Government of **Western Australia**
Department of **Water**

Groundwater pumping to control the watertable at Dumbleyung

Salinity and land use impacts series

Report No. SLUI 51
May 2009

Looking after all our water needs

Groundwater pumping to control the watertable at Dumbleyung

by

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Department of Water

Salinity and land use impacts series

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Much of this report is based on data and information collected by Shawan Dogramaci, formerly Salinity and Water Resource Recovery branch, Department of Water. Phil Commander and Ryan Vogwill reviewed report drafts.

For more information about this report, contact Nick Cox

Cover photo: Production bore for pumping groundwater from a Dumbleyung palaeochannel
Photographer : Rachel McDougall

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Summary

The Engineering Evaluation Initiative (EEI) was established in 2002 to evaluate various engineering solutions to Wheatbelt salinity. This report describes the effectiveness of groundwater pumping to manage the watertable at a site near Dumbleyung.

The primary objective was to determine whether single-bore pumping is a viable option to stabilise the watertable. The method was to pump water from a semi-confined palaeochannel aquifer, causing the shallow watertable above it to decline.

Department of Water commissioned 16 bores in 2006 with depths 4–63 m. The airlift yields were 0.25–2.3 L/s, and depth to water 1.6–2.3 m. Salinity was 35 000–55 000 mg/L TDS (total dissolved solids) and pH 2.9–5.5.

The Dumbleyung palaeochannels are about 50 m thick and 300–2300 m wide, as determined from surface geophysics. A typical Dumbleyung palaeochannel bore log was, from the surface: 20 m interbedded sand, 20 m clay, 20 m sand and then bedrock.

An 8-hour aquifer test, pumping at 1.2 L/s, resulted in 22 m drawdown in the pumping bore and 0.08 m in a similar depth monitoring bore 50 m away. The palaeochannel sands had a hydraulic conductivity of 0.5–2.5 m/d (metres per day) and storativity from 0.0001–0.00002. Palaeochannel pumping rates are limited to small discharges because the sand permeability is low.

The bore was pumped again, at about 2 L/s, from 18 July 2006 to 29 May 2007. This long-term pumping caused a watertable decline over a maximum of 3 hectares, with about 0.5 m decline within about 1 hectare. There was no measurable drawdown in either intermediate-depth or deep bores beyond 100 m.

The project demonstrated that palaeochannel pumping has few benefits and high costs if used to recover agricultural land. It may have use to protect high-value assets. The Dumbleyung project costs, excluding Department of Water staff time, were about $85 000 to lower the watertable by less than 0.5 m over about one hectare.

1 Introduction

Broad Wheatbelt valleys with fertile soils were being cleared of deep-rooted perennial vegetation since 1900, resulting in rising saline watertables and crop damage. The most severe land salinisation occurs in valley bottoms where groundwater discharges upward in alluvial sediments (Williamson et al. 2001). As a result, in most of Western Australia's Wheatbelt the watertable is less than 2 metres below the surface in low-lying areas.

Crop damage occurs where there is less than two metres to the watertable (Nulsen 1981). It is, therefore, important to find practical methods to keep the watertable below this depth. One method is by farm-scale groundwater pumping.

The Engineering Evaluation Initiative (EEI) was established in 2002 to evaluate various engineering solutions to Wheatbelt salinity without damaging the environment. It was a $4 million priority project under the National Action Plan for Salinity and Water Quality. The EEI consists of three programs:

1. Evaluation of specific engineering options at farm scale (1–2 farms)
2. Regional drainage options
3. Safe disposal of saline water

Other EEI projects considered how to lower watertables in areas where crop production was affected by rising soil salinity. Dogramaci et al. (2009) describe palaeochannel pumping in the Tammin area, about 250 km east of Perth.

This report describes the effectiveness of groundwater pumping to manage the watertable at Dumbleyung. Dumbleyung crops are not greatly affected by salinity yet and the primary objective is to decide whether small-scale pumping might be a viable option to stabilise the watertable.

1.1 Project objectives

The general project objective was to determine if groundwater pumping can manage the watertable in the Dumbleyung area. The primary question is whether it is possible to lower the watertable by pumping deeper palaeochannel sands. Specific objectives were:

1. Describe the configuration of the palaeochannel aquifer (Section 3).
2. Determine aquifer characteristics (Section 4).
3. Describe the potential to lower the watertable by depressurising the underlying palaeochannel aquifer (Section 5).
4. Review costs, benefits and the practicality of groundwater pumping to maintain or recover agricultural land (Section 6).

1.2 Palaeochannel pumping concept

The purpose of groundwater pumping for salinity management is to pump a confined palaeochannel aquifer (Fig. 1), causing the shallow watertable above it to decline. If groundwater pumping can lower the watertable, then crops would be protected and less-saline groundwaters would discharge to wetlands, streams and rivers.

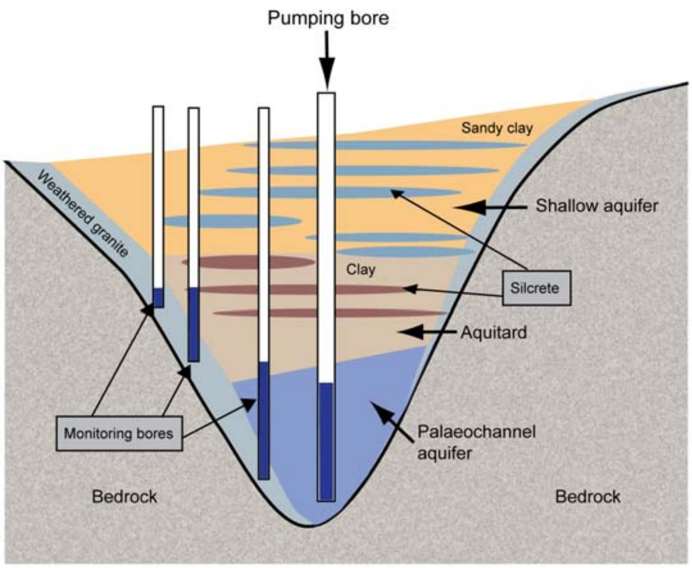

Figure 1 Conceptual palaeochannel pumping proposal

To increase the likelihood of success, it is important to understand how the local hydrogeology responds to pumping. Groundwater pumping causes a depression cone that expands outwards from the pumping bore till reaching some stable shape. This stable shape happens when inflow (recharge) equals outflow (discharge) and to result in a steady state. The depression cone shape is determined by the pumping rate and hydrogeologic characteristics such as hydraulic conductivity and storativity.

Hydraulic conductivity describes the ability of subsurface materials to transmit water and storativity describes the ability to release water. To differentiate the two terms by example, clay can release (storativity) much water because it can contain 50% porosity but clay can only transmit (hydraulic conductivity) groundwater very slowly. On the other hand, sand can more readily release water and transmit it. Greater detail on hydraulic conductivity and storativity can be found in texts such as Freeze and Cherry (1979).

Weathered rock and saprolite yield about 0.5-3 L/s (George 1991); adequate for domestic use but not for irrigation or public supply without constant pumping to large storage tanks.

1.3 Dumbleyung drilling program

The Western Australia's Department of Water contracted Wheatbelt Drilling to drill and complete 16 bores in March 2006 in order to describe site hydrogeology. They used rotary air blast rigs for shallow- and intermediate-depth bores and mud rotary rigs for deep bores (Table 1).

Table 1 Bore definitions used in this report

Descriptor	Depth (m)
Shallow	4
Intermediate	17–20
Deep	43–63

Table 2 summarises the bore information for these bores. Six sites had two bores (about 20 and 50 m deep) to determine vertical groundwater flow direction. The bores were 4–63 m deep, had airlift yields 0.25–2.3 L/s, and depth to water 1.6–2.3 m below land surface. Salinity varied from 35 000 to 55 000 mg/L[1]. total dissolved solids. The pH range was 2.9–5.5.

Dogramaci (2006) gives bore location and identification, construction, geologic data, hydrogeological data, sample logs, and bore development (yields)[2]. The pumping bore (60914943) diameter was 100 millimetres and all others were 50 millimetres. Casing material was class 9 plain and slotted PVC. Screen and gravel annulus details are given in Appendix A.

[1] This report converts 1 μS/cm to 0.55 mg/L.

[2] Dogramaci (2006) has discrepancies. For example, bore 60914953 (DY005D) depth is variously reported as 44.8, 44, 60.5, and 43 m in the report. Therefore, Table 2 uses only Dogramaci's (2006) 'log of samples' tables for consistency.

Table 2 Bore information summary

Bore[1]	Pumping bore distance (m)	Depth (m)	Screen interval (m below surface)	Water level[2] (m below surface)	Salinity[3] (mg/L))	Airlift yield (L/s)	pH	Comments
60914943	0	63	14–20; 49–60	1.77	51 000	2.3	3.8	Pumping bore
60914944	55	20	17–20	1.83	51 000	0.75	3.2	Next to 60914945
60914945	55	58	52–58	1.57	50 000	1.5	4.0	Next to 60914944
60914946	210	20	17–20	1.53	49 000	1.0	3.6	Next to 60914947
60914947	210	54	48–54	1.57	56 000	0.75	3.6	Next to 60914946
60914948	555	20	17–20	2.25	49 000	1.5	3.6	Next to 60914949
60914949	555	60	54-60	2.25	55 000	2	3.1	Next to 60914948
60914950	115	20	17–20	1.95	51 000	1	4.0	Next to 60914951
60914951	115	54	48–54	2.05	50 000	1	3.1	Next to 60914950
60914952	230	20	17–20	1.79	51 000	1.0	3.5	Next to 60914953
60914953	230	43	39–45	1.78	51 000	0.5	3.3	Next to 60914952
60914954	345	17	17–20	1.79	51 000	1.5	2.9	
60914955	315	20	17–20	1.98	50 000	1.5	3.1	Next to 60914956
60914956	315	60	54–60	1.84	45 000	1.5	4.3	Next to 60914955
60914957	505	4	3–4	2.21	36 000	0.25	3.5	
60914958	800	4	3–4	2.8	40 000	0.25	3.5	

1 This report uses the unique Australian Water Resources Council bore reference number to avoid uncertainty.

2 Water level measured when drilled.

3 This report converts 1 μS/cm to 0.55 mg/L.

1.4 Previous investigations

Commander et al. (2001) describe the transition of ancient landforms to the present, using clear illustrations. Leonhard (2000) describes the Dumbleyung 1:250 000 Sheet area in detail including location, climate, physiography, vegetation, geology, hydrogeology, water quality, salinisation and groundwater development: he uses term ‘paleaodrainages’ not ‘palaeochannels’. Waterhouse et al. (1994) describe the 60-km long Beaufort palaeochannel, with characteristics similar to those described in this report.

Clarke et al. (2000) describe Wheatbelt hydrogeology and report statistical hydraulic conductivity values based on over 100 tests. Dogramaci et al. (2009) describe groundwater pumping to lower the watertable near Tammin, 150 km east of Perth.

Maesepp & Kowald (2005) recommend a Dumbleyung pumping site based on geophysics, discussions with land owners, and aquifer test results at Fence Road (Global Groundwater 2003).

George et al. (2008) describe how salinity is a recurring natural feature of the Wheatbelt and currently appears to be reoccupying landscapes made saline by previous climate changes.

