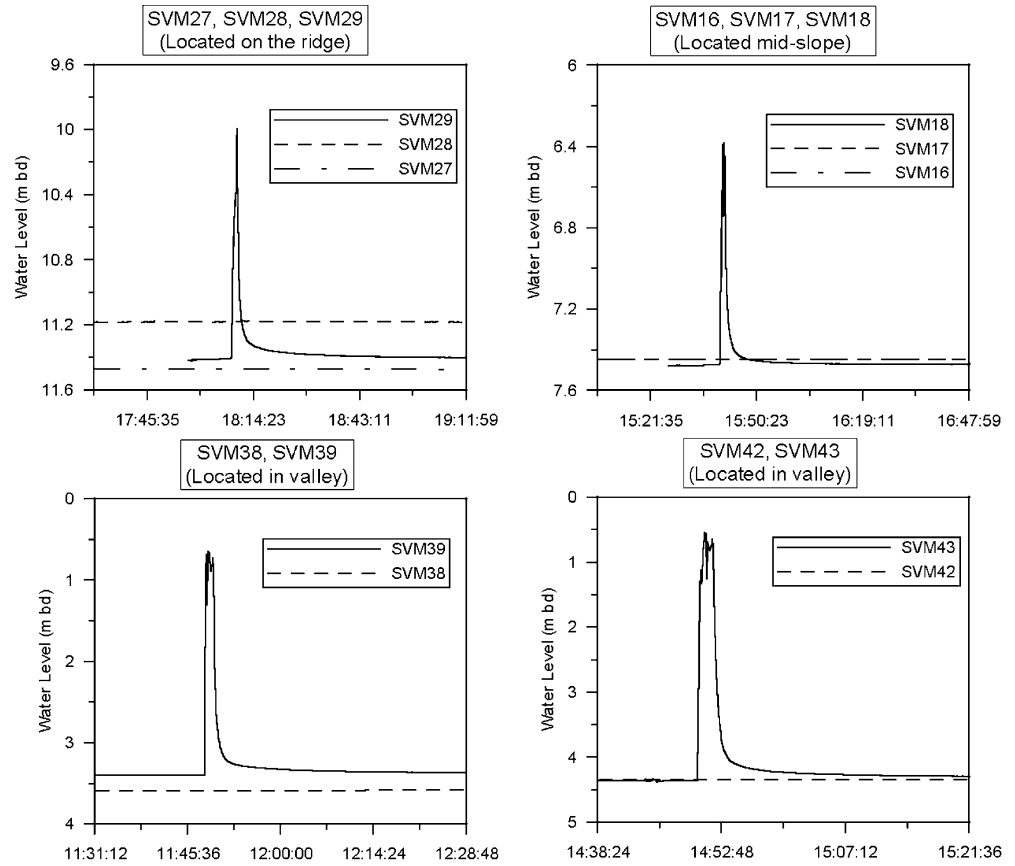
### Testing of Bore Construction

Within the Southern Valley all monitoring bores are constructed with 50-mm nominal diameter UPVC, slotted

