Department of Water
Government of Western Australia

Hydrogeology of the Leederville aquifer in the western Busselton–Capel Groundwater Area

By D.Schafer, S.Johnson and A.Kern

Looking after all our water needs

Department of Water

Hydrogeological record series

Report no. HG31

August 2008

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August 2008

ISSN 1329-542X (print)
ISSN 1834-9188 (online)

ISBN 978-1-921508-85-1 (print)
ISBN 978-1-921508-86-8 (online)

Acknowledgements

The Department of Water would like to thank the following for their contribution to this publication: David Schafer, Seth Johnson and Alex Kern of the Water Resource Assessment Branch.

The recommended reference for this publication is *Schafer, DB, Johnson, SL, and Kern, AM, 2008, Hydrogeology of the Leederville aquifer in the western Busselton-Capel Groundwater Area, Department of Water, Hydrogeological Record Series, HG31*.

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Summary

The western portion of the Busselton–Capel Groundwater Area is a major tourist destination and wine-growing region. The continuing development of the horticultural industry has resulted in the need to better understand groundwater resources in this part of the Southern Perth Basin.

Groundwater investigations in the vicinity of Cowaramup involved a comprehensive review of coal exploration data, followed by the installation of monitoring bores into the Leederville aquifer. Fourteen monitoring bores at seven sites were constructed to redefine the stratigraphy of the Leederville aquifer, and undertake ongoing monitoring of water levels.

The drilling investigation demonstrated that the Leederville aquifer is a multi-layered sedimentary sequence. It can be subdivided into six distinct members (from upper to lower): the Quindalup, Upper Mowen, Lower Mowen, Upper Vasse, Lower Vasse and Yelverton. This interpretation was based on stratigraphical relationships and hydrogeological properties; however, it must be noted that the Leederville aquifer is extremely heterogenous in nature with poor lateral continuity of individual beds. The Sue Coal Measures were encountered at the base of the Leederville aquifer in the deepest monitoring bores.

The Leederville aquifer outcrops throughout the Blackwood Plateau. Beneath the Swan Coastal Plain, it is concealed by a thin, unconfined superficial aquifer but is locally interconnected where confining beds are absent. The Upper Vasse Member is considered to be the most prospective aquifer within the Leederville aquifer, due to its high proportion of sand beds. The Leederville aquifer becomes more consolidated with depth; hence, permeability will also decrease.

The investigation has confirmed the presence of an east-west groundwater-flow divide in the Leederville aquifer north of the Margaret River, from where groundwater flows to the north and south. There is an active, shallow groundwater system that maintains a number of permanent pools along Margaret River, as well as a deeper groundwater system.

Groundwater is generally fresh, less than 500 mg/L TDS, throughout much of Leederville aquifer. Groundwater age dating using chlorofluorocarbons (CFC) and carbon-14 techniques indicates that modern recharge is occurring in the vicinity of the groundwater flow divide. The groundwater becomes progressively older with depth and down gradient along the direction of groundwater flow, up to 29 000 years towards Margaret River and towards the coast.

There are more than 20 permanent pools along Margaret River, which are considered the important potential groundwater-dependent ecosystem. Monitoring of groundwater and pool levels confirms that the Leederville aquifer and Margaret River are directly connected. The riverine pools are considered extremely robust with managed groundwater abstraction likely to have negligible impact on pool levels. It is

considered that the riverine pools are more impacted by direct surface water abstraction than indirect groundwater abstraction.

Results from this investigation will form the basis of a groundwater resource assessment including both the Cowaramup and Dunsborough–Vasse subareas. A sub-regional, numerical groundwater-flow model is being developed to assess the impacts of modifying allocation on groundwater dependent ecosystems and neighbouring subareas. Groundwater modelling outputs will contribute to the setting of new allocation limits in the western part of the Busselton–Capel Groundwater Area.

1 Introduction

1.1 Background

Since early 1999, the Department of Water has been refusing groundwater licence applications from the Leederville aquifer in the Cowaramup subarea, as licensed allocations exceed the existing allocation limits. Johnson (2000) completed a groundwater resource assessment indicating that substantial groundwater resources may be available from the Leederville aquifer for use by the local viticultural industry. It was recommended that a groundwater investigation would be required, prior to recommending modifications to the allocation limit.

Most groundwater allocation and use in the region is related to horticultural and viticultural activities. The expansion of the Margaret River wine-growing region, to the east of the town, has resulted in a dramatic change in viticultural practices. Wine growing in the region was historically established on the gravelly soils of the Leeuwin Complex; however, changes in the types of grape, and fertiliser and water application rates, have resulted in development of broad-acre irrigation in the sandy soils overlying the Perth Basin.

The wine industry previously utilised groundwater from shallow soaks or bores; however, the refusal to issue further groundwater licences has forced the industry to capture surface and rain waters. Large dams, with capacities of 200 000 kL, have been constructed throughout the area to meet their water requirements. In most cases, these dams have been excavated to such a depth that they tap into shallow groundwater resources.

Groundwater investigations in the Cowaramup groundwater subarea (Fig .1), funded under the State Groundwater Investigation Program, were completed in 2006. The investigation involved the installation of 14 groundwater monitoring bores to improve understanding of the hydrogeology and groundwater resources. A number of complementary studies on groundwater age dating, hydrochemistry and permanency of pools along Margaret River were also undertaken. A numerical groundwater model is being finalised as the basis for modifying the existing allocation limits for the Leederville aquifer within the western portion of the Busselton–Capel Groundwater Area (Schafer and Johnson, *in prep*).

1.2 Location

The study focused on the western portion of the Busselton–Capel Groundwater Area (Fig. 1). The drilling investigations were confined to the Cowaramup subarea with the new monitoring bore sites located approximately 10 km east of Cowaramup between Gale Road in the north and Rosa Brook Road in the south. All sites can be readily accessed via bitumen roads and well-graded tracks.

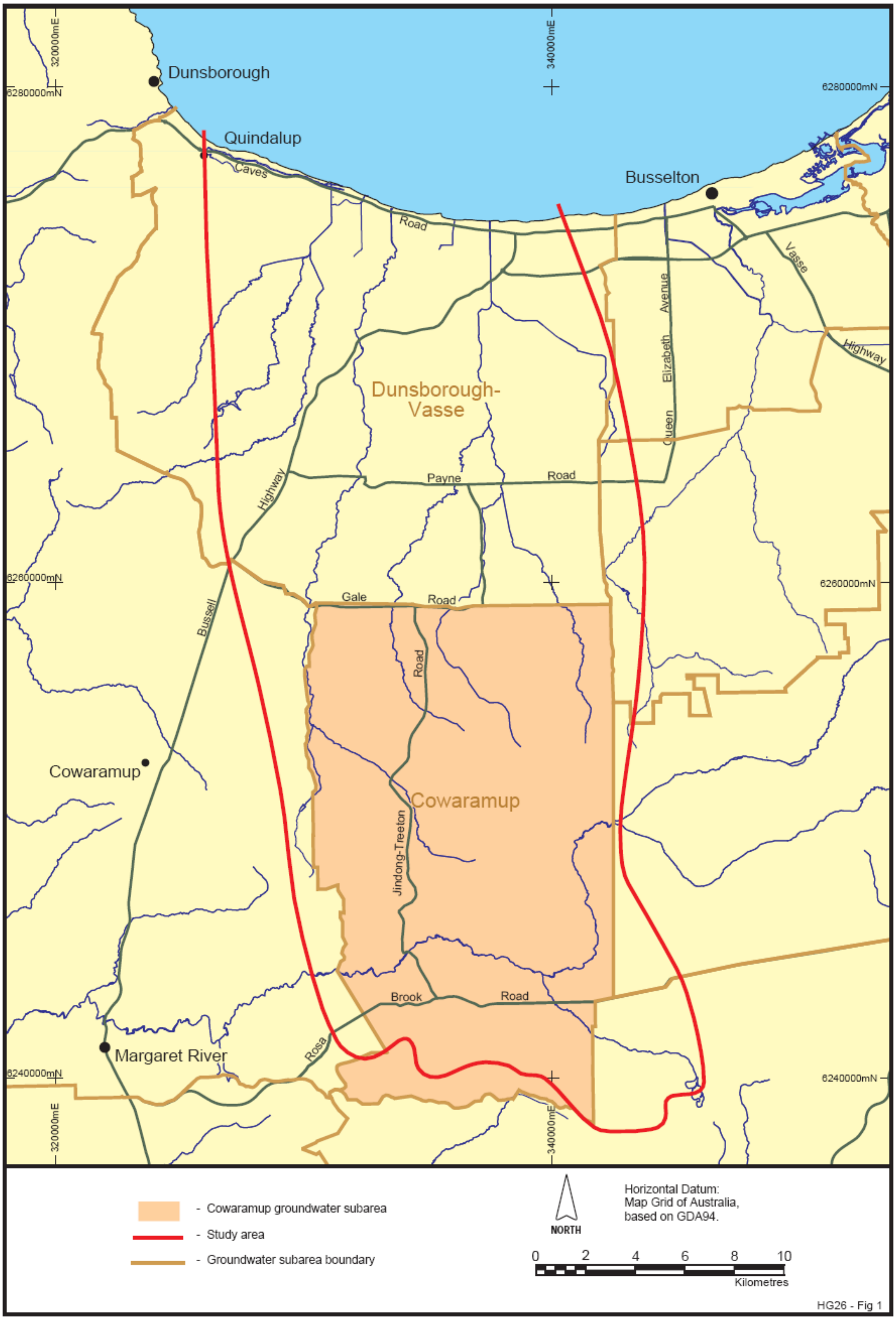


Figure 1 Location

The larger study area, which has the same boundary as the sub-regional numerical groundwater model, includes the Cowaramup subarea as well as the Dunsborough–Vasse subarea in the north (Fig. 1). This was recommended by Johnson (2000) who indicated that the Cowaramup subarea is considered the recharge area for the Dunsborough–Vasse subarea. Consequently, any reassessment of the allocation limits in the Cowaramup subarea needs to consider potential effects on the more northerly subarea.

1.3 Climate

The climate is Mediterranean with cool wet winters and hot dry summers. Average annual rainfall varies from 800 mm/year at Geographe Bay to about 1000 mm/year near Margaret River. Most rainfall occurs from May to September. Annual potential evaporation is about 1100 mm. Rainfall exceeds evaporation only during the winter.

1.4 Physiography

There are four main physiographic units comprising the Swan Coastal Plain, Whicher Scarp, Yelverton Shelf and Blackwood Plateau (Marnham et al., 2000). The flat-lying Swan Coastal Plain occupies approximately the northern third of the study area (Fig. 2). It is bounded to the south by the Whicher Scarp, which steeply rises in elevation from approximately 40 to 60 m AHD, and the Yelverton Shelf that rises steadily in elevation to 90 m AHD. The southern half of the study area lies within the Blackwood Plateau, which is dissected by watercourses and is highly undulating with elevations between 80 and 150 m AHD.

A number of drainage systems cover the northern part of the study area including Mary Brook, Annie Brook, Station Gully, Carbunup River, and the Dawson Gully-Buayanyup River (Fig. 3). These surface water features drain from the Blackwood Plateau down the Yelverton and Whicher Scarps into coastal wetlands or Geographe Bay. An extensive agricultural drainage network is developed at the base of the Whicher Scarp in the Jindong area, as well as in the coastal Quindalup and Broadwater areas. In the south of the study area, drainage is dominated by the east-west trending Margaret River, which includes the Mowen River as a major tributary and significant, permanent pools along its reaches.

In addition to the surface water drainages, there are many wetland features and areas subject to seasonal inundation, such as the coastal wetlands between Quindalup and Busselton.

1.5 Vegetation

Most native vegetation has been cleared for horticultural purposes, especially on the Swan Coastal Plain (Fig. 3). There are only small, isolated pockets of remnant vegetation throughout the northern part of the study area, whereas in the south, across most of the Cowaramup subarea, there are large tracts of State Forest and Conservation Reserve.

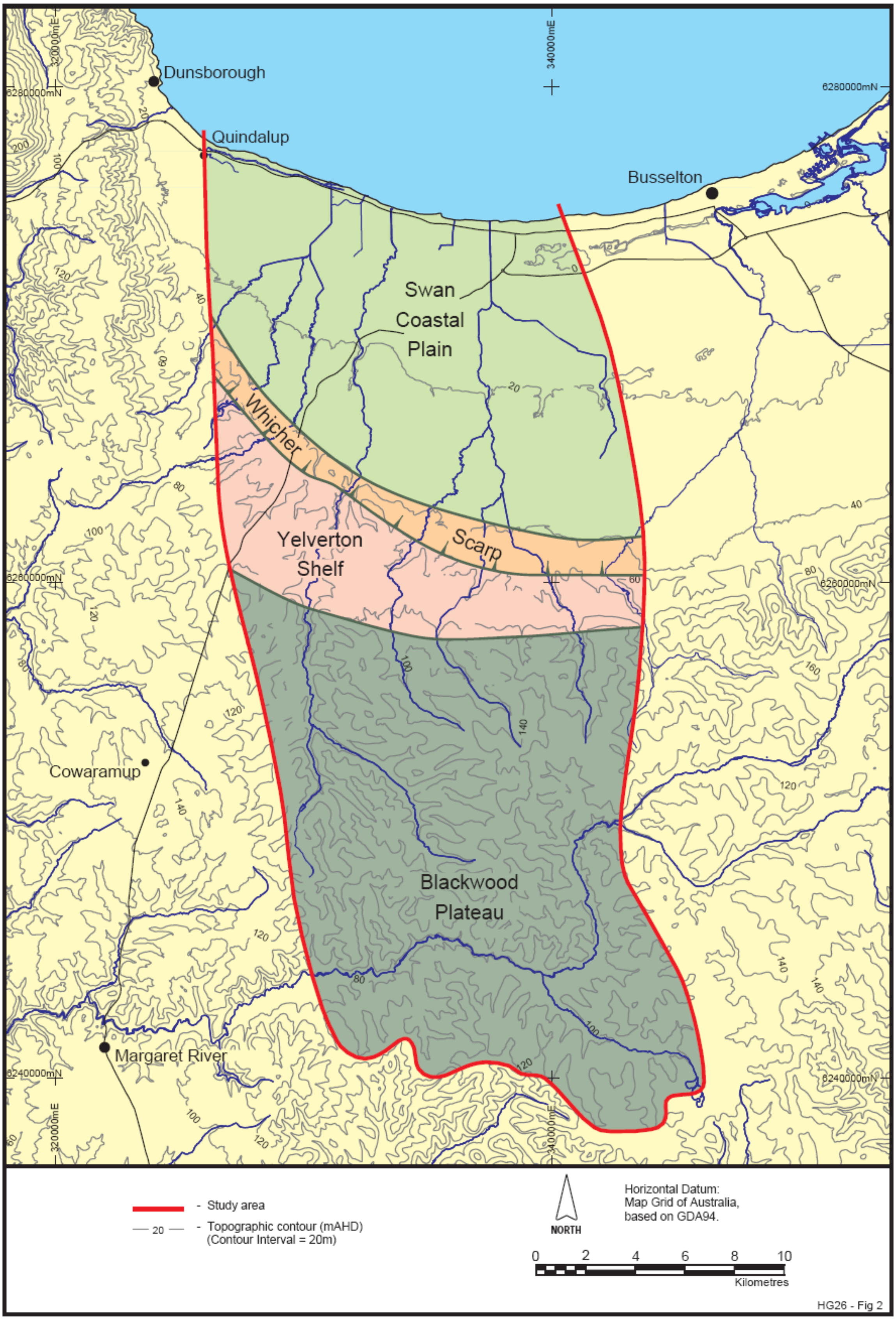


Figure 2 Physiography

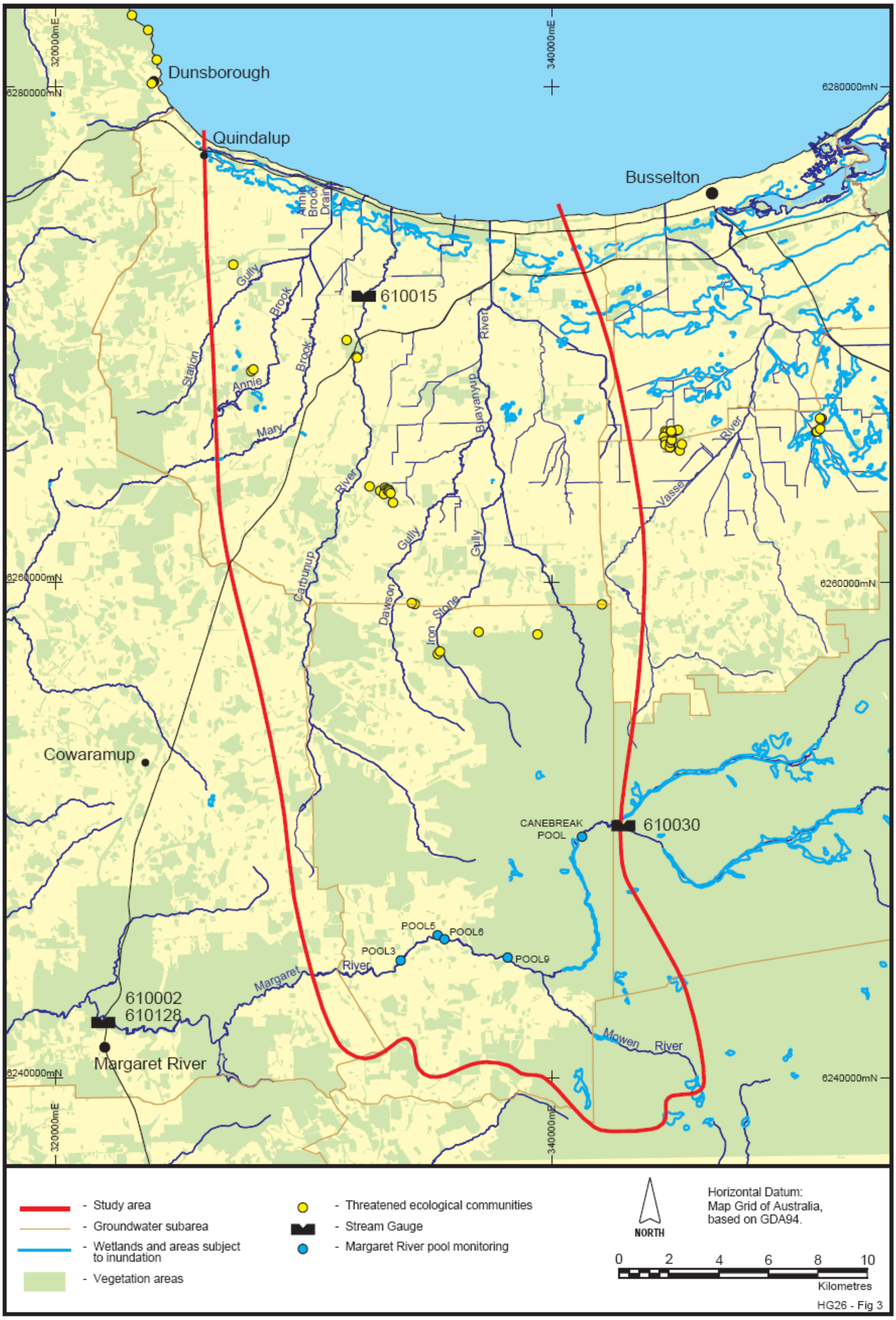


Figure 3 Surface drainage and areas of remnant vegetation

On the Blackwood Plateau, shallow groundwater may potentially support fringing vegetation associated with permanent pools and springs along Margaret River. Most of the remnant native vegetation on the Swan Coastal Plain has some degree of groundwater dependency due to the presence of a shallow watertable in the superficial aquifer.

1.6 Land use

Land use is predominantly mixed farming with horticulture, pasture production, viticulture, olives, plantation forestry, dairying and grazing. Soils suitable for horticultural production, such as the alluvial Marybrook soils, occur as large areas across the Swan Coastal Plain and alluvial flats within Margaret River (Tille and Lantzke, 1990). In coastal areas, there is widespread urban and light industrial development between Dunsborough and Busselton with future pressure for groundwater related to new developments around Margaret River and Cowaramup.

There is currently no active mining in the study area. Mineral exploration has focused on coal-bed methane and coal seams in the Sue Coal Measures, as well as mineral sand deposits in the Yoganup Formation at the base of the Whicher Scarp.

1.7 Previous work

Since the early 1960s, there have been a variety of geological and hydrogeological studies throughout the area. This has included structural and stratigraphical interpretations of the southern Perth Basin, coal and petroleum exploration by various mining companies, as well as regional groundwater exploration and groundwater resource assessments by the Geological Survey of Western Australia. In recent years, there have been a number of studies on the potential groundwater dependency of different ecosystems.

1.7.1 Stratigraphy and structural geology

West Australian Petroleum Pty Ltd (WAPET) conducted the first comprehensive review of the Perth Basin between 1954 and 1958. The results of this investigation were incorporated into the regional description of basin geology by Playford et al. (1976).

Iasky (1993) refined the structural interpretation of the southern Perth Basin from seismic data generated by petroleum and coal exploration. This work better defined the extent of the Vasse Shelf, where the potentially economic coal deposits have been located.

Johnson (2002) subdivided the Leederville Formation into two lithostratigraphic members being the Quindalup and Vasse Members. Water Corporation (2005) further refined this work to include the Mowen Member between the Quindalup and Vasse Members.

1.7.2 Coal exploration

The Permian Sue Coal Measures have been the primary target of coal exploration. There have been more than 100 coal exploration holes drilled throughout the Vasse Shelf (Le Blanc Smith and Kristensen, 1998).

BHP-Dampier Mining, Griffin Coal Mining Company Pty Ltd, Mallina Holdings Ltd, Bond Corporation and CRA Exploration Pty Ltd (now Rio Tinto Pty Ltd) have all been involved in coal exploration across the area (Fig. 4). Recent exploration has been conducted by Vasse River Coalfield Pty Ltd, who currently manages the mineral exploration tenements over the coalfield.

Lithological logs of the Leederville Formation detailed in mining company reports are generally of variable quality, as the formation was considered overburden by coal exploration geologists. There is a suite of down-hole geophysical data for most exploratory drill holes providing useful information on the lithological nature of the Leederville Formation; however, there is no groundwater information contained in the coal exploration reports.

1.7.3 Groundwater investigations

Two lines of deep exploratory water bores have been drilled across the study area, as shown in Figure 4. From north to south, the hydrogeological drilling includes the Quindalup Line — QL bore series — between 1966 and 1980 (Wharton, 1981), and the Cowaramup Line — CL bore series — in 1988 (Appleyard, 1991). Shallower bores were drilled on the Swan Coastal Plain in 1983–84 (Hirschberg, 1989). Additional bores were installed to monitor groundwater abstraction around Jindong — BJM bore series (Panasiewicz, 1996).

The regional hydrogeology and groundwater resources of the southern Perth Basin were described by Thorpe and Baddock (1994), who provided an inventory of divertible groundwater resources. The study quantified groundwater resources according to salinity and provided estimates of storage, sustainable yield, recharge rates and contamination vulnerability.

Johnson (2000) completed a groundwater resource assessment of the Cowaramup subarea suggesting that substantial groundwater resources may be available from the Leederville aquifer. This work recommended additional groundwater investigation including the installation of a more comprehensive monitoring bore network.

Gilgallon (2003 a,b,c) reviewed monitoring bore hydrographs, trends in water quality and the use of shallow groundwater resources in the Cowaramup and Naturaliste subareas. It highlighted significant groundwater abstraction from the shallow groundwater system via dams positioned below the watertable.

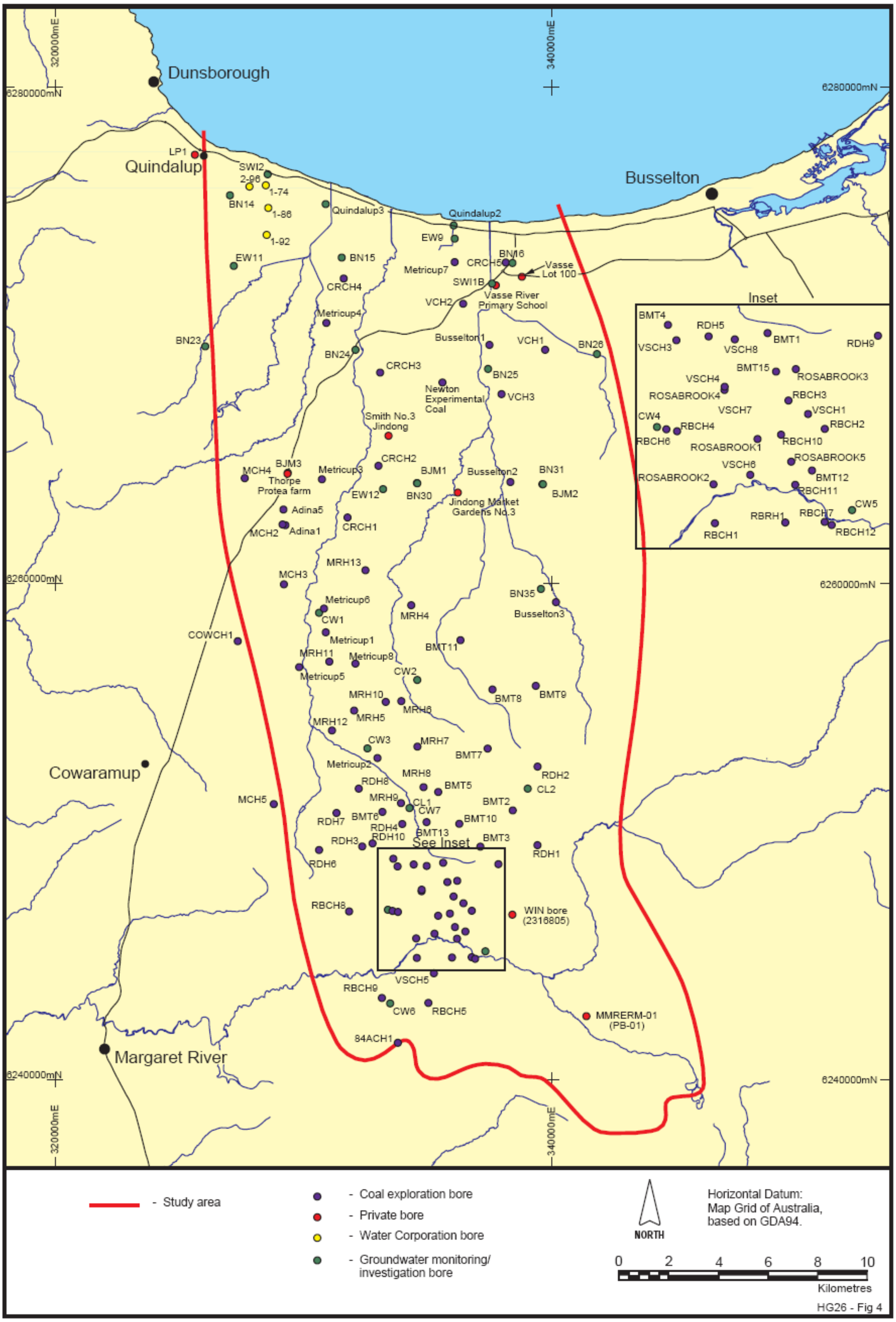


Figure 4 Groundwater monitoring bores and coal exploration drill holes

As part of the Water Corporation's proposal for the South West Yarragadee aquifer, a detailed re-evaluation of the regional hydrogeology of the southern Perth Basin was undertaken (Water Corporation, 2005). This interpretation was adopted into the development of the South West Aquifer Modelling System (SWAMS), which is a regional, groundwater-flow model that covers the whole southern Perth Basin (Sun, 2005).