2 Study area description

The Dumbleyung study area (Fig. 2) is about 200 km east of Bunbury and 15 km east of Lake Dumbleyung and town (Fig. 3). The main land use is agriculture including sheep, wool and wheat. The area is flat and has been cleared for agriculture

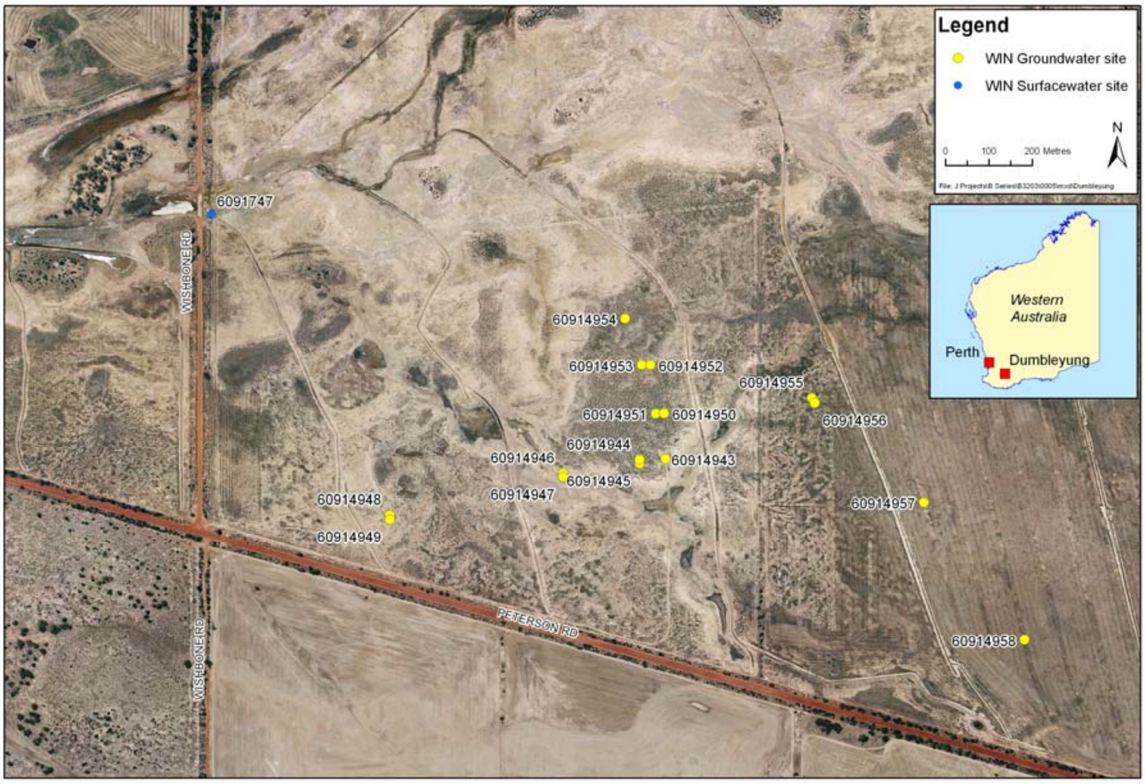

Figure *2* *Dumbleyung site in south-west Western Australia*

The climate is semi-arid with hot summers and cool winters. At Lake Grace, 60 km north-east of Dumbleyung, mean daily maximum and minimum temperatures in January are 32 °C and 15 °C and in July are 15 °C and 5 °C.

Average annual rainfall decreases to the east and north, ranging from 535 mm at Kojonup (90 km south-east of the Dumbleyung site) to 354 mm at Lake Grace. The Dumbleyung rainfall is about 400 mm/yr. Though most rainfall occurs between May and September, January and February thunderstorms have delivered the highest daily rainfall events. Rainfall has generally decreased from 1993 to 2006 (Fig. 4).

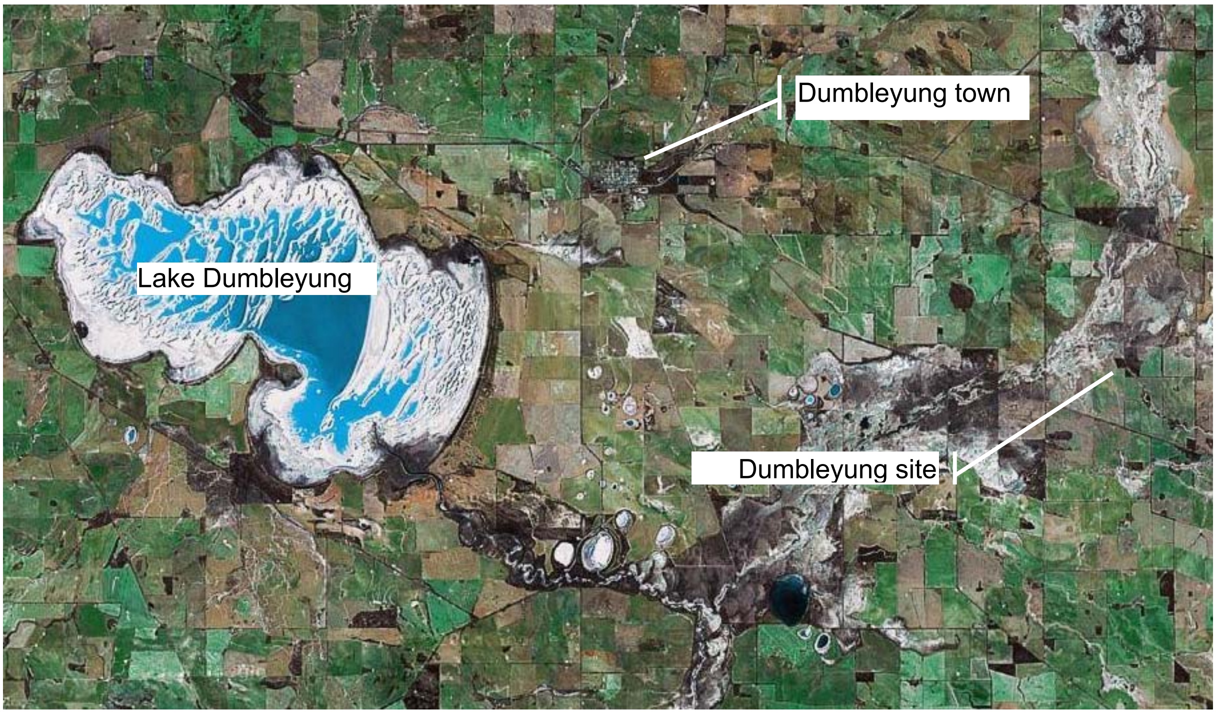

Figure 3 Dumbleyung area

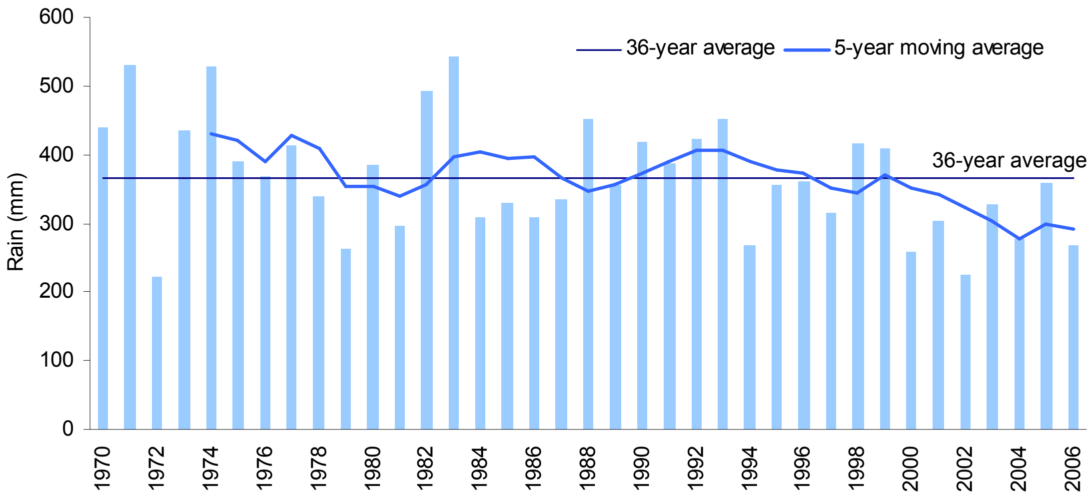

Figure 4 Dumbleyung rainfall (Post Office)

Potential evaporation ranges from 1800 mm/yr in the south-west to 2200 mm/yr in the north-east (Bureau of Meteorology 1999).

3 Palaeochannel location and dimensions

Few palaeochannels are mapped and defined in the Wheatbelt because there has been little economic need for their development. Agriculture has had no practical use for the Wheatbelt's saline groundwater.

This report describes the Dumbleyung site palaeochannel in order to determine whether palaeochannel pumping could lower the watertable. Palaeochannels (infilled former rivers) provide up to 10 L/s (Department of Fisheries web site) to gold mines east of the Wheatbelt.

Dumbleyung palaeochannels are typically within the boundaries of current drainages and floodplains, about 50 m thick and 300–2300 m wide, as determined using surface geophysics. Section 4 describes palaeochannel fill and associated hydrogeology.

3.1 Palaeochannels within current stream channels

Waterhouse et al. (1994) describe the 60-km long Beaufort River palaeochannel about 80 km south-west of the Dumbleyung study site. Cody (1994) describes the Coblinine River palaeochannel about 10 km west of the Dumbleyung study site. Sediment thickness in these palaeochannels is 50–60 m with basal sediment about 200–500 m wide overlying weathered bedrock. Depth to water in both is typically less than 5 m. Salinity was greater than 14 000 mg/L total dissolved solids (Cody 1994; Leonhard 2000).

Leonhard (2000, sheet SI 50-7) shows the Beaufort River and Coblinine River palaeochannels, Tertiary alluvial and lacustrine deposits. This same sheet (section C to D) also gives a geologic cross section from Dumbleyung Lake to 70 km eastward, including the Dumbleyung site.

The Dumbleyung palaeochannel, at the confluence of Dongolocking Creek and Lefroy River, may be similar to the Beaufort and Coblinine River palaeochannels (Fig. 5) within current alluvial drainage.

3.2 Palaeochannels defined using surface geophysics

Palaeochannels were mapped in greater detail using surface geophysics. Curtin University Department of Exploration Geophysics and Cooperative Research Centre for Landscape Environments and Mineral Exploration used gravity and transient electromagnetic geophysics methods to map palaeochannels. Field data were collected in April and May 2004 and results published in Wilkes et al. (2005).

Figure 6 (from Wilkes et al. (2005) shows interpreted palaeochannel boundaries as white lines and channel centres with yellow lines. Blue lines in the figure represent gravity surveys and red lines represent transient electromagnetic surveys used to interpret palaeochannels. Black numbers are geophysical survey lines. The resulting palaeochannel dimensions are summarised in Table 3.

