Hydrogeology of the eastern Scott Coastal Plain

by

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1. Introduction

1.1. Background

Groundwater in the eastern Scott Coastal Plain is currently being abstracted for irrigated agriculture and has been used in the past for mineral sands mining. There is increasing demand for groundwater from the Yarragadee aquifer for irrigation on the eastern Scott Coastal Plain. There is also demand for public water supply further north on the Blackwood Plateau under the Water Corporation's Integrated Water Supply Scheme, which may affect groundwater resources on the Scott Coastal Plain (Water Corporation, 2005).

The eastern Scott Coastal Plain contains ecologically and socially significant fresh water lakes as well as numerous wetlands, located in the D'Entrecasteaux National Park. Lake Jasper and Lake Quitjup are important features of local Aboriginal culture, while Lake Jasper is a registered heritage site and an important Australian Nature Conservation Agency wetland (ANCA, 1993). Both lakes are habitats for avian and aquatic life.

Proposed increases in groundwater abstraction may impact groundwater levels near the lakes, directly affecting the lake water levels. To address the potential ecological impacts associated with increased abstraction, various studies are being undertaken to determine ecological and social water requirements and the economic value of water to the regional users.

This investigation will provide geological and hydrogeological data to improve the conceptual groundwater model used by the Department. New groundwater monitoring bores, constructed for this project, will be used to monitor changes in water levels due to groundwater abstraction on the eastern Scott Coastal Plain.

1.2. Location

The Scott Coastal Plain is on the southern coast of Western Australia approximately 270 km south of Perth. The investigation area is located approximately 40 km east of Augusta on the eastern half of the Scott Coastal Plain (Figure 1). Bore sites are located on Jangardup Road, Black Point Road and Fouracres Road (Figure 2).

1.3. Climate

The eastern Scott Coastal Plain experiences warm dry summers and cool wet winters. Average annual rainfall is around 1000 mm/yr. Most rainfall occurs from May through to September, with average monthly rainfall for these months exceeding 100 mm. Average annual evaporation is 1200 to 1400 mm and monthly evaporation rates from May through to September range from 40 to 65 mm on the Scott Coastal Plain. In the summer months, monthly actual evaporation exceeds 100 mm. Rainfall exceeds evaporation only during the winter months.

1.4. Physiography

The Scott Coastal Plain is bordered by the Leeuwin-Naturaliste Ridge to the west, the Blackwood Plateau to the north and the Darling Plateau to the east. The Scott Coastal Plain extends along the southern end of the Blackwood Plateau from Augusta to Point D'Entrecasteaux (Baxter, 1977). The Scott Coastal Plain and Blackwood Plateau are separated by the Barlee Scarp (Figure 1). Average surface elevations on the Barlee Scarp drop from in excess of 80 m AHD on the Blackwood Plateau to 40 m AHD on the eastern Scott Coastal Plain.

The Quindalup, Milyeannup, Warren and Donnelly dune and shoreline systems are present on the Scott Coastal Plain and are geomorphically equivalent to those on the Swan Coastal Plain (Baxter, 1977). These dune systems run parallel to the present shoreline and the Quindalup dunes are still being deposited along the coast.

The eastern Scott Coastal Plain is an internally drained area of the Scott Coastal Plain (Figure 1). The average surface elevation is 40 m AHD, though the coastal dune elevation is up to 140 m AHD. Lake Jasper and Lake Quitjup are situated in a flat-lying area behind the coastal dunes and the entire eastern portion of the coastal plain is subject to seasonal inundation.

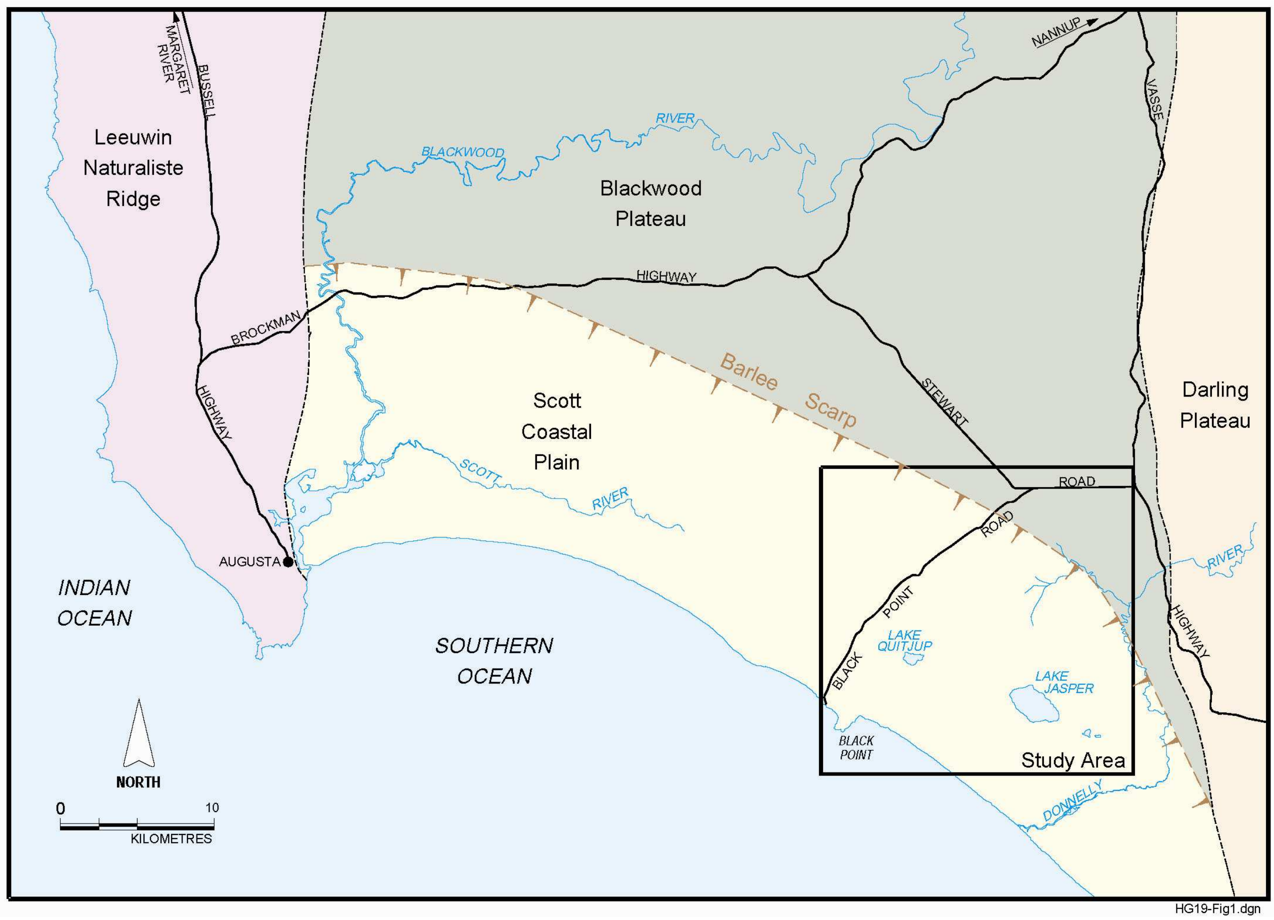

Figure 1. Location and physiography. The study area is located on the eastern half of the Scott Coastal Plain and referred to as the eastern Scott Coastal Plain.

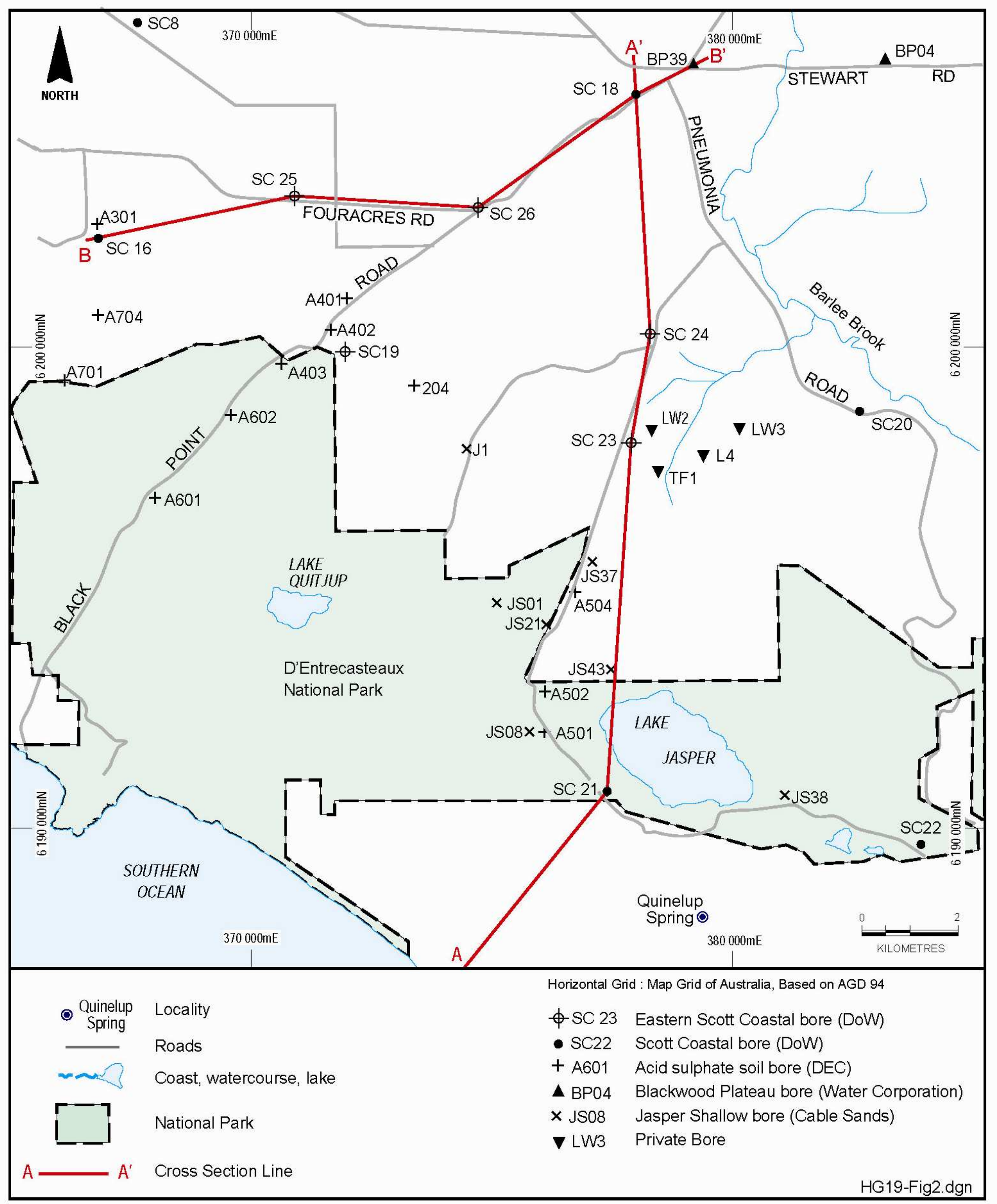

Figure 2. Bore location map.