1.7.4 Ecological studies

Aquaterra (2002), contracted by the Water and Rivers Commission, completed a study of the environmental dependence of vegetation on surface and groundwater resources in the Busselton–Capel Groundwater Area. Conceptual water balance models were developed for key vegetation types. It demonstrated that deep-rooted Jarrah forest has little to no groundwater dependency, coastal bushland has potential groundwater dependency, and coastal wetlands are considered dependent on shallow groundwater in the superficial aquifer.

Hyde (2006) summarised the ecological water requirements of groundwater dependent ecosystems in the South West. The report identified areas where the different ecosystems with potential groundwater dependency may occur and recommended ongoing monitoring requirements.

Wetland Research and Management (2007) produced a desktop review of the ecological values of seven South West rivers including Margaret River and Cowaramup Brook. The review describes the flora and fauna of these waterways and identifies endemic, threatened and endangered species.

2 Investigation program

2.1 Scope and purpose

The purpose of the Cowaramup groundwater investigation was to better define the hydrogeology and groundwater resources of the shallow and deep groundwater systems in the Leederville aquifer. More specific objectives were to determine the location of the groundwater-flow divide, identify areas of groundwater recharge and discharge, understand groundwater-surface water interaction, and estimate sustainable yield from the aquifer.

This document details the results of the drilling investigation and provides a regional appreciation of all new and previous groundwater information. These new interpretations and subsequent monitoring will be incorporated into a numerical groundwater-flow model of the western Busselton–Capel Groundwater Area. The model forms the basis of the groundwater resource assessment and will be used to make predictions of potential impacts to the water balance by altering allocation limits.

2.2 Drilling and bore construction

The drilling investigation involved the installation of 14 monitoring bores at seven sites within the Cowaramup subarea. The drilling was undertaken between January and May 2006 by Delta Consultancy and Drilling Services Pty Ltd using a mud-rotary (Edson 5000W) drilling rig. The bore sites are designated by the prefix CW (Cowaramup), followed by the site number, and either ‘A’ for deep bores or ‘B’ for shallow bores. Table 1 provides a summary of the monitoring bore construction with full details in Schafer et al. (2006).

The deep bores range in depth from 102 m (bore CW6B) to 230 m (bore CW2B) at the base of the Leederville aquifer; the shallow bores ranging in depth from 28 m (bore CW4A) to 66 m (bore CW7A) were positioned in an upper aquifer interval near the watertable.

The monitoring bores are largely orientated in a north-south configuration (Fig. 5). Most sites are located within shire reserves belonging to the Shire of Busselton (Site CW1) and Shire of Augusta-Margaret River (sites CW2, 3, 5 and 6). The exceptions are site CW4 located on private land at the intersection of Osmington and Jindong-Treeton Roads (Location 2288) and site CW7 located on private land (Location 2254) near Cowaramup Line bore CL1.

The deep bores at sites CW1 to CW5 and CW7 were constructed with fibre reinforced plastic (FRP) blank casing with pressure-cement grouting of the annulus and stainless steel screens being naturally packed. The deep bore at site CW6 was constructed using Class 12 and Class 18 PVC main casing with tremie grouting of the annulus, screens run in-line and gravel packing.

Bore	Date Drilled	Easting (MGA94)	Northing (MGA94)	Total Depth (m)	Main Casing Type	Main Casing Diameter (mm)	Screen Interval (m bgl)	Screen Diameter (mm)	Screened Formation	Top of stand-pipe (m AHD)	Natural Surface (m AHD)	Water Level May 2006 (m AHD)	TDS (mg/L)	pH
CW01A	9-Jan-06 to 1 Feb 06	330639	6258819	196.4	FRP	101.1 ID	155 - 167	65 NB	Leederville	83.096	82.402	62.48	250	9.2
CW01B	30-Jan-06 to 1-Feb-06			50	PVC	53 ID	44 - 50	50 NB	Leederville	83.418	82.647	65.84	340	6.4
CW02A	1-Feb-06 to 38777	334594	6256112	230	FRP	101.1 ID	170.5 - 182.5	65 NB	Leederville	117.432	116.733	84.32	230	6.4
CW02B	27-Feb-06 to 1-Mar-06			50.5	PVC	53 ID	43.5 - 49.5	50 NB	Leederville	117.304	116.663	96.95	340	6.3
CW03A	2-Mar-06 to 38802	332587	6253354	202.5	FRP	101.1 ID	162 - 174	65 NB	Leederville	108.447	107.736	86.92	210	6.7
CW03B	23-Mar-06 to 26-Mar-06			56.8	PVC	53 ID	50 - 56	50 NB	Leederville	108.453	107.836	93.01	180	5.9
CW04A	25-Mar-06 To 38818	333410	6246847	183	FRP	101.1 ID	133 - 139	65 NB	Leederville	96.86	96.131	89.48	160	6.6
CW04B	9-Apr-06 to 11-Apr-06			28.5	PVC	53 ID	21.5 - 27.5	50 NB	Leederville	96.812	96.05	92.48	250	6.5
CW05A	18-Apr-06 to 38835	337340	6245171	130	FRP	101.1 ID	101.2 - 107.2	65 NB	Leederville	98.568	97.782	87.31	190	7.2
CW05B	28-Apr-06 to 2-May-06			36	PVC	53 ID	29 - 35	50 NB	Leederville	98.56	97.854	81.65	260	6.1
CW06A	4-May-06 to 38844	333503	6243073	102.2	PVC	96.70 ID	79 - 85	80 NB	Leederville	102.15	101.463	84.64	190	7.1
CW06B	8-May-06 to 10-May-06			34.5	PVC	53 ID	30.5 - 33.5	50 NB	Leederville	102.231	101.51	86.86	540	4.8
CW07A	11-May-06 to 38867	334279	6250947	182	FRP	101.1 ID	168 - 180	65 NB	Leederville	97.275	96.657	86.91	210	6.7
CW07B	25-May-06 to 30-May-06			66	PVC	53 ID	59 - 65	50 NB	Leederville	97.531	96.9	94.57	230	6.4

Table 1 Details of monitoring bore construction

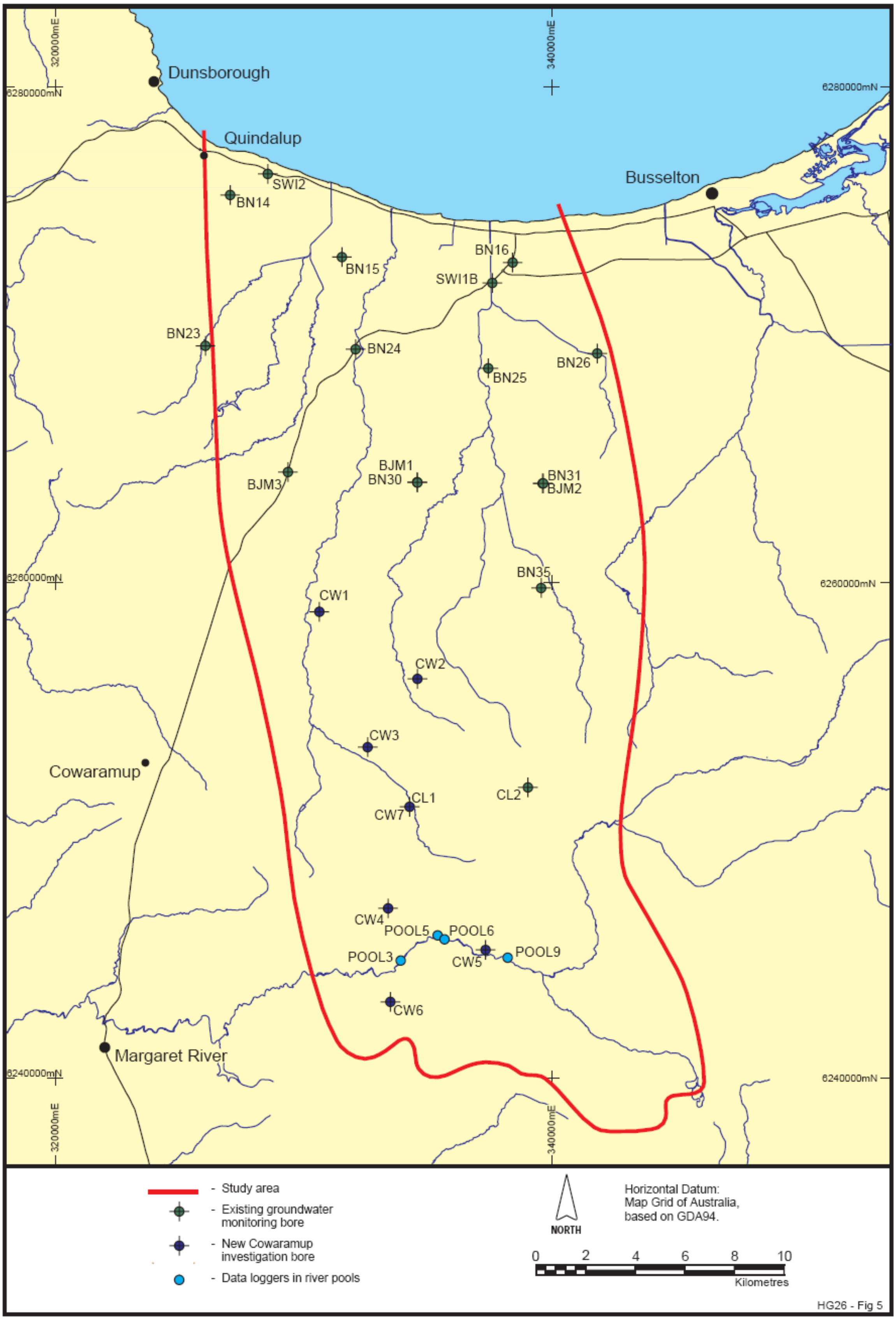


Figure 5 Groundwater monitoring bore network

A cement plug was installed at the bottom of most deep bores to seal off the Sue Coal Measures and prevent inter-aquifer flow.

All shallow bores were constructed using 50 mm PVC blank casing. Screens in the shallow bores comprise slotted PVC that was run in-line with the main PVC casing. Gravel pack was installed in the annulus to a depth of 25 m above the top of the screen with any remaining annulus backfilled with drill cuttings.

Lithological samples were collected and logged at 1 m intervals with selected samples taken for palynological analysis. Prior to bore construction, geophysical logs (gamma and long and short normal resistivity) were run open-hole in each deep hole to assist with the selection of screen position.

All bores were developed by airlifting and jetting until all drilling fluid was removed and the water became clear. During airlifting, the flow rate and salinity were monitored until both had stabilised.

2.3 Water sampling

Following bore development, an airlift water sample was collected for chemical analysis. The unfiltered, unpreserved samples were stored in airtight PVC containers and analysed by the National Measurement Institute (NMI) laboratory. Pumped, air-free water samples were collected as part of a more comprehensive hydrogeochemical study, which is described in Section 2.6.

2.4 Levelling and monitoring

All bores have been levelled to Australian Height Datum (AHD) by Thomson Consulting Surveyors. Surveyed levels were obtained for the top of the standpipe, top of casing, headworks plinth and at ground level for each monitoring bore.

Water level monitoring of the new bores commenced in May 2006. Monthly measurements were collected for the first two years to establish baseline information and ensure that each bore was operational. Monitoring results suggest that the bores are functioning appropriately and providing representative water level responses. Bore hydrographs are presented in Appendix A.

The Department of Water has 61 monitoring bores at 27 sites throughout the study area, primarily shallow bores in the north (Fig. 5). These bores are monitored at least twice a year for water levels at the end of the summer (March/April) and the end of the winter (September/October).

2.5 Margaret River pool survey

Permanent pools along Margaret River are important water features. A study was conducted to measure the bathymetry and monitor water level fluctuation in four riverine pools, in order to establish groundwater-surface water connectivity. Data loggers were installed to measure changes in water level at 15 minute intervals.

Field conductivity, dissolved oxygen, pH and temperature measurements were also collected at monthly intervals. The pools were monitored between December 2006 and April 2007.

2.6 Isotope and hydrochemical study

An isotopic and hydrochemical study was undertaken by CSIRO Land and Water to assess groundwater residence times in the Leederville aquifer. The study involved the use of carbon-14 and chlorofluorocarbon (CFC) dating techniques to assess recharge and groundwater flow patterns.

In order to gain a regional appreciation, 24 bores at ten locations were sampled for carbon-14 (^{14}C), carbon-13 (^{13}C), CFC, oxygen-18 (^{18}O), deuterium (^{2}H), radon-222 (^{222}Rn), and major ions. The bores were purged by the Department of Water, prior to on-site measurement and sample collection by CSIRO staff. The analytical work was completed by the Isotope Analytical Service Laboratories of CSIRO Land and Water in Adelaide. The key findings are summarised in Chapter 5.

2.7 Groundwater-flow model

A sub-regional numerical groundwater-flow model covering the western portion of the Busselton–Capel Groundwater Area is being constructed and calibrated by the Department of Water, with support from CyMod Systems. The primary objective of the model is to evaluate and predict groundwater abstraction impacts due to a number of abstraction and climatic scenarios. Modelling results are also to be used to estimate sustainable yield considering throughflow and recharge (including recharge induced by abstraction). A report is being finalised that details the development of the groundwater model, modelling results and makes some recommendations for modifying allocation limits (Schafer and Johnson, *in prep*).

3 Geology

3.1 Regional setting

The regional geology is dominated by a Cretaceous sedimentary sequence that was deposited within a major graben structure in the southern Perth Basin. The graben structure is situated between the Archaean Yilgarn Craton in the east and the Proterozoic Leeuwin Complex to the west. The major north-south trending Busselton Fault subdivides the graben structure into two major structural units: the deep Bunbury Trough to the east and a relatively shallow fault block, known as the Vasse Shelf, to the west. The study area is situated on the western side of the graben structure, entirely within the Vasse Shelf (Fig. 6).

The Cretaceous Leederville Formation unconformably overlies Permian sedimentary rocks. The Busselton Fault delineates the eastern edge of the Vasse Shelf and the study area. The Cretaceous sequence appears to extend across and is not affected by the Busselton Fault. The western edge of the Vasse Shelf is bound by the Dunsborough Fault, which separates the sedimentary deposits of the Vasse Shelf from the gneissic rocks of the Leeuwin Complex. The Dunsborough Fault also marks the western boundary of the study area.

There has been extensive faulting of the Permian rocks on the Vasse Shelf. The Wirring Fault delineates an uplifted part of the Vasse Shelf known as the Treeton Terrace (Hocking, 1994). Movement along these faults and weathering processes have created an undulating surface at the top of the Permian sequence upon which the Cretaceous sediments were deposited. The top of the Permian sequence will form the base of the groundwater-flow model. The overlying Cretaceous and Quaternary sediments are believed to be largely unfaulted, although there is evidence of fracturing and small-scale faulting of these sediments (Water Corporation, 2005).

Along the western margin, the Cretaceous sediments directly overlie the Dunsborough Fault and basement rocks of the Leeuwin Complex. To the south of the Wirring Fault and the study area, the Cretaceous sediments probably overlie the Triassic Lesueur Sandstone; east of the Busselton Fault, outside the study area, the Cretaceous sediments overlie the Jurassic Yarragadee Formation.

3.2 Stratigraphy

The stratigraphic units in the study area are described in order of deposition and summarised in Table 2. The Cretaceous Leederville Formation unconformably overlies Permian deposits and comprises a sequence of onshore fluviatile (river) and paludal (swamp) deposits. The sediments are essentially flat-lying with a gentle slope to the north and have a thick weathering profile, up to about 25 m thick, where outcropping occurs on the Blackwood Plateau.

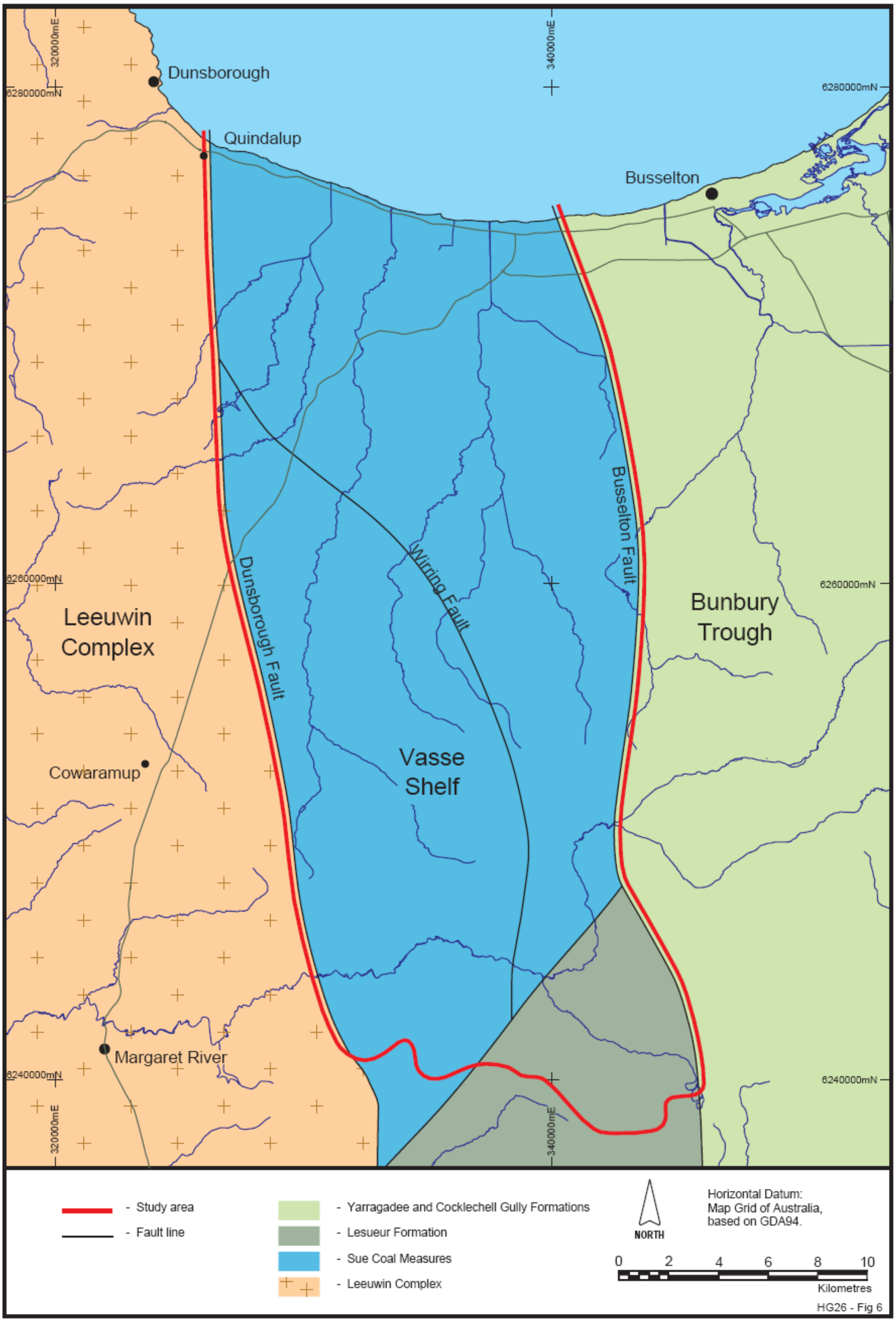


Figure 6 Pre-Cretaceous geology

Table 2 Stratigraphic sequence

Age	Stratigraphy	Thickness (m)	Lithology	Aquifer
Quaternary – Late Tertiary	Superficial formations			
	Tamala Limestone	3–9	Calcarenite, sand with shell debris	Superficial aquifer
	Bassendean Sand		Fine to medium sub-rounded quartz sand	Superficial aquifer
	Guildford Formation		Sandy silt and clay, ferruginised horizons	Local aquitard
	Yoganup Formation		White coarse sand, locally heavy minerals	Superficial aquifer
Cretaceous	Leederville Formation			
	Quindalup	0–33	Glauconitic silty clay, associated with sand and organic clay. Often has basal bed of coarse sand with minor clay	Leederville aquifer (local aquifer)
	Upper Mowen	0–7	Lignite seams and black carbonaceous clay, minor sand	Leederville aquifer (Confining bed)
	Lower Mowen	8–43	Interbedded organic clay and sand, thin lignite seam, very clayey with minor sand	Leederville aquifer (minor aquifer)
	Upper Vasse	12–25	Interbedded sand and clay with minor lignite, common sandy beds (5 m+)	Leederville aquifer
	Lower Vasse	20–75	Consolidated grey clay and sand with common cemented bands	Leederville aquifer
	Yelverton	10–85	Well consolidated grey/olive clay and sand, rare thin lignite seams	Leederville aquifer (minor aquifer)
Permian	Sue Group			
	Sue Coal Measures	200+	Sandstone, minor shale and coal seams	Sue aquifer

Pliocene-Quaternary superficial deposits thinly cover most of the Swan Coastal Plain. In these superficial deposits, a ferruginised zone has developed due to watertable fluctuation in many areas. Ferruginised hardpans have also developed at the base of watercourses and drains throughout the study area.

Figure 7 shows the position of three geological cross-sections that show the stratigraphic relationship between units from a north-south (Fig. 8) and east-west (Fig. 9) perspective.