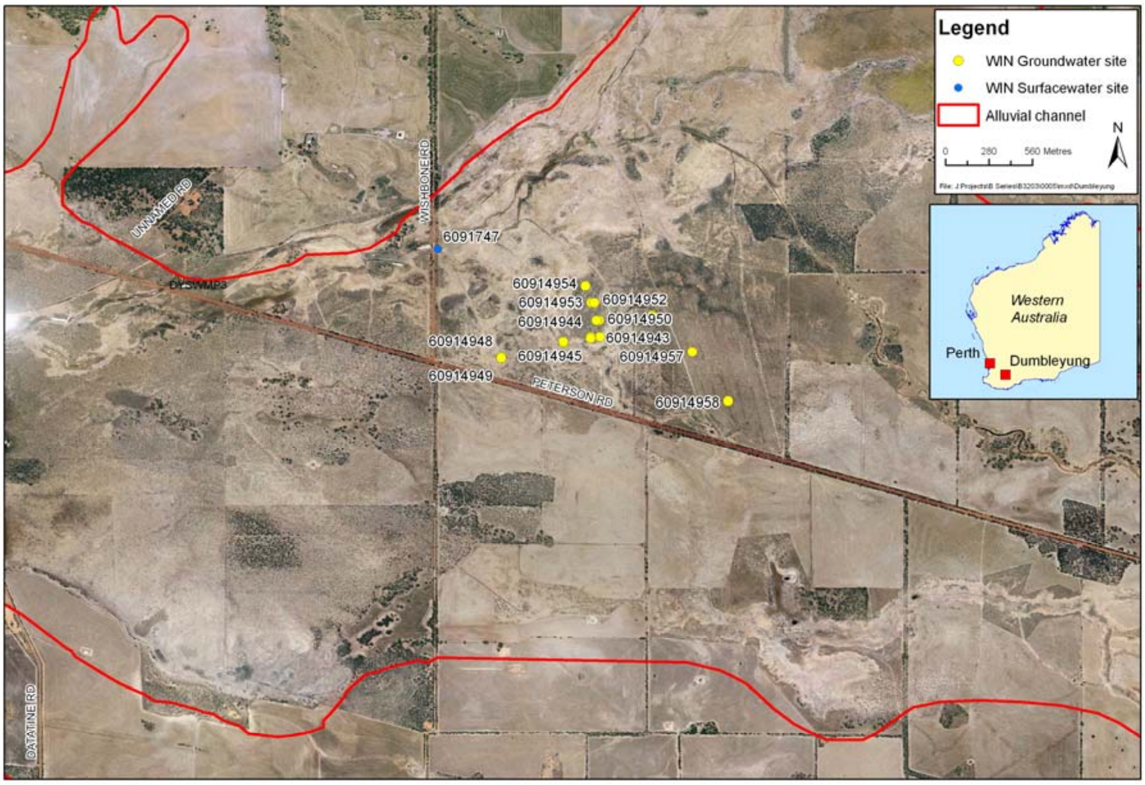

Figure 5 Dumbleyung alluvial channel

Pumping bore 60914943 was established at the site (Fig. 6) based on the advice of Wilkes et al. (2005). It overlies a palaeochannel as well as being near agricultural land for monitoring change.

Table 3 Palaeochannel dimensions indicated by geophysical survey

Geophysical survey line	Width (m)	Maximum depth (m)
1000	300	55
2000	500	45
3000	1000	45
4000	2300	45
5000	1400	40
7000	900	40
8000	--	45
9	1400	55

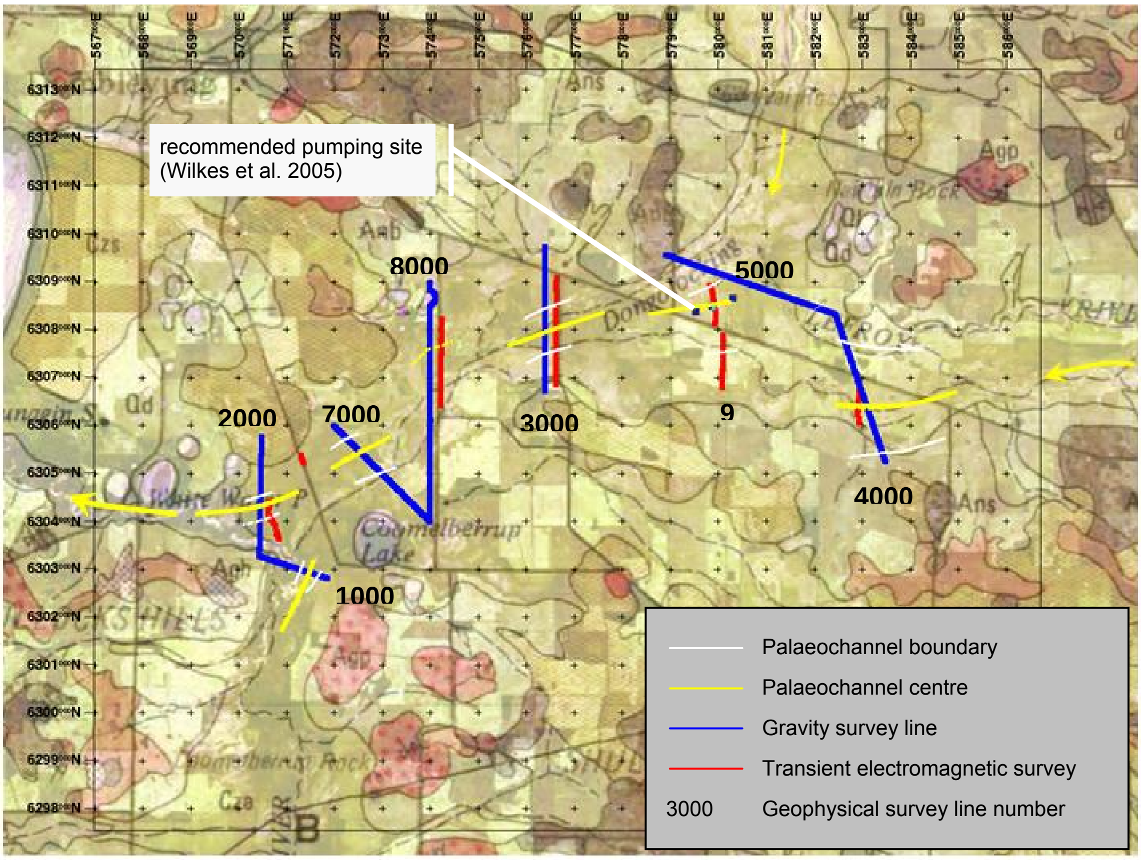

Figure 6 Geophysics-based palaeochannels

3.3 Geologic cross sections

Bore logs were used to create two cross sections (Fig. 7). The longer south-west to north-east cross section A–B is shown as the blue line, and the south to north cross section C–D as the red line.

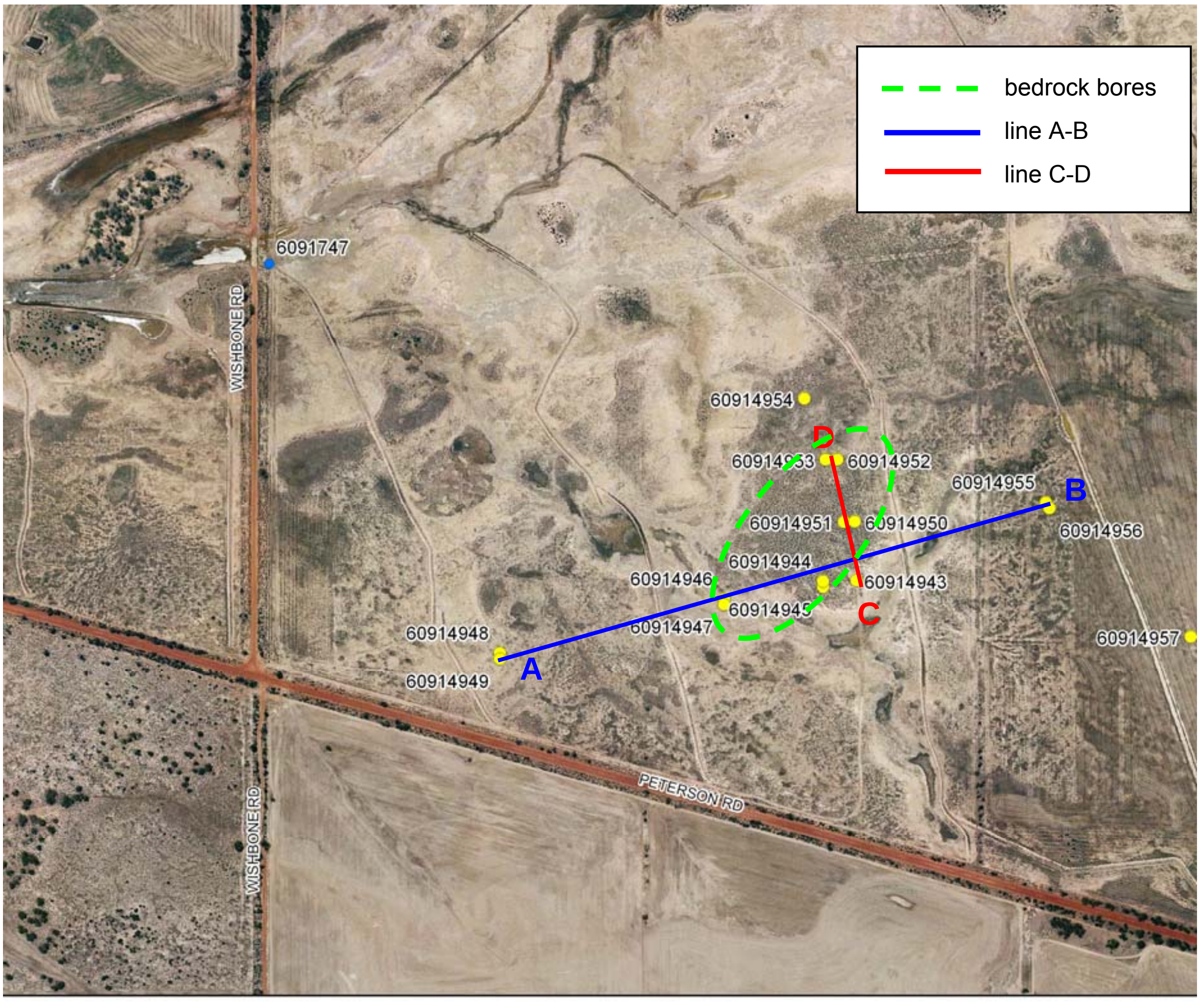

Figure 7 Geologic cross section lines

The basal sand thickness varies more than the middle confining clay thickness in the two geologic cross sections. In cross section A–B (Fig. 8), the middle confining clay layer is 15–30 m thick and the underlying palaeochannel basal sand is 5–25 m thick.