2. Investigation

2.1. Previous investigations

Exploratory drilling was undertaken by the Geological Survey of Western Australia in 1992 to provide a regional assessment of the hydrogeology of the Scott Coastal Plain (Baddock, 1995). The assessment concluded that the superficial formations, including the Yoganup Formation, Guildford Formation, Tamala Limestone and Safety Bay Sand, directly overlay the Yarragadee Formation on the eastern Scott Coastal Plain.

Various reports have been compiled for Cable Sands on the environmental impact related to mineral sands mining in the area (Rockwater, 1989; Turner *et al*., 1996). Turner *et al.* (1996) assessed groundwater-surface water interactions near Lake Jasper as part of a feasibility study into the extension of the Jangardup Mineral Sand Mine, which was operated by Cable Sands Pty Ltd. This study resulted in an improved understanding of the groundwater contribution and flow through Lake Jasper.

Rockwater (2004) reviewed the geology and hydrogeology of the eastern Scott Coastal Plain, as part of a study into groundwater abstraction from the South West Yarragadee aquifer by the Water Corporation. This work by Rockwater was incorporated into a detailed study of the regional hydrogeology of the southern Perth Basin (Water Corporation, 2005), which identified the eastern Scott Coastal Plain as being host to environmentally significant wetlands, including Lake Jasper.

2.2. Scope and purpose

The hydrogeological interpretation by Rockwater (2004) has been adopted in the second version South West Aquifer Modelling System (SWAMS v.2). The model is a tool that is used as part of groundwater resource assessment by the Department of Water. The SWAMS v.2 regional groundwater model has been developed to simulate groundwater flow in all aquifers, provide estimates for water budgets in aquifers and also for use in predicting effects of drawdown over the south west of Western Australia (Varma, 2006).

Rockwater (2004) described the presence of a coffee rock or impermeable peaty layer in some parts of the superficial formations on the eastern Scott Coastal Plain. This layer would slow vertical leakage of groundwater from the superficial aquifer into the Yarragadee aquifer. In other areas, there is direct connection between the two aquifers, where the sandy superficial aquifer directly overlies the Yarragadee aquifer.

However, due to insufficient geological and hydrogeological information in the investigation area, the existence of a continuous, impervious layer situated between the superficial and Yarragadee aquifers could not be confirmed. Similarly, the extent of the different formations within the eastern Scott Coastal Plain was uncertain since only regional drilling had been undertaken. Knowing whether there is a continuous impermeable layer at the base of the superficial formation is essential for correct estimation of vertical leakage rates from the superficial aquifer to the Yarragadee aquifer in the event of drawdown induced by abstraction. This investigation was designed to provide the required information on the extent, thickness and lithology of the superficial formations on the Scott Coastal Plain.

This investigation is part of the Department of Water State Groundwater Investigation Program (SGIP), having the objectives to:

- improve understanding of geology and hydrogeology in an area north-northwest of Lake Jasper;
- identify any impeding layers between the superficial formations and the Yarragadee Formation;
- improve understanding of the interconnectivity between aquifers, in particular the superficial aquifer and Yarragadee aquifer; and
- establish new groundwater monitoring bores on the eastern Scott Coastal Plain.

The Department of Water and other agencies will use the results of this investigation to refine the conceptual geology in the SWAMS v.2 numerical groundwater model in order to improve confidence in the predicted impacts of increased groundwater abstraction. Future groundwater users will also benefit from the geological and hydrogeological data that has resulted from this investigation.

2.3. Eastern Scott Coastal Plain investigation

A drilling investigation was undertaken on the eastern Scott Coastal Plain, north-west of Lake Jasper, to obtain geological and hydrogeological data. Five sites were selected in an area where the Yarragadee Formation was believed to be either outcropping at the surface or sub-cropping directly below the superficial formations.

The sites are situated to the north and north-west of Lake Jasper and are accessible by bitumen and gravel roads. Sites SC 19, SC 23 and SC 24 are situated adjacent to road reserves where boggy conditions and flooding are common following winter rain.

The monitoring bores were drilled in April 2006 by Aquatech Drilling using a mud-rotary rig fitted with a blade drill-bit. Five sites were drilled and two or three piezometers installed at each site. The deep bores, up to 40 m depth, were drilled into the upper part of the Yarragadee Formation or Leederville Formation to monitor groundwater fluctuations within the aquifer. The intermediate bores were positioned above any clay layer that was intersected in the deep bores to observe head differences caused by its presence. A shallow bore was drilled to monitor the watertable.

All bores were constructed with 50 mm PVC pipe. The PVC slotted sections for the deep and intermediate bores comprised 3 m length, 0.5 mm-slotted, 50 mm PVC, whilst the shallow bores were constructed using 1 m lengths of slotted PVC. Bores were set in place and gravel packed to 1.5 m above the slotted interval and tremmie-grouted to surface with cement slurry. The holes were backfilled and standpipes were installed over each piezometer.

Lithological samples were collected and logged at 1 m intervals with selected samples taken for palynological analysis. Geophysical logging of the deep bore at each site was conducted using a gamma-ray tool.

Upon completion, bores were developed by airlifting and groundwater samples taken for chemical analysis. The unfiltered, unpreserved samples were stored in airtight PVC containers and analysed by the National Measurement Institute.

Detailed information pertaining to drilling and bore construction has been compiled into a bore completion report (Irwin, 2006).

Table 1. Bore completion data.

	Bore coordinates AMG zone 50		Construction			Elevation		Casing		Hydrogeology			
Bore	Easting	Northing	Start	Finish	Total Depth (m bns)	Natural Surface (m AHD)	TOC (m AHD)	PVC depth (m bns)	Slotted section (m bns)	Screened Geological Formation	Potentiometric Head (m AHD) April 2006	Salinity TDS (mg/L)	Airlift Yield (m^3/d)
SC 19B	371755	6199800	18/04/2006	20/04/2006	29	39.943	40.608	0.5-26	26-29	Jy	37.003	230	32
SC 19C	371755	6199800	18/04/2006	20/04/2006	13	39.959	40.609	0.5-10	10-13	Q	38.639	170	34
SC 19D	371755	6199800	18/04/2006	20/04/2006	8	39.942	40.612	0.5-7	7-8	Q	38.692	200	57
SC 23A	377620	6198025	10/04/2006	11/04/2006	38.5	52.227	52.827	0.5-35.5	35.5-38.5	Jy	40.627	150	13
SC 23B	377620	6198025	10/04/2006	11/04/2006	15	52.231	52.835	0.5-12	12-15	Kl	47.971	110	29
SC 23C	377620	6198025	10/04/2006	11/04/2006	5	52.258	52.854	0.5-4	4-5	Kl	48.038	-	-
SC 24A	378260	6200040	12/04/2006	13/04/2006	33.5	48.297	48.859	0.5-30.5	30.5-33.5	Kl	44.177	140	22
SC 24B	378260	6200040	12/04/2006	13/04/2006	17	48.483	48.883	0.5-14	14-17	Kl	44.383	130	18
SC 24C	378260	6200040	12/04/2006	13/04/2006	8	48.289	48.904	0.5-7	7-8	Kl	44.389	100	13
SC 25A	370665	6203065	19/04/2006	21/04/2006	31.5	50.937	51.578	0.5-28.5	28.5-31.5	Jy	40.977	270	22
SC 25B	370665	6203065	19/04/2006	21/04/2006	15	50.943	51.536	0.5-12	12-15	Jy	42.073	510	-
SC 26A	374590	6202810	20/04/2006	21/04/2006	39	49.773	50.246	0.5-36	36-39	Jy	41.803	520	48
SC 26B	374590	6202810	20/04/2006	21/04/2006	12	49.655	50.221	0.5-9	9-12	Kl	45.205	140	11

Q = Quaternary; Kl = Leederville Formation ; Jy = Yarragadee Formation
TDS = total dissolved solids (mg/L)

m bns = metres below natural surface
m AHD = metres above Australian Height Datum

3. Geology

3.1. Setting

The investigation area is located within the southern Perth Basin on the eastern side of the Bunbury Trough, which is situated between the Darling Fault and the Dunsborough Fault. Sediments in the Bunbury Trough range from the Early Permian to Quaternary periods (Iasky, 1993). The Permian to Jurassic sediments have undergone faulting and were uplifted and eroded prior to deposition of the Early Cretaceous Bunbury Basalt and Leederville Formation. Erosion in the Pleistocene has provided a surface on which the superficial formations were deposited, which is defined as the Scott Coastal Plain.

3.2. Stratigraphy

The superficial formations are present to the south along the coast where they unconformably overlie the Yarragadee Formation, Bunbury Basalt and Leederville Formation. The Yarragadee and Leederville Formations outcrop further north, where the superficial formations are absent (Figure 3). The Bunbury Basalt outcrops or sub-crops beneath the superficial formations west and north-west of Lake Jasper and on the coast near Black Point. The basalt occurs on the Neocomian unconformity, which exists between the Yarragadee Formation and the Leederville Formation.

3.2.1 Yarragadee Formation

The Yarragadee Formation outcrops in the north-west part of the investigation area at sites SC 25 and SC 8 and is overlain by the Leederville Formation inland and the superficial formations toward the coast. Only the upper part of the formation was intersected at sites SC 19, SC 23, SC 25 and SC 26.

The Yarragadee Formation comprises unconsolidated sand interbedded with silty clay. The sand units are white due to the presence of micaceous, kaolinitic clay and contain angular to sub-rounded, very coarse to gravel-sized quartz grains. The quartz is mostly clear to white with some purple-blue tinted grains. Rare-pebble size grains were also observed. There are thin beds of medium-grained, iron-cemented sand within these gravel beds.

The Yarragadee Formation is characterised by a low gamma-ray count of less than 50 API units. The formation has been divided up into four distinctive units, known as units 1, 2, 3 and 4. The units are defined by their lithology, geophysical signature and age (Water Corporation, 2005). Unit 2 is present near the surface within the investigation area.

The Yarragadee Formation was intercepted at all sites except at site SC 24. Palynological samples taken from clay layers in bores SC 24A, SC 25A and SC 26A were barren. Field identification of the Leederville and Yarragadee Formation is difficult as the source of the Leederville Formation is reworked Yarragadee Formation (Baddock, 1995). However, the Yarragadee Formation does have a relatively lower incidence of silty-clay to clay beds, which aid in its identification.