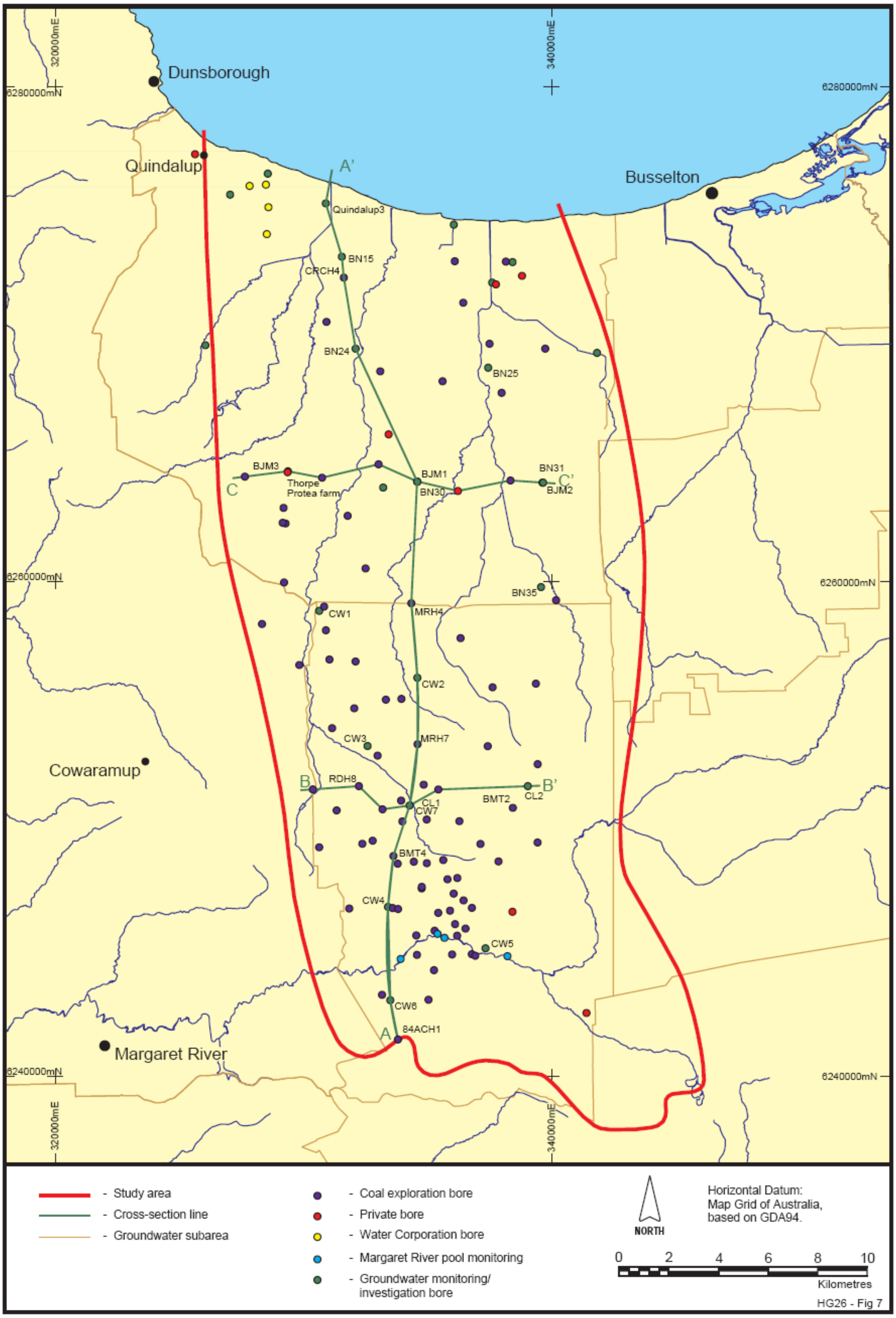


Figure 7 Position of geological cross-sections

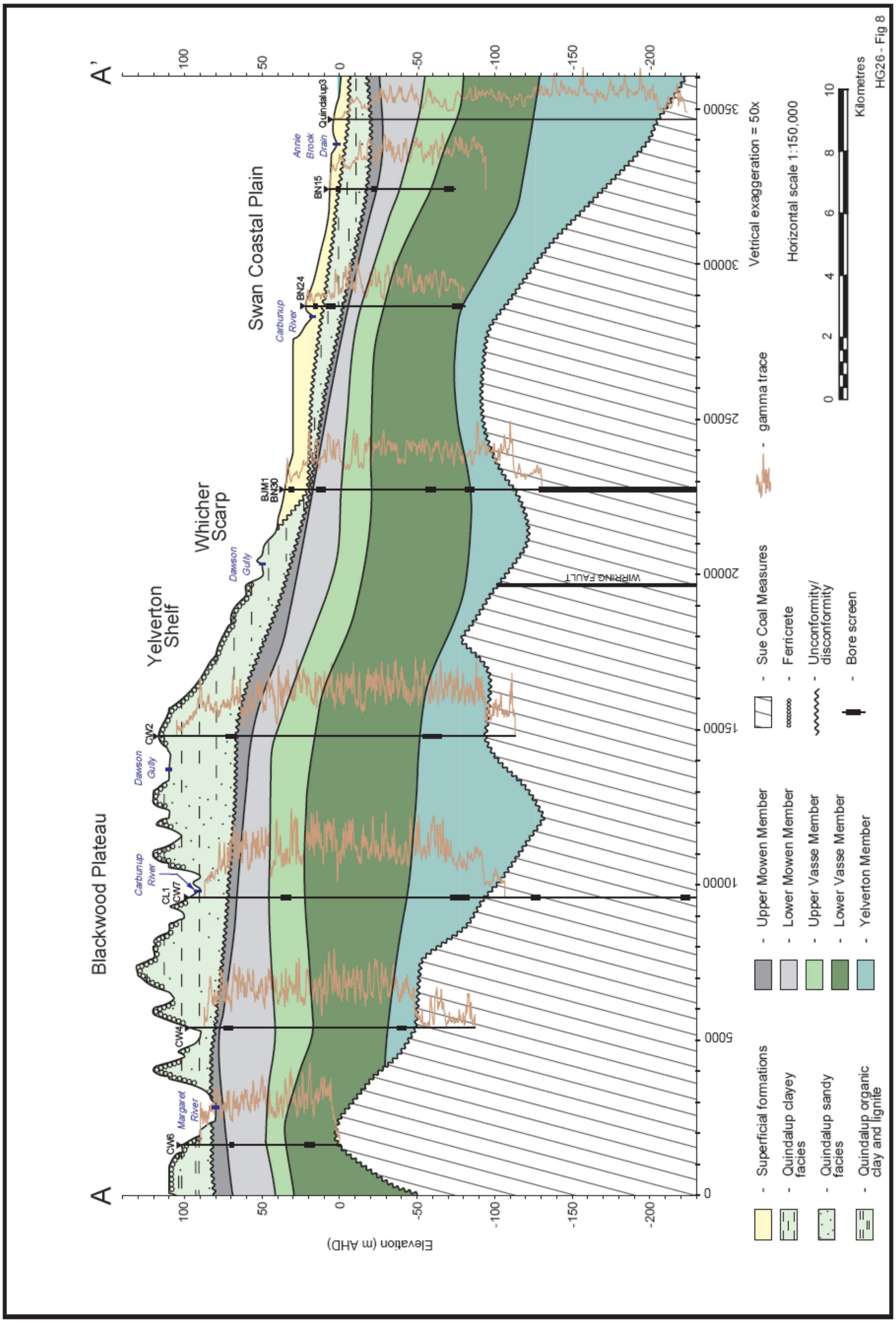


Figure 8 Stratigraphical cross-section A–A’

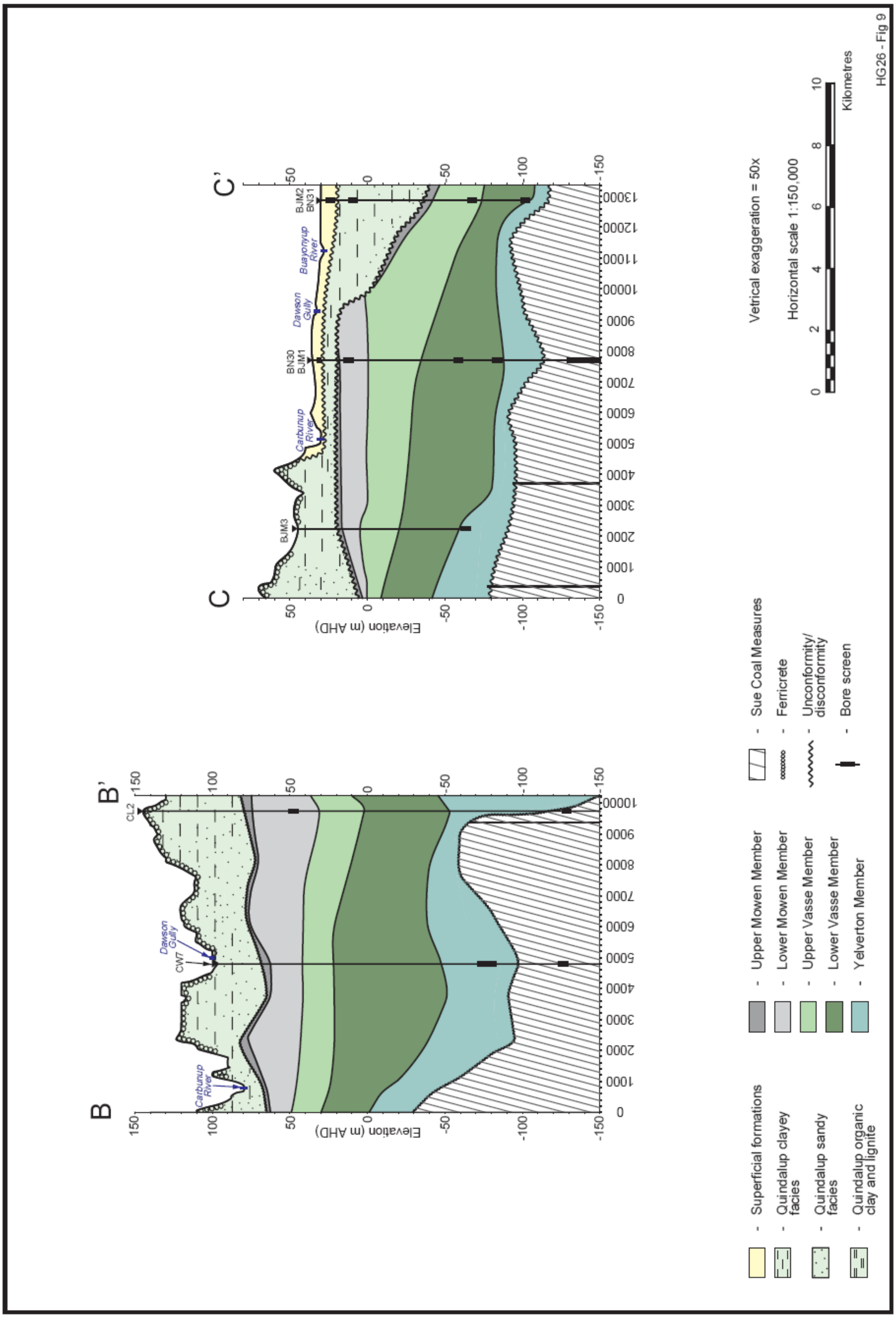


Figure 9 Stratigraphical cross-sections B–B’ and C–C’

3.2.1 Leeuwin Complex

The Leeuwin Complex consists of intensely deformed and metamorphosed Proterozoic rocks, which include granite gneiss and granulite. These rocks outcrop to the west of the Dunsborough Fault (Fig. 6). Two coal exploration bores, MCH5 and COWCH1, demonstrate that the Leederville Formation, in places, partially overlies basement rocks in the vicinity of the Dunsborough Fault.

3.2.2 Sue Coal Measures

The Sue Coal Measures of the Sue Group are Early to Late Permian in age and occur within the Vasse Shelf. They consist of interbedded sequences of fine to very coarse-grained sandstone, micaceous siltstone, laminated carbonaceous shale, mudstone and seams of coal (Le Blanc Smith and Kristensen, 1998). The sandstone beds are often highly consolidated and well cemented. Coal seams within the Sue Coal Measures are typically thin, being less than 5 m thick.

The Sue Coal Measures were heavily faulted and tilted during the early Cretaceous (Crostella and Backhouse, 2000; Le Blanc Smith and Kristensen, 1998). They form an angular unconformity with the overlying Leederville Formation. The drilling investigations encountered different lithologies including coal, siltstone and fine to coarse-grained sandstone associated with the Sue Coal Measures. The top of the Sue Coal Measures often appears to be slightly weathered.

A low gamma count and an occasional increase in the resistivity values distinguish the Sue Coal Measures on geophysical bore traces (Fig. 10). Palynology confirms the Sue Coal Measures at Early to Middle Permian in age and that the depositional environment was probably fluviatile (Backhouse, 2006).

3.2.3 Leederville Formation

The Cretaceous Leederville Formation unconformably overlies the Sue Coal Measures. The Leederville Formation is up to 260 m thick in the study area. Contours at the base of the Leederville Formation (Fig. 11) suggest the presence of east and north-trending palaeovalley features that drained away from the Treeton Terrace. The east-trending palaeovalley is believed to have significantly influenced the deposition of sediments.

The sedimentary sequence in the Leederville Formation shows a progression from proximal near the Leeuwin Complex to regional deposition in the more eastern parts. The regional depositional system is generally fining upward from sands to organic clay and lignite. Towards the top of the sequence, a shallow marine transgression deposited near-shore and marine clay sediments.

Generally the Leederville Formation becomes more clayey towards the Dunsborough Fault in the north-west of the study area near Quindalup. In the south of the study area, Johnson (2000) suggested that the Leederville Formation is sandier with minor conglomerate due its close proximity to the Leeuwin Complex.

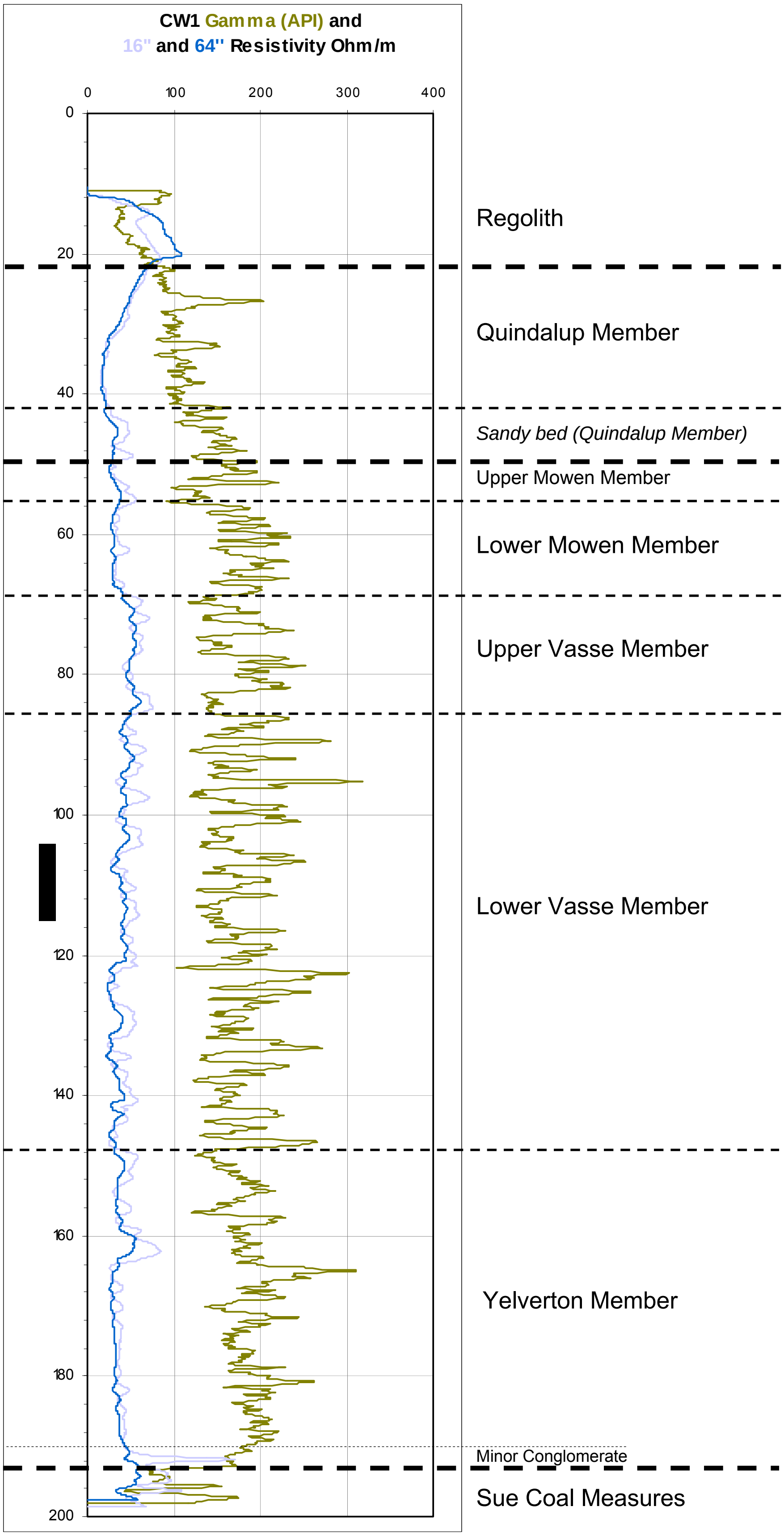


Figure 10 Geophysical log of Bore CW1

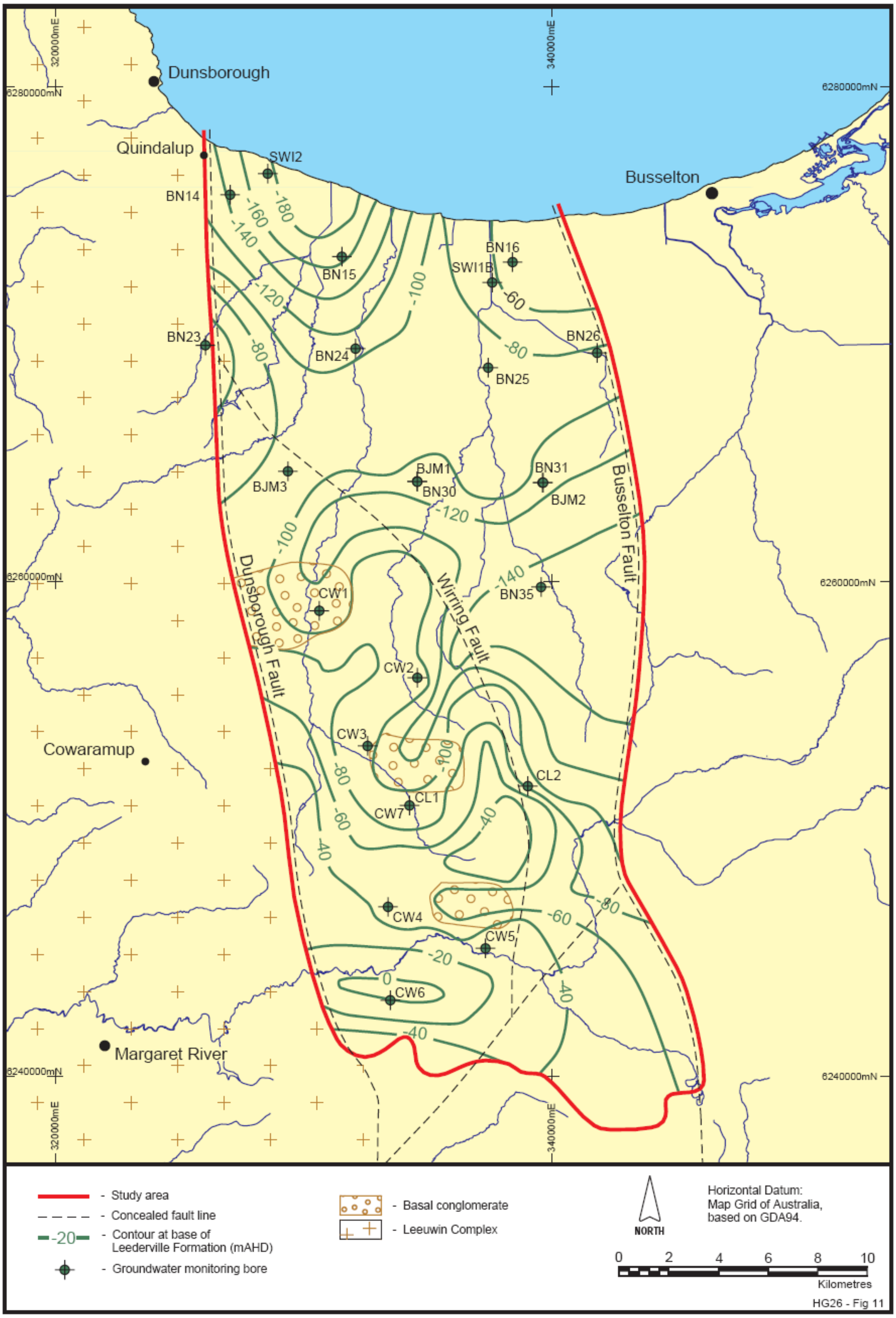


Figure 11 Base of the Leederville Formation and Yelverton Member

Based on lithological and geophysical bore logs, the Leederville Formation has been subdivided into six members — Yelverton, Lower Vasse, Upper Vasse, Lower Mowen, Upper Mowen and Quindalup Members. Figure 10 shows the stratigraphic relationship of these members and their indicative geophysical traces (gamma and resistivity).

At the base of the Leederville Formation, the Yelverton Member comprises well-weathered and reworked deposits. A series of interbedded sands and grey clays with cemented bands occurs throughout the Lower Vasse Member. The Upper Vasse Member also contains interbedded sand and grey clay but has thicker sand beds. The sequence becomes more carbonaceous in the Lower Mowen Member with lignite seams and organic clay being more common. The Upper Mowen Member is a thin unit comprising lignite and organic clay with minor sand beds. The Quindalup Member, the uppermost member of the Leederville Formation, is highly variable in nature with distinctive clayey and sandy facies.

Yelverton Member

The Yelverton Member is deposited on the unconformity with the Permian Sue Coal Measures and extends throughout the study area (Fig. 11). The unit has a variable thickness of between 10 to 75 m, with the thickest part in the north.

The Yelverton Member consists of thinly interbedded clays and sands with individual sand beds rarely exceeding 1 m thick. There are also minor thin lignite seams, pebble conglomerate beds and cemented horizons. The depositional environmental is considered to be a broad alluvial fan originating from the Leeuwin Block.

Individual sand and clay beds are generally not laterally continuous and may pinch out at scales less than 1 km. The unit is well consolidated and proved difficult to penetrate during the drilling investigations.

Sand grains are generally poorly sorted, fine to very coarse, angular to subangular and have a predominantly quartzo-feldspathic composition with a high proportion of fresh and weathered feldspars. The clay is generally olive-grey with some green glauconitic clay observed in bores CW1 and CW2. Accessory minerals such as garnet and ilmenite with some pyrite are also common.

There is a basal unit up to 10 m thick in places, but it is highly localised and is frequently absent (Fig. 11). Its nature and composition ranges from granitic boulder conglomerate to fine clayey sand and silt. This unit is identified by the presence of iron oxide-stained grains. The fine sand and silty sediments could be interpreted as reworked and/or weathered Sue Coal Measures.

A red granitic boulder conglomerate at the base of the Yelverton Member has been observed in a number of coal exploration holes and bore CW1 (Fig. 11). This conglomerate has been interpreted as being reworked material from the Leeuwin Block (Johnson, 2000).

The Yelverton Member is characterised by a highly variable gamma trace but has distinguishably finer-scale variations when compared with the overlying Lower Vasse Member (Fig. 10). Palynology indicates that the Yelverton Member belongs to the Balmeiopsis limbata spore pollen zone that is Barremian to Early Aptian (121–116 Ma) in age (Backhouse, 2006). The palynology assemblage indicates a fluviatile depositional environment. Glauconitic clays in some deeper holes indicate that the base of this member may also have been deposited in a marginal marine environment.

Lower Vasse Member

The Lower Vasse Member overlies the Yelverton Member and extends throughout the study area (Fig. 12). The unit has a variable thickness between 20 to 75 m with the thickest part in the north. It consists of thinly interbedded clay and sand with individual sand beds that are generally 1 to 3 m thick but can be up to 5 m thick.

The unit is moderately consolidated and contains numerous, thin (about 30 cm), cemented bands. The cemented bands are believed to be composed of calcite and siderite with minor pyritic and ferruginous horizons. Individual sand and clay beds within the Lower Vasse Member are not considered laterally continuous and are believed to pinch out at scales of less than 1 km.

Sand grains are generally fine to very coarse, sub-angular, and predominantly quartzo-feldspathic comprising white feldspar and grey quartz. Clays are generally grey in colour. Lignite seams are rare in this member. Accessory minerals such as ilmenite, pyrite and chlorite are common.

The Lower Vasse Member is characterised by a high variable gamma count (Fig. 10). Palynology indicates that the Lower Vasse Member belongs to the Balmeiopsis limbata spore pollen zone that is Barremian to Early Aptian (121–116 Ma) in age and was deposited in a fluviatile environment (Backhouse, 2006). Water Corporation (2005) suggested that the Lower Vasse Member was probably equivalent to the Mariginiup Member identified in the Perth Region as described by Davidson (1995).

Upper Vasse Member

The Upper Vasse Member overlies the Lower Vasse Member and extends throughout the study area (Fig. 13). The unit is generally up to 25 m in thickness. It is characterised by frequent thick (up to 5 m) sand horizons interbedded with clay. Individual sand and clay beds are generally not laterally continuous and often pinch out at scales of less than 1 km. However, the Upper Vasse Member as a whole is considered as being laterally continuous.

Sand grains are generally poorly sorted, fine to very coarse, angular to sub-angular, and predominantly quartzo-feldspathic comprising white feldspar and grey quartz. The clay is generally dense and grey in colour. There are also thin lignite seams. Accessory minerals such as ilmenite, pyrite and chlorite are common.