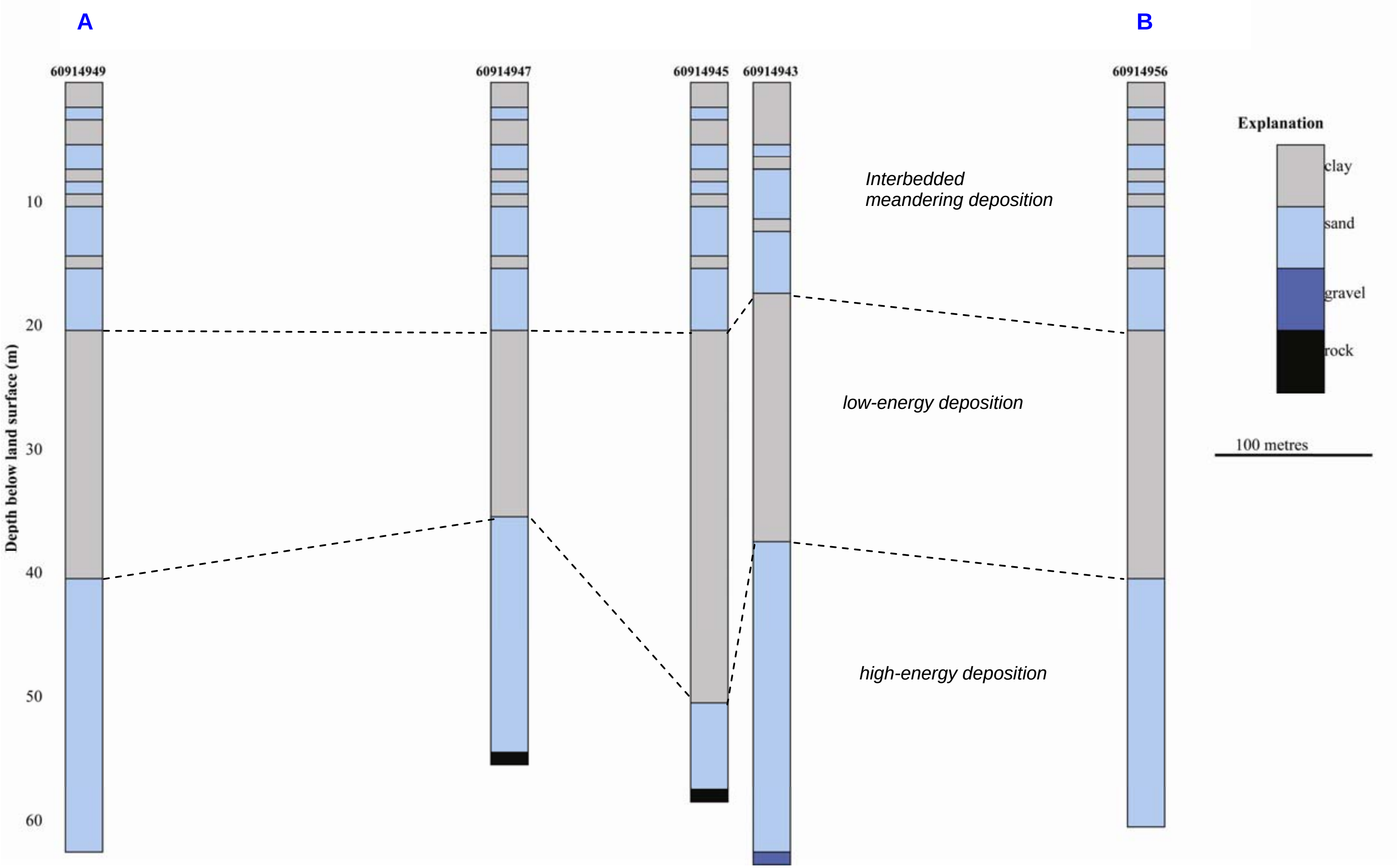

Figure 8 Geologic cross section A–B

In the shorter cross section C–D, the thickness of middle confining clay layer is 20–30 m and of the underlying palaeochannel basal sand 2–25 m.

Geophysical methods described in Section 0 were useful in determining greater palaeochannel depth, specifically the siting of pumping bore 60914943. This bore may be within an incised stream palaeochannel because it is at least 5 m lower than bore site 60914945 55 m to its west. Bedrock was encountered at higher elevations in central bores 60914945, 60914947, 60914951, and 60914953 (shown within a dashed green oval in Fig. 7).

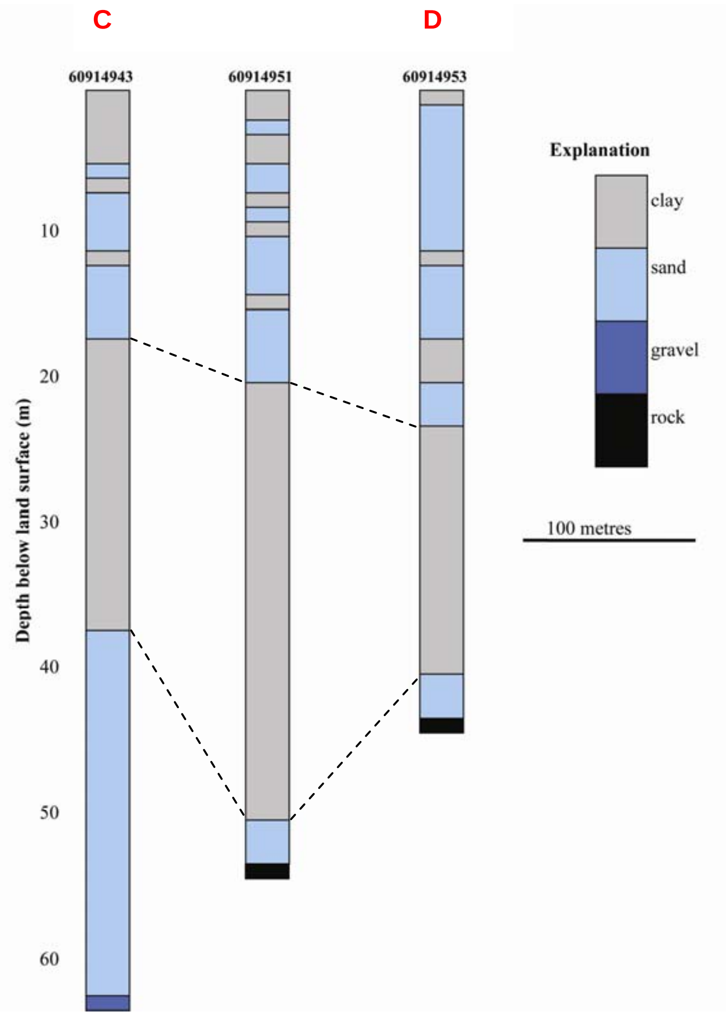

Figure 9 Geologic cross section C–D

4 Palaeochannel hydrogeologic characteristics

The two essential geologic features of the Wheatbelt (Fig. 10) are sediment-filled alluvial channels within a landscape of deeply weathered saprolite (a kind of regolith) from land surface to underlying bedrock. Regional saprolite thickness is typically less than 30 m and isolated palaeochannels are typically less than 60 m thick.

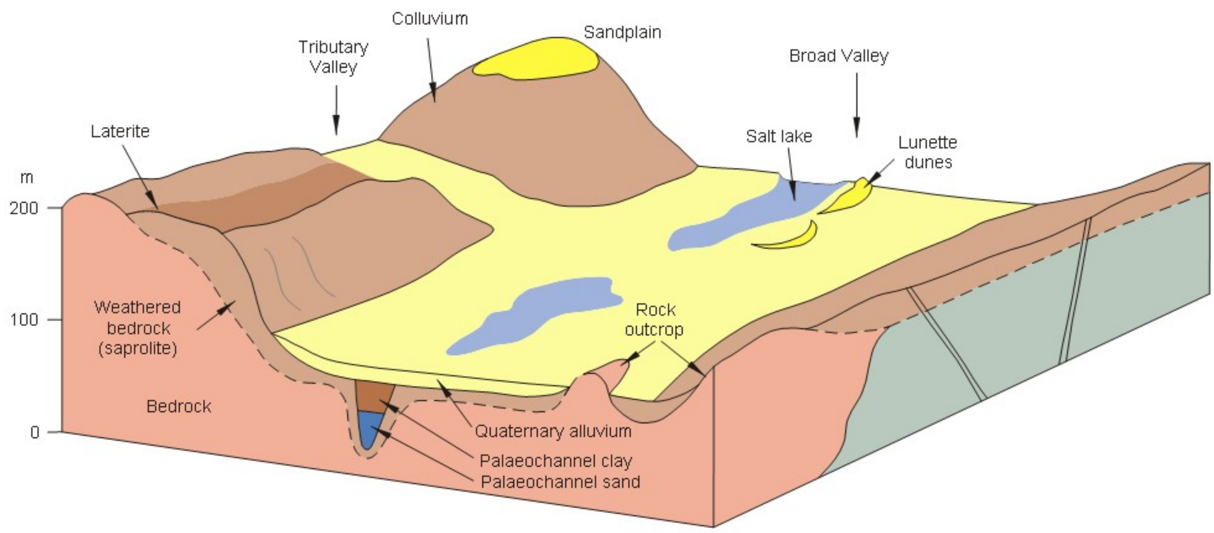

Figure 10 Wheatbelt block diagram (Commander et al. 2001)

Commander et al. (2001) describe the evolution of Wheatbelt landscapes and hydrogeology. Leonhard (2000) describes Dumbleyung hydrogeology and includes a palaeodrainage map. The regional watertable depth varies from about 5 to 20 m (Leonhard 2000).

4.1 General Wheatbelt palaeochannel hydrogeology

Leonhard (2000) describes palaeochannels as infilled with Tertiary sediments and reworked alluvium. These infilled deposits consist of an upper clay and silt of meandering variable-energy deposition, overlying interbedded sand and clayey sand. The sequence of infilled sediment expresses the geologic history. Deep sands were deposited in the more distant geologic past when gradients were steeper with higher energy deposition. More geologically recent, clays were deposited during flatter landscapes in low-energy conditions.

Palaeochannel sands are typically the most permeable lithology in the Wheatbelt (Table 4), constrained by clays above, bedrock below, and saprolite on both sides (Fig. 10).

Table 4 Wheatbelt permeabilities

Lithology	Hydraulic conductivity (m/d)	Measured	Estimated	Source
Clay and sand	0.1		✓	Freeze & Cherry (1979, p. 29, Table 2.2)
Saprolite	0.75	✓		Clarke et al. (2000, p. 560, Table 1)
Palaeochannel clay	0.01	✓		Clarke et al. (2000, p. 560, Table 1)
Palaeochannel sand	3.61	✓		Clarke et al. (2000, p. 560, Table 1)
Bedrock granite/gneiss	0.0000001		✓	Freeze & Cherry (1979, p. 29, Table 2.2)

Palaeochannel watertables are typically within 5 m of the surface (Leonhard 2000).

Palaeochannel salinities are typically 14 000–30 000 mg/L (Leonhard 2000). Slow recharge and groundwater movements are caused by overlying clays and low bed gradients. Groundwater discharges upward into salt lakes and claypans where it evaporates.

4.2 Dumbleyung palaeochannel hydrogeology

Typical Dumbleyung palaeochannel lithology includes upper interbedded sands and a lower sand, separated by a 20-m-thick clay (Table 5). The channel is cut within the weathered gneiss that forms the broad valley floor.

Table 5 Typical Dumbleyung palaeochannel bore log

Lithology	Depth (m)	Thickness (m)
Clay	0–2	2
Interbedded sand and clay	2–20	18
Clay	20–40	20
Sand	40–60	20
Bedrock	60	--

There is a similar lithologic sequence for all 0–40 m deep monitor bores (Fig. 11). Bores 60914945, 60914951 and 60914953 have thinner basal sands than the other bores.

The 20-m thick clay layer separates the upper interbedded sand and the deeper sand. Measurement and test data may not express this separation because bore annuli are gravel packed, allowing some degree of hydraulic connection between upper and lower aquifers.

Leonhard(2000 Table 2) reports palaeochannels have moderate to major aquifer potential and describes Dumbleyung palaeochannels as having:

> *…..basal gravel and sand deposits within palaeodrainages and other associated sediments in palaeochannel tributaries have high permeabilities and contain significant quantities of groundwater.*

And further:

> *These deposits form major aquifers with extensive supplies of brackish to saline groundwater, and local, minor supplies of fresh groundwater.*

Leonhard (2000) does not report permeability values though in the Tammin investigation Dogramaci et al. (2009) do not report high permeabilities, significant yields or freshwater. Palaeochannel sands have greater permeabilities than adjacent saprolite and a palaeochannel hydraulic conductivity value of 2 is four times greater than Wheatbelt saprolite hydraulic conductivity values of 0.5 m/d (Clarke et al. 2000).