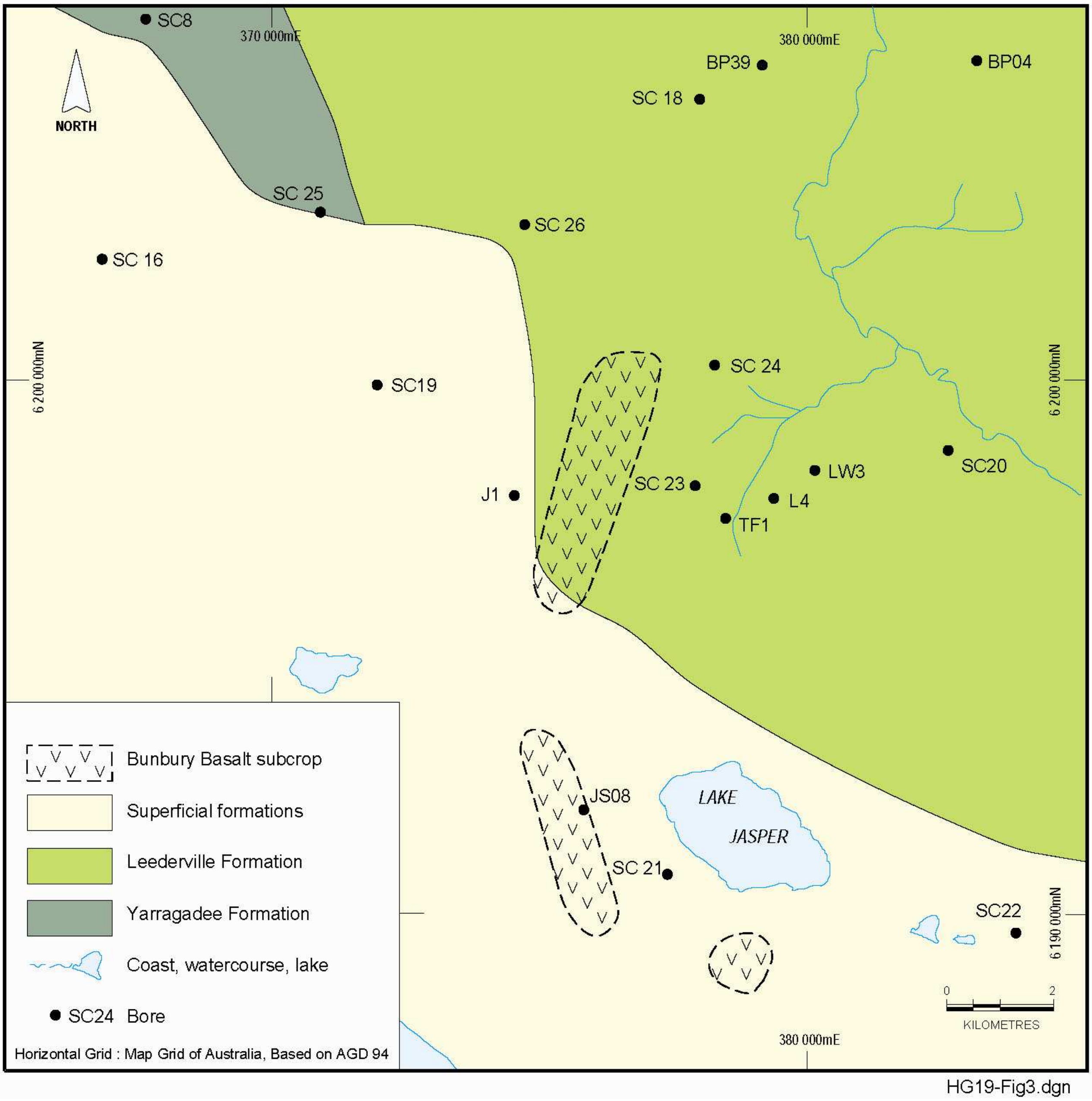

Figure 3. Surface geology.

3.2.2 Bunbury Basalt

The Bunbury Basalt is a tholeitic, vesicular basalt that disconformably overlies the Yarragadee Formation and is conformably overlain by the Leederville Formation (Playford *et al*., 1976). The Bunbury Basalt was not intersected in this drilling program, though its presence in the area is known from magnetic surveys and previous drilling (Baddock, 1995; Turner *et al.*, 1996). Bunbury Basalt was intersected in Cable Sands Pty Ltd bore JS 08 at 4.2 m bgl (~38 m AHD), though its elevation is highly variable across the plain (Turner *et al.*, 1996).

The basalt is discontinuous and unconformably overlies the Yarragadee Formation, outcropping at Black Point and at places on the Scott Coastal Plain (Baddock, 1995). Its close proximity to the surface correlates to topographic highs over the area, though in places it is covered by the coastal dunes. The basalt forms a southerly-trending ridge north of Lake Jasper, which coincides with the absence of superficial formations.

3.2.3 Leederville Formation

The Leederville Formation was intersected from the surface to various depths at sites SC 23, SC 24 and SC 26. The Leederville Formation outcrops on both the Scott Coastal Plain and Blackwood Plateau, increasing in thickness to the north and east (Figure 4). The formation has been eroded in places to the west and south-west of the outcropping Bunbury Basalt. The Leederville Formation may extend beneath the superficial formations to the south-east, partially underlying Lake Jasper (Figure 6).

The Leederville Formation consists of consolidated, greyish-white, silty-sandy clay interbedded with grey to black clays. Clayey sand beds up to 6 m thick were intersected and comprised coarse to gravelly sands, which are similar in lithology to the Yarragadee Formation. Rare well-rounded pebbles of quartz and quartzite were intersected in SC 26 at approximately 12 m depth below ground level, indicating coarser grained sand beds occur within the formation.

The grey to dark-coloured clay beds are laminated (approximately 1 mm) in some places. In bore SC 26A a thin and very hard band of iron-cemented sands was intercepted at 20 m below ground level, which coincides with the change in gamma-ray count. Cementation at the base of the Leederville Formation has also been reported in some of the Blackwood Plateau bores (e.g. BP 04).

The Leederville Formation lithology is similar to the Yarragadee Formation, though the Leederville Formation can be distinguished from the Yarragadee Formation by a higher gamma-ray count, averaging 50 to 75 API and up to 100 API units. The gamma-ray count for the Yarragadee Formation unit 2 averages less than 50 API units.

Palynological assemblages in samples from SC 23A were from the *Balmeiopsis limbata* spore-pollen zones, consistent with the Leederville Formation, which is late Valanginian to Barremian-Aptian in age (Backhouse, 2006b). The assemblage in SC 23A contains one pollen spore (*Retitriletes tenuis*) belonging to the Murphy's shaft assemblage, which is rare (Backhouse, 2006b). Other samples from the Leederville Formation were barren (Backhouse, 2006c and 2006e)

Precise age determination was not possible in these samples because of poor preservation of samples due to oxidation. However, the Lower Vasse Member of the Leederville has been identified in the nearby bore BP 04A as Valanginian to early Aptian, probably Barremian (Water Corporation, 2005). The sediments identified as being from the Cretaceous in this investigation were previously defined as superficial formation clays belonging to the Guildford Formation (Baddock, 1995).

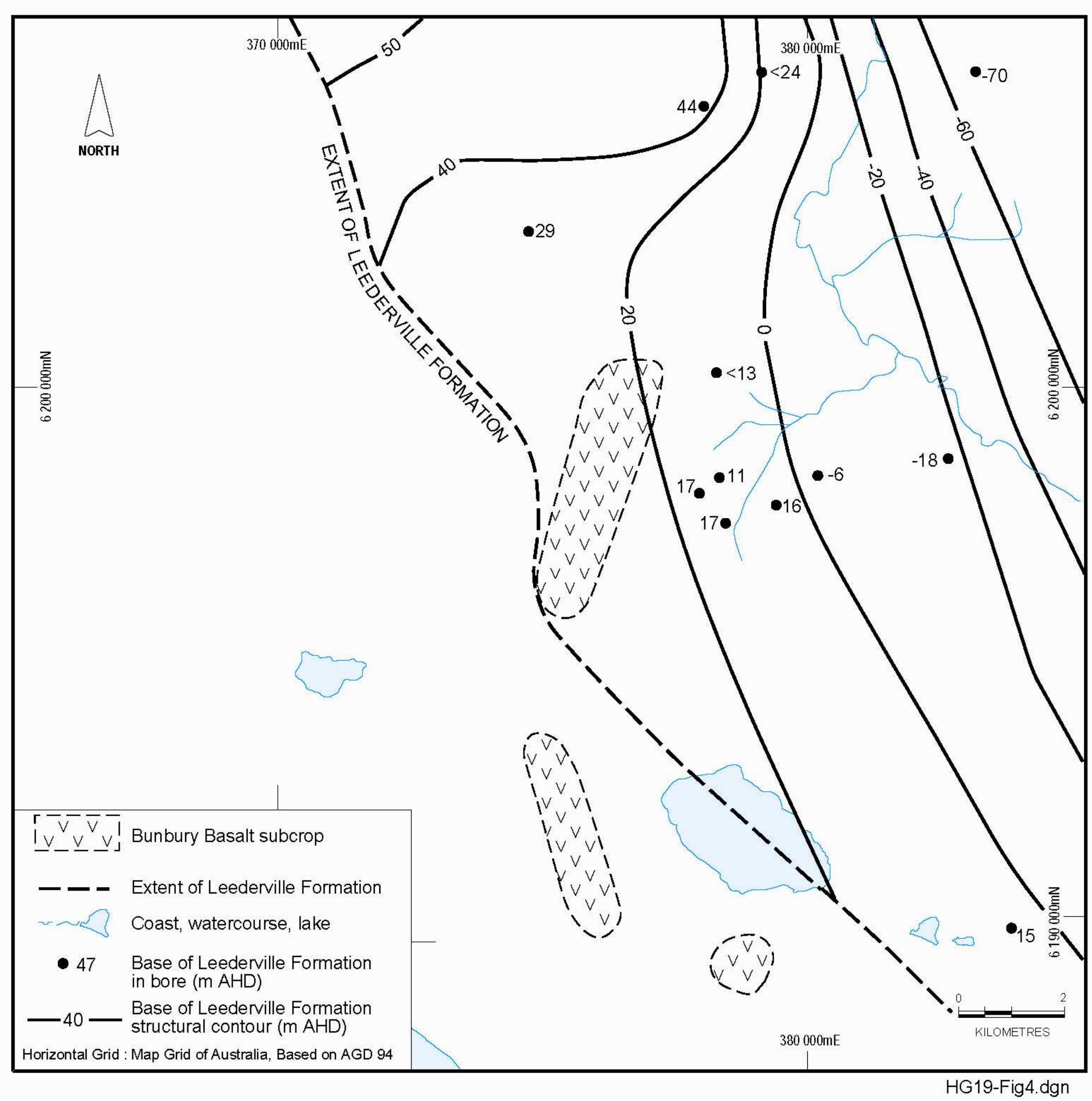

Figure 4. Base of the Leederville Formation.