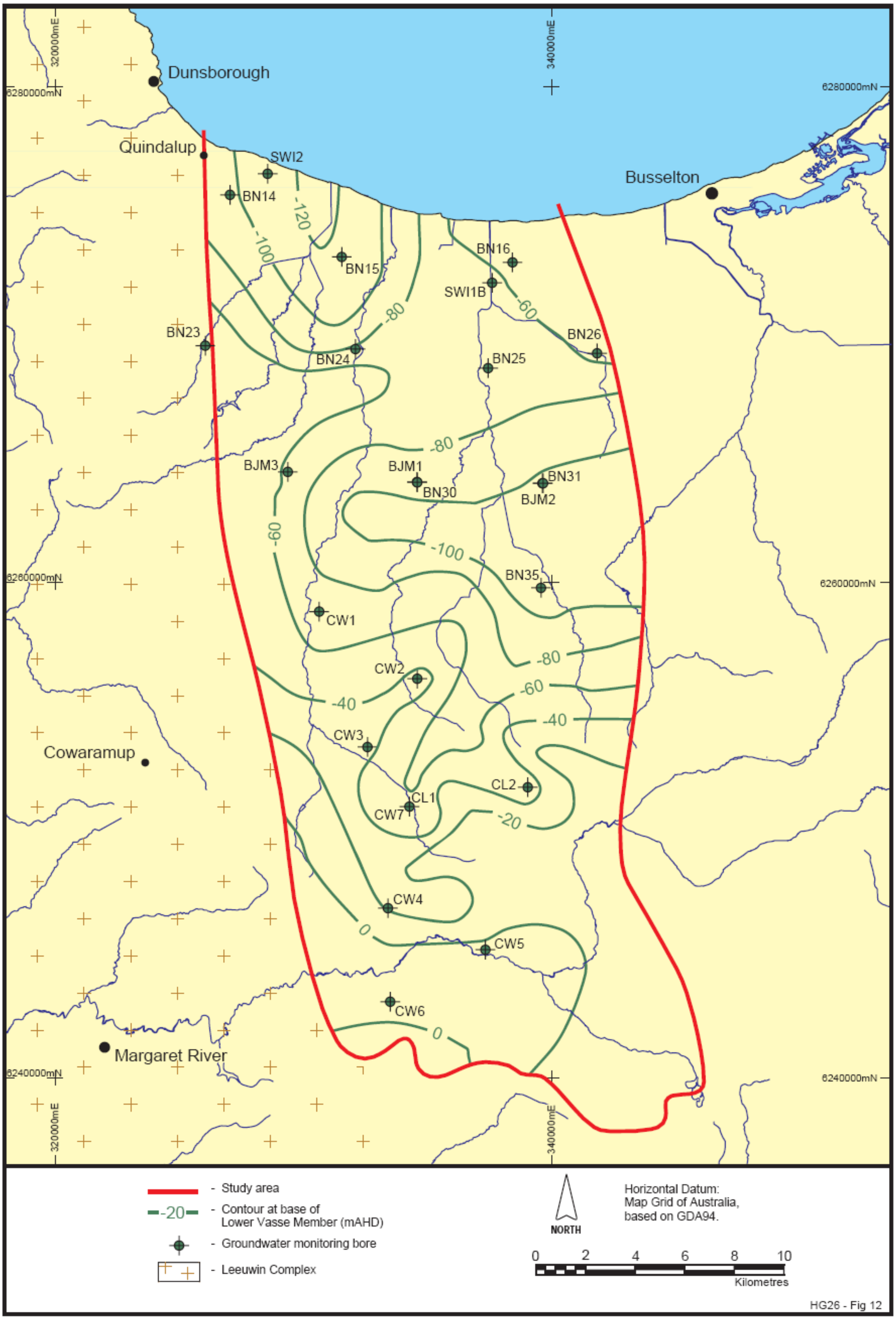


Figure 12 Base of the Lower Vasse Member

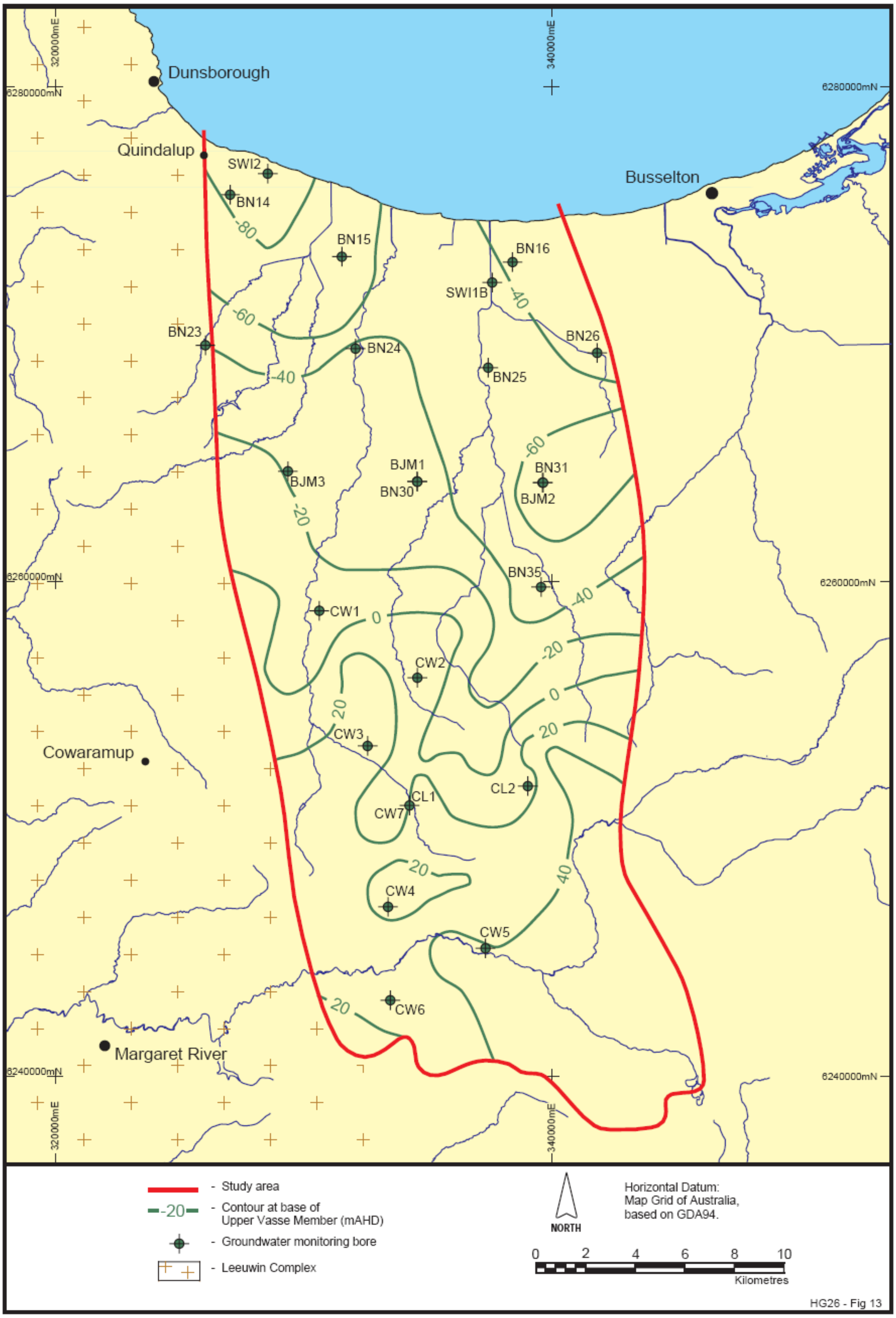


Figure 13 Base of the Upper Vasse Member

The Upper Vasse Member is characterised by low gamma responses over 2 to 5 m suggesting sand beds that are separated by high spiky gamma counts related to clay interbeds (Fig. 10). Palynology indicates that the Upper Vasse Member belongs to the Balmeiopsis limbata spore pollen zone that is Barremian to Early Aptian (121–116Ma) in age (Backhouse, 2006). The palynology assemblage suggests a fluviatile depositional environment. Water Corporation (2005) suggested this member is probably equivalent to the Wanneroo Member in the Perth Region as described by Davidson (1995).

Lower Mowen Member

The Lower Mowen Member overlies the Upper Vasse Member. It is continuous throughout the study area; however, is believed to be incised by deep valleys such as Margaret River and at the base of the Whicher Scarp (Fig. 14). Erosion and deposition has probably reduced the thickness of this member beneath the Swan Coastal Plain.

The unit consists of thick clay interbedded with individual sand beds that are typically 1 to 3 m thick. It is carbonaceous with lignite seams increasing towards the top. Individual sand and clay beds are not laterally continuous and often pinch out at scales of less than 1 km.

Sand grains are generally poorly sorted, fine to very fine, angular to sub-angular, and predominantly comprise white feldspar and grey quartz. Clays are generally dark grey to black in colour. Accessory minerals such as ilmenite and pyrite are common.

The Lower Mowen Member is characterised by large spiky sections (5 to 15 m) of high gamma count with occasional small intervals (1 to 3 m) of low gamma count representing sand beds (Fig. 10). Palynology indicates that the Lower Mowen Member belongs to the Balmeiopsis limbata spore pollen zone that is Barremian to Early Aptian (121—116 Ma) in age (Backhouse, 2006). The palynology assemblage indicates a fluviatile depositional environment. Water Corporation (2005) suggested the Mowen Member is an equivalent of the Pinjar Member in the Perth Region, as described by Davidson (1995).

Upper Mowen Member

The Upper Mowen Member forms a thin (less than 7 m) horizon of highly carbonaceous clay and lignite above the Lower Mowen Member. It is characterised by occasional coarse sand beds that are separated by clay and lignite seams. Lignite seams up to 1 m thick have been observed in bore CW2. Individual lignite and clay beds are not laterally continuous and often pinch out at scales of less than 1 km. In places a band of carbonaceous beds can be traced throughout large sections of the member.

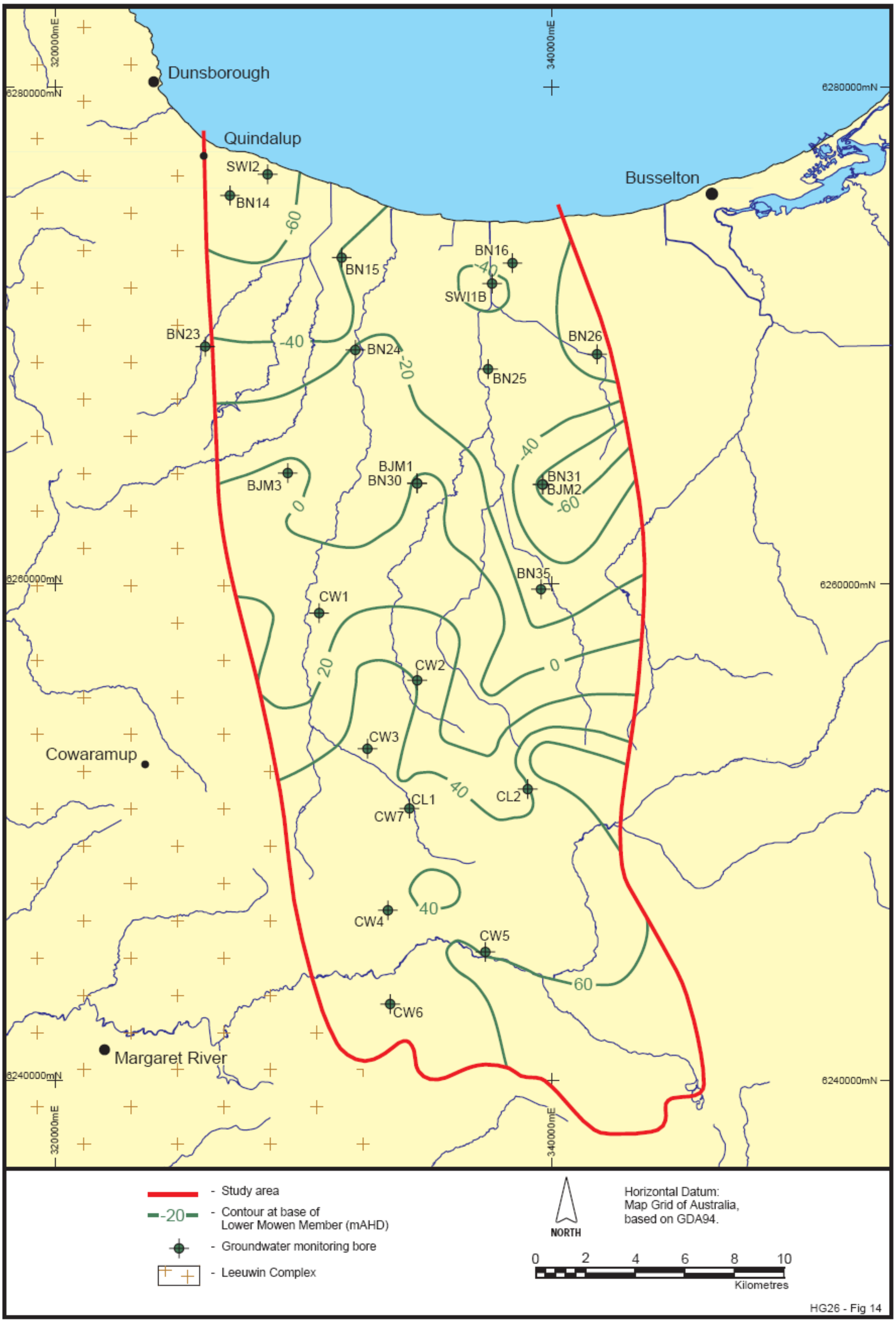


Figure 14 Base of the Lower Mowen Member

The clay is generally black through to olive in colour and is distinctively oily. The lignite seams consist of low grade coal with some plant fabric still clearly visible. Clay beds in the Upper Mowen Member tend to have lower gamma counts compared to the clayey horizons in underlying members. The lignite seams are identified by very low gamma counts.

Palynology indicates that the Upper Mowen Member belongs to the Balmeiopsis limbata spore pollen zone that is Barremian to Early Aptian (121–116Ma) in age (Backhouse, 2006). The presence of lignite indicates a paludal (swampy) depositional environment.

Quindalup Member

The Quindalup Member overlies the Upper Mowen Member and is considered the uppermost unit of the Leederville Formation. The member is up to 30 m thick with the thickest sequences in the north of the study area (Fig. 15). It extends over most of the study area but is absent from the lower reaches of Margaret River and the base of the Whicher Scarp near bore BN30.

The unit typically comprises a fine-grained sequence of organic black clays with minor lignite seams and green glauconitic clay. It is believed that some of the individual beds may have significant lateral continuity (>1 km). The base of the member is marked by a thin sandy horizon up to 5 m thick.

A coarse sandy facies has been identified within the Quindalup Member to the north of Margaret River (Fig. 15). This facies comprises poorly sorted, fine to very coarse, sub-rounded, quartzo-feldspathic sands.

The Quindalup Member has a distinctive low gamma count, which is easily distinguished from the higher gamma count of the underlying members of the Leederville Formation (Fig. 10). Palynology indicates that the Quindalup Member is Aptian (118–113Ma) in age (Backhouse, 2006) and suggests a shallow marine depositional environment. The sandy facies may represent reworking during a marine transgression.

3.2.4 Surficial deposits

A lateritic weathering profile covers much of the Blackwood Plateau and Whicher Scarp. The weathering profile has developed on the Leederville Formation and comprises a residual ferruginous duricrust overlying pallid clay and sand of variable thickness up to 22 m in bore CW2. Hillslopes typically comprise gravelly colluvial deposits, while valleys consist of a thin, sandy alluvial cover. In many places, a ferruginous hardpan has also developed in drainage depressions.

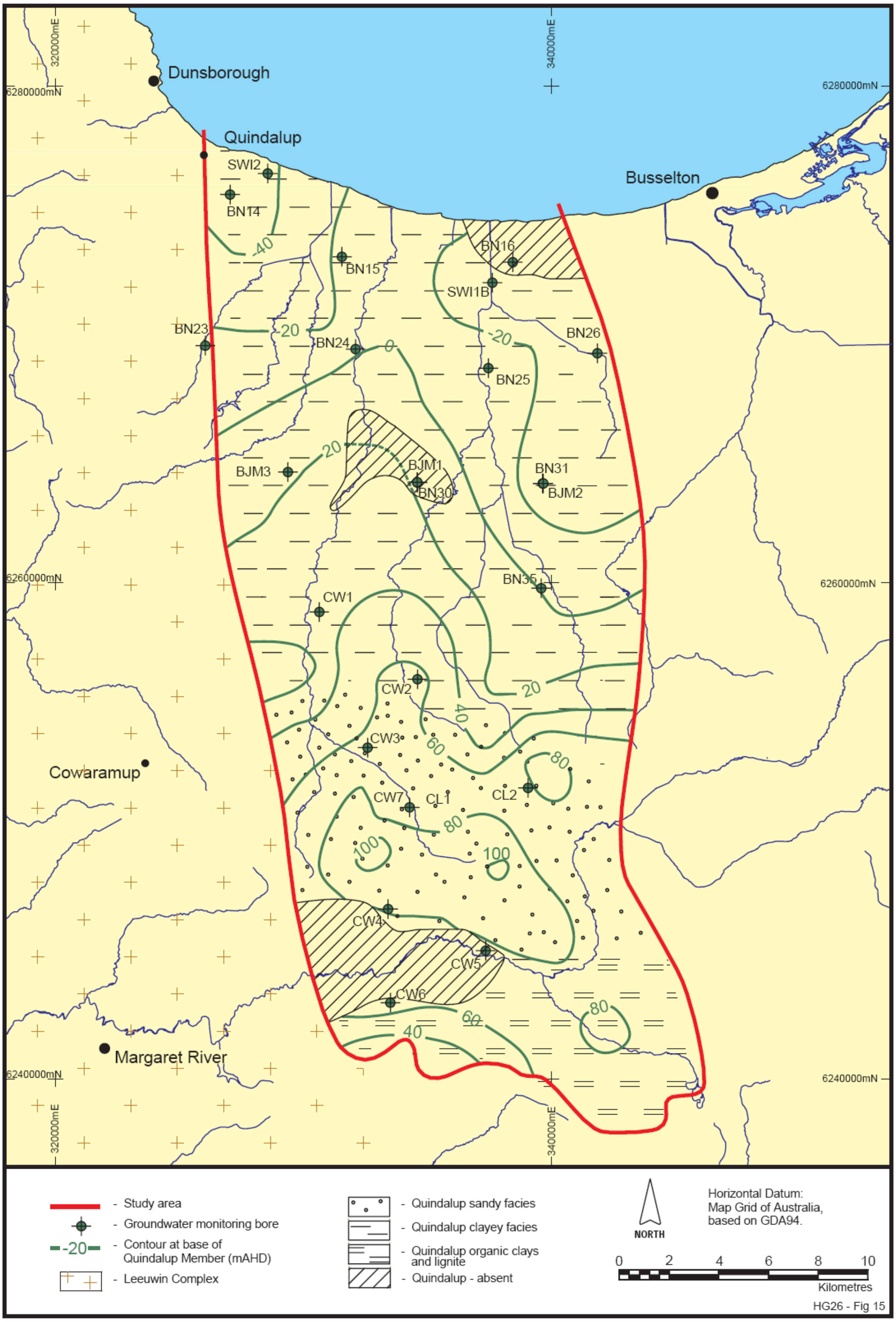


Figure 15 Facies distribution and contours at base of Quindalup Member

3.2.5 Superficial formations

On the Swan Coastal Plain, there is a thin cover of Late Pliocene – Pleistocene (3–0.01Ma) and Holocene (<11 500 years) sediments that are collectively known as the superficial formations. The sediments directly overlie the Leederville Formation, and were laid down in a range of depositional environments from alluvial, swamp, estuarine and shoreline settings. These deposits are typically very thin, less than 10 m in thickness. The geology and distribution of the superficial formations are described in more detail by Hirschberg (1989).

Yoganup Formation

The oldest superficial deposit is the Yoganup Formation, which occurs along the base of the Whicher Scarp. It comprises leached and ferruginous beach sand with localised concentrations of heavy minerals. The deposit varies in width from 500 m to 2000 m, but has been covered by alluvial deposits of the Guildford Formation.

Guildford Formation

The Guildford Formation covers much of the Swan Coastal Plain, approximately 6 to 8 km wide inland from the coast. It is a composite unit of interfingering alluvial clay and sand, and beach sand.

Bassendean Sand

The Bassendean Sand consists of quartz-rich dunal sand that generally overlies or abuts the Guildford Formation.

Tamala Limestone

The Tamala Limestone occurs as a narrow belt about 2 km wide along the coast. It consists of yellow to grey, weakly-cemented calcarenite with abundant shell fragments. In low-lying areas, it is overlain by estuarine and wetland deposits.

3.3 Geological history

The sediments within the study area are positioned within the southern Perth Basin, which was created due to large fault block movements during a long episode of trans-tensional rifting in the Permian to the early Cretaceous (Iasky and Lockwood, 2004).

Deposition of the Leederville Formation was a regional event that occurred during the subsidence phase after separation of the Australian and greater Indian land masses (Iasky, 1993; Iasky and Lockwood, 2004). As such, the Cretaceous sediments are largely unfaulted. The Leederville Formation was deposited in the early Cretaceous from about 121Ma to 116Ma, which corresponds to the time of the last Bunbury Basalt flow at 123Ma (Wilde, 1999) and the start of a period of global high sea levels (Backhouse, 1988).

As the Australian continent continued to drift northward (about 35 Ma), chemical weathering due to higher rainfall resulted in the development of the lateritic weathering profiles on the Blackwood Plateau. The superficial formations of the Swan Coastal Plain were deposited during marine transgression events in the Late Pliocene to the Pleistocene (0.1 to 3 Ma). The deposition of coastal estuarine and lagoonal sediments occurred in the Holocene through to the present.

4 Hydrogeology

4.1 Groundwater occurrence

There are two regional aquifer systems in the study area: the superficial aquifer and the Leederville aquifer. The superficial aquifer is a thin unconfined aquifer that only occurs on the Swan Coastal Plain. The Leederville aquifer is a major multi-layered sedimentary aquifer that extends throughout the study area. The Leederville aquifer has been subdivided into six distinct members – Quindalup, Upper Mowen, Lower Mowen, Upper Vasse, Lower Vasse and Yelverton Members. For the most part, the Leederville aquifer is a confined system.

There is limited interconnection between the superficial aquifer and the Leederville aquifer beneath the Swan Coastal Plain due to the presence of confining beds. The Leederville aquifer is underlain by the Sue aquifer, which has minor groundwater resources within localised fracture systems.

4.2 Superficial aquifer

The superficial aquifer forms an unconfined aquifer beneath the Swan Coastal Plain. It is thin with a saturated thickness of generally less than 5 m, and collectively includes the Tamala Limestone, Bassendean Sand, Guildford Formation and Yoganup Formation. Consequently, there is a large variation in permeability, ranging from the relatively impermeable Guildford Formation through to the more permeable units of the Yoganup Formation, Bassendean Sand and Tamala Limestone. The hydrogeology of the superficial aquifer is discussed in more detail by Hirschberg (1989).

4.2.1 Recharge

The superficial aquifer is recharged primarily by direct infiltration of rainfall. As much of the Swan Coastal Plain has been cleared of native vegetation, the potential for recharge is expected to be higher in cleared areas.

The superficial aquifer is often fully recharged or saturated during the winter resulting in large areas of waterlogging or ponding of water; however, the extensive drainage network across the Swan Coastal Plain captures and diverts much of this excess water towards the ocean.

The presence of ferruginised zones (i.e. ‘coffee rock’) in the Yoganup and Guildford Formations may impede recharge in the superficial aquifer. Immediately adjacent to the coast and further inland in the Buayanyup catchment, areas of upwards heads will also inhibit recharge.

4.2.2 Watertable configuration

Watertable contours for the superficial aquifer essentially follow the land surface, falling from about 35 m AHD at the base of the Whicher Scarp to 0 m AHD at the coast (Fig. 16). Groundwater flow is generally northward with a low hydraulic gradient of about 0.003. Towards the coast, the hydraulic gradient decreases owing to more permeable Tamala Limestone.

Depth to watertable in the superficial aquifer ranges up to 5 m below surface. The watertable is deepest in areas of higher topography near the Whicher Scarp. Deep drains and streams can locally influence the watertable.

Natural seasonal variation of the watertable is typically less than 2 m with the highest level being at the end of winter and lowest at the end of summer (Table 3). Groundwater abstraction from the underlying Leederville aquifer has produced large water level variations in some areas especially in the Jindong area (near monitoring bore BN24S), where water level fluctuations of more than 4 m are common.

Table 3 Water level change in the superficial aquifer

Bore	Screen interval (m bgl)	Water level in superficial aquifer			Seasonal fluctuation (m)	Head difference between superficial and Leederville aquifers		
		March 1985 (mAHD)	April 2006 (mAHD)	Change 1985-2006 (mAHD)		1985 (m)	2006 (m)	Change 1985-2006 (m)
BN14S	2.5-5.5	1.99	1.54	-0.45 ↓	1.85	1.77 ↓	4.18 ↓	2.41
BN15S	4.0 -7.0	4.22	4.05	-0.17 ↓	0.73	0.98 ↓	9.12 ↓	8.14
BN16S	2.6-5.6	0.40	0.32	-0.08 ↓	1.39	-0.91 ↑	-0.49 ↑	0.42
BN23S	7.8-13.8	32.86	32.35	-0.51 ↓	1.68	9.53 ↓	12.42 ↓	2.89
BN24S	4.0-7.0	16.17	15.70	-0.47 ↓	3.78	2.87 ↓	31.27 ↓	28.40
BN25S	3.5-9.5	13.58	13.29	-0.29 ↓	1.66	-2.66 ↑	-0.50 ↑	2.16
BN26S	5.5-8.5	9.19	9.40	0.21 ↓	1.43	-0.19 ↑	2.80 ↓	2.99
BN30S	2.5-5.5	31.39	31.29	-0.10 ↓	1.43	10.29 ↓	25.43 ↓	15.14
BN31S	2.5-5.5	26.98	26.81	-0.17 ↓	1.99	-3.06 ↑	0.36 ↓	3.42

↑ - upwards heads ↓ - downwards heads

Between 1985 and 2006, there has been a reversal of groundwater flow from upward (discharge) to downward (recharge) across much of the Swan Coastal Plain (Table 3). This reversal is largely due to the effects of groundwater abstraction from the Leederville aquifer. There is some upward flow in the lower reaches of the Buayanyup River related to groundwater discharge from the Leederville aquifer into the superficial aquifer (Fig. 16). It is important to note that this area of discharge is slowly contracting.

There is limited interconnection between the superficial and Leederville aquifers beneath the Swan Coastal Plain. Both aquifers are largely separated by the clayey Quindalup and Lower Mowen Members, which act as confining layers. In some specific areas, there would be improved hydraulic connection where the sandier portion of the Quindalup Member is present beneath the superficial aquifer.

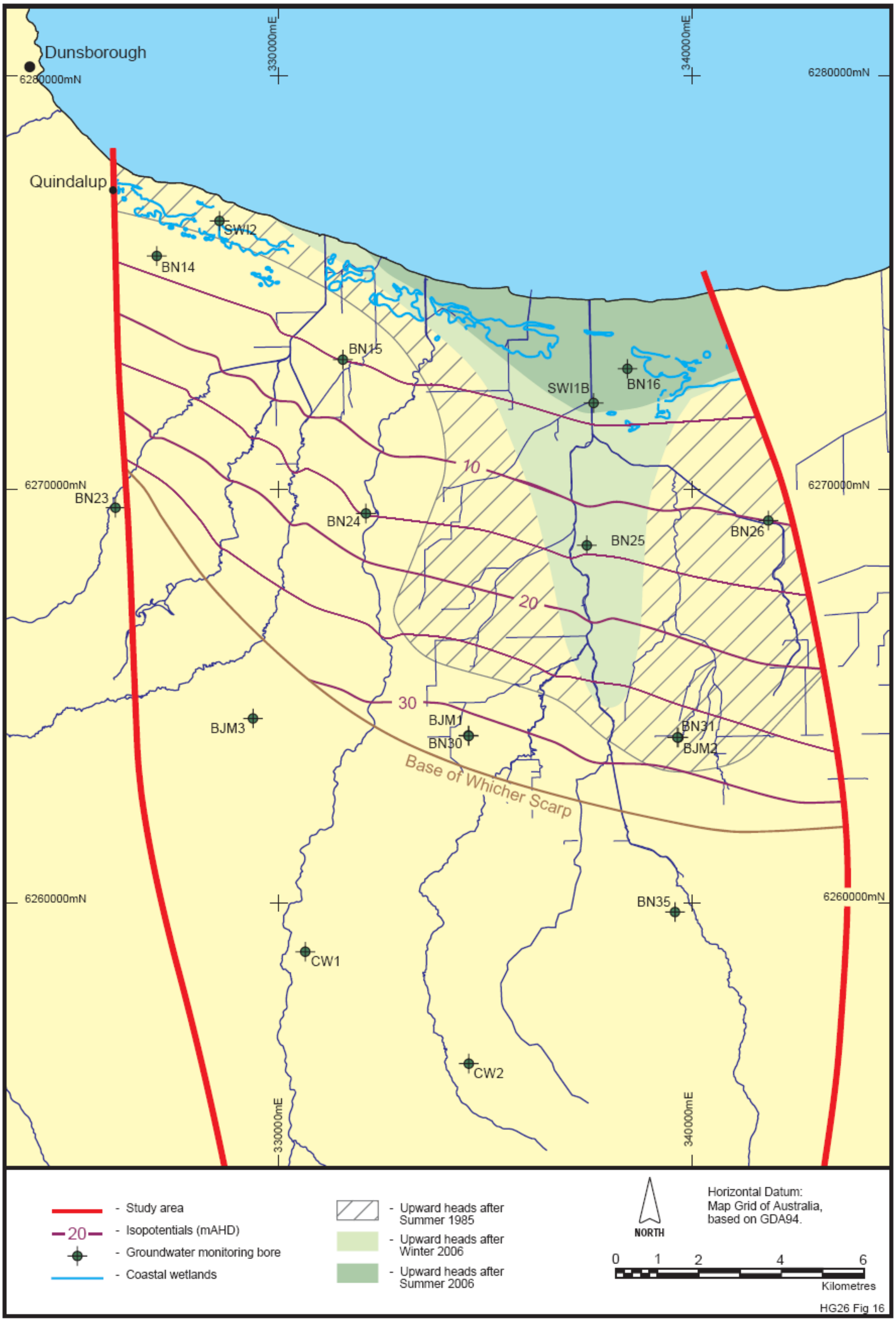


Figure 16 Watertable contours in the superficial aquifer

4.2.3 Discharge

As the winter wet season progresses and the watertable rises, there is groundwater discharge from the superficial aquifer into natural watercourses and network of agricultural drains. In addition, groundwater discharges from the superficial aquifer into coastal swamps and wetlands, and into Geographe Bay above the saltwater interface.