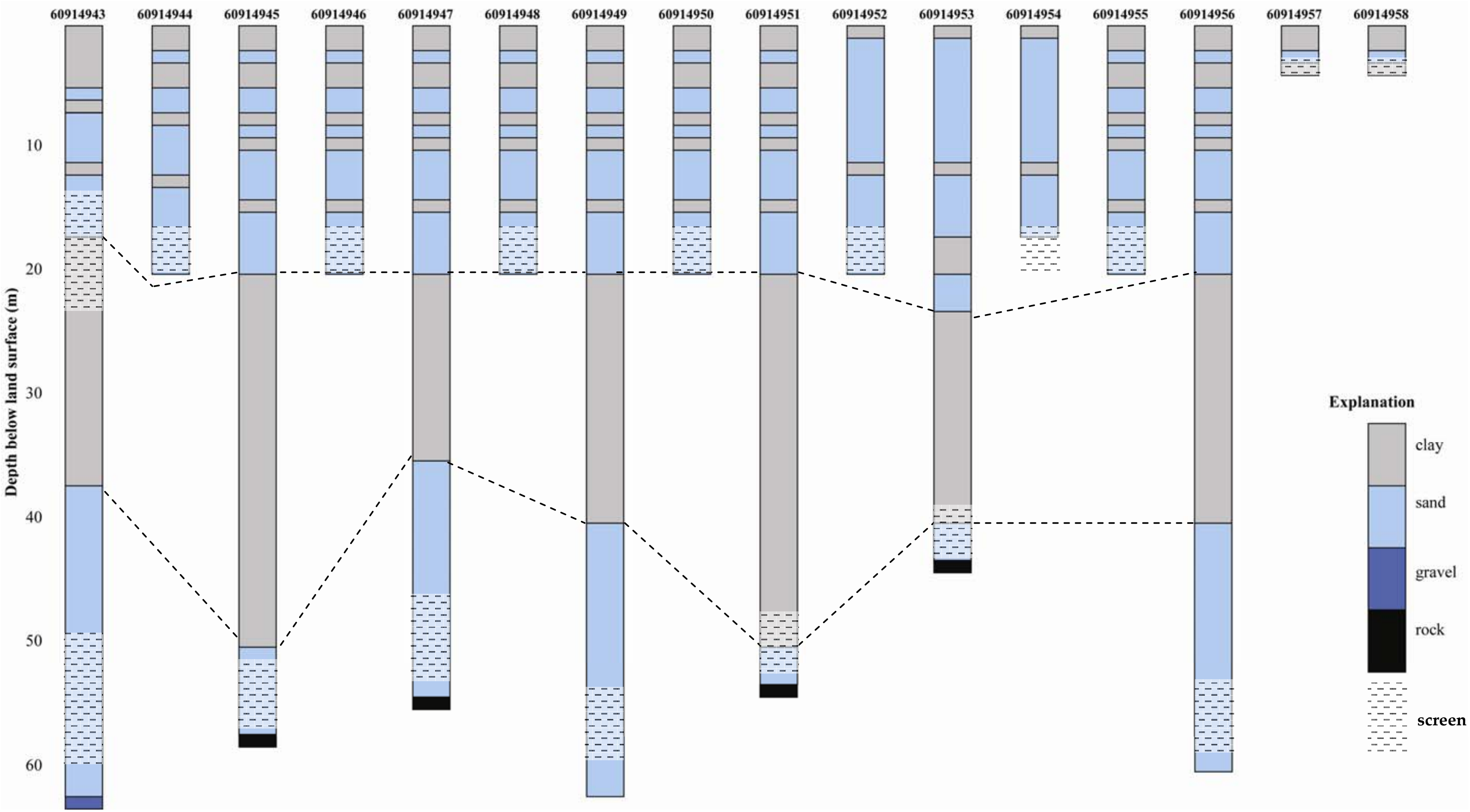

Figure 11 Dumbleyung bore logs

4.2.1 Salinity and pH

The median salinity for all the bores (Table 2) was about 51 000mg/L. The median shallow salinity (38 000 mg/L) was distinctly lower than intermediate-depth and deep salinities (both 51 000 mg/L). Though the reported salinity values for the intermediate-depth and deep bores are similar, the actual salinities may differ because bore completion connected the two aquifers by gravel-packed annuli (see Section 1.2).

The pH of shallow, intermediate, and deep groundwaters were similar (Table 2) with a median value of 3.5 and range 2.9 (bore 60914954) to 5.5 (bore 60914945).

Discharging saline and acidic groundwater to local waterways may damage downstream ecology and riparian margins.

4.2.2 Bore yields

The median yield for all the bores was about 1 L/s. The median shallow bore yield (0.25 L/s) was distinctly lower than the yields from intermediate and deep bores (1 L/s and 1.5 L/s respectively). Bore yields were reported at drilling completion, using airlift estimates.

4.2.3 Water levels

Median depth to water for all the bores was 1.8 m, with the median shallow bore level (2.5 m) distinctly higher than the 1.8 m of intermediate and deep bores. Water level data also indicate this is a recharge area (water moves downward) because shallow bores have a higher water levels (heads) than the deeper bores.

Bore water levels were reported at drilling completion. Static water levels (Table 2) for all bores were within about 1.3 m of one another, suggesting some hydraulic connection between aquifer sands. Though reported water level values are similar for the intermediate and deep bores, actual water levels may differ because bore completion connected the two aquifers by gravel-packed annuli (see Section 1.2.

5 Watertable management

Watertables may be managed by reducing the amount of rainfall that infiltrates to groundwater (groundwater recharge) or by removing groundwater (groundwater discharge), for example, lowering watertables by pumping.

Leonhard (2000) suggests this is not likely because the weathered bedrock aquifers have low permeability and low yields when pumped. He suggests instead land-management techniques to reduce infiltration before it adds to groundwater.

> *These techniques involve greater interception of rainfall, such as harvesting surface runoff and reducing rainfall infiltration by increasing evapotranspiration. Areas that respond more readily to these techniques are generally high in the catchment, where most of the groundwater recharge takes place.*

Aquifer test characteristics become useful in predicting drawdown with different pumping rates and especially when inserted into groundwater models that link aquifer layers over a region.

5.1 Aquifer test description

The eight-hour aquifer test was designed by S Dogramaci (Department of Water, Salinity and Water Resource Recovery Branch) and performed by Jeff Ingleton (Wheatbelt Water Drilling) in about March 2006 (based on dates of drilling invoices). The 1.2 L/s pumping rate (S Dogramaci 2008, written communication, 2 October) was read from a flow meter at the discharge point.

Water levels were measured in the pumping bore 60914943 and in two monitor bores (60914944 and 60914945) 50 m east of the pumping bore. The shallower bore 60914944 monitored shallow effects while bore 60914945 (58 m deep) monitored a composite of deep and shallow effects because it is open to both aquifers by way of the gravel annulus.

5.2 Aquifer test results

Drawdown in the pumping bore 60914943 was 22 m and 0.08m in bore 60914945 50 m away. Sands near the base of the palaeochannel have a hydraulic conductivity 0.5–2.5 m/d, derived from applying the Hantush (1960) curve to aquifer-test data. Storativity ranged from 0.0001 to 0.00002.

The Hantush equation does not fully fit all the test data because some aquifer-test assumptions (Appendix C) were not met, therefore two fits were applied. Data from bore 60914945 (Appendix D), the nearest bore to similar depth, was analysed using early data and late data.

The Hantush (1960)-type curve (blue line in Fig. 12) fits the first 30 minutes of data reasonably well because the early depression cone can expand without interruption or boundary; it had not reached the saprolite boundary yet after 30 minutes of pumping. At about 30 minutes, the depression cone reaches the end of the palaeochannel sands and extends into the lower permeability saprolite. After the depression cone reaches the saprolite boundary, there is much greater drawdown than Hantush or Theis (red line in Fig. 12) can predict. For this reason, data before 30 minutes represents only the palaeochannel sands.

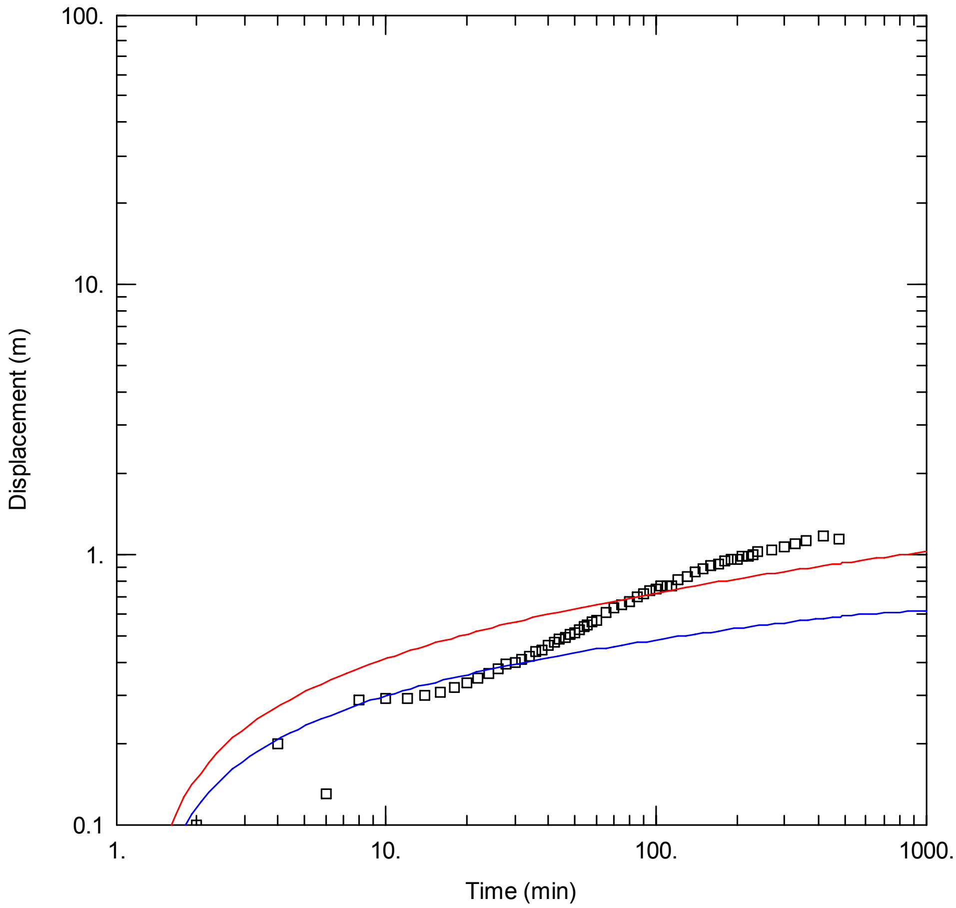

Figure 12 Aquifer test interpretation using bore 60914945's early data

Hydraulic conductivity is determined by the equation:

$$K = \frac{T}{b} = \frac{\frac{63m^2}{d}}{\frac{25m}{1}} \approx \frac{2.5m}{d} \qquad \textit{Equation 1}$$

where:

K = hydraulic conductivity

T = transmissivity = 63 m^2/d from Hantush solution (Fig. 12)

b = saturated aquifer thickness ≈ 25 m for cumulative sand thickness

The value 2.5 m/d is typical of a sorted sand (Freeze & Cherry 1979, Table 2.2). This fit does not show boundary conditions when the depression cone reached the sides of the palaeochannel. For this reason, Figure 12 is a more reasonable interpretation than Figure 13 because the depression cone caused by pumping should reach a low- or no-flow boundary as Figure 12 shows. Figure 13 shows no boundary and therefore is less reasonable.

The Theis and Hantush equations—using the test pumping rate, palaeochannel width, and typical hydraulic conductivity palaeochannel sands— predict that the depression cone reaches the palaeochannel boundary within two hours. After the depression cone reaches the boundary, the test data rise above the type curves as shown in Figure 12.