**Fig. 10** Measured groundwater-level response within the shallow aquifer after first rainfall (2001)



**Fig. 11** Bore connection tests showing no response in bedrock or Zersatz aquifers

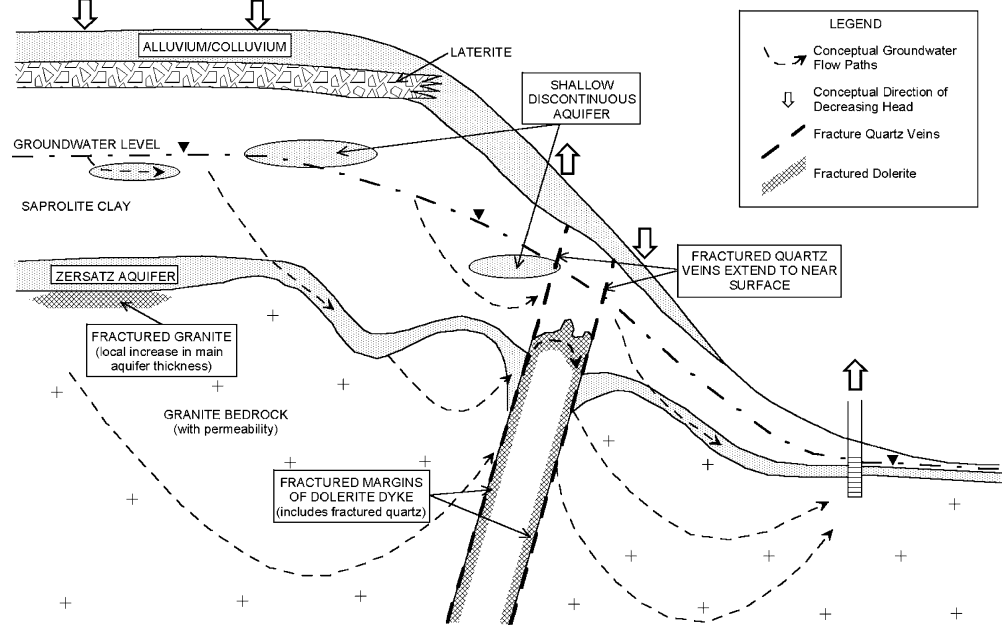


over a single aquifer with graded filter pack installed over the open area and sealed using bentonite clay. At each location, three separate bores (arranged in a triangle and separated by about 1 m) have been constructed in this

manner to monitor each of the three aquifers (when present). However, it was considered possible that the monitoring bores may have provided the hydraulic connection between aquifers. To test this, water was



**Fig. 12** Conceptual hydrogeology of the Augustus River catchment



injected into the shallow monitoring bore of each of the monitoring stations such that a downward head prevailed. During the time of water injection, groundwater levels were measured in each individual monitoring bore at that test site. If the bores were providing the connection between the aquifers, an instantaneous response would be measured in the bores monitoring the deeper aquifers. This was not found to be the case, as is highlighted in Fig. 11. All sites tested within the Southern Valley showed little or no response to water injection into the shallow aquifer.

## Discussion

The main hydrogeological process which has been the focus of this paper is the effect which dolerite dykes and associated fractured quartz veins have on the hydrogeology of the catchment. In the sections above, we identified how the dolerite dykes and associated fractured quartz veins affect the groundwater flow pattern (both laterally and vertically) and indirectly increase the vertical hydraulic connection between the aquifers and promote episodic recharge to the shallow aquifer. Some of these hydrogeological features are summarised in the conceptual model for the site presented in Fig. 12. Through this conceptual model we support the hypothesis that dolerite dykes form conduits for groundwater flow within the Augustus River catchment. This conclusion is based on the review of existing drilling and groundwater monitoring data, along with detailed measurements of groundwater-level responses and barometric pressure changes in multiple aquifers during several rainfall events.

The developed conceptual model has provided a greater understanding of the groundwater flow paths and

the aquifer interactions. Further, the results of this study have provided average hydraulic conductivity estimates of each of the aquifers and also estimated the annual recharge within the catchment based on a steady-state, lumped parameter chloride mass-balance technique.

This field study demonstrates how geological characterisation and long-term groundwater monitoring data can be used in conjunction to assess the hydrogeological framework of a catchment. Detailed measurement of groundwater levels, rainfall and barometric pressure can also provide valuable insight into defining the hydrogeology of a catchment. In these investigations, such measurements have allowed an assessment of the hydrogeological significance of dolerite dykes within the catchment.

An improved understanding of the hydrogeology of weathered rock catchments, in particular the hydrogeological significance of dolerite dykes, is integral for the management of the various problems related to increased salinity within the many towns of Western Australia. Similar investigations to those undertaken in this study could be conducted in other catchments of the Yilgarn Craton, especially those which have high risk of salinisation. Such studies could be conducted at a relatively low cost and provide invaluable information related to the management or remediation of salinity problems.

The outcomes of this study, including the conceptual site model, will assist plan future hydrogeological investigations both on a local and regional scale. On a local scale the results of the study will assist Worsley Alumina Pty Ltd in establishing a suitable groundwater monitoring bore network. On a more regional scale the investigation and characterisation methods could be used by others in surrounding catchments, particularly in those which have, or will experience problems of increased groundwater

levels and salinity, a major threat to many towns within Australia. In addition, the hydrogeological significance of dolerite dykes within the many varied catchments of Australia is complex and this study provides an unique insight into the hydrogeological significance of dolerite dykes located within the Augustus River catchment.

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