4.3 Leederville aquifer

4.3.1 Characteristics

The Leederville aquifer is a multi-layered aquifer system comprising discontinuous interbedded sequences of sand and clay. It includes all six distinct members of the Leederville Formation — Quindalup, Upper Mowen, Lower Mowen, Upper Vasse, Lower Vasse and Yelverton Members. Figure 17 shows a schematic hydrogeological section through the Leederville aquifer.

The Leederville aquifer extensively outcrops throughout the Blackwood Plateau. Beneath the Swan Coastal Plain, it is overlain by the superficial aquifer and is locally interconnected where confining beds are absent. The Leederville aquifer overlies the Sue aquifer throughout the study area. To the west, the Leederville aquifer is believed to, in places, slightly overlap the Dunsborough Fault onto the Leeuwin Complex. Outside the study area, the Leederville aquifer is underlain by the Yarragadee aquifer to the east of the Busselton Fault, and the Lesueur aquifer in the south.

Sandy beds or horizons constitute the main aquifer or water-bearing zones within the Leederville aquifer. The Leederville aquifer becomes more consolidated with depth; hence, permeability will also decrease.

Quindalup Member

The Quindalup Member consists mostly of marine and estuarine clays that are generally laterally continuous. A sandy facies is present in an area north of Margaret River, which is considered to be more prospective as an aquifer.

Beneath the Swan Coastal Plain, the Quindalup Member is generally thin (less than 10 m thick) except near Quindalup where it may be up to 40 m thick. It is completely absent at the base of the Whicher Scarp in the vicinity of the Carbunup River, and in the north-east corner of the study area where the Sue Coal Measures subcrop.

In the northern part of the Blackwood Plateau, the Quindalup Member is 30 to 50 m thick but becomes sandier and thins significantly towards Margaret River. It is completely absent from the lower parts of Margaret River. South of Margaret River, it changes lithology to comprise carbonaceous (organic) clay with minor lignite.

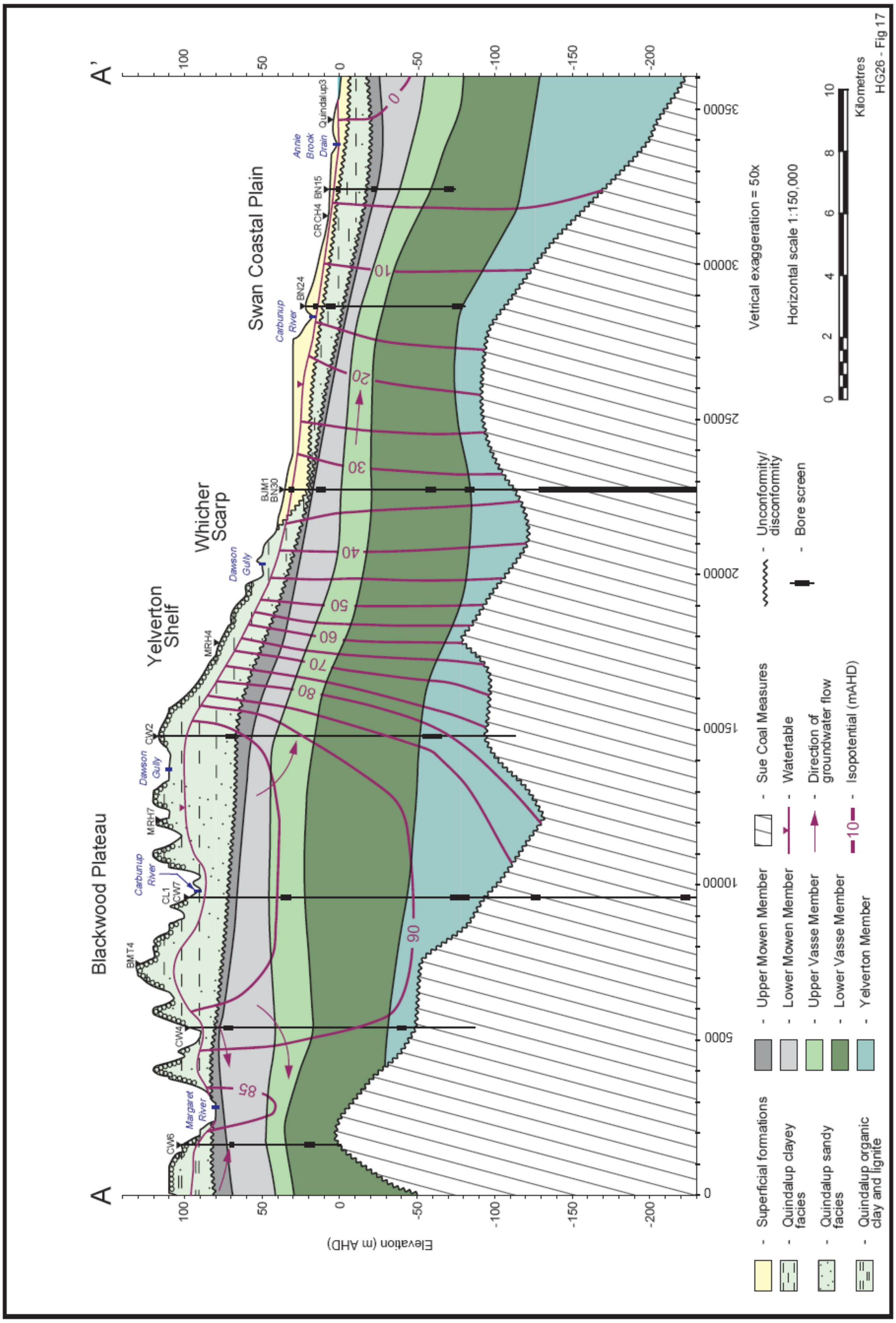


Figure 17 Schematic hydrogeological section A–A'

The Quindalup Member is generally considered an aquitard. Although, it is believed that the sandier facies of the Quindalup Member may be an important near-surface local aquifer; however, there are no groundwater monitoring bores in this member.

At the base of the member is a thin, sandy aquifer (less than 10 m thick). It could be considered to have potential for shallow bores, particularly in the northern Blackwood Plateau as it is the first significant aquifer encountered during drilling. The basal sand horizon is relatively unconsolidated compared to sandy beds in the underlying members.

Upper Mowen and Lower Mowen Members

The Upper Mowen and Lower Mowen Members comprise lignitic and organic clay beds of the Upper Mowen Member and the dominant clay interbeds of the Lower Mowen Member. They typically range in thickness from 20 to 40 m, but thin significantly in the lower reaches of the Margaret River valley and at the base of the Whicher Scarp.

The Upper Mowen and Lower Mowen Members are interpreted to form a leaky aquitard. The discontinuous nature of individual clay and sand interbeds may provide localised flow paths and may contribute significantly to vertical leakage. The continuity of individual beds is considered highly variable but continuous beds of 500 to 1000 m may be common. The position and permanency of the riverine pools in Margaret River is believed to be related to lithological variation in the Upper Mowen and Lower Mowen Members.

Upper Vasse Member

The Upper Vasse Member is considered the most promising aquifer within the Leederville aquifer, due to its high percentage (typically 65–75%) of sand beds. Individually sand beds are relatively thick, often up to 5 m, but are not considered laterally continuous.

The member extends throughout the study area and is up to 25 m thick. It is less consolidated than the underlying Lower Vasse and Yelverton Members, and consequently is believed to have high horizontal hydraulic conductivities in comparison. The discontinuous clay interbeds will reduce the vertical hydraulic conductivity through this aquifer.

Lower Vasse and Yelverton Members

The Lower Vasse and Yelverton Members form the deepest aquifer system in the Leederville aquifer. They have a combined thickness of between 30 and 125 m, and consist of thinly interbedded clays and sands with individual sand beds less than 3 m thick and are well consolidated. A series of cemented bands at the top of the Lower Vasse Member are believed to impede vertical groundwater flow. Despite the high proportion of clay and cement bands, the Lower Vasse and Yelverton Members have localised sand beds that may form important aquifer horizons.

Vertical recharge from the overlying Upper Vasse aquifer is probably limited due to cemented bands and clay interbeds. However, Water Corporation (2005) suggested that there may be significant horizontal conductivity (between 0.3 and 1 m/day) in the Lower Vasse and Yelverton members.

The development of high-yielding bores in the Lower Vasse and Yelverton Members will require large screen intervals. Long-term abstraction from these members has shown localised depressurisation effects, which are most evident in areas of increased groundwater abstraction at Jindong.

4.3.2 Recharge

The Leederville aquifer is recharged directly by rainfall infiltration on the Blackwood Plateau in areas of downward potentiometric head (Fig. 17). Most recharge is believed to occur in the area of topographic high coinciding with an east-west groundwater flow divide and in the vicinity of CW2 and CW4. In areas away from the divide, the hydraulic gradient is sufficiently steep to enable the recharge water to be transmitted as horizontal groundwater flow. The amount of recharge will vary considerably depending on land use, vegetation cover and surface geology.

On the Blackwood Plateau, the amount of recharge is controlled by deeply incised valleys that drain excess rainfall. Areas of higher recharge are associated with cleared areas and where the sandy facies of the Quindalup Member outcrops. Colluvial slopes are likely to have higher recharge than hill tops that may have a thick weathering profile. Ferruginised hardpan and areas of discharge along watercourses will inhibit recharge.

Recharge will vary seasonally with most recharge believed to occur in the early winter when catchments are dry and the watertable is low. As the watertable rises and intersects the drainages, any additional rainfall recharge is rejected or effectively removed from the groundwater system as streamflow or taken up through evapotranspiration.

Recharge into the Leederville aquifer from the underlying superficial aquifer may occur where confining beds are largely absent or the sandy facies of the Quindalup Member is present beneath the Swan Coastal Plain, and where there is a downward hydraulic gradient.

4.3.3 Groundwater flow

Groundwater flow in the Leederville aquifer is dominated by a regional groundwater-flow divide located to the north of Margaret River (Fig. 18 and 19). The flow divide extends east-west across the study area and separates groundwater flow into northerly and southerly-trending flow systems. Potentiometric levels at the height of the divide reach up to 95 m AHD near Canebreak Pool in the upper reaches of

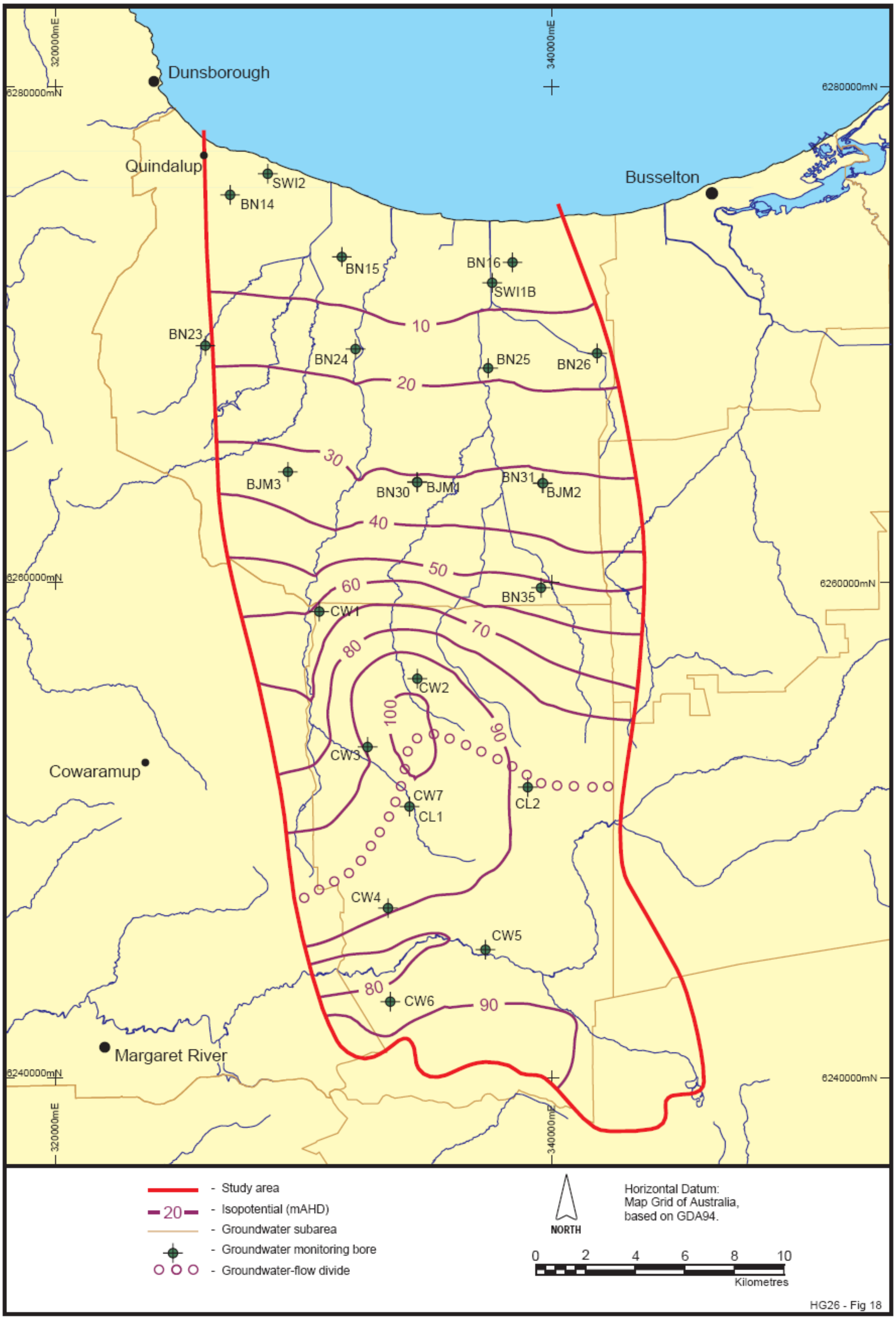


Figure 18 Isopotentials for intermediate bores in the Leederville aquifer

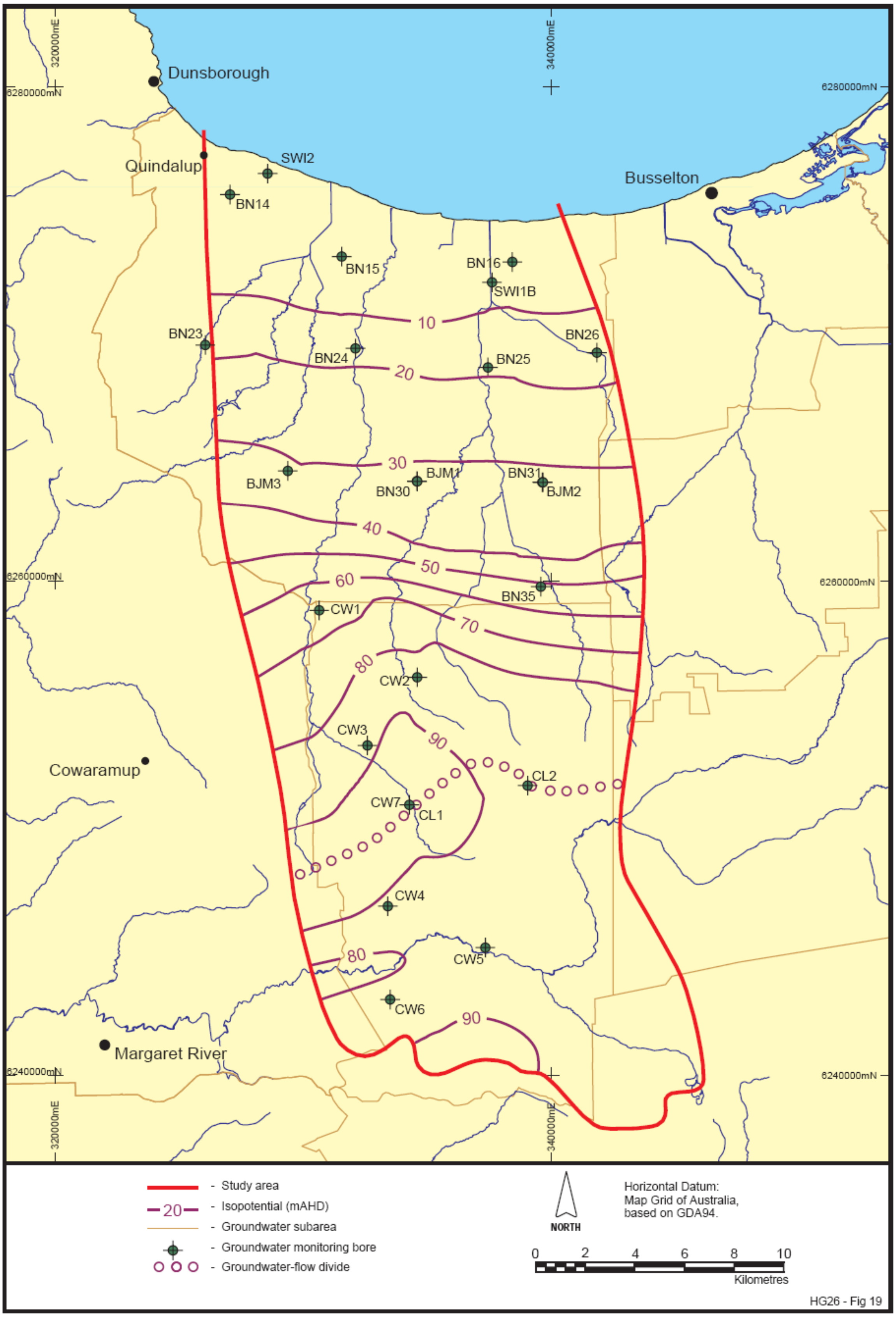


Figure 19 Isopotentials for deep bores in the Leederville aquifer

Margaret River. The groundwater-flow divide corresponds with the topographic divide on the Blackwood Plateau.

There is a large loss of potentiometric head in the Leederville aquifer down the Whicher Scarp. The potentiometric head decreases from about 85 m AHD on the Blackwood Plateau to about 35 m AHD on the Swan Coastal Plain, which has resulted in a steep hydraulic gradient (Fig. 18). Groundwater is believed to discharge into watercourses and wetlands across the Whicher Scarp, as well as through evapotranspiration loss.

Beneath the Swan Coastal Plain, groundwater flow is northward to the coast. In places, groundwater abstraction has locally distorted the isopotentials in the deeper Leederville aquifer, particularly in the Jindong area near bores BJM1, BN24 and SWI2. To the south of the groundwater-flow divide, the potentiometric head is strongly influenced by Margaret River.

Groundwater flow in the Leederville aquifer is dominated by two distinct systems. There is a shallow flow system in the Quindalup and Upper Mowen Members that is strongly influenced by topography and a deeper, more regional flow system in the Vasse and Yelverton Members.

The shallow groundwater flow system is strongly influenced by Margaret River, where it supports more than twenty large permanent pools. Shallow groundwater flows from areas of high topography. There is also groundwater discharge along the Yelverton Shelf and Whicher Scarp, which act as a broad seepage face with high evapotranspiration and the presence of swampy areas.

In the deeper Leederville aquifer, associated with the Upper Vasse, Lower Vasse and Yelverton Members, groundwater moves northward discharging in Geographe Bay and southward toward the Blackwood River catchment. Most groundwater flow in the deep Leederville aquifer is predominantly horizontal, especially in areas away from the groundwater-flow divide.

The rate of flow and interconnection between the Leederville and superficial aquifers is dependent on the hydraulic conductivity of the intervening layers. Beneath the Swan Coastal Plain, the Leederville and superficial aquifers are largely separated by the clayey Quindalup and Lower Mowen Members, which act as semi-confining layers. In some specific areas, there would be improved hydraulic connection where the sandy Quindalup Member is present beneath the superficial aquifer.

Groundwater flow between the Leederville aquifer and the underlying Sue aquifer is considered very small due to the low permeability of the Sue aquifer. In addition, there is no appreciable westward flow or interconnection with the basement rocks of the Leeuwin Complex.

4.3.4 Water level fluctuation

On the Blackwood Plateau, water levels in the Quindalup and Upper Vasse Members fluctuate seasonally by 1 to 2 m/yr. Bores screened at deeper levels in the Lower Vasse and Yelverton Members show little seasonal variation (typically less than 0.25 m/yr) suggesting the deeper Leederville aquifer is largely disconnected from the shallow groundwater flow system.

Beneath the Swan Coastal Plain, the water level in bores screened at both intermediate and deep screen intervals of the Leederville aquifer fluctuate by 1 to 4 m. There are large variations in water level, up to 22 m/year, in the Lower Vasse and Yelverton Members related to groundwater abstraction in the Jindong area.

Artesian flow is possible from bores that are drilled near Margaret River. A number of coal exploration bores RBCH11 and RBCH12 (Fig. 4) near Margaret River are reported to have shown small artesian flows.

4.3.5 Discharge

Most groundwater discharge from the Leederville aquifer is associated with the shallow groundwater flow system. The main discharge occurs within the Margaret River valley in the south and at the base of the Whicher Scarp seepage face in the north.

The Margaret River valley is an area of upward potentiometric head and an important discharge area. Isopotentials suggest that shallow groundwater discharges towards and into Margaret River. Prior to the 1970s, Margaret River was a perennial system with groundwater baseflow. Under the current lower rainfall conditions, there is no measurable baseflow but there are many riverine pools that remain permanent throughout summer. The permanency of these pools is dependent on groundwater discharge from the upper members of the Leederville aquifer.

Along the Yelverton Shelf and Whicher Scarp, there is a broad seepage face with most discharge from evaporation losses from wetlands and high rates of evapotranspiration. The base of valleys of north-trending drainage systems, including the Carbunup River, Dawson Gully and Ironstone Gully, are possible discharge areas with seasonal seepage.

Groundwater from the deeper Leederville aquifer probably discharges over a saltwater interface along the coast. To the south, the deep groundwater flow system discharges into the Blackwood River. Groundwater discharge from the Leederville aquifer into the Sue aquifer is considered negligible.

4.4 Sue aquifer

The Sue aquifer consists of well-consolidated sandstone, siltstone and coal of the Sue Group, which has been locally fractured. Groundwater movement in the Sue aquifer is restricted to localised, open fractures in the sandstone and coal seams.

Groundwater flow and interconnectivity between the Leederville and Sue aquifers is considered negligible.

5 Groundwater quality

5.1 Salinity

5.1.1 Superficial aquifer

Groundwater salinity in the superficial aquifer ranges from fresh to saline up to 12 000 mg/L Total Dissolved Solids (TDS). The salinity generally increases toward the coast. There is a saltwater interface present; however, the inland extent of the saltwater interface is not well understood.

Fresh groundwater with salinity less than 500 mg/L TDS occurs throughout much of the Carbunup River catchment and in inland parts of the Buayanyup River catchment to the east. Pockets of more brackish groundwater (less than 1000 mg/L TDS) are associated with areas with shallow watertable and the presence of the clayey Guildford Formation, which are more prone to evapotranspiration.

Brackish to saline water (less than 5000 mg/L TDS) is associated with a system of coastal lakes. It is likely that the salinity has been concentrated by evaporation processes, as well as high salt inputs from rain and marine aerosols near the coast.

Gilgallon (2003c) suggested that groundwater salinity is highest at the end of summer due to evaporation processes.

5.1.2 Leederville aquifer

Groundwater in the Leederville aquifer is generally fresh, being less than 500 mg/L TDS. Groundwater salinity tends to increase in the flow direction away from the flow divide (Figs. 20 and 21). The lowest groundwater salinity is present near the flow divide (near bores CW3 and CW7) confirming that it is an active recharge or intake area.

The pattern of groundwater salinity is broadly consistent with the groundwater flow direction (Fig. 22). Turner and Dighton (2008) suggest that this indicates discrete flow systems are present related to stratigraphy and proximity to recharge zones.

There is a trend of decreasing groundwater salinity with depth, which may suggest that the older groundwater was recharged under slightly different climatic conditions than at present (Turner and Dighton, 2008). Recharge in the past may have had lower salt content as the coast was substantially further west than the present coastline during a period of lower sea levels.