The depositional environment of the Leederville Formation is probably fluvial to lacustrine. The high clay content in the sandier beds of the formations can be attributed to feldspar and mica weathering. The sandier beds are interbedded with denser alluvial clays. The grey clays intersected at SC 26 are laminated, indicating multiple-successive deposition, such as in a fluvial channel during low-energy flow events. Higher energy deposition and transportation is also evident by the presence of well-rounded pebbles of quartzite.

3.2.4 Superficial formations

The superficial formations consist of flat-lying, sandy to peaty-organic lacustrine sequences inland that adjoin the coastal dunes and limestone on the southern coast. The formations extend approximately 10 km inland. The Yoganup Formation exists along the base of the Barlee Scarp and is enriched with mineral sands. Mineral exploration drilling carried out by Cable Sands has mapped the mineral sand deposits extending beneath Lake Jasper, which are believed to be the Donnelly shoreline (A. Heptinstall, *pers. comm.*).

The inland sediments of the superficial formations have previously been assigned to the Guildford Formation, though their presence on the eastern Scott Coastal Plain is believed to be less extensive than described by Baddock (1995). Towards the coast, the Safety Bay Sand forms the Quindalup dunes, which overlies the Tamala Limestone. The limestone can be seen to outcrop in high cliffs on the southern coast and has been weathered to sand further inland. The inland extent of the Tamala Limestone is unknown and it was not intersected by the investigation drilling.

The superficial formations were only intersected in SC 19. They consist of dark to pale brown and yellow-brown organic sand. The grains are fine to gravel-sized, sub-rounded to well-rounded and moderately well-sorted quartz with minor feldspar. The quartz is predominantly white, clear and brown, but there are minor opaque and translucent purple-blue coloured grains as well, which is characteristic of the Yarragadee Formation. Organic matter and thin bands of iron-cemented, medium to coarse sands occur near surface. Thin layers of iron-cemented sand that occur within the formation have been shown in other areas to be discontinuous (URS, 2005).

At the base of the superficial formations there is a 2 to 3 m bed of brown silty sandy clay, which appears to be a superficial deposit, although a sparse palynological assemblage suggests that it may be of Cretaceous origin (Backhouse, 2006a). Similar brown silt has also been identified at Jangardup 1 and SC 21. Palynological analysis of a sample taken below this brown silt in SC 21 gave a Quaternary age (Backhouse, 1992b).

The superficial formations taper out to the north as the elevation increases, onlapping the Yarragadee Formation, Leederville Formation and Bunbury Basalt (Figure 5). Superficial formations increase in thickness towards the coast, ranging from 10 m or less up to 40 m thick west of Lake Jasper, where a deep gully has been mapped near the basalt by Bemax Resources (A. Heptinstall, *pers.comm.)*. The total thickness of the superficial formations exceeds 100 m near the coast, where dunes cover the Tamala Limestone, reaching up to 160 m above sea level.

The sandy superficial formations at SC 19 are predominantly quartz, which is highlighted by the low gamma-ray count. Baddock (1995) confirmed the presence of Quaternary sediments at SC 16A (15-16 m bgl) and SC 21A (11-12 m bgl) using palynology (Backhouse, 1992a and 1992b). Gamma-ray logging for both SC 19 and SC 21 gave a consistently low gamma-ray count, except for the silty sandy clay at the base of the superficial formations, where the gamma-ray count was higher.

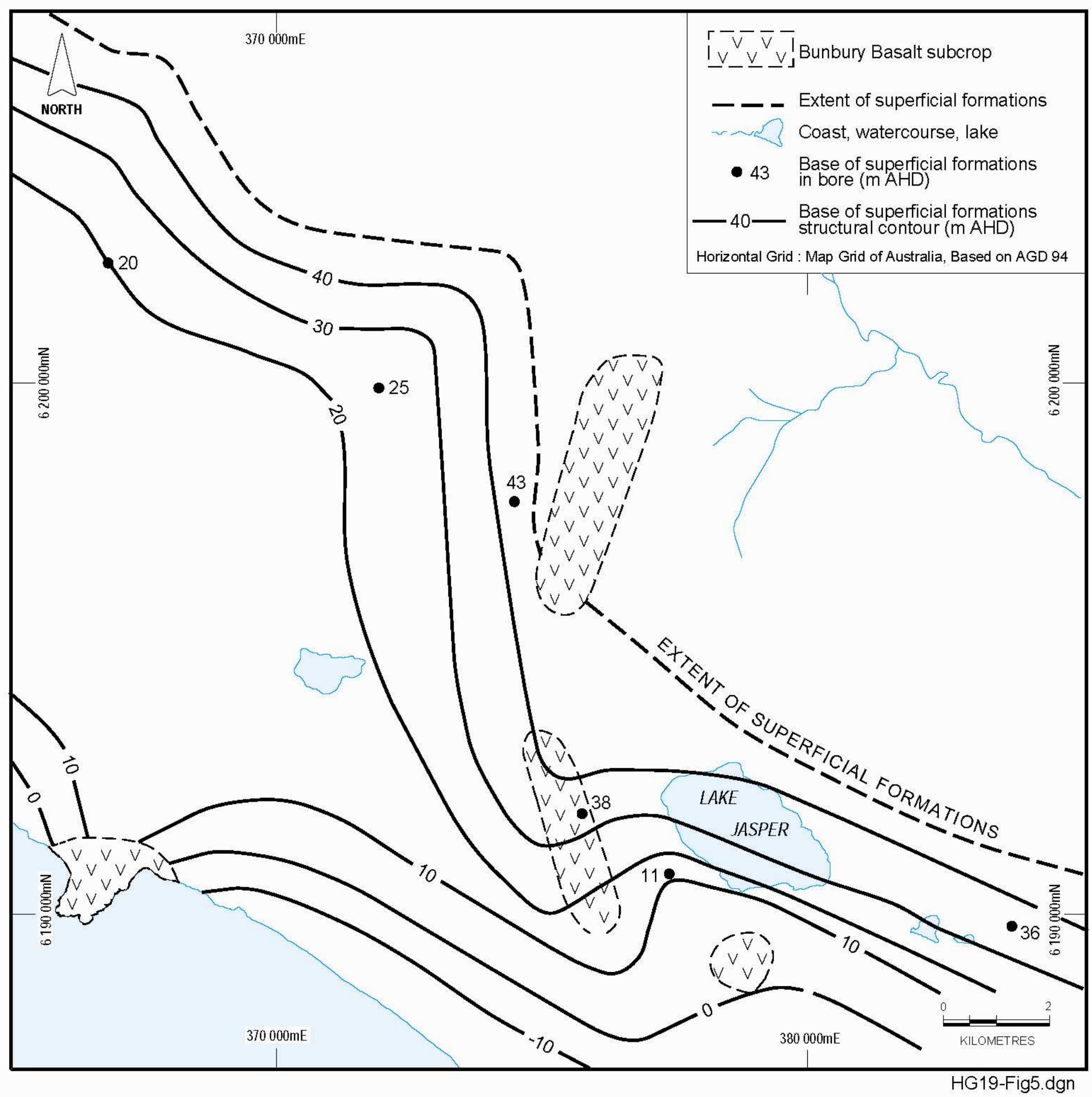

Figure 5. Base of the superficial formations.

4. Hydrogeology

4.1. Groundwater occurrence

Three aquifers were intersected during the eastern Scott Coastal Plain groundwater investigation; the superficial aquifer, Leederville aquifer and Yarragadee aquifer. The superficial aquifer and the Leederville aquifer are both unconfined aquifers on the Scott Coastal Plain, comprising the superficial formations and Leederville Formation respectively. Within the Leederville aquifer there exists semi-confining layers that reduce its vertical permeability and make it behave as a confining layer to underlying aquifers. The Yarragadee aquifer is locally confined to varying degrees where it is overlain by the Bunbury Basalt, Leederville aquifer or the superficial aquifer. The Yarragadee aquifer is unconfined where it outcrops in the north-west section of the investigation area (Figure 3).

Groundwater is an important contributor to surface water features on the eastern Scott Coastal Plain. Throughout the coastal plain the watertable is generally less than 5 m below the ground surface deepening beneath the coastal dunes and on the Blackwood Plateau (Figure 6 and Figure 7). Groundwater flows through Lake Jasper and Lake Quitjup from the superficial aquifer (Turner *et al.*, 1996; URS, 2005) and groundwater discharges from the Leederville aquifer into Barlee Brook on the eastern side of the investigation area.

4.1.1 Superficial aquifer

The superficial aquifer extends along the coast and up to 14 km inland on the Scott Coastal Plain. The saturated thickness of the aquifer is up to 20 m, which increases with aquifer thickness towards the coast. Saturated thickness may be less within the Tamala Limestone due to karstic features (Rockwater, 2004). The flat topography in this area is reflected by the watertable, which lies just beneath the surface in most places.

The watertable is near the surface in low-lying areas in the summer months and flooding occurs extensively in winter. Due to the high watertable, groundwater contributes to Lake Jasper and Lake Quitjup. At Lake Jasper groundwater throughflow is from north-west to south-east, while at Lake Quitjup groundwater flow appears to be north-east to south-west (Figure 8). The watertable can exceed 100 m below ground level in the coastal dunes.

Recharge to the superficial aquifer occurs via three processes. Rainfall recharge is the dominant inflow to the superficial aquifer, while upward leakage from the underlying Yarragadee aquifer and from lateral flow of groundwater discharging from the Leederville aquifer also occur (Figure 6 and Figure 7).

In SC 19C and SC 19D, there are slightly higher water levels in the upper than the lower levels of the superficial formation (Appendix 1), which may be due to slow leakage of rainfall recharge through the aquifer. The presence of iron oxide-cemented layers within the formation would contribute to restricted vertical flow within the aquifer. However, the upper and lower levels of the aquifer are connected and over summer equilibrium water levels are attained, as seen in the initial measurements taken in April and May 2006, before winter rainfall.