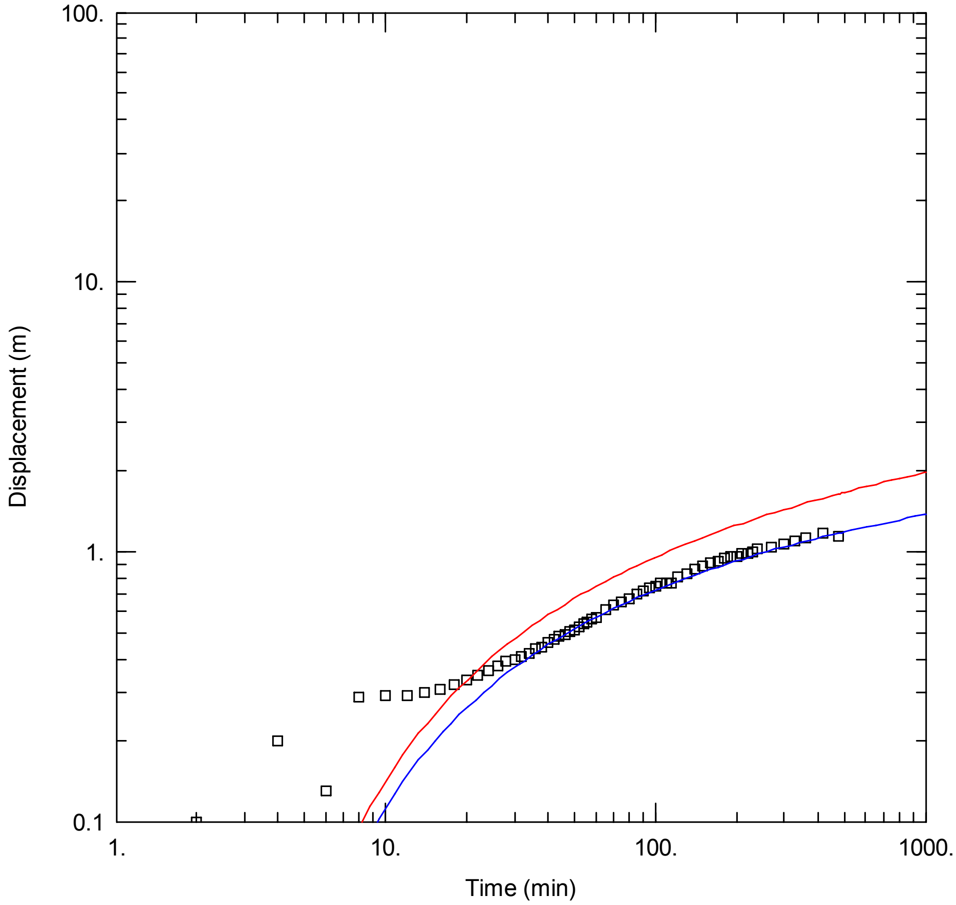

Figure 13 Aquifer test interpretation using bore 60914945's late data

Hydraulic conductivity is determined by the equation:

$$K = \frac{T}{b} = \frac{\frac{18m^2}{d}}{\frac{25m}{1}} \approx \frac{0.5m}{d} \qquad \textit{Equation 2}$$

where:

K = hydraulic conductivity

T = transmissivity = 18 m^2/d from Hantush solution (Fig. 13)

b = saturated aquifer thickness ≈ 25 m for cumulative sand thickness

The value 0.5 m/d is typical of a silty sand (Freeze & Cherry 1979, Table 2.2). The test-determined storativity was 0.0001.

Figures 12 and 13 include the Theis equation (red line) to show the relative difference that a confined (Theis) and semi-confined (Hantush) aquifer makes on drawdown. For example, if the deep sands were fully confined, there would have been 1 m of drawdown at 100 minutes instead of the measured 0.7 m for semi-confined conditions.

The Hantush equation and method requires that specific hydrogeologic and test conditions are met. The main deviations from equation assumptions for the Dumbleyung aquifer test are that the aquifer is neither infinite in areal extent nor isotropic.

5.3 Long-term pumping results

In this section distances between monitor bores and the pumping bore are rounded to simplify and generalise about data and trends. For example, Figures 16–18 represent bore distances as 50, 100, and 200 m rather than the actual 55, 115, 210 m (see Table 2 for detailed bore information).

Bore 60914943 was pumped at about 2 L/s from 18 July 2006 to 29 May 2007 with a long (February–March) gap (Figure 14) and some shorter gaps. Figures 16–18 show the non-pumping days shaded in order to emphasise the pumping period.

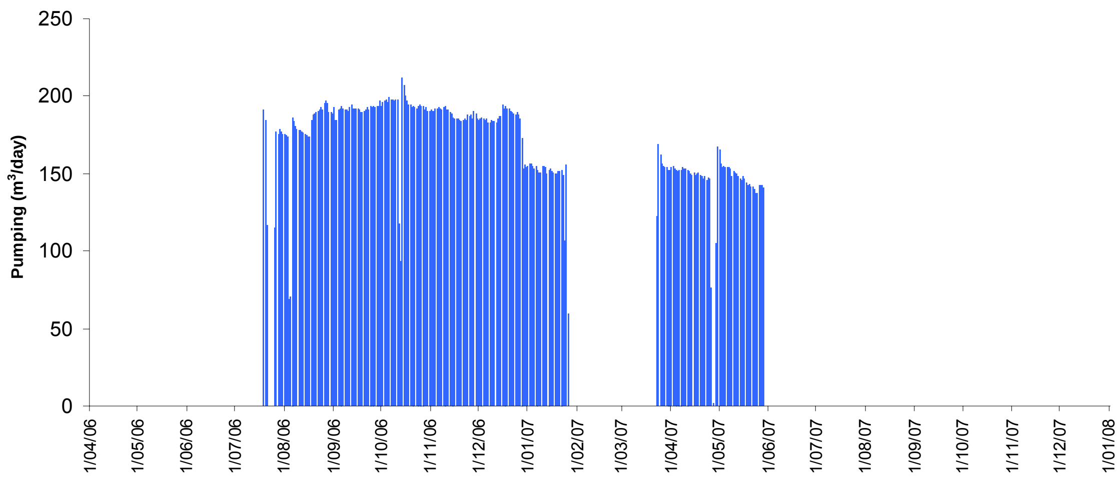

Figure 14 Pumping discharge (July 2006 – May 2007)

The March water-level rise (Figs 16–18) was likely caused primarily by the pump shut-down rather than rain (Fig. 15).

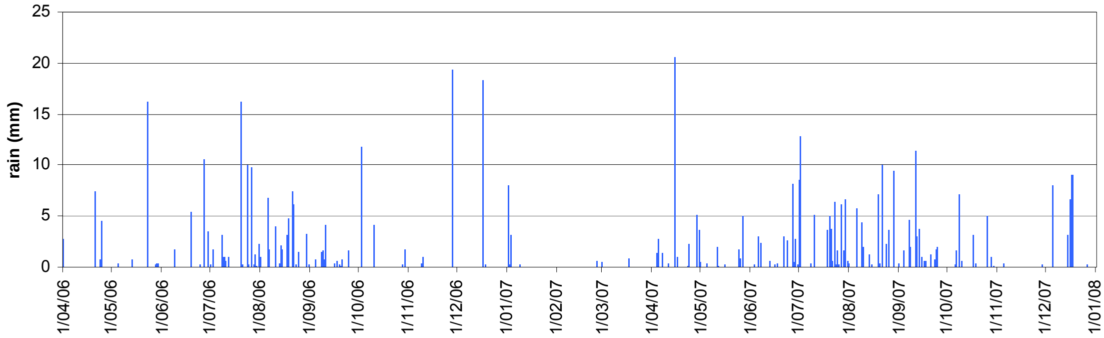

Figure 15 Dumbleyung rainfall 2006–07

All but one of the bore water levels remained within about 1.5 m of one another during the 19 months of pumping. The exception was bore 60914945 which, at 50-m distance, was clearly affected by the pumping bore (Fig. 16). The next three hydrographs examine how sets of intermediate and deep monitor bores at 50, 100, and 200 m responded to pumping.

At 50 m (Fig. 16), water in the deeper bore is clearly affected by pumping (2 m decline) and the intermediate-depth is much less affected (about 0.5 m decline).

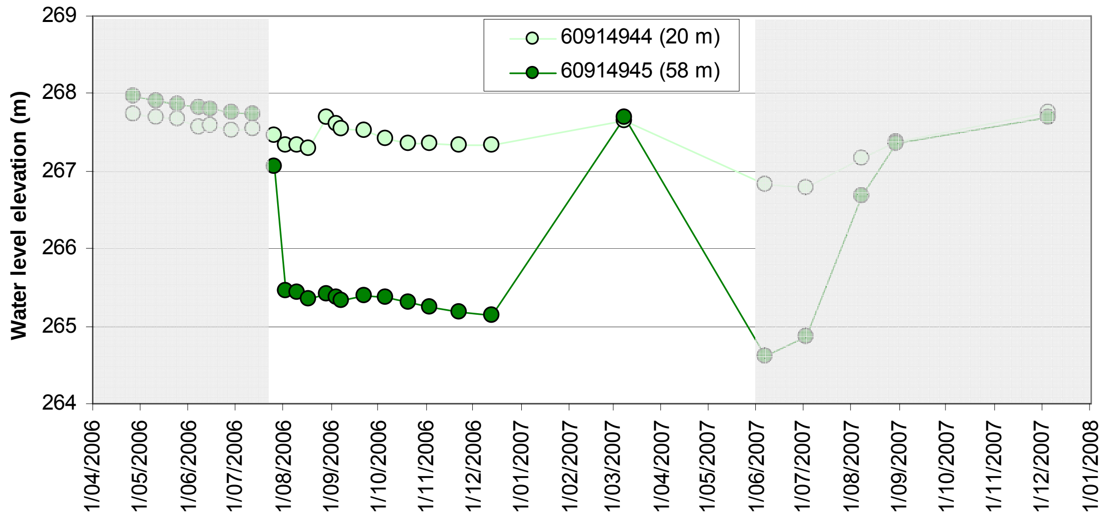

Figure 16 Bore hydrographs 50 m from the pumping bore

At 100 m, pumping effects in monitor bores are much less noticeable. Though Figure 17 shows there is less than 0.5 m decline in the deeper bore, there is no visible decline in the shallower bore.

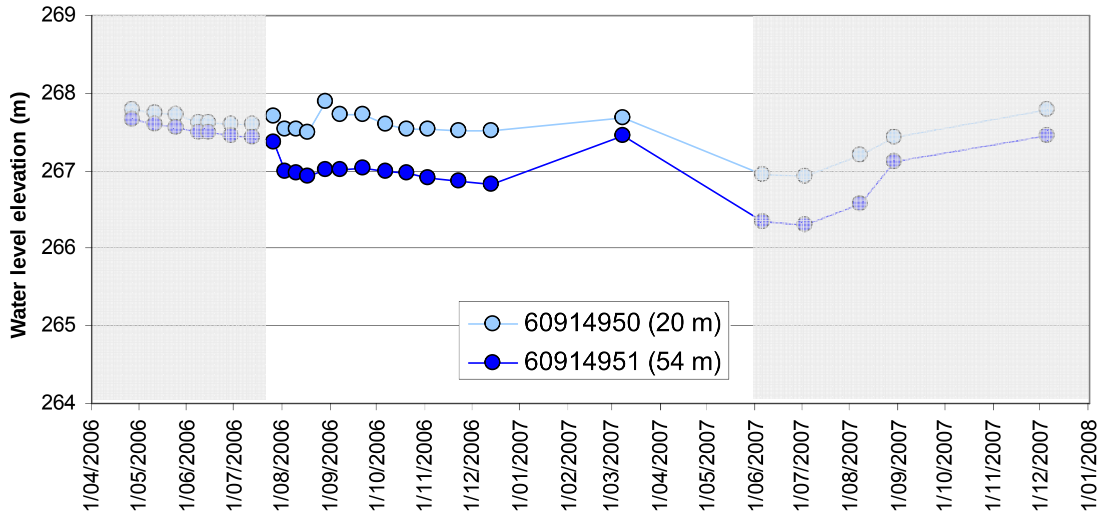

Figure 17 Bore hydrographs 100 m from pumping bore

As there are no visible pumping effects at 200 m (Fig. 18) in either deep or intermediate-depth bores, any measurable pumping effect ends within 200 m of the pumping bore.