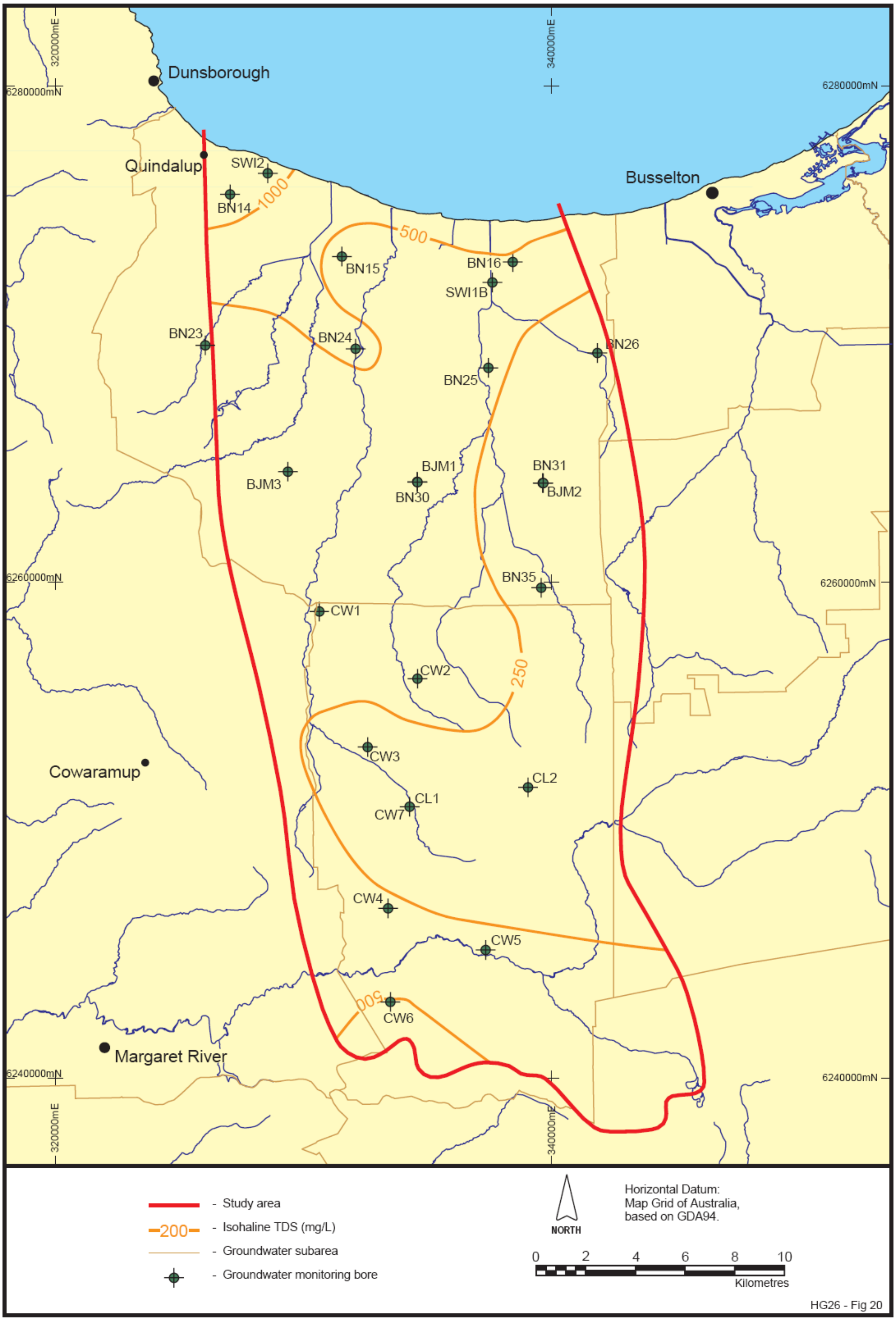


Figure 20 Isohalines for intermediate bores in the Leederville aquifer

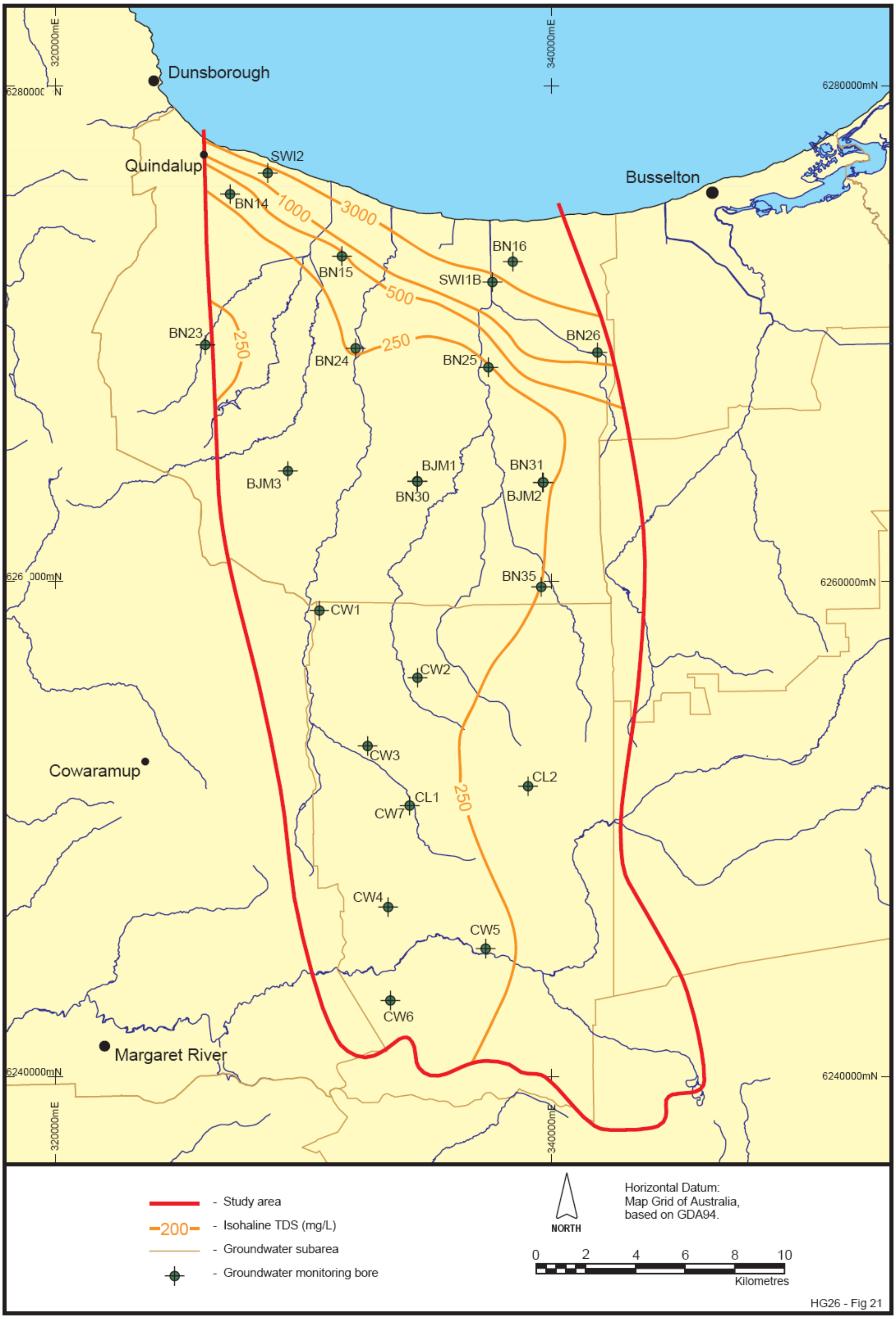


Figure 21 Isohalines for deep bores in the Leederville aquifer

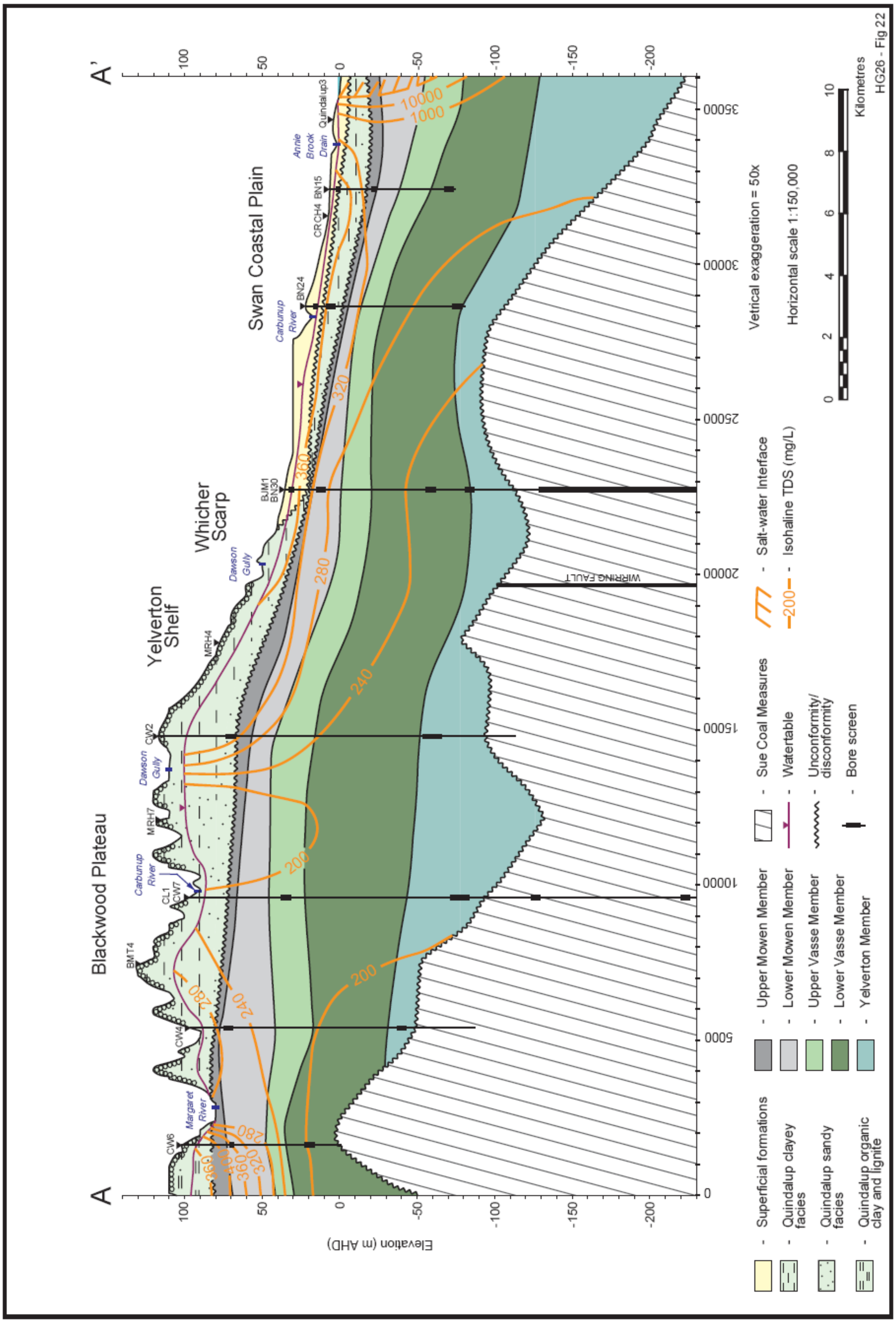


Figure 22 Isohalines along cross section A–A’

Table 4 shows comparisons in groundwater salinity between data collected in 1984 (Hirschberg, 1989) and 2006. Bores BN25 and BN30 have lightly increased in salinity by around 30 to 50 mg/L TDS, while bore BN15I is approximately unchanged between 1984 and 2006.

Table 4 Groundwater salinity TDS mg/L in selected bores (1984 and 2006)

Date	BN15I	BN15D	BN25I	BN25D	BN30I	BN30D
Mar 1984	320	341	254	285	250	251
Nov 2006	319	351	291	332	284	306

The position of the saltwater interface in the Leederville aquifer is poorly understood along the coastline. Wharton (1981) mentioned the possibility of a saltwater interface from observations on a private bore in between Quindalup Line bores Q1 and Q2. It is considered that ongoing groundwater abstraction from the Leederville aquifer has some potential to influence the saltwater interface.

5.2 Hydrochemistry

5.2.1 Major ions

The results of chemical analyses of groundwater are presented in Table 5, and the major ions from the chemical analyses are plotted on a Piper trilinear diagram in Figure 23.

Most shallow to immediate waters are of sodium chloride type reflecting their derivation (through precipitation) from marine aerosols. This is confirmed by the composition of the major ions being close to that of seawater. There is a distinct trend in groundwater evolution with depth (Fig. 23), as the bicarbonate content increases. In the deepest parts of the Leederville aquifer, groundwater is a mixture of sodium chloride, and calcium and bicarbonate types.

Chloride

The source of all chloride is from marine aerosols in rainfall. Chloride concentrations are consistently lowest at the base of the Leederville aquifer. The lowest chloride contents are found in the vicinity of the groundwater-flow divide on the Blackwood Plateau near bores CW3, CW7 and CW2. There is only a slight decrease in chloride content with depth at the groundwater-flow divide; however, there is a greater contrast away from the divide between the top and the base of the aquifer.

Chloride is considered a conservative tracer. Chloride distribution in the Leederville aquifer confirms that the area of highest recharge is near the groundwater-flow divide on the Blackwood Plateau. After recharging, groundwater flows to the north and south with evaporation concentrating chloride in areas of shallow watertable.

Monitoring Bore	Date	Top of screen (m bgl)	Bottom of screen (m bgl)	General characteristics: pH -log[H$^+$]	General characteristics: TDS (calc) (mg/l)	General characteristics: EC (µS/cm)	General characteristics: DO (mg/L)	Anions: Cl^- (mg/L)	Anions: CO_3^{2-} (as $CaCO_3$) (mg/L)	Anions: F^- (mg/L)	Anions: HCO_3^- (mg/L)	Anions: N-NO_3^- (mg/L)	Anions: SO_4^{2-} (mg/L)	Cations: Ca^{2+} (mg/L)	Cations: Fe^{2+} (Sol) (mg/L)	Cations: K^+ (mg/L)	Cations: Mg^{2+} (mg/L)	Cations: Na^+ (mg/L)	Complexes: SiO_2 (mg/L)
BN30S	8/11/06	2.5	5.5	5.77	407	650	1.3	110	-	-	10	-	123.8	12.5	44.5	5.8	11.7	78	10.3
BN15S	9/11/06	4	7	5.61	432	669	0.4	134	-	-	40	0.7	94.3	4.3	0.1	2.2	15.6	121.2	19.4
BN25S	9/11/06	3.5	9.5	5.72	356	608	0.1	152	-	-	25	-	14.9	4.5	23.7	8.1	14.3	84.4	28.6
BN30I	8/11/06	20	26	5.74	284	468	0.2	100	-	0.1	22	-	12.8	4.5	30.6	7.7	11.2	56.9	38.5
BN25I	9/11/06	22.4	25.4	5.72	291	479	0.1	103	-	0.1	28	-	12.3	3.9	27.6	8.4	11.4	62.4	33.8
CW4B	7/11/06	21.5	27.5	5.19	247	387	0.1	101	-	-	9	-	12.8	2.4	10.5	13	8.4	53.2	36.8
BN15I	9/11/06	27	30	5.98	319	524	0.3	119	-	0.3	32	-	10.5	13.5	27.5	8.6	12.9	55.6	39.3
CW6B	6/11/06	30.5	33.5	4.93	417	724	0.2	198	-	-	-	-	28.4	6.4	16.3	14.2	14.2	105.2	34
CW5B	6/11/06	29	35	5.43	318	480	0.1	107	-	0.1	26	-	16.8	2.2	36.9	11.6	10.0	70.6	37.3
CW2B	8/11/06	43.5	49.5	5.25	226	377	0.1	90	-	-	11	-	12.5	1.9	18.9	5.4	6.5	54.1	25.6
CW1B	8/11/06	44	50	5.32	271	436	0.1	103	-	-	16	-	12.8	2.3	24.1	8	7.3	60.6	36.6
CW3B	7/11/06	50	56	5.6	197	306	0.1	62	-	-	20	-	7.3	1.2	24.4	7	5.2	40.1	29.7
CW7B	7/11/06	59	65	5.11	214	339	0.1	86	-	-	6	-	11.6	2.4	10.1	12.5	7.2	43.8	34
BN15D	9/11/06	74	80	6.32	351	520	0.1	105	-	0.2	79	-	11	33.4	12.4	8.9	10.3	51.8	39.4
CW6A	6/11/06	79	85	7.16	264	353	0.1	61	-	0.3	97	0.1	7.2	10.4	0.6	11.7	6.9	54.3	14.3
BN25D	10/11/06	91	97	6.86	332	436	0.07	62	-	0.1	140	-	9	24.4	1.4	8.4	11.8	54.6	20.1
BN30D	8/11/06	91	97	7.47	306	383	0.1	43	-	-	143	-	8.3	31.8	0.6	7.4	8.3	43.7	19.5
CW5A	6/11/06	101.2	107.2	7.09	278	366	0.1	67	-	0.3	85	-	8.5	22.1	8.0	10.7	5.5	43.5	27.4
BJM1B	9/11/06	116	122	7.78	319	396	0.08	42	-	0.1	155	-	8.8	35.6	0.3	7.3	7.5	43.4	18.9
CW4A	7/11/06	133	139	6.24	285	330	0.1	60	-	0.2	94	-	7	17.8	8.8	11.3	5.7	39.7	40.8
CW1A	9/11/06	155	167	7.52	342	379	0.1	48	-	0.2	171	-	8.1	23.9	0.6	7.7	5.9	51.8	25.1
CW3A	7/11/06	162	174	6.3	288	352	0.1	60	-	0.2	85	-	9.1	16.4	7.5	14	4.4	44.8	46.6
CW7A	7/11/06	168	180	6.17	243	297	0.1	46	-	0.3	69	-	10.2	9.2	8.6	9.9	6.2	39.2	44.2
CW2A	7/11/06	170.5	182.5	5.87	265	364	0.1	77	-	0.1	35	-	9.5	4.9	22.2	10.9	8.7	41.4	55.7
Australian Drinking Water Guidelines **Health Guideline Values**										1.5		50	500						
Australian Drinking Water Guidelines **Aestheic Guideline Values**				6.5-8.5	500		>85%	250	200*		200*		250	200*	0.3			180	
Water Quality Guidelines (2000) **Primary Industries: Irrigation**				<5 high corros. pot. 5-6 likely corros. pot.		1000 (apple) 1700 (potato) 2000 (lucerne) 4000 (olive)		175 (grape) 175-350(pot.) 250-700 (lucerne)	>350 fouling potential	1 - long term 2 - short term	no trigger value, but can cause scaling	5 - long term 25-125 - short term			0.2 - long term 10 - short term			115 (grape) 115-230 (pot.) 230-460 (lucerne)	
Water Quality Guidelines (2000) **Primary Industries: Livestock**					2000 (poultry) 2500 (dairy) 4000 (beef) 5000 (sheep)					2			1000				>2000		

Table 5 Selected chemical analyses of groundwater

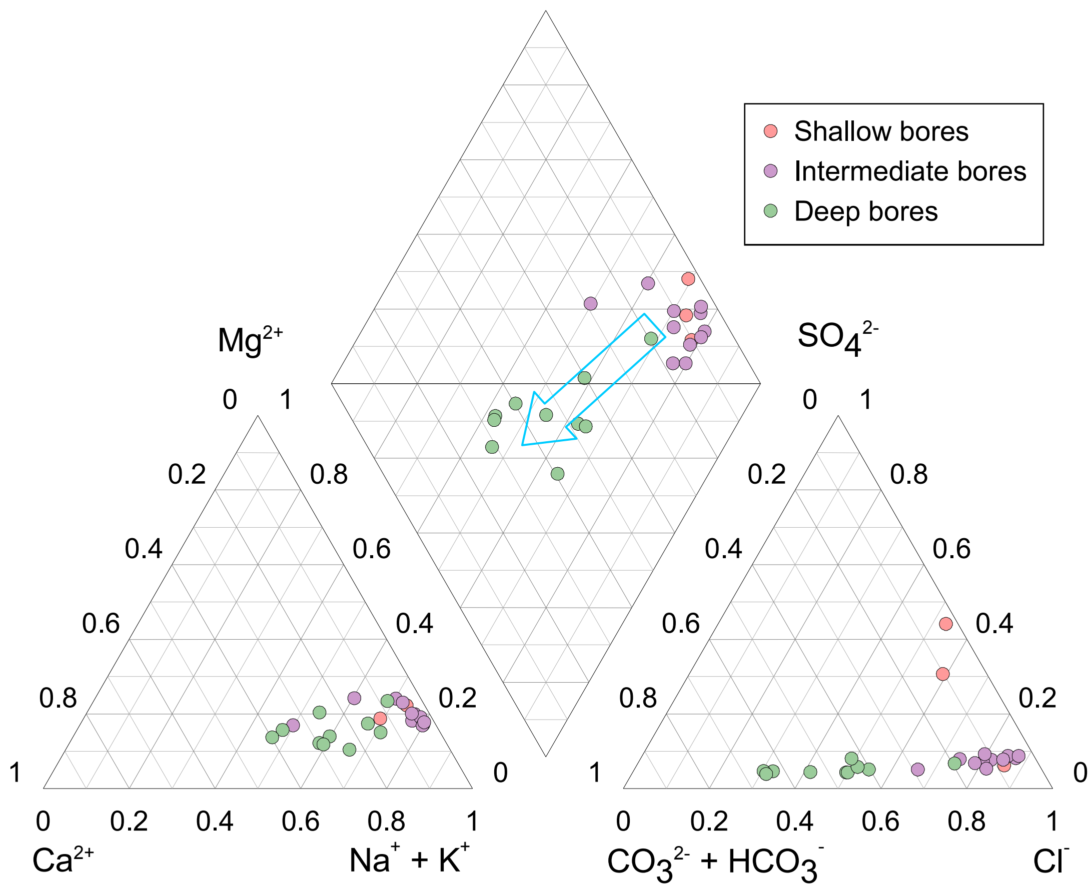


Figure 23 Piper trilinear diagram of selected chemical analyses of groundwaters

Bicarbonate

Bicarbonate concentrations increase significantly with depth and range from 6 mg/L up to 171 mg/L. There is a close association between changes in bicarbonate and pH and depth. Deeper waters have higher concentrations of bicarbonate and to a lesser extent of calcium; as such they are consequently 'harder' than shallower waters and have scaling potential.

Sulphate

The sulphate concentrations in the groundwater are naturally occurring and typically less than 30 mg/L. The higher concentrations in shallow bores, such as 90 mg/L in bores BN15S and BN30S, may have resulted from oxidation of sulphides within peaty deposits.

5.2.2 Dissolved iron

Groundwater is generally high in dissolved iron up to 45 mg/L. The high dissolved-iron concentrations are probably derived from the presence of pyrite (iron sulphide) in the shale interbeds or possibly the reduction of ferric oxides in ferruginous horizons.

The dissolution of iron is common due to the reducing conditions in the Leederville aquifer.

5.2.3 pH

The pH of groundwater ranges from 4.9 to 7.8 (Fig. 24). Shallow groundwater, less than approximately 70 m depth, generally has pH values of less than 6. The low pH groundwater in shallow and intermediate parts of the aquifer is believed to be the product of pyrite oxidation. Groundwater pH of less than 5.5 has a significant corrosion potential.

The deeper groundwater is typically neutral (pH 6.5 to 7.5). These waters are high in bicarbonate which acts as a buffer producing more neutral conditions.

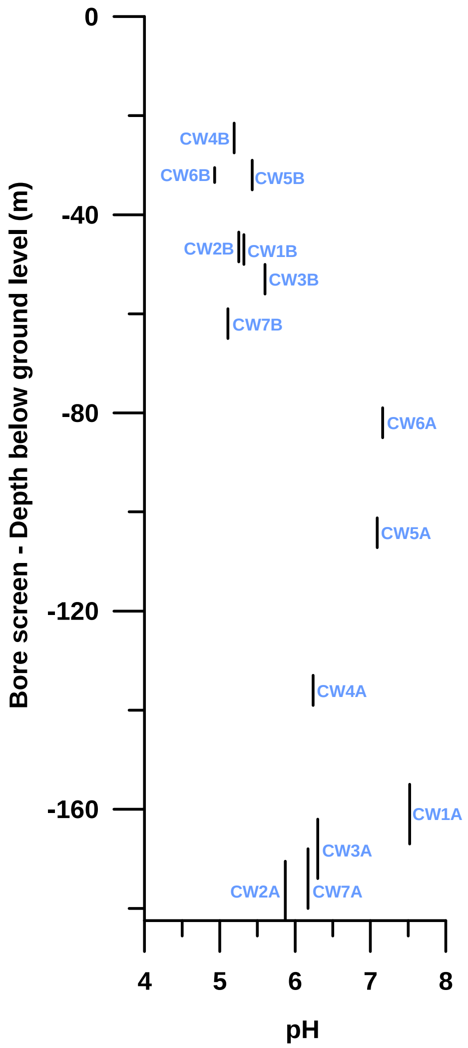


Figure 24 Plot of pH and depth in selected bores

6 Groundwater age

A program of sampling and analysis of groundwater age was undertaken by CSIRO Land and Water Science (Turner and Dighton, 2008). The objective was to provide estimates of groundwater age along a north-south transect paralleling the direction of groundwater flow, as a calibration tool for estimating recharge rates and groundwater travel times in the Leederville aquifer.

Air-free groundwater samples were collected from 24 bores at ten separate locations and up to three depth intervals within the aquifer. The different intervals were considered representative of the different members within the Leederville aquifer. The samples were collected from bores orientated along the direction of groundwater flow from the flow-divide northward to Geographe Bay and in a southerly direction toward Margaret River. A full discussion of the sampling and analysis protocol is given in Turner and Dighton (2008).

Techniques for groundwater age dating included measurements of carbon-14 (^{14}C) activity and concentrations of chlorofluorocarbons (CFC). The presence of CFC–12 is a useful indicator of groundwater recharged in the past 50 years when industrial production of these compounds began. Carbon–14 provides an estimate of groundwater age for older waters up to 35 000 years. This dual tracer approach was adopted in order to determine the extent and mixing of ‘recent’ and ‘old’ groundwater.

Results from the groundwater age study are presented in Table 6. Carbon–14 ages and the inferred isochrons have been plotted on a south-north hydrogeological cross-section shown in Figure 25.

6.1 CFC dating results

CFCs are man-made organic compounds which have been produced over the past 50 years for a number of industrial and domestic purposes. They have been used extensively across the globe in refrigeration, air conditioning and aerosols, which is led to steadily increasing concentrations of CFC in the atmosphere. Consequently, the presence of CFC in groundwater indicates rainfall recharge during the past 50 years.

Concentrations of CFC were detected in the shallow bores BN15S and BN30S, intermediate bores BN15I and BN30I on the Swan Coastal Plain, and intermediate bore CW4B on the Blackwood Plateau. It can be postulated that there is active, modern groundwater recharge taking place at these sites.

Strangely, CFCs were not detected in shallow bore BN25S, located in the lower Buayanyup catchment, probably due to discharge from the Leederville aquifer preventing rainfall recharge. In contrast, bores BN15 and BN30 are located in the Carbunup catchment and the upper Buayanyup catchment with downward potentiometric heads and more likely to be areas of active, modern recharge.

The presence of CFCs in bores CW4B and CW7B suggests that there may be active mixing of younger and older groundwaters in the Leederville aquifer. This is most likely to occur in more active recharge zones on the Blackwood Plateau. Except for these two bores, there were no other confirmed CFCs in the Leederville aquifer.

6.2 Carbon-14 dating results

The residence time of ‘older’ groundwater within an aquifer may be estimated using the natural abundance of carbon–14. The determination of carbon–14 activity in groundwater has become a widely used tool for determining groundwater age relationships and absolute groundwater age (Turner and Dighton, 2008).