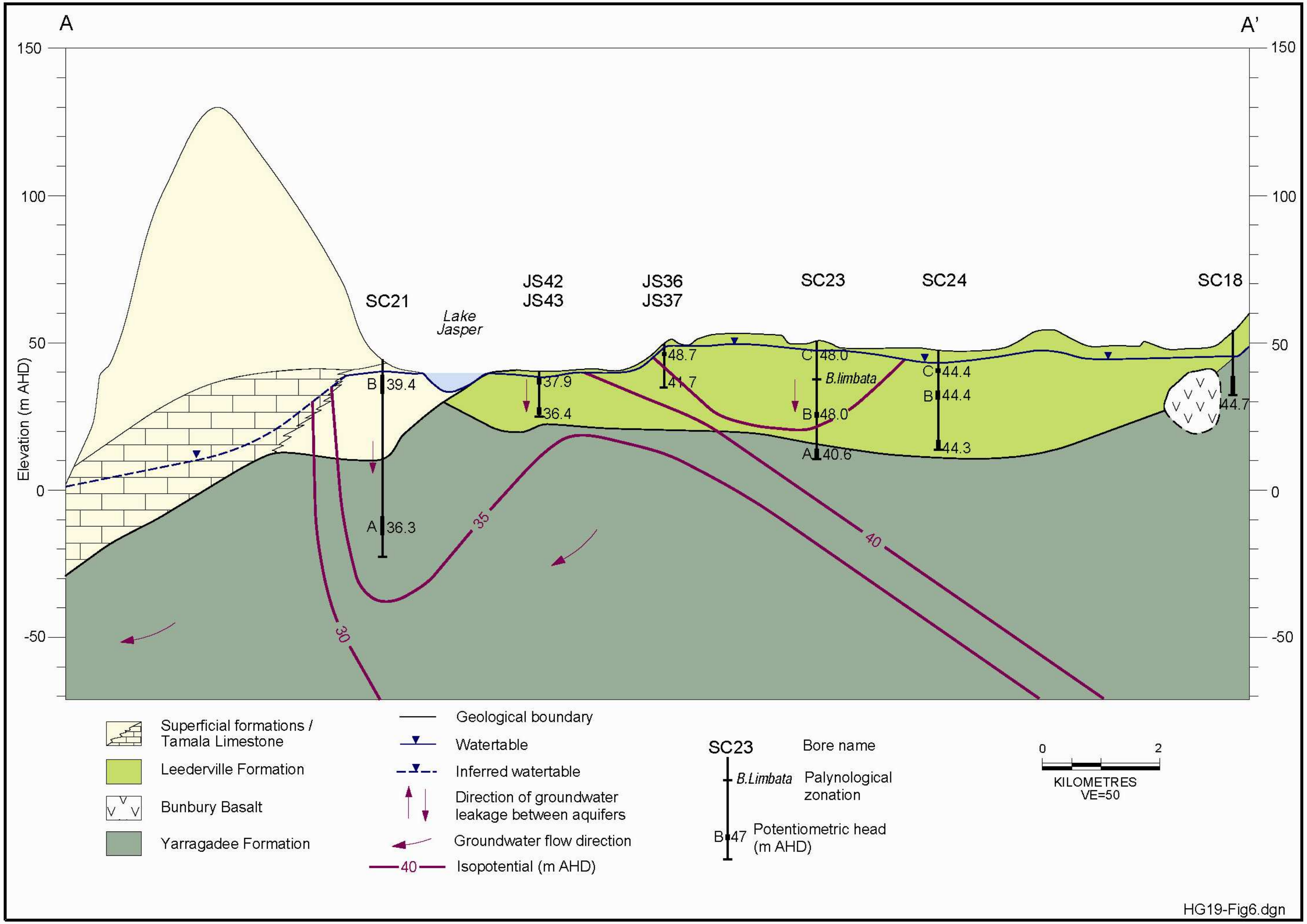

Figure 6. Hydrogeological cross section A-A'.

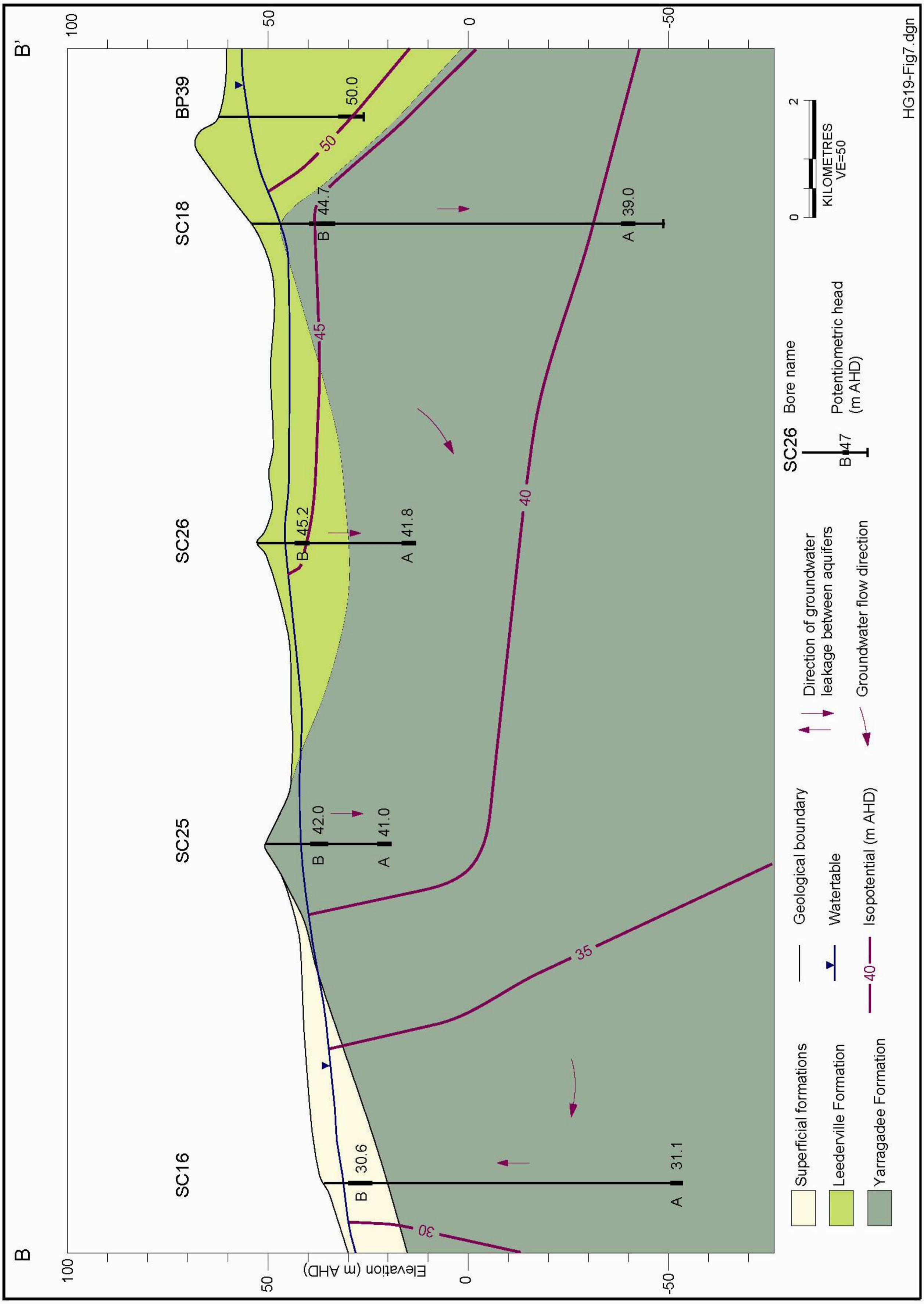

Figure 7. Hydrogeological cross section B-B'.

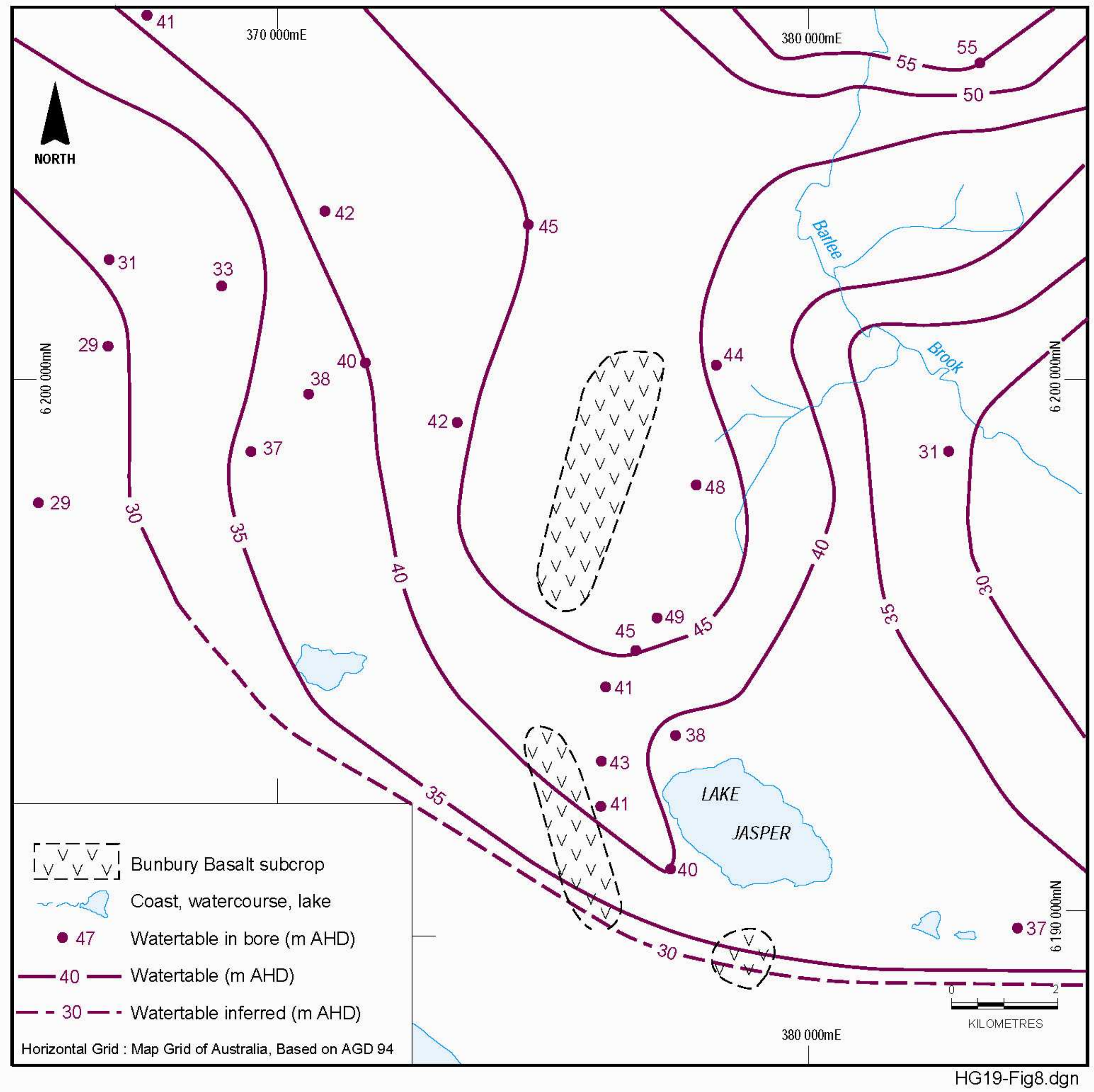

Figure 8. Watertable contours. Composite of April measurements (2003 to 2006).