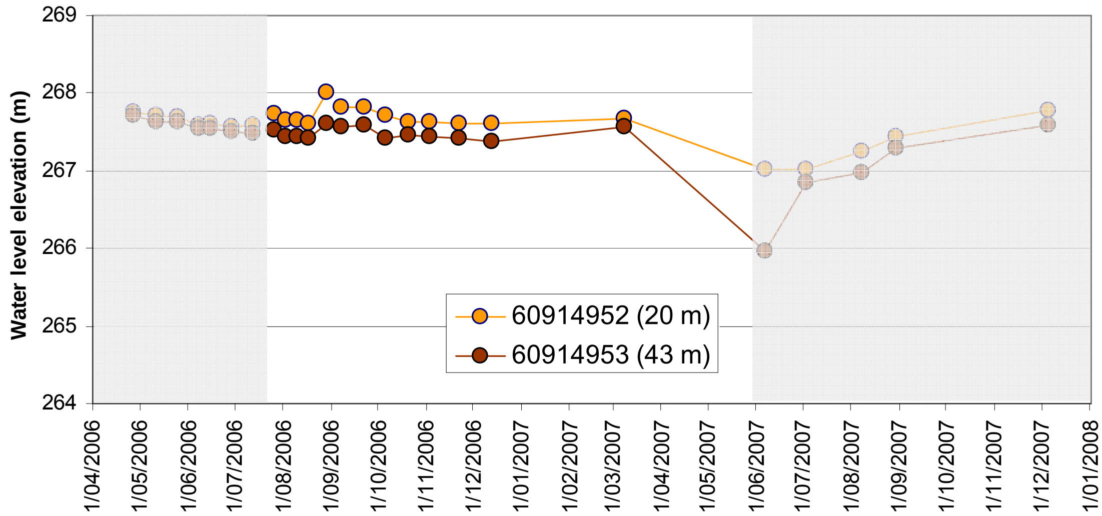

Figure 18 Bore hydrographs 200m from pumping bore

Water levels in intermediate-depth bores are higher than water levels in the deep bores for two of the three double-bore sites. This downward gradient defines a recharge area in which any water added to the land surface has a potential to move downward with a rate depending on vertical permeability. Groundwater would, therefore, discharge somewhere at lower elevation away from the site.

The exception is the monitor site 50 m from the pumping bore with discharge characteristics. Before long-term pumping, the site shows discharge characteristics (Fig. 16) with the deep bore having a higher water level than the intermediate-depth bore. The condition reverses after pumping starts and recharge dominates as nearby pumping causes groundwater to move downwards and to the pumping bore. Three months after pumping stopped, water level recovered to the same depth in both intermediate-depth and deep bores. Though similar water levels in two depths at the same site indicates they are open to the same aquifer, in this study it likely indicates long-term pumping has increased the hydraulic connection between intermediate-depth and deep bores by means of uncontrolled groundwater flow within the gravel annulus.

Long-term pumping of bore 60914943 at 2 L/s caused a watertable decline over a maximum of 3 hectares. The watertable declined more than 0.5 m within 50 m of the pumping bore (about 1 hectare). Bores of similar depth to the pumping bore had bigger water level declines. There was no measurable drawdown at distances greater than 200 m in either intermediate-depth or deep bores (Fig. 19).

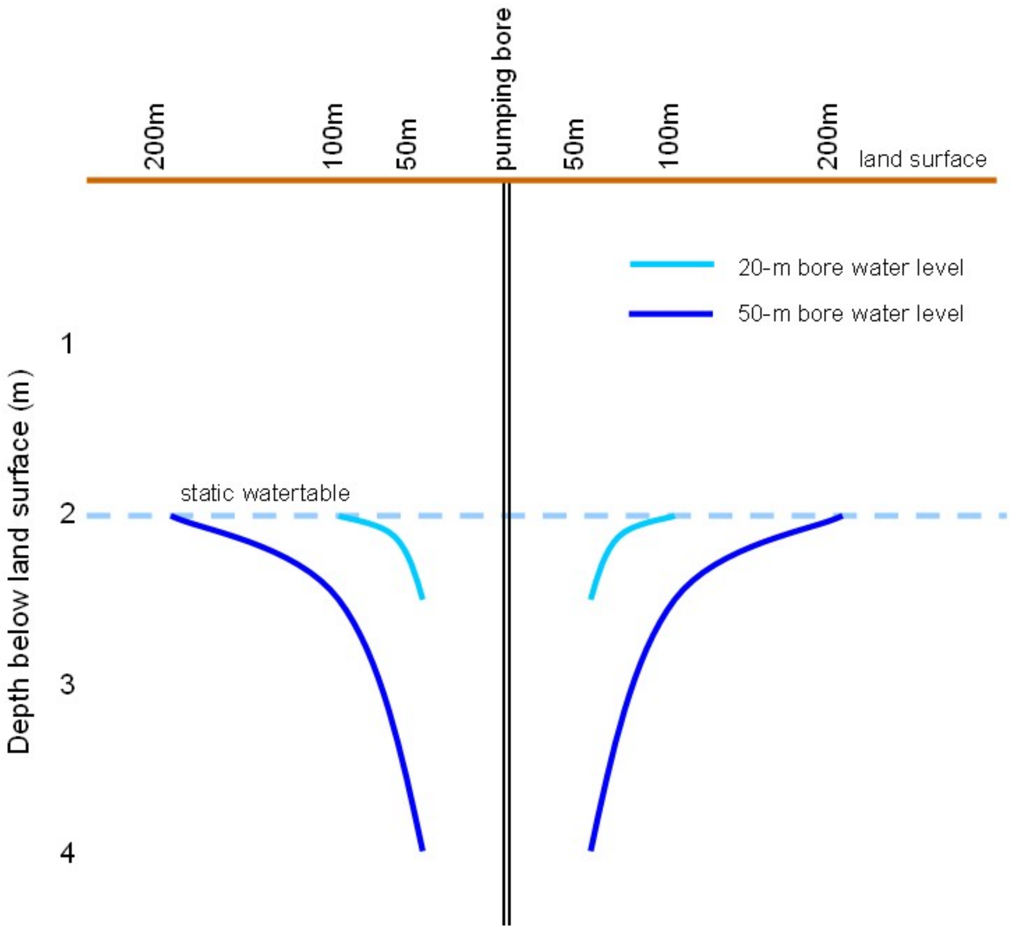

Figure 19 Generalised long-term pumping effects

6 Costs and benefits

The Dumbleyung project costs, excluding Department of Water staff time, were about $85 000 (Table 6). Annual operating costs to lower the watertable by 0.5 m over 3 hectares of agricultural land would cost about $20 000 (S Dogramaci 2008, written notes).

Farmers would incur costs for geophysics, drilling the pumping bore, generator and pumping costs of around $55 000.

Table 6 Dumbleyung project costs

Description	Cost ($)	Comments
Geophysics	15 765	To determine palaeochannel location
Bore drilling	33 462	16 monitor bores and pumping bore
Generator and pump	28 938	For pumping bore 60914943
Monitoring materials and maintenance	6 984	
Total	85 149	

7 Conclusions

Palaeochannels are difficult to locate and it is expensive to establish bores and pump them for long periods. Running pumps for longer than a few months requires long-term maintenance with occasional pump failures. Palaeochannel pumping lowers the watertable but not by much and not far away. Furthermore, when pumping stops, the original watertable level returns within days.

This report's four objectives, given in Section 1.1, are summarised below.

Describe the configuration of the palaeochannel aquifer.

> The Dumbleyung palaeochannel near the confluence of the Dongolocking Creek and Lefroy River (Fig. 6) is about 50-m deep and 300–2300 m wide.

Determine aquifer characteristics.

> Palaeochannel sands extend from about 40–60 m below the surface and have greater permeability than underlying bedrock or adjacent saprolite. Hydraulic conductivity is about 2 m/d and storativity is about 0.00002. Accuracy is limited by unmet test assumptions (poor test design).

Describe the potential to lower the watertable by depressurising the underlying palaeochannel aquifer.

> Palaeochannel pumping rates are limited to small discharges because permeabilities are low — greater than surrounding saprolites but still low. The result is that watertable declines are small and drawdown is local rather than 'farm scale'. Pumping at 2 L/s lowered the watertable by 0.5 m within 50 m of the pumping bore.

Review costs, benefits and the practicality of groundwater pumping to maintain or recover agricultural land.

> Palaeochannel pumping at the Dumbleyung site had few benefits and significant costs that means it is an unlikely option to recover agricultural land. Annual costs, after initial establishment costs, would be $20 000 to lower a watertable by 0.5 m within 50 m of a pumping bore.

Glossary

Term/symbol	Units	Definition
AHD	m	Australian height datum
Annulus		Space between casing and bore wall
Aquifer		Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs.
b	m	Aquifer thickness
EEI		Engineering Evaluation Initiative
K	m/d	Hydraulic conductivity; the ability to transmit groundwater
L		Litre
m		Metre
PVC		polyvinyl chloride
Regolith		The upper part of the earth's surface that has been altered by weathering processes. It includes both soil and weathered bedrock.
s		Second
Saprolite		Chemically-weathered rock, soft and friable, that retains structure of the parent rock because it is not transported; saprolite is the part of the regolith that is altered by water, oxygen, carbon dioxide and organic acids.
Storativity		The ability the release groundwater measured as volume per unit area of aquifer
Salinity	mg/L	Common measure of salinity Total dissolved solids
Transmissivity	m^2/d	The ability of an aquifer thickness to transmit groundwater
weathered rock		Decay and crumbled remainder resulting from rock exposed to processes such as chemical action of air and rain, plants and bacteria and temperature change.