Carbon–14 is continually produced in the upper atmosphere by the action of cosmic rays on nitrogen atoms. It is quickly oxidised to CO_2 which enters groundwater in the unsaturated zone as dissolved CO_2, and as carbonate and bicarbonate ions.

The radioactivity decay of carbon–14 (half-life of 5730 years) can be used as a measure of the carbon residence time after the carbon–14 has moved below the watertable. It is therefore suggested that carbon–14 can be used for determining groundwater residence times of up to 35 000 years.

Table 6 shows the carbon-14 results in order of increasing groundwater age. There is a noticeable trend of increasing groundwater age with depth.

6.1.1 Superficial aquifer

Carbon-14 results for bores BN15S, BN25S and BN30S suggest young groundwater is present within the superficial aquifer. The youngest groundwater in the superficial aquifer is present in bores BN30S (modern) and BN15S (600 years), compared to the relatively older groundwater (3300 years) in bore BN25S (Table 6).

The young groundwater age in bores BN30S and BN15S is indicative of modern, direct rainfall recharge into the superficial aquifer. The older groundwater at bore BN25S, located in the lower Buayanyup catchment and an area of upward potentiometric head, suggests potential mixing with deeper groundwater from the Leederville aquifer.

6.1.2 Leederville aquifer

The age of the groundwater in the Leederville aquifer increases rapidly with depth (Fig. 25). The results exhibit a significant trend of increasing groundwater age with depth confirming the presence of shallow and deep groundwater flow systems.

The shallow flow system, related to the Quindalup, Mowen and Upper Vasse Members, has indicative groundwater ages between 1000 and 9000 years, while the deeper flow system associated with the Lower Vasse and Yelverton Members has indicative groundwater ages of between 11 000 and 30 000 years.

Groundwater age distribution within the Leederville aquifer confirms that groundwater age increases along the direction of groundwater flow (Fig. 25). The youngest groundwater in the Leederville aquifer is found in bores CW2, CW3 and CW7 (1300 to 3800 years), which suggests significant groundwater recharge in the vicinity of the flow divide. Groundwater becomes progressively older, up to 29 000 years, towards Margaret River and the coast.

Table 6 Carbon–14 results for selected bores

Monitoring Bore	Top of screen (m bgl)	Bottom of screen (m bgl)	Carbon-14 age (years)
BN30S	2.5	5.5	0
BN15S	4	7	600
BN25S	3.5	9.5	3300
BN30I	20	26	6050
BN25I	22.4	25.4	3700
CW4B	21.5	27.5	5320
BN15I	27	30	9200
CW6B	30.5	33.5	2790
CW5B	29	35	5020
CW2B	43.5	49.5	1280
CW1B	44	50	1710
CW3B	50	56	3300
CW7B	59	65	3800
BN15D	74	80	16100
CW6A	79	85	26670
BN25D	91	97	20700
BN30D	91	97	24550
CW5A	101.2	107.2	21560
BJM1B	116	122	26080
CW4A	133	139	23250
CW1A	155	167	28000
CW3A	162	174	15560
CW7A	168	180	11460
CW2A	170.5	182.5	11430

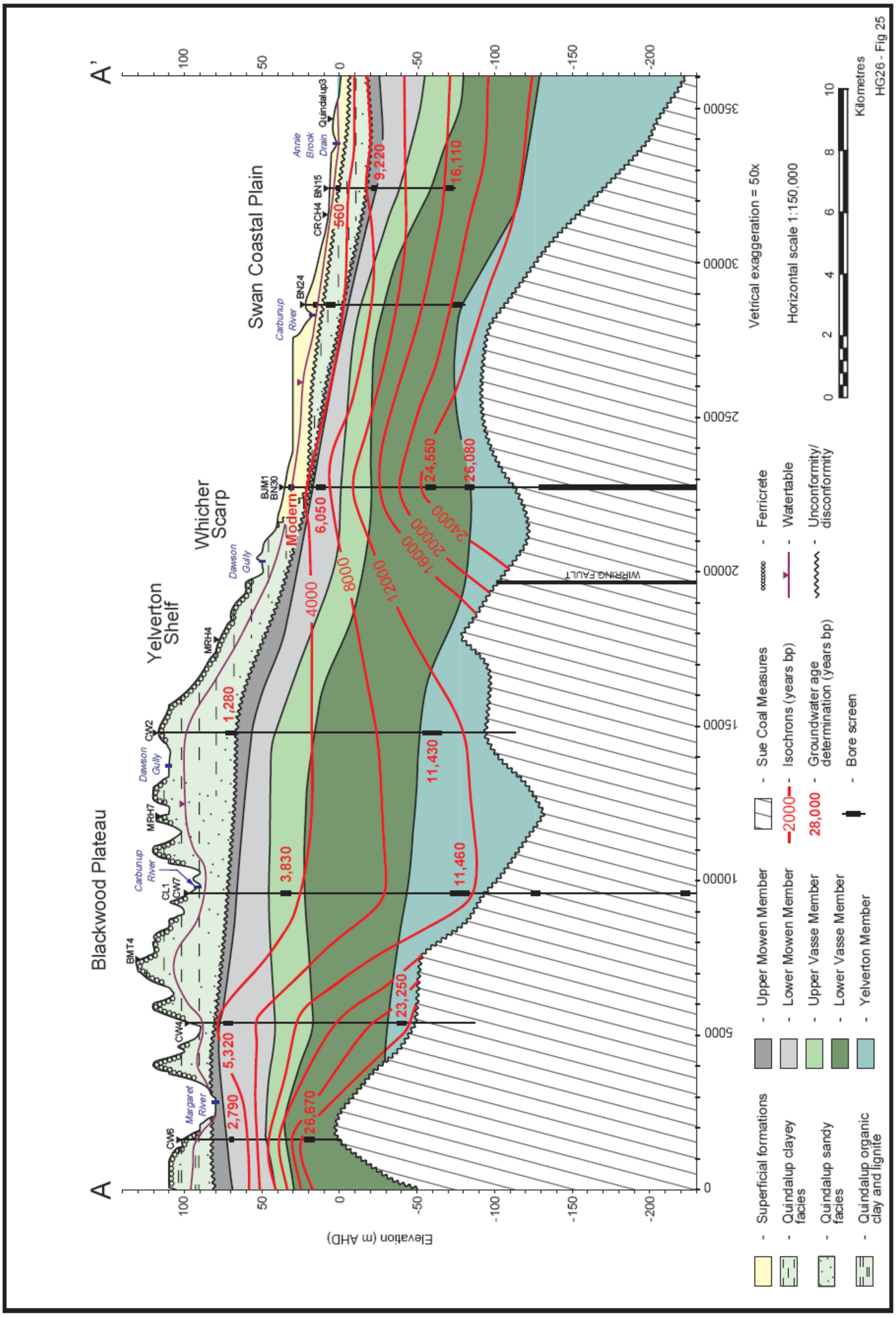


Figure 25 Distribution of groundwater age in the Leederville aquifer

7 Groundwater resource development

7.1 Estimation of groundwater resources

Current allocation limits in the Leederville aquifer are based on estimates of throughflow by Hirschberg (1989). The amount of steady state throughflow on the Vasse Shelf was estimated at 1.6 GL/yr; however, due to aquifer thickness and additional recharge the allocation limit was set at 6.4 GL/yr for the previous Broadwater-Jindong, Quindalup-Vasse and Cowaramup subareas (WAWA, 1995).

Thorpe and Baddock (1994) estimated groundwater resources in the Leederville aquifer, based on groundwater dating. It was estimated that the shallow portion of the Leederville aquifer received 8.4% of rainfall recharge (80 mm/yr) while the deeper Leederville aquifer received about 2% of rainfall recharge (20 mm/yr). Johnson (2000) applied these recharge rates to the Cowaramup subarea and suggested that 16 GL/yr and 4 GL/yr recharges the shallow and deep Leederville aquifer respectively.

The estimates by Johnson (2000) suggest that the current allocations from the Leederville aquifer are considered conservative and that more groundwater could be allocated. As the Cowaramup subarea is the recharge area for the Dunsborough–Vasse subarea, it is important that a reassessment of the allocation limits in this subarea is also considered.

7.2 Current use and water demand

Groundwater usage is dominated by the horticultural and viticultural industries. There is also town water supply at Quindalup in the north-west of the study area. Actual groundwater usage can only be estimated as there is poor metering of abstraction, especially from the numerous small horticultural users.

At present, the licensing and allocation of groundwater resources is managed under the Busselton–Capel Groundwater Area — Management Plan (WAWA, 1995). As a result of the South West Yarragadee proposal (Water Corporation, 2005), the Department of Water recognised the need to update its management plan to incorporate the improved understanding of groundwater resources as well as consider increased regional water demand from irrigation and the potential effects of reduced rainfall.

A new water allocation management plan for the South West groundwater areas (Department of Water, *in prep*) is in final draft and has been distributed for public comment at the same time as the compilation of this document. In this new management plan, the groundwater allocation for the Leederville aquifer in the Cowaramup subarea is proposed to increase from 350 ML/yr to 1.5 GL/yr, based on initial results from this investigation and the installation of the new, more comprehensive monitoring bore network.

Despite the changes in the Cowaramup subarea, the Leederville aquifer is slightly over allocated in the Dunsborough–Vasse subarea (Table 7). The enforcement of the groundwater allocation limits in WAWA (1995) has meant that demand for water is at critical levels with many applications for groundwater allocations being refused or left pending. It is predicted that groundwater demand to meet regional development and expansion will only increase into the future.

Currently, most licensed groundwater allocations in the superficial and Leederville aquifers are concentrated within the Swan Coastal Plain near Jindong and the Carbunup River valley (Fig. 26). In contrast, groundwater in the Cowaramup subarea is relatively under-utilised with abstraction from soaks and dams intersecting the watertable and a small number of bores within the shallow Leederville aquifer.

Table 7 Groundwater resource allocation from aquifers

Groundwater subarea	Aquifer	Allocation limit (kL/year)	Current licensed allocation (kL/year)	Estimated exempt use (kL/year)	Water available (kL/year)
Cowaramup	Superficial	900 000	619 700	50 000	230 300
	Leederville	1 500 000	724 000	0	775 200
Dunsborough–Vasse	Superficial	4 500 000	3 333 050	500 000	666 950
	Leederville	5 400 000	5 425 595	0	-25 595

There are a number of licensed surface water allocations from permanent pools in the Margaret River (Fig. 27) in the Cowaramup subarea. At present, about 530 ML/year of surface water is allocated in the study area. Most surface water demand is focused around Margaret River and its tributaries, probably because there are no available groundwater allocations from the Leederville aquifer. To the west of the study area, the Water Corporation have a surface water allocation of 1 GL/year for the Margaret River town water supply.

7.2.1 Superficial aquifer

Current abstraction

There is widespread groundwater abstraction from shallow bores within the superficial aquifer. More than 3.3 GL/year of groundwater is allocated throughout the Swan Coastal Plain (Table 7). The thin, clayey nature of the superficial aquifer means that bore yields are generally very small with most groundwater licences being under 50 000 kL/year. There are larger licences, up to 250 000 kL/year, where groundwater is abstracted from the Yoganup Formation at the base of the Whicher Scarp.

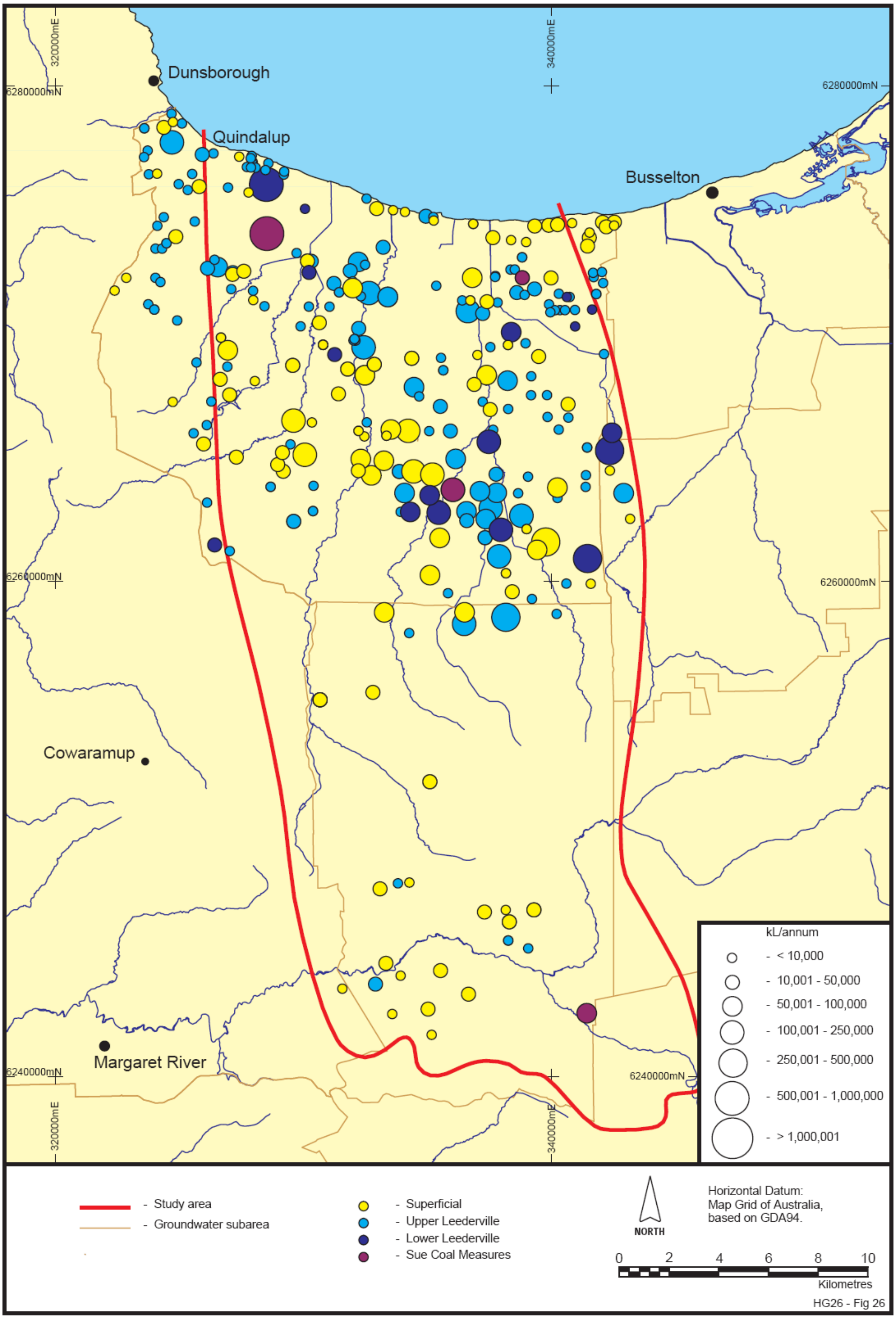


Figure 26 Licensed groundwater allocation (May 2008)

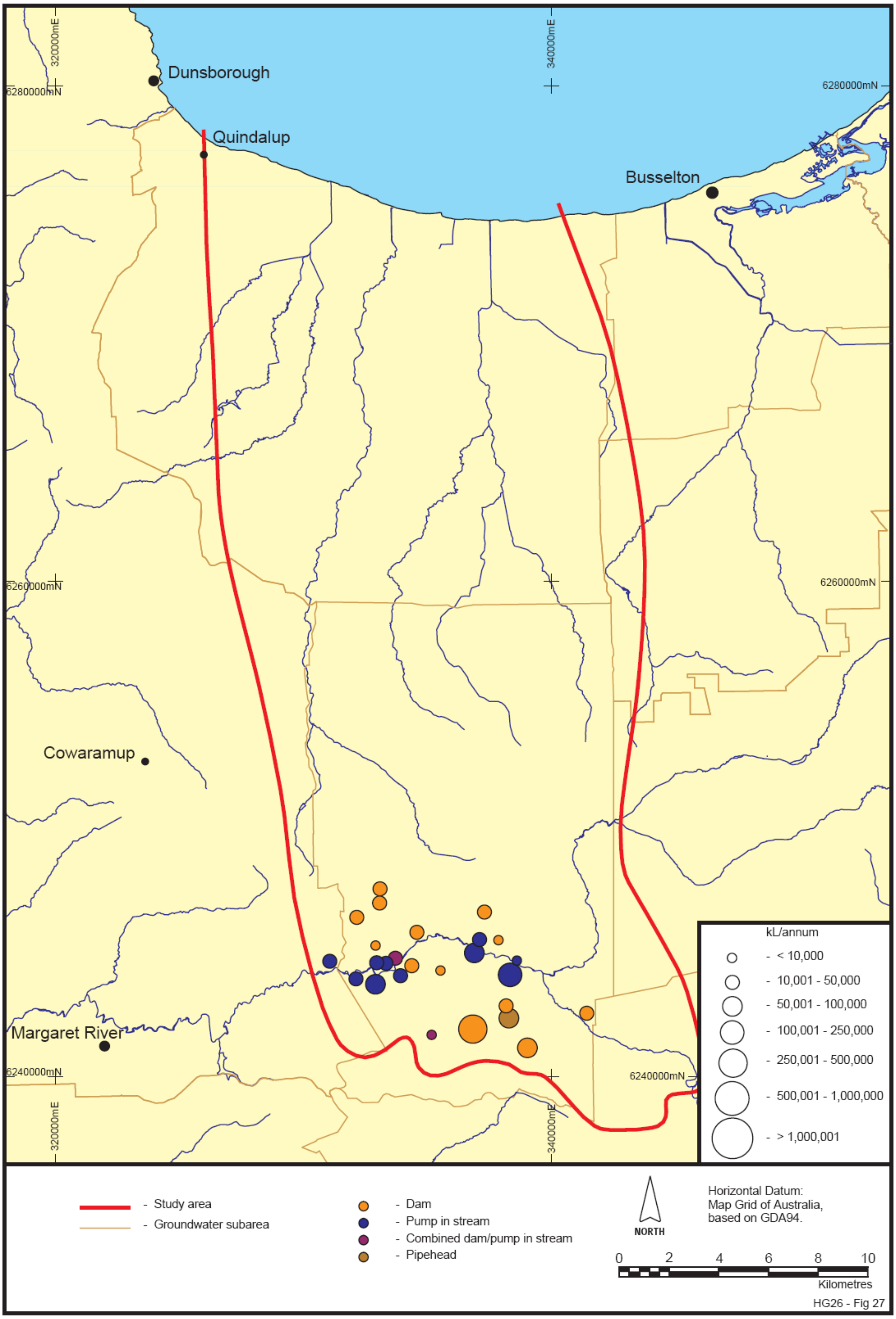


Figure 27 Licensed surface water allocation (May 2008)

For allocation purposes, there is a superficial aquifer in the Cowaramup subarea to account for shallow groundwater abstraction from the Leederville aquifer, which includes soaks and dams excavated below the watertable. There are no superficial formations in the subarea, as such it will be recommended that the aquifer is renamed either 'surficial' or 'shallow Leederville'.

Effects of abstraction

Groundwater abstraction is generally well spread across the superficial aquifer. A comparison of water level data presented by Hirschberg (1989) and current monitoring data in 2008 has shown a slight decline in water levels of about 0.1 to 0.5 m over 20 years. There has been no major localised distortion of water level contours due to over-abstraction, suggesting current allocation limits are sustainable and in balance with recharge.

There has been a contraction in the area of upward heads from the Leederville aquifer, which is restricted to an area near the coast and along the Buayanyup River. It is probably related to abstraction from the Leederville aquifer rather than over-abstraction of the superficial aquifer.

Bores BN24S and BN30S show a significant increase in downward heads from the superficial aquifer to the Leederville aquifer in the period from 1985 to 2006. This differential in downward head is a direct result of local abstraction from the deeper Leederville aquifer.

Potential abstraction

There is still groundwater allocation available in the superficial aquifer within the Jindong, Broadwater, Quindalup and Vasse subareas (Table 7). This is largely due to the superficial aquifer being extremely thin, clayey and unusable in most localities.

7.2.2 Leederville aquifer

Current abstraction

In the Carbunup River valley and around the horticultural precinct of Jindong, there is large groundwater abstraction from the Leederville aquifer. Most abstraction is primarily during the summer months. Water levels in the Leederville aquifer show quite dramatic fluctuations related to this abstraction; however, water levels always tend to fully recover during the winter.

Total groundwater allocation from the Leederville aquifer in the study area is 7.2 GL/year. The existing management plan (WAWA, 1995) separated the Leederville aquifer into an Upper Leederville and Lower Leederville; however, this separation has been removed in the proposed management plan by Department of

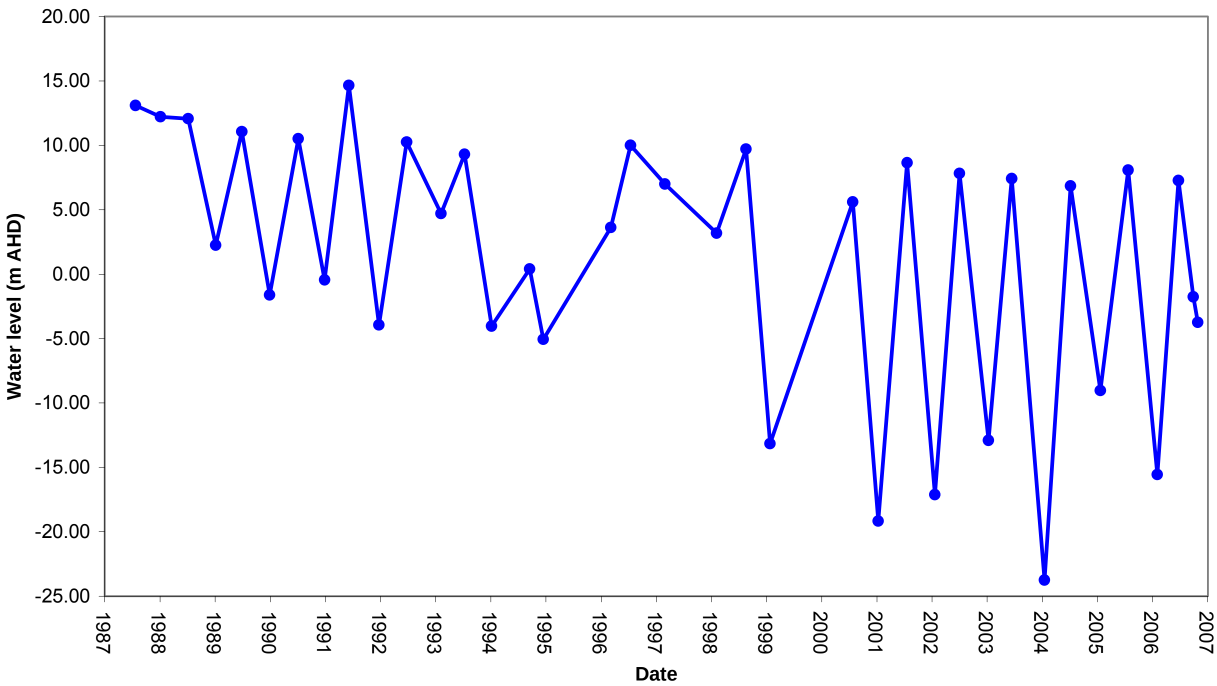
Water (2008). The purpose of the separation was to encourage full utilisation and to spread abstraction deeper into the aquifer.

Effects of abstraction

There are long-term hydrographs with more than 10 years of data for many monitoring bores on the Swan Coastal Plain. There has been a small decline in water levels between 1989 and 2006 in both the intermediate bores (0.1 to 4.5 m decline) and the deep bores (0.5 to 5 m decline).

Some hydrographs show short-term depressurisation of the deeper Lower Vasse and Yelverton Members related to intense periods of groundwater abstraction. These impacts are considered highly localised and relate to closely-spaced horticultural water abstraction along the Carbunup River (bore BN24D – see Figure 28), around Jindong (bore BN30) and the Quindalup town water supply borefield (bore SWI2). In all cases, potentiometric levels have always fully recovered by the end of the winter.

Figure 28 Hydrograph for Bore BN24D



Limited long-term hydrographs for the Cowaramup subarea at bores CL1 and CL2 show relatively stable conditions. There may be a slight decline in the order of 1 to 2 m between 1987 and 2007 in the Leederville aquifer, which is probably related to declining annual rainfall rather groundwater abstraction (Fig. 28).

It is also unknown whether the saltwater interface has migrated landward as a result of changing water levels across the Swan Coastal Plain. The main area of concern is in the vicinity of the Quindalup town water supply.

Potential abstraction

Areas of potential future abstraction will have to be carefully evaluated. Johnson (2000) suggested that there are groundwater resources potentially available in the Cowaramup subarea, particularly to the north of Margaret River. The primary purpose of this study is to reassess the allocation limits in the Leederville aquifer and determine whether these allocation limits can be modified with negligible impact.

It will be necessary to evaluate the impact on neighbouring subareas and Margaret River pools using a numerical groundwater-flow model before the allocation limits can be modified. Hydrographs are showing little to no long-term water level decline due to abstraction; as such, it is considered there is still scope for increasing allocation limits in the Leederville aquifer.

7.2.3 Sue aquifer

Current abstraction

Current licensed allocation from the Sue aquifer is 1 GL/year, largely abstracted for the Quindalup town water supply. There is still a further 3 GL/year of groundwater allocation available (Department of Water, *in prep*).

Effects of abstraction

There are insufficient monitoring bores in the Sue aquifer to assess the impacts of abstraction. The hydrographs for the bore BJM1A show large water level fluctuations related to groundwater abstraction from the Leederville aquifer in the Jindong area.

Potential abstraction

The Sue aquifer is considered to be a localised aquifer system. Previous groundwater exploration has failed to identify sustainable, long-term groundwater resources. There is only potential for a high-yielding bore where a fracture in the sandstone or coal seam is encountered.

7.3 Environmental considerations

There are two important environmental considerations in the study area: climate change and maintaining groundwater dependent ecosystems. These two issues must be evaluated and factored into any long-term assessment of groundwater resource development and management.

7.3.1 Climate change

The South West of Western Australia has been experiencing a drier climate over the past 30 years. There has been a dramatic decline in autumn and early winter rainfall in the order of 10–15% since the mid-1970s (IOCI, 2002). The reduction in rainfall is likely to continue into the foreseeable future with less recharge into aquifers and lower, less frequent streamflow (IOCI, 2005).