Deep bores at SC 16 (Figure 7) and SC 20 (not shown) have an upward head from the Yarragadee aquifer into the superficial aquifer, indicating potential for upward leakage. Some lateral flow from the Leederville aquifer is also likely to recharge the superficial aquifer. The Leedervill aquifer forms part of the unconfined groundwater system north of the superficial aquifer. Groundwater in the Leederville aquifer flows towards the coast, discharging from the Leederville aquifer into the laterally adjacent superficial aquifer (Figure 8). High clay content in the Leederville aquifer limits flow into the superficial aquifer, making rainfall the dominant mechanism for recharge to the superficial aquifer.

Groundwater flow in the unconfined system incorporates both the superficial aquifer and Leederville aquifer. The flow direction is generally towards the coast except in the vicinity of Lake Jasper and Barlee Brook, where flow is to the south-east (Figure 8). A groundwater mound to the north-west of Lake Jasper forms around the Bunbury Basalt where there is a local topographic high near the basalt and in the Leederville aquifer. Groundwater flows to the east, west and south from the mound and also provides perennial stream flow into the tributaries of Barlee Brook.

Water that enters the superficial aquifer is discharged into surface water bodies, other aquifers and out to sea. Groundwater discharges from the superficial aquifer into Lake Jasper, Lake Quitjup and Barlee Brook and also discharges to the coast. There are downward potentiometric heads from the superficial aquifer into the underlying Yarragadee and Leederville aquifers, indicating groundwater leakage will occur into the underlying aquifer. Bores SC 16 and SC 20 have potentiometric heads in the underlying aquifer that are higher than the superficial watertable, so upward leakage is likely in these instances.

The difference in heads between the superficial aquifer and the Yarragadee aquifer affects the rate of leakage between aquifers. Changes to the hydraulic gradient caused by abstraction from Yarragadee aquifer will lead to changes at the watertable. The presence of the brown silty sandy clay layer at the base of the superficial formations will also affect the rate of downward leakage, as seen at SC 19. This layer acts as an impermeable boundary, limiting the rate of groundwater flow between the superficial aquifer and the Yarragadee aquifer.

Groundwater salinity in the superficial aquifer at SC 19 ranges from 200 mg/L total dissolved solids (TDS) in the upper part of the aquifer (bore SC 19D) to 170 mg/L TDS in the lower part of the aquifer (bore SC 19C), which is fresh (Table 2). The slightly higher salinity within the upper aquifer is likely to be caused by evaporation concentrating dissolved solids within the groundwater. The groundwater in the superficial aquifer was brown stained and had an earthy-organic and a sulfurous odour.

4.1.2 Leederville aquifer

The Leederville aquifer outcrops to the north and also underlies the superficial aquifer. The average saturated thickness of the aquifer is 30 m, increasing up to 110 m at the Water Corporation bore BP 04 in the north-east and decreasing to 5 m near outcropping Bunbury Basalt and Yarragadee Formation. The watertable that was intersected in bores was an average of 4 to 5 m below ground level (Figure 6 and Figure 7). Salinity in all bores is less than 150 mg/L TDS (Table 2), indicating that groundwater is fresh.

The presence of clay beds within the Leederville aquifer results in a low vertical hydraulic conductivity. The clay beds cause the Leederville aquifer to act as a semi-confining layer to the underlying aquifers. This is highlighted by the large differences in hydraulic head where it overlies the Yarragadee aquifer (Figure 6 and Figure 7). Head differences range from 4 m to 8 m in all bores that screen both the Leederville aquifer and the underlying Yarragadee aquifer, including SC 23A/SC 23B, SC 24A/SC 24B and SC 26A/SC 26B (Appendix 1). The large head difference indicates that groundwater leakage from the Leederville aquifer into the Yarragadee aquifer is restricted.

Flooding occurs in areas where the Leederville aquifer outcrops since a combination of flat landscape and the presence of low permeability layers within the aquifer result in a slow infiltration rate. Rainfall recharge is received in the upper part of the Leederville aquifer where it outcrops and slowly leaks down into the lower part of the aquifer due to the presence of low permeability clay beds. Hydrographs for the Leederville aquifer

(Appendix 1) show that hydraulic heads within the upper aquifer (SC 24C) rise in response to rainfall at a faster rate than the lower aquifer (SC 24B and SC 24A).

Watertable contours show that groundwater flow is generally towards the coast as the Leederville aquifer discharges into the superficial aquifer (Figure 8). Groundwater contours in the Leederville aquifer also indicate that groundwater mounds reflect topography, with the Blackwood Plateau to the north and the Bunbury Basalt to the west both having higher groundwater levels. In the lower areas surrounding the Barlee Brook, contours indicate that groundwater is feeding the surface drainage.

4.1.3 Yarragadee aquifer

The Yarragadee aquifer is a regional aquifer, present over most of the southern Perth Basin and the eastern Scott Coastal Plain. The aquifer is shallow and outcrops on the eastern Scott Coastal Plain and becomes progressively deeper further north on the Blackwood Plateau (Water Corporation, 2005). The Yarragadee aquifer is locally confined on the eastern Scott Coastal Plain beneath both the Leederville and the superficial aquifers, except in places where it outcrops. In this investigation, only the upper part of the Yarragadee aquifer has been investigated and discussed.

Rainfall recharges into the Yarragadee aquifer where it outcrops in an area surrounding SC 8 and SC 25. The outcrop of Yarragadee Formation in the study area is small, so vertical leakage from overlying aquifers is likely to contribute more greatly than rainfall to the Yarragadee aquifer in this area. Downward groundwater leakage occurs from the overlying Leederville aquifer and superficial aquifer into the Yarragadee aquifer (Figure 6). Leakage from the Leederville aquifer into the Yarragadee aquifer is limited owing to low permeability clay beds within the Leederville aquifer.

Groundwater flow through the upper part of the Yarragadee aquifer is south to south-west toward the coast, with the isopotentials deflected to the east in the vicinity of the Bunbury Basalt (Figure 9). The Yarragadee aquifer discharges offshore. The hydraulic gradient in the Yarragadee aquifer is low in comparison to the unconfined system, though it increases in the vicinity of the Donnelly River, which may be receiving groundwater from the aquifer. There is artesian flow near the coast in bore SC 20A.

Groundwater salinity in the Yarragadee aquifer ranges from 150 to 520 mg/L TDS, which is fresh to marginal (Table 2). Salinity at SC 23A is the lowest, where the Yarragadee aquifer is semi-confined by the Leederville aquifer. The highest salinity occurs where the Yarragadee aquifer is unconfined, in bores SC 25B and SC 26A.

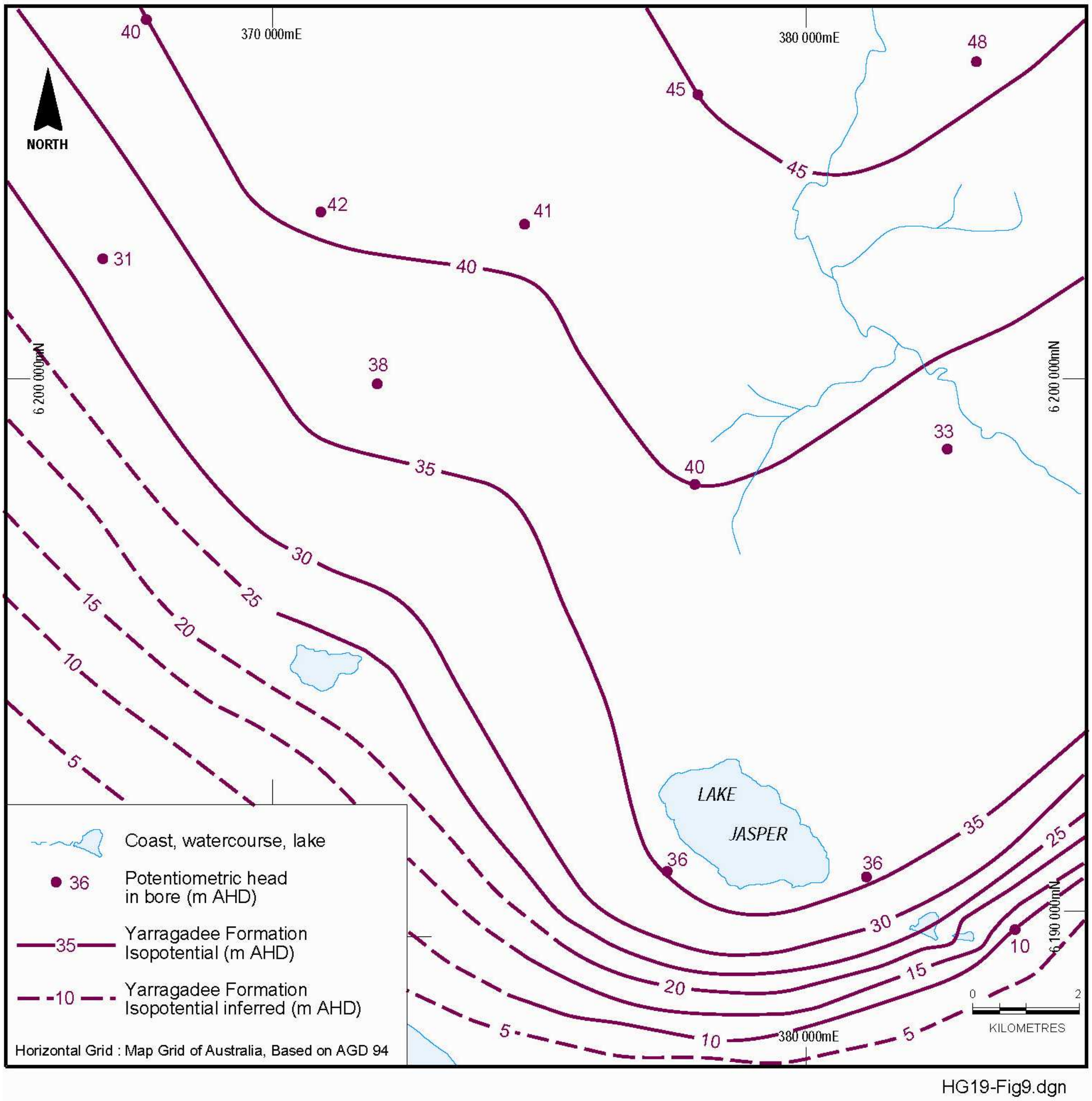

Figure 9. Isopotentials in the top Yarragadee Formation.