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Appendices

Appendix A — Bore screen and gravel-filled annulus[7]

Bore	Depth[8] (m)	Upper screen (m)	Lower screen (m)	Gravel (m)	Comments
60914943	63	14-20	49-60	4–60	Upper screen open to sand and clay; gravel annulus connects upper and lower sand aquifers
60914944	20	17-20	none	3–20	
60914945	58	52-58	none	20–58	Gravel annulus connects upper and lower sands
60914946	20	17-20	none	2–20	
60914947	54	48-54	none	25–54	Gravel annulus connects clay and deeper sand
60914948	20	17-20	none	3–20	
60914949	60	54-60	none	25–60	Gravel annulus connects clay and deeper sand
60914950	20	17-20	none	17–20	
60914951	54	48-54	none	20-54	Screen and gravel annulus connects clay and deeper sand
60914952	20	17-20	none	2–20	
60914953	43	39-45	none	20–45	Gravel annulus connects clay and deeper sand; screen and gravel annulus deeper than bore depth
60914954	17	17-20	none	2–20	Screen and gravel annulus deeper than bore depth
60914955	20	17-20	none	3–20	
60914956	60	54-60	none	25–60	Gravel annulus connects clay and deeper sand
60914957	4	3-4	none	3–4	
60914958	4	3-4	none	3–4	

[7] Sourced from Dogramaci S 2006

[8] Based on bore log where there is a discrepancy

Appendix B — Bore lithology logs

Bore 60914943

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Grey red clay with minor angular sand
2.0–3.0	Clay	Grey red clay, minor fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains.
5.0–7.0	Sand	Red ferruginised sand, angular to sub-angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm.
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand
20.0–28.0	Clay	Grey fine sand in fine clay matrix
28.0–30.0	Sandy clay	Gray angular to sub-angular fine to medium sand in fine clay
30.0–31.0	Clay	Light grey minor fine to medium quartz sand in clay matrix
31.0–35.0	Clay	Grey minor fine to medium quartz sand in clay matrix
35.0–36.0	Sandy clay	Dark grey angular fine to medium sand
36.0–38.0	Sandy clay	Dark grey angular medium ferruginised sand and silcrete fragments up to 3 mm
38.0–39.0	Sandy clay	Dark grey angular fine to medium sand
39.0–40.0	Sandy clay	Light grey fine angular to sub-angular quartz sand
40.0–62.0	Sand	Grey angular to sub-angular fine to medium quartz sand
62.0-63.0	Gravel	Grey rounded riverbed gravel

Bore 60914944

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains.
5.0–7.0	Sand	Red ferruginised sand, angular to sub-angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm.
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5 mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand

Bore 60914945

Depth (m)	Lithology	Description
0.0–1.0	Sandy Clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains.
5.0–7.0	Sand	Red ferruginised sand, angular to sub angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm.
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar

Depth (m)	Lithology	Description
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand
20.0–30.0	Clay	Grey fine sand in fine clay matrix
30.0–31.0	Clay	Light grey minor fine to medium quartz sand in clay matrix
31.0–35.0	Clay	Grey minor fine to medium quartz sand in clay matrix
35.0–43.0	Sandy clay	Grey angular fine to medium sand
43.0–50.0	Sandy clay	Light grey fine angular to sub-angular quartz sand
50.0–57.0	Sand	Dark grey angular to sub-angular fine to medium quartz sand
57.0–58.0	Bedrock	Dark grey granite fragments, coarse angular sand

Bore 60914946

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains.
5.0–7.0	Sand	Red ferruginised sand, angular to sub angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm.
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand

Depth (m)	Lithology	Description
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5 mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand

Bore 60914947

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains
5.0–7.0	Sand	Red ferruginised sand, angular to sub angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand

Depth (m)	Lithology	Description
20.0–30.0	Clay	Grey fine sand in fine clay matrix
30.0–31.0	Clay	Light grey minor fine to medium quartz sand in clay matrix
31.0–35.0	Clay	Grey minor fine to medium quartz sand in clay matrix
35.0–40.0	Sand	Grey angular fine to medium sand
40.0–43.0	Sand	Grey angular medium sand
43.0–50.0	Sandy	Light grey fine angular to sub-angular quartz sand
50.0–54.0	Sand	Dark grey angular to sub-angular fine to medium quartz sand
54.0	Bedrock	Granite

Bore 60914948

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains.
5.0–7.0	Sand	Red ferruginised sand, angular to sub angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm.
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand

Bore 60914949

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains.
5.0–7.0	Sand	Red ferruginised sand, angular to sub angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm.
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand
20.0–31.0	Clay	Grey fine sand in fine clay matrix
31.0–35.0	Clay	Grey minor fine to medium quartz sand in clay matrix
35.0–40.0	Clay	Grey clay minor angular fine sand
40.0–43.0	Sand	Grey angular medium sand
43.0–50.0	Sandy	Light grey fine angular to sub-angular quartz sand
50.0–60.0	Sand	Grey angular to sub-angular fine to medium quartz sand

Bore 60914950

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand

Depth (m)	Lithology	Description
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains.
5.0–7.0	Sand	Red ferruginised sand, angular to sub angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm.
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand

Bore 60914951

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains
5.0–7.0	Sand	Red ferruginised sand, angular to sub-angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5 mm embedded in clay matrix. The

Depth (m)	Lithology	Description
		texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand
20.0–30.0	Clay	Grey fine sand in fine clay matrix
30.0–31.0	Clay	Light grey minor fine to medium quartz sand in clay matrix
31.0–35.0	Clay	Grey minor fine to medium quartz sand in clay matrix
35.0–43.0	Sandy clay	Grey angular fine to medium sand
43.0–50.0	Sandy clay	Light grey fine angular to sub-angular quartz sand
50.0–53.0	Sand	Dark grey angular to sub-angular fine to medium quartz sand
53.0–54.0	Bedrock	Dark grey granite fragments, coarse angular sand

Bore 60914952

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Sand	Red grey ferruginised angular sand
2.0–11.0	Sand	Red ferruginised angular sand
11.0–12.0	Sandy clay	Red ferruginised sand, angular to sub angular quartz sand
12.0–20.0	Sand	Grey angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains

Bore 60914953

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Sand	Red grey ferruginised angular sand
2.0–11.0	Sand	Red ferruginised angular sand
11.0–12.0	Sandy clay	Red ferruginised sand, angular to sub-angular quartz sand
12.0–17.0	Sand	Grey angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains

Depth (m)	Lithology	Description
17.0–20.0	Sand clay	Cream sandy clay patches of grey, fine to medium sand, quartz grains up to 5 mm
20.0–23.0	Sand	Grey sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
23.0–40.0	Clay	Grey to pink fine clay, minor fine quartz sand embedded in clay
40.0–43.0	Sand	Dark grey angular sub-angular quartz grains up to 5 mm quartz sand
43.0	Granite	Bedrock

Bore 60914954

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Orange yellow sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Sand	Light cream pink ferruginised angular sand
2.0–11.0	Sand	Light red ferruginised angular sand
11.0–12.0	Sandy clay	Red ferruginised sand, angular to sub-angular quartz sand
12.0–17.0	Sand	Grey angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains.

Bore 60914955

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains
5.0–7.0	Sand	Red ferruginised sand, angular to sub angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5 mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains

Depth (m)	Lithology	Description
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand

Bore 60914956

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Red clay with minor angular sand
2.0–3.0	Sand	Red, fine to medium ferruginised angular sand
3.0–5.0	Sandy clay	Pink sandy clay, angular iron stained chip-rock up to 10 mm, rounded ironstone pebbles, and minor angular to sub-angular quartz grains
5.0–7.0	Sand	Red ferruginised sand, angular to sub angular quartz sand
7.0–8.0	Sand clay	Grey sandy clay patches of grey fine to medium sand, quartz grains up to 5 mm
8.0–9.0	Sand	Red ferruginised sandy clay, medium to coarse sand, angular sub-angular quartz sand, occasional pink feldspar
9.0–10.0	Sand clay	Red ferruginised angular to sub-angular sand
10.0–11.0	Sand	Grey angular sub-angular quartz grains up to 3 mm quartz sand
11.0–12.0	Sand	Pink grey sandy clay, quartz grains up to 5 mm embedded in clay matrix. The texture resembles that of insitu weathered granite.
12.0–13.0	Sandy	Light pink angular to sub-angular quartz grains embedded in clay matrix
13.0–14.0	Sand	Grey pink moderately ferruginised quartz sand up to 5 mm
14.0–15.0	Sandy clay	Grey fine to medium silcrete chips moderate clay
15.0–17.0	Sand	Grey red, angular quartz sand occasional pink feldspar grains
17.0–18.0	Sand	Cream angular quartz sand occasional pink feldspar grains
18.0–19.0	Sand	Light pink angular to sub-angular quartz grains
19.0–20.0	Sand	Grey angular to sub-angular quartz sand
20.0–31.0	Clay	Grey fine sand in fine clay matrix
31.0–35.0	Clay	Grey minor fine to medium quartz sand in clay matrix
35.0–40.0	Clay	Grey clay minor angular fine sand
40.0–43.0	Sand	Grey angular medium sand
43.0–50.0	Sandy	Light grey fine angular to sub-angular quartz sand
50.0–60.0	Sand	Grey angular to sub-angular fine to medium quartz sand

Bore 60914957

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Pink lightly ferruginised clay with minor angular sand
2.0–3.0	Sand	Pink, fine to medium ferruginised angular sand
3.0–4.0	Sandy clay	Light cream sandy clay, angular iron stained quartz grains

Bore 60914958

Depth (m)	Lithology	Description
0.0–1.0	Sandy clay	Grey sandy clay, fine to medium sub-angular sand, poorly sorted
1.0–2.0	Clay	Pink lightly ferruginised clay with minor angular sand
2.0–3.0	Sand	Pink, fine to medium ferruginised angular sand
3.0–4.0	Sandy clay	Light cream sandy clay, angular iron stained quartz grains

Appendix C — Hantush semi-confined assumptions

Assumption	Met	Partly met	Unmet	Test comments
The aquifer is bounded on the bottom by a confining layer.	✓			
All geologic formations are horizontal and of infinite horizontal extent.			✓	Pumping effects likely to reach palaeochannel sides.
The potentiometric surface of the aquifer is horizontal prior to the start of pumping.	✓			
The potentiometric surface of the aquifer is not changing with time prior to the start of the pumping.	✓			
All changes in the position of the potentiometric surface are due to the effect of the pumping well alone.	✓			
The aquifer is homogeneous and isotropic.		✓		
All flow is radial toward the well.	✓			
Groundwater flow is horizontal.	✓			
Darcy's law is valid.	✓			
Groundwater has a constant density and viscosity.	✓			
The pumping well and the observation wells are fully penetrating; i.e., they are screened over the entire thickness of the aquifer.		✓		Pumping and observation wells open to full depth by grave-packed annuli.
The pumping well has an infinitesimal diameter and is 100% efficient.		✓		
The aquifer is confined top and bottom.		✓		Pumping and observation wells open to full depth by grave-packed annuli.
There is no source of recharge to the aquifer.	✓			
The aquifer is compressible and water is released instantaneously from the aquifer as the head is lowered.	✓			Pumping and observation wells open to full depth by grave-packed annuli.
The well is pumped at a constant rate.		✓		
The aquifer is bounded on the top by an aquitard..	✓			
The aquitard is overlain by an unconfined aquifer, known as the *source bed.*		✓		No distinctive unconfined aquifer.
The watertable in the source bed does not fall during pumping of the aquifer.			✓	Pumping and observation wells open to full depth by grave-packed annuli.
Groundwater flow in the aquitard is vertical.	✓			
The aquifer is compressible, and water drains instantaneously with a decline in head.	✓			

Appendix D — Aquifer test data for bore 60914945

Time into test (min)	Drawdown (m)
0	0.00
2	0.10
4	0.20
6	0.13
8	0.29
10	0.29
12	0.29
14	0.30
16	0.31
18	0.32
20	0.34
22	0.35
24	0.36
26	0.38
28	0.39
30	0.40
32	0.41
34	0.42
36	0.44
38	0.45
40	0.46
42	0.47
44	0.49
46	0.50
48	0.51
50	0.52
52	0.53
54	0.54
56	0.55
58	0.56
60	0.57

Time into test (min)	Drawdown (m)
65	0.61
70	0.63
75	0.65
80	0.67
85	0.69
90	0.72
95	0.73
100	0.75
105	0.76
110	0.76
115	0.77
120	0.81
130	0.83
140	0.87
150	0.88
160	0.91
170	0.93
180	0.95
190	0.96
200	0.97
210	0.98
220	0.99
230	1.00
240	1.02
270	1.04
300	1.07
330	1.10
360	1.13
420	1.17
480	1.14

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