Given the uncertainties of climate change, any predictive groundwater modelling must consider declining rainfall as a 'real' possibility. The SWAMS model (Water Corporation, 2005) was calibrated over the 1990 to 2003 period, which was about 7% lower than the long-term average. It has been proposed that modelling of future allocation scenarios must consider even lower recharge rates (Varma et al., 2006).

7.3.2 Groundwater dependent ecosystems

Areas of shallow watertable and groundwater discharge such as springs, wetlands and rivers may potentially support groundwater dependent ecosystems. It is likely that groundwater contribution to surface water features plays an important function in maintaining streamflow and/or wetland water levels.

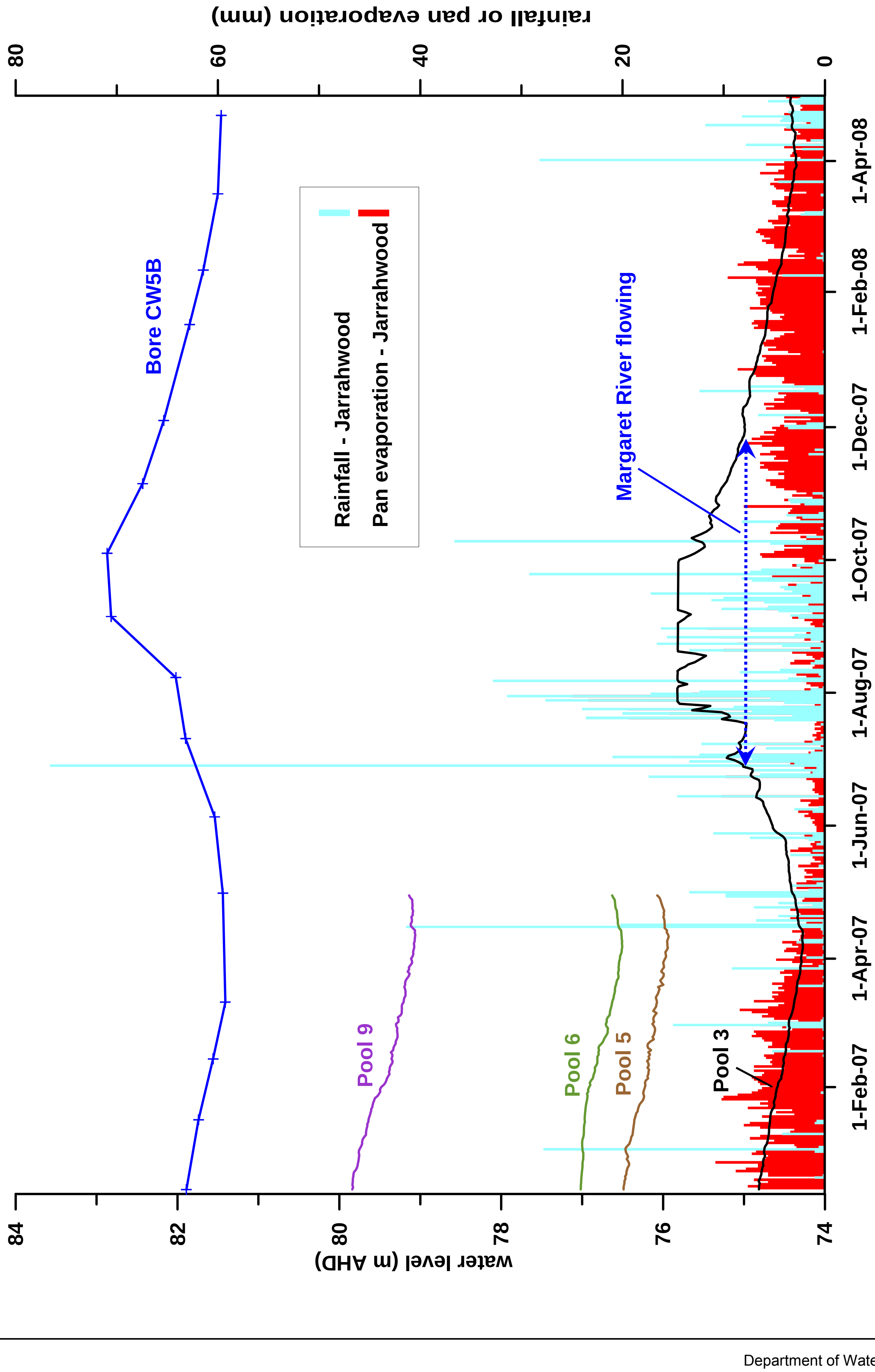
The riverine pools in Margaret River are recognised as an important potential groundwater dependent ecosystem (GDE). This investigation has focused on gaining a better appreciation of the water level changes within the pools and how groundwater resources contribute to their permanency. Though not studied in this investigation, there are other potential GDEs associated with areas of groundwater discharge along the Carbunup River, and coastal wetlands that are considered dependent on shallow groundwater in the superficial aquifer.

There are more than 20 permanent pools along Margaret River. A bathymetric study was undertaken on nine pools to determine pool volumes. Data loggers were also installed in four selected pools to measure changes in water level at 15 minute intervals and to establish indicative water balances for each system. Field conductivity, dissolved oxygen, pH and temperature measurements were also collected at monthly intervals.

Monitoring of groundwater and pool levels confirms that the Leederville aquifer and Margaret River are directly connected. Fluctuations in the pool levels largely mirror water level change in the aquifer, as in bore CW5B (Fig. 29). The general decline in the pools and groundwater levels appears to be closely related to climate (rainfall and evaporation), particularly during the measurement period from December 2006 to April 2007.

The riverine pools are deep, up to 6 m in depth. There are also small daily oscillations in all pools related to evapotranspiration processes. Daily fluctuations of more than 10 mm can be attributed to direct surface water abstraction (Fig. 29). Surface water abstraction is occurring in many of the pools, which amplifies decline in the pool levels. It is apparent that the permanency of the riverine pool is more under threat from direct surface water abstraction than from indirect groundwater abstraction.

Figure 29 Water levels in selected Margaret River pools



The riverine pools are considered extremely robust and it is suggested that managed groundwater abstraction would have negligible impact on pool levels. In most pools, the rate of surface water abstraction is such that the groundwater inflow into the pool replaces any abstracted water, thus maintaining the pool level at or near the regional watertable. However, large surface water abstraction from Pool 9 is resulting in greater rates of pool level decline.

The robustness of the riverine pools is further highlighted by surface water abstraction at Pool 3 (Fig. 5). This pool is more than 6 m deep, has an estimated volume of 36 300 kL and has surface water allocations of up to 48 600 kL/year. Despite surface water allocations being greater than the estimated volume, the pool was permanent throughout the summer with only a small decline in pool level. This highlights that most water abstracted from the pool is derived from groundwater contribution from the Leederville aquifer.

The salinity of pool water appears to be reasonably constant between pools, ranging from 260 to 300 mg/L TDS at the start of summer. There is a slight increase (about 10%) in salinity over the summer months, which can be attributed to evaporation processes. The salinity of the pool water at the beginning of summer is similar to that of groundwater, highlighting direct connection between the pools and the Leederville aquifer.

8 Conclusions

The Cowaramup groundwater investigation involved the installation of fourteen new monitoring bores into the Leederville aquifer within the western portion of the Busselton–Capel Groundwater Area. The improved understanding of the hydrogeology will contribute to a reassessment of groundwater allocation limits for the Leederville aquifer. Additional studies were also undertaken to complement the investigation, including hydrochemistry, groundwater age dating, as well as monitoring of the pools along Margaret River.

The drilling investigation demonstrated that the Leederville aquifer is a multi-layered sedimentary sequence. It can be subdivided into six distinct members (from upper to lower): Quindalup, Upper Mowen, Lower Mowen, Upper Vasse, Lower Vasse and Yelverton. This interpretation was based on stratigraphical relationships and hydrogeological properties; however, it must be noted that the Leederville aquifer is extremely heterogenous in nature with poor lateral continuity of individual beds. The Sue Coal Measures were encountered at the base of the Leederville aquifer in the deepest monitoring bores.

The Leederville aquifer outcrops throughout the Blackwood Plateau. Beneath the Swan Coastal Plain, it is concealed by a thin, unconfined superficial aquifer but is locally interconnected where confining beds are absent. The Upper Vasse Member is considered to be the most promising aquifer within the Leederville aquifer, due to its high percentage of sand beds. The Leederville aquifer becomes more consolidated with depth; hence, permeability will also decrease.

The investigation has confirmed the presence of an east-west groundwater-flow divide in the Leederville aquifer north of the Margaret River, from where groundwater flows to the north and south. There is an active, shallow groundwater system that maintains a number of permanent pools along Margaret River, as well as a more dormant, deeper groundwater system.

Groundwater is generally fresh, less than 500 mg/L TDS, throughout much of Leederville aquifer. Groundwater age dating using chlorofluorocarbons (CFC) and carbon-14 techniques indicates that modern recharge is occurring in the vicinity of the groundwater flow divide. The groundwater becomes progressively older with depth and down gradient along the direction of groundwater flow, up to 29 000 years towards Margaret River and the coast.

There are more than 20 permanent pools along Margaret River, which are considered the important potential groundwater-dependent ecosystem. Monitoring of groundwater and pool levels confirms that the Leederville aquifer and Margaret River are directly connected. The riverine pools are considered extremely robust with managed groundwater abstraction likely to have negligible impact on pool levels. It is considered that the riverine pools are more impacted by direct surface water abstraction than indirect groundwater abstraction.

Results from this investigation will form the basis of a groundwater resource assessment including both the Cowaramup and Dunsborough–Vasse subareas. A sub-regional, numerical groundwater-flow model is being developed to assess the impacts of modifying allocation on groundwater dependent ecosystems and neighbouring subareas. Groundwater modelling outputs will contribute to the setting of new allocation limits in the western part of the Busselton–Capel Groundwater Area.

Appendices

Appendix A – Hydrographs of CW-prefixed bores

This appendix contains the hydrographs for the new monitoring bores installed during the Cowaramup investigation. Hydrographs for the following monitoring sites have been presented:

CW1 Monitoring site - Bores CW1A, CW1B

CW2 Monitoring site - Bores CW1A, CW1B

CW3 Monitoring site - Bores CW1A, CW1B

CW4 Monitoring site - Bores CW1A, CW1B

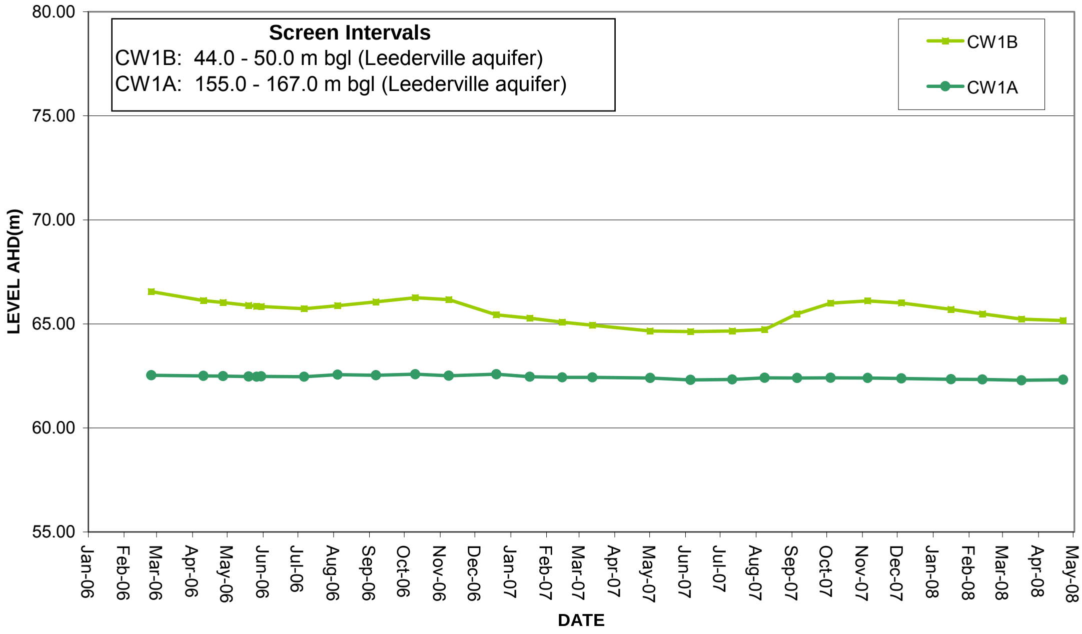
CW5 Monitoring site - Bores CW1A, CW1B

CW6 Monitoring site - Bores CW1A, CW1B

CW7 Monitoring site - Bores CW1A, CW1B

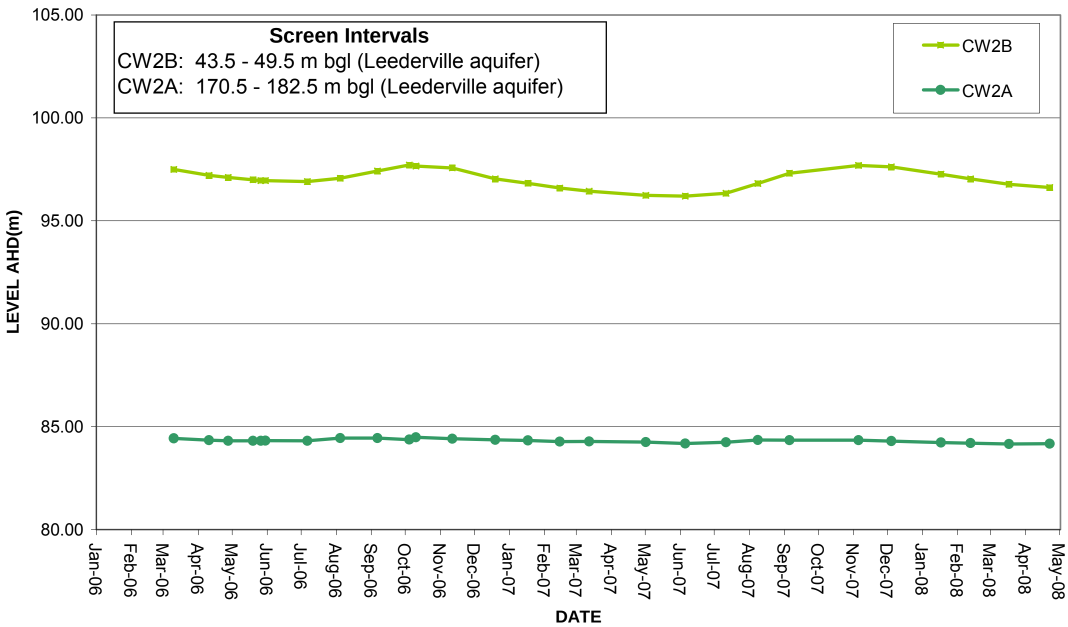
CW1 Monitoring bore site

Easting = 330639 Northing = 6258819 Ground level = 82.53 mAHD



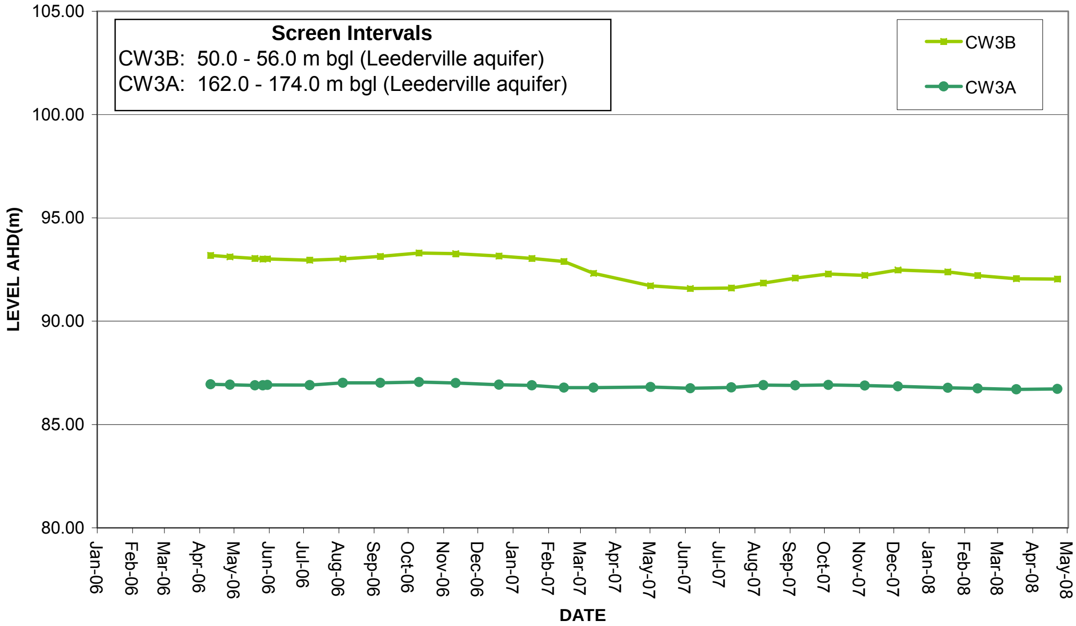
CW2 Monitoring bore site

Easting = 334594 Northing = 6256112 Ground level = 116.70 mAHD



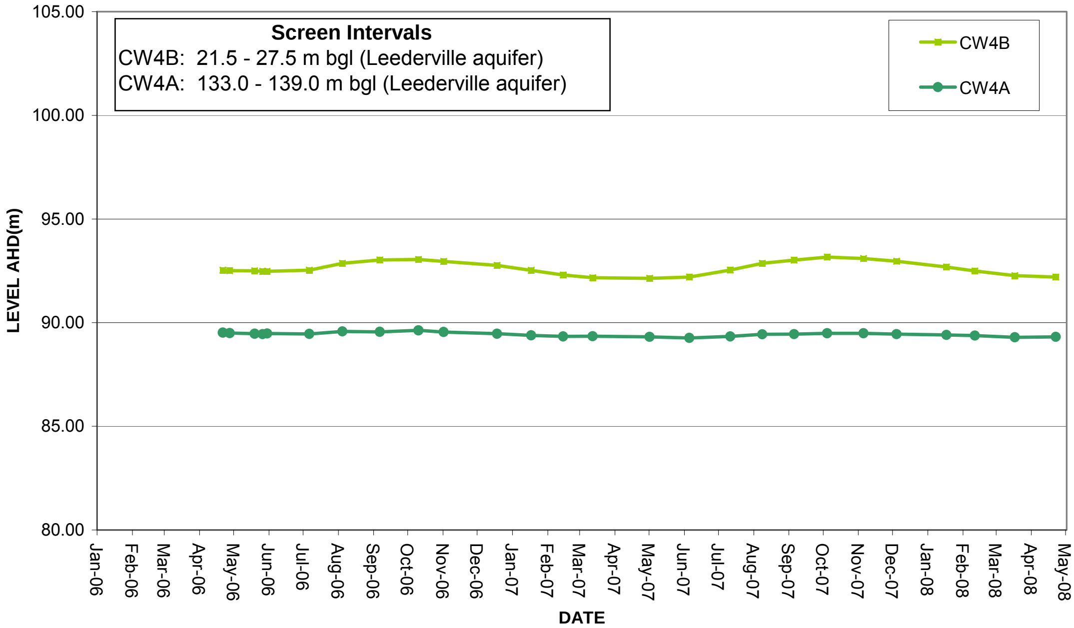
CW3 Monitoring bore site

Easting = 332587 Northing = 6253354 Ground level = 107.79 mAHD



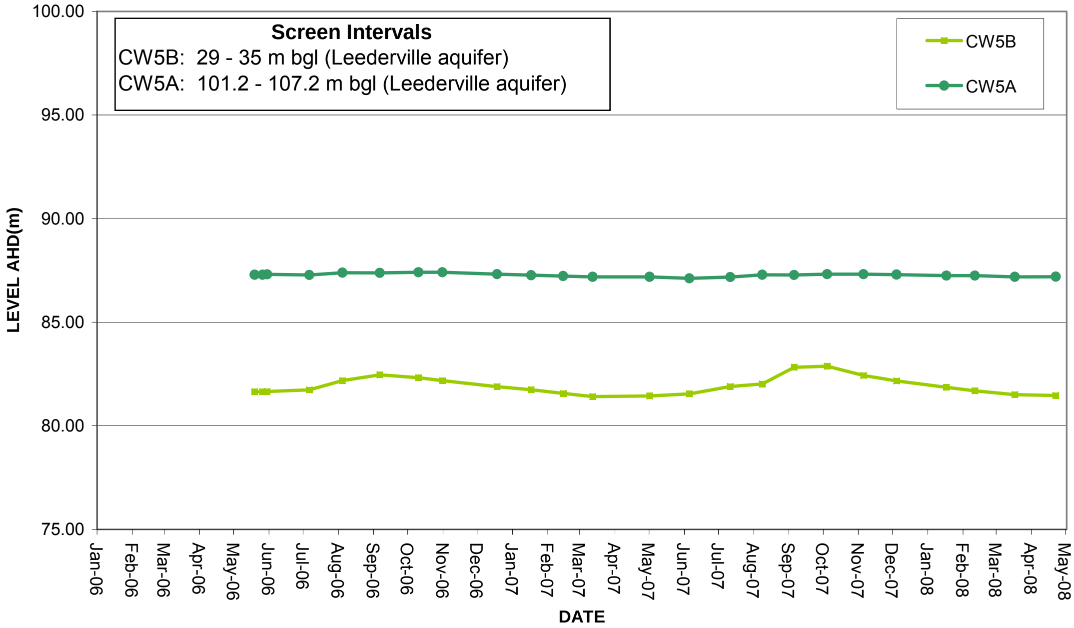
CW4 Monitoring bore site

Easting = 333410 Northing = 6246847 Ground level = 96.09 mAHD



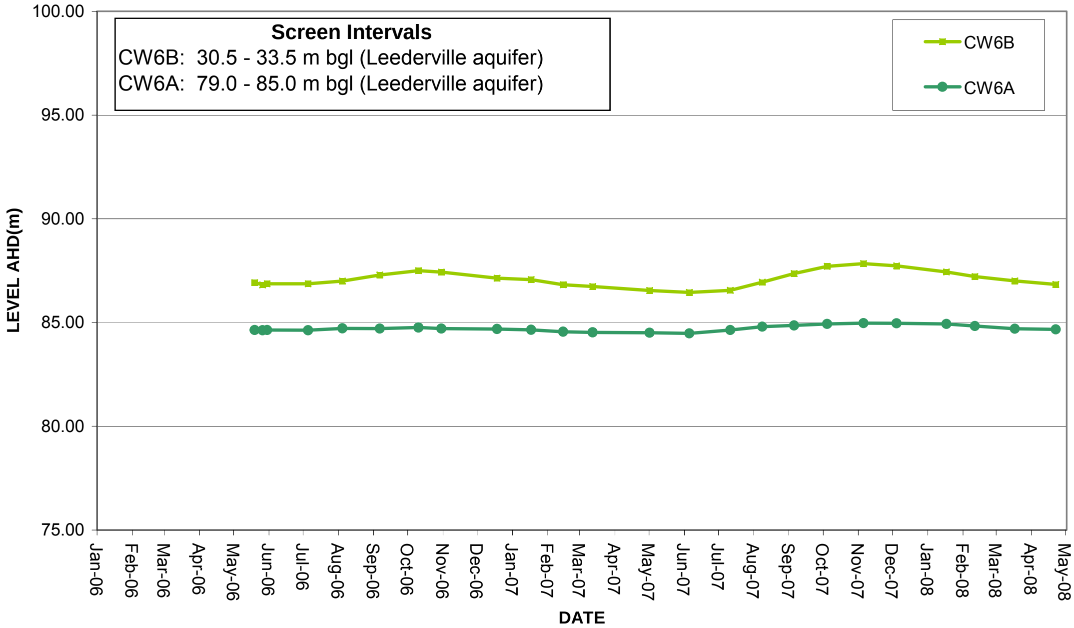
CW5 Monitoring bore site

Easting = 337340 Northing = 6245171 Ground level = 98.32 mAHD



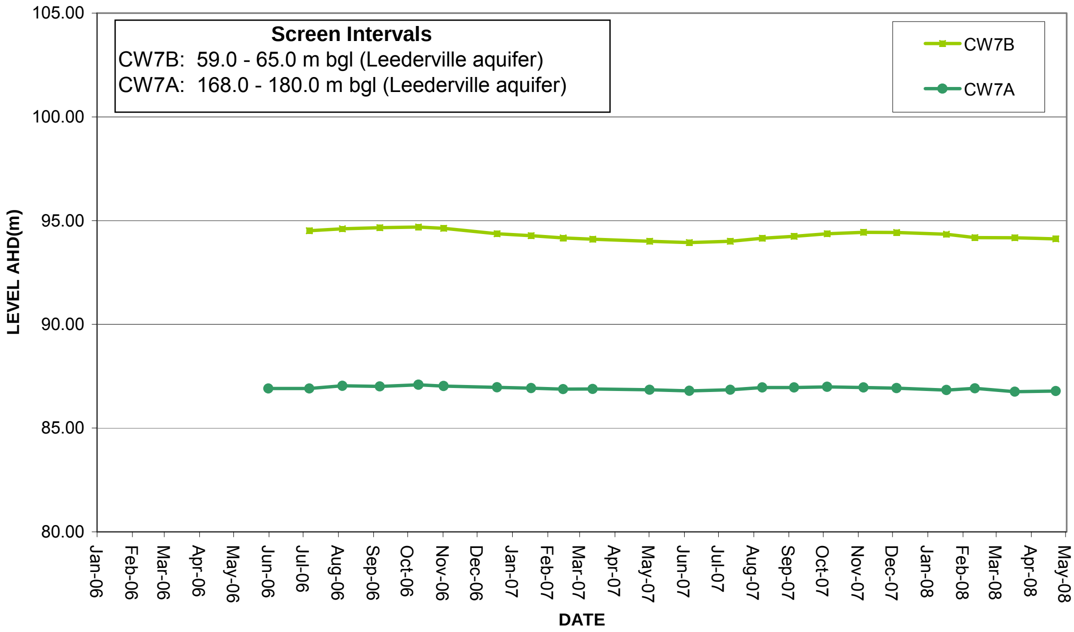
CW6 Monitoring bore site

Easting = 333503 Northing = 6243073 Ground level = 101.49 mAHD



CW7 Monitoring bore site

Easting = 334279 Northing = 6250947 Ground level = 96.78 mAHD



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