5. Hydrochemistry

There is no systematic, spatial change in salinity either vertically or horizontally within aquifers (Table 2). Salinity at SC 26A and SC 25B is higher than in other bores, with TDS exceeding 500 mg/L. All other bores contain fresh groundwater, with TDS less than 500 mg/L. The groundwater is sodium chloride dominant in all bores. Sulfurous gas could be smelt during airlifting of SC 19C and SC 19D, indicating reducing conditions within the groundwater in the superficial aquifer.

Nitrate concentrations in SC 23B and SC 23C are comparatively high at 14 mg/L and 70 mg/L respectively. This may be related to leaching of fertiliser into the groundwater from nearby farms. Nitrate concentration decreases with depth at site SC 23, indicating that the source is surface water and that the concentration is being naturally attenuated through dilution or microbial activity. The lateral extent of the shallow groundwater-nitrate enrichment is unknown. Nitrate concentrations at other sites are generally less than 0.5 mg/L (Table 2).

Table 2. Groundwater chemical analysis for April 2006.

Bore	pH	EC at 25°C mS/m	TDS (Evap)	Ca	Mg	Na	K	CO_3^{2-} as $CaCO_3$	HCO_3^{-} as $CaCO_3$	Cl^{-}	SO_4^{2-}	Nitrate as NO3	Nitrate as NO_3-N	Silica as SiO_2	B	F
			mg/L													
SC 23A	6.7	-	150	1	3	30	3	<1	15	50	11	0.043	0.01	-	0.038	<0.2
SC 23B	6.5	-	110	<1	3	20	1	<1	11	20	9	14	3.1	-	0.026	<0.2
SC 23C	5.2	-	-	<1	<1	-	2	<1	52	-	-	70	16		0.47	<0.2
SC 24A	6.4	-	140	<1	4	30	3	<1	10	40	5	0.062	0.014	-	0.015	<0.2
SC 24B	6.3	-	130	<1	5	30	<1	<1	7	50	<5	0.15	0.034	-	0.018	<0.2
SC 24C	6.3	-	100	1	2	20	<1	<1	5	30	<5	0.29	0.066	-	0.019	<0.2
SC 19B	6.1	24	230	1	5	30	<1	-	7	50	6	-	-	7.7	0.016	<0.2
SC 19C	6.2	32	170	1	6	40	<1	-	8	70	6	-	-	7.9	0.019	<0.2
SC 19D	5.5	38	200	2	10	50	2	-	5	80	20	-	-	5.5	0.019	<0.2
SC 25A	6.2	51	270	3	9	70	1	-	9	120	11	-	-	7.8	0.026	<0.2
SC 25B	5	97	510	5	19	150	2	-	2	260	32	-	-	6.9	0.062	<0.2
SC 26A	5.8	100	520	3	13	160	2	-	5	260	31	-	-	15	0.051	<0.2
SC 26B	6.5	25	140	1	4	40	1	-	8	60	10	-	-	11	0.033	<0.2

6. Conclusions and recommendations

The drilling undertaken by the Department of Water in the eastern Scott Coastal Plain has improved the understanding of local area geology and hydrogeology. Four new sites (SC 23 to SC 26) were drilled, and the superficial formation and upper Yarragadee Formation was drilled at the pre-existing site, SC 19. Following drilling, two or three piezometers were installed at each site. As a result of this investigation, the extent of the superficial formations, Leederville Formation and the Yarragadee Formation have been better defined.

The superficial aquifer was intersected only at SC 19, indicating that the northern extent of the superficial formations is less than was previously described by Baddock (1995) and Rockwater (2004). Instead, palynology, geophysics and lithological data have indicated that Leederville Formation is present in areas where it was previously interpreted as Guildford Formation. The Leederville aquifer contains low permeability layers, which restrict recharge to the Yarragadee Formation. The Leederville aquifer is absent beneath the superficial formations closer to the coast, thus allowing hydraulic connection of the superficial and Yarragadee aquifers.

There is no new evidence for the continuity of a peaty layer and coffee rock within the superficial formations, since the superficial formations were not intersected at any of the new sites. As described in previous investigations, a minor impermeable bed of brown silty, sandy-clay is present in SC 19 at the base of the superficial formations. A similar impermeable layer within the Jangardup 1 bore and in SC 21 suggest that it is part of the superficial formations, though conflicting palynological data from samples at SC 19 has indicated that the layer is of Cretaceous origin. The assumption of layer continuity is an important aspect of the SWAMS v.2 model, since both the Superficial and Yarragadee aquifers are highly permeable.

Although the investigation has reinterpreted the spatial extent of the formations, the lithology is consistent with the conceptual geological model used for SWAMS v.2. The most significant difference is that the boundary between the superficial formations and the Mesozoic formations is much closer to the coast. Reclassification of the geology does not require changes to the hydrogeological parameters assigned to different aquifers in SWAMS version 2.0 as the renamed aquifer has the same properties as the previous model.

Groundwater on the eastern Scott Coastal Plain is mainly fresh with some groundwater having marginal salinity. Nitrate enrichment of groundwater in areas surrounding farming operations is occurring locally near to bore SC 23. This may be due to runoff and infiltration from nearby agricultural land.

The new monitoring bores will be monitored monthly for the first two years. Following this, the bores will be added to the existed monitoring network, where they should be monitored at least twice yearly. Groundwater will be sampled in the future for analysis of nitrate concentrations to determine changes occurring due to seasonal runoff.

The superficial formations were absent at all of the new drilling sites. Future investigations should target areas where the superficial formations are present to the west of Lake Jasper to monitor inflow to the lake. This will also confirm the existence of a continuous impermeable layer, noted at the base of the superficial formations in other locations. Further drilling north of Lake Jasper, where it is currently believed that the Leederville Formation is underlying the lake would enhance understanding of groundwater-lake water interactions by identifying the boundary where superficial formations directly overlie the Yarragadee Formation.

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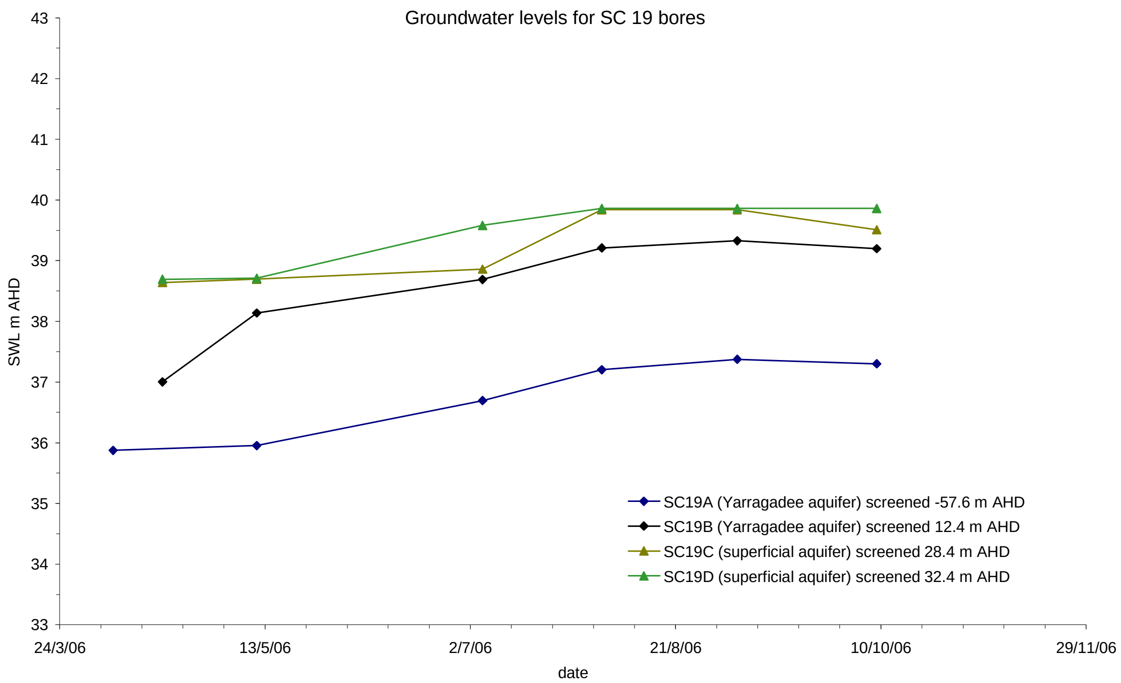
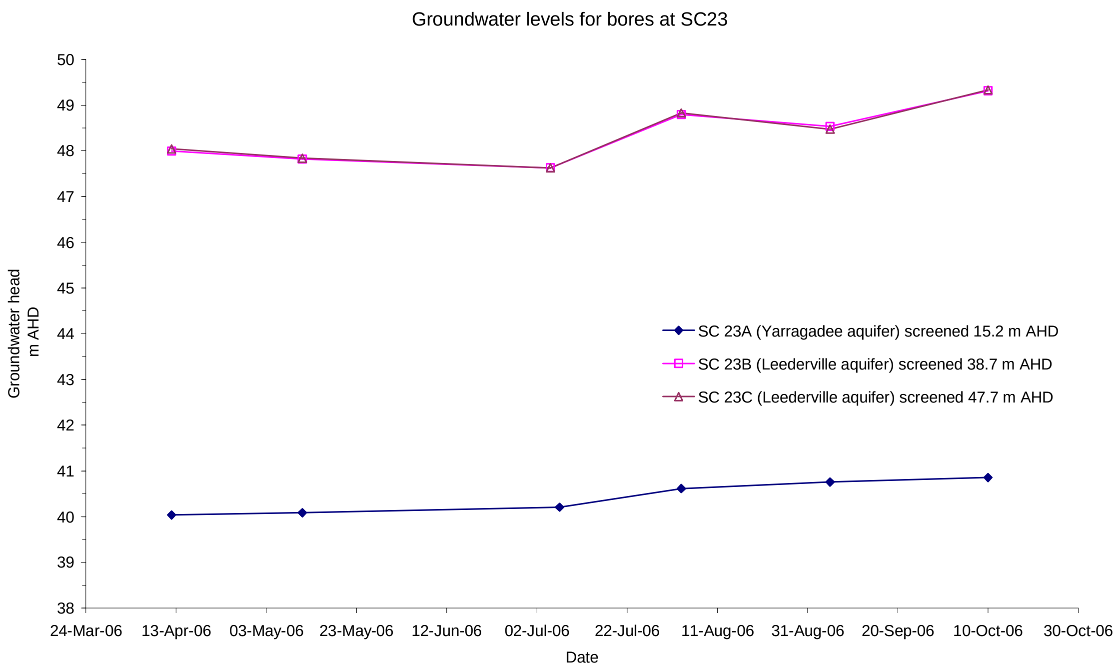
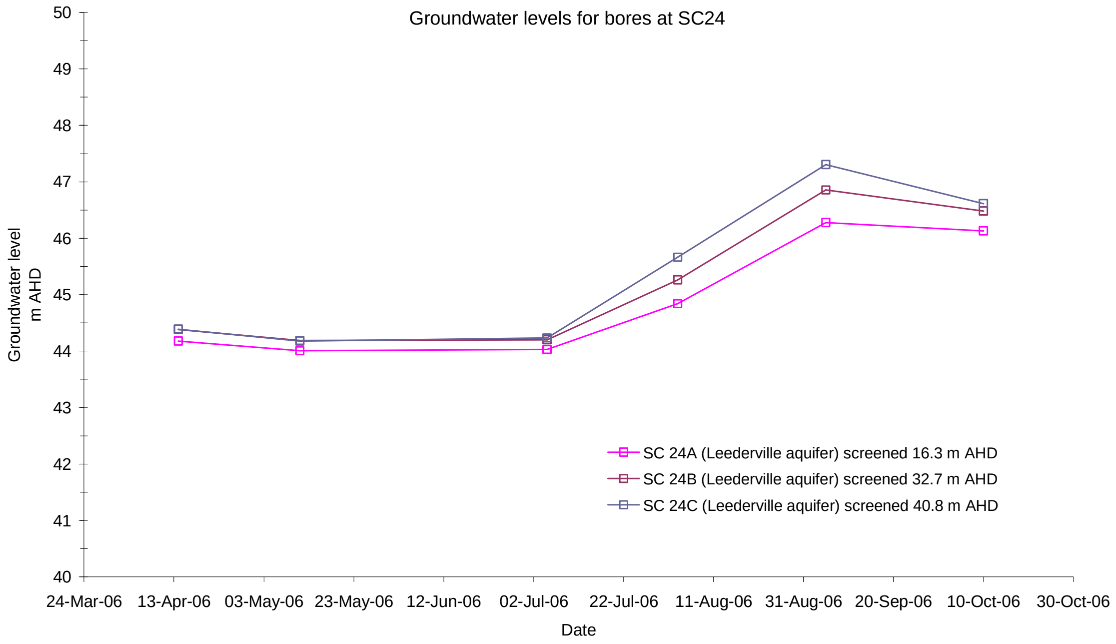
8. Appendix 1.

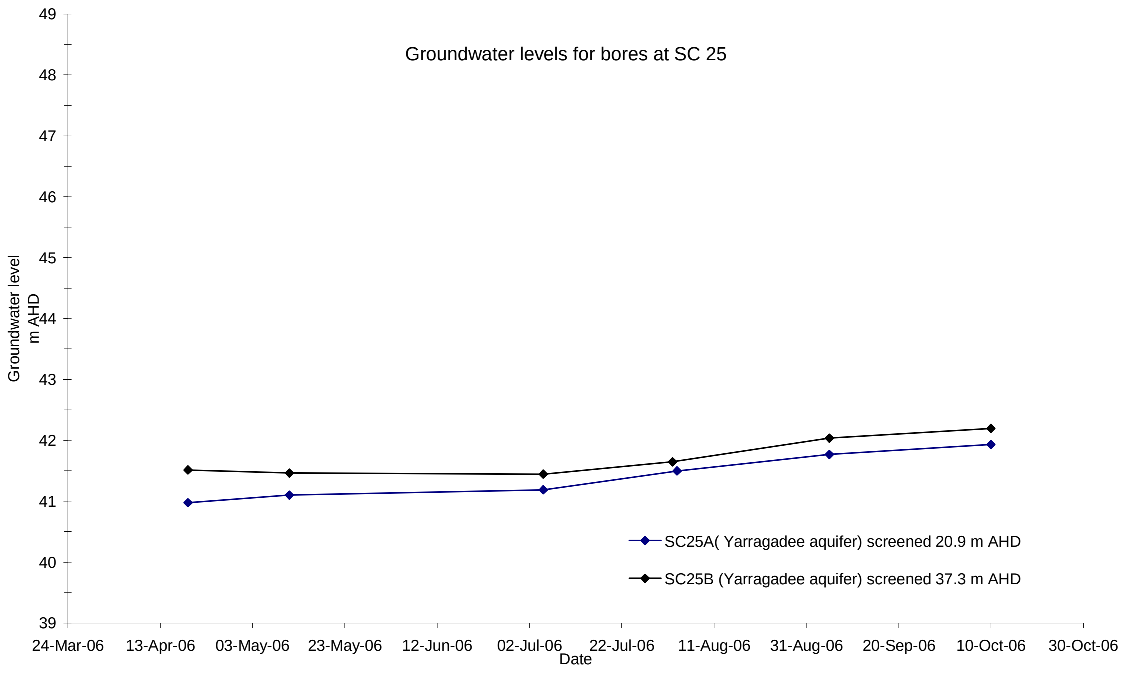
Hydrographs for eastern Scott Coastal Plain Investigation bores, drilled in April 2006

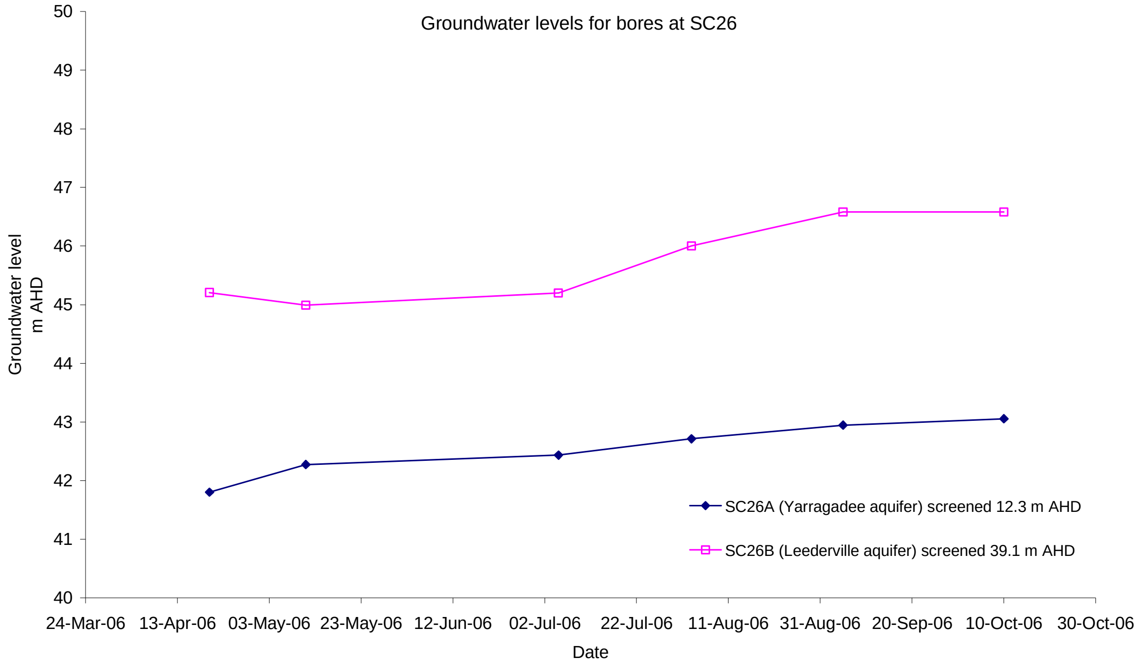
Monthly groundwater level monitoring data, April – October 2006


Groundwater levels for SC 19 bores
SWL m AHD
43
42
41
40
39
38
37
36
35
34
33
24/3/06
13/5/06
2/7/06
21/8/06
10/10/06
29/11/06
date
SC19A (Yarragadee aquifer) screened -57.6 m AHD
SC19B (Yarragadee aquifer) screened 12.4 m AHD
SC19C (superficial aquifer) screened 28.4 m AHD
SC19D (superficial aquifer) screened 32.4 m AHD


Groundwater levels for bores at SC23
Groundwater head m AHD
50
49
48
47
46
45
44
43
42
41
40
39
38
24-Mar-06
13-Apr-06
03-May-06
23-May-06
12-Jun-06
02-Jul-06
22-Jul-06
11-Aug-06
31-Aug-06
20-Sep-06
10-Oct-06
30-Oct-06
Date
SC 23A (Yarragadee aquifer) screened 15.2 m AHD
SC 23B (Leederville aquifer) screened 38.7 m AHD
SC 23C (Leederville aquifer) screened 47.7 m AHD


Groundwater levels for bores at SC24
Groundwater level m AHD
50
49
48
47
46
45
44
43
42
41
40
SC 24A (Leederville aquifer) screened 16.3 m AHD
SC 24B (Leederville aquifer) screened 32.7 m AHD
SC 24C (Leederville aquifer) screened 40.8 m AHD
24-Mar-06
13-Apr-06
03-May-06
23-May-06
12-Jun-06
02-Jul-06
22-Jul-06
11-Aug-06
31-Aug-06
20-Sep-06
10-Oct-06
30-Oct-06
Date


Groundwater levels for bores at SC 25
Groundwater level m AHD
49
48
47
46
45
44
43
42
41
40
39
SC25A(Yarragadee aquifer) screened 20.9 m AHD
SC25B (Yarragadee aquifer) screened 37.3 m AHD
24-Mar-06
13-Apr-06
03-May-06
23-May-06
12-Jun-06
02-Jul-06
22-Jul-06
11-Aug-06
31-Aug-06
20-Sep-06
10-Oct-06
30-Oct-06
Date


Groundwater levels for bores at SC26
Groundwater level m AHD
50
49
48
47
46
45
44
43
42
41
40
24-Mar-06
13-Apr-06
03-May-06
23-May-06
12-Jun-06
02-Jul-06
22-Jul-06
11-Aug-06
31-Aug-06
20-Sep-06
10-Oct-06
30-Oct-06
Date
SC26A (Yarragadee aquifer) screened 12.3 m AHD
SC26B (Leederville aquifer) screened 39.1 m AHD