Department of Primary Industries and Regional Development
Department of Water and Environmental Regulation
GOVERNMENT OF WESTERN AUSTRALIA
ROYALTIES FOR REGIONS

Albany hinterland
prospective groundwater resources map
Explanatory notes

Hydrogeological Map series
Report no. HM 12
August 2017

Albany hinterland prospective groundwater resources map

Explanatory notes

Department of Water
Hydrogeological Map series
Report no. HM 12
August 2017

Department of Water and Environmental Regulation
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7000
Facsimile +61 8 6364 7001
National Relay Service 13 36 77
www.dwer.wa.gov.au

ISBN (online) 978-1-925524-48-2 ISSN (online) 2208-4207

Acknowledgements

The Department of Water and Environmental Regulation would like to thank the following for their contribution to this publication: Sheryl Ryan, Andrew Maughan and Cahit Yesertener. Review and editing was undertaken by Alex Kern, Scott Macaulay, Jon-Philippe Pigois and Sandie McHugh. This project was made possible by the Western Australian Government's Royalties for Regions program.

Recommended reference

Ryan SA, Maughan A & Yesertener C 2017, *Albany hinterland prospective groundwater resources map explanatory notes,* Hydrogeological map series, HM12, Department of Water and Environmental Regulation, Government of Western Australia, Perth

Cover photograph: View from Albany port to the Albany hinterland.

Disclaimer

The Department of Water and Environmental Regulation was established by the Government of Western Australia on 1 July 2017. It is a result of the amalgamation of the Department of Environmental Regulation, Department of Water and the Office of the Environmental Protection Authority. This publication may contain references to previous government departments and programs. Please email the Department of Water and Environmental Regulation to clarify any specific information.

This publication is available at our website www.dwer.wa.gov.au or for those with special needs it can be made available in alternative formats such as audio, large print, or Braille.

Contents

Figures

Tables

1 Introduction

With its relatively cooler, temperate climate, the Albany hinterland area is considered to have strong potential for agricultural expansion. Also, the area has been recognised in the *Great Southern regional blueprint* (GSDC 2014) as ‘the most significant hotspot for competing water demand in the Great Southern’. Therefore, identifying prospective sources of potable and fit-for-purpose groundwater is essential to provide diversification options for industry and agriculture. The former Department of Water (the department, now the Department of Water and Environmental Regulation) recognised the importance of this in the *Great Southern regional water supply strategy* (DoW 2014a) with Strategy 4 – Investigate groundwater and surface water resources to support regional development.

In 2013 the department began an investigation in the Albany hinterland area to map prospective groundwater resources and provide information on water availability. This project is part of the South Coast Groundwater Investigation, made possible by the Government of Western Australia, Royalties for Regions groundwater availability, investigation and planning initiative.

These explanatory notes accompany the *Albany hinterland prospective groundwater resources map.* The map shows the location, spatial extent, water quality and conceptual hydrogeological cross-sections for four prospective groundwater resource areas:

- King River area
- Kalgan River area
- Manypeaks area
- Nanarup area

The map may be used to guide further investigations to validate the yield, quality and volume of potential water supplies. The map can be downloaded from the Department of Water and Environmental Regulation website at www.dwer.wa.gov.au.

2 About the map

The *Albany hinterland prospective groundwater resources map* shows the interpreted distribution of prospective resources across the investigation area. The Albany hinterland is located on Western Australia's south coast, extending north-west to north-east of the Albany urban area (Figure 1). The area is approximately 1200 km^2 in size and encompasses the localities of Torbay and Redmond in the west and Manypeaks in the east.

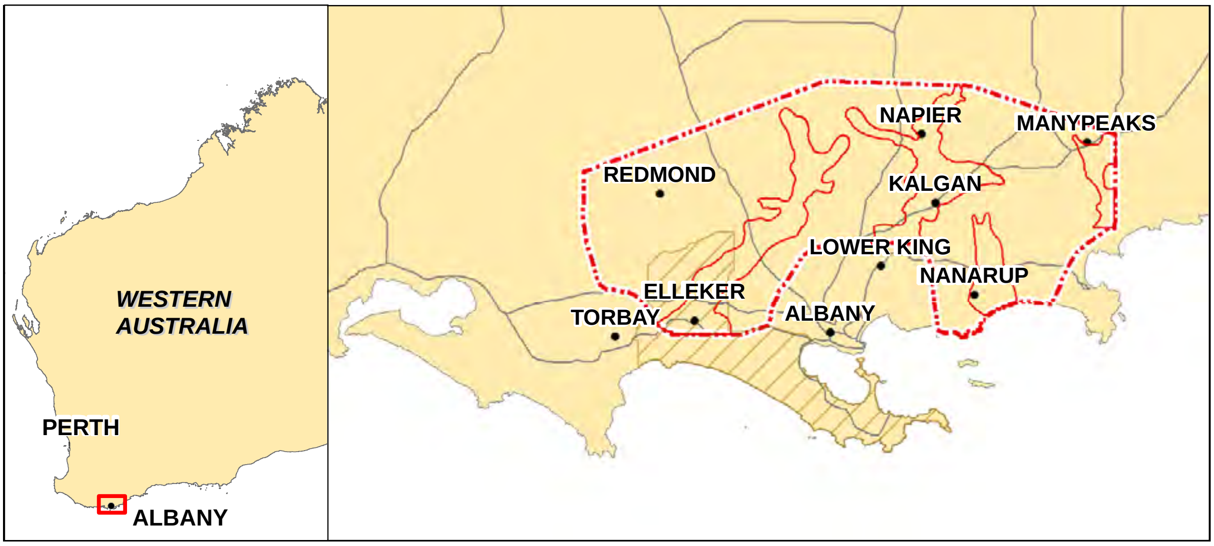


Figure 1 Locality map and investigation area

Four prospective groundwater resource areas were identified through an airborne electromagnetic (AEM) survey, interpretation of existing and new borehole data and surface geology mapping. These resources are the King River, Kalgan River, Manypeaks and Nanarup groundwater resource areas. Table 1 summarises stratigraphy and aquifer details and Figure 2 is a generalised hydrogeological cross-section though the study area.

Groundwater resources suitable for moderate- to large-scale use are stored in sandy sediments of the Werillup Formation, which were deposited within palaeochannels formed in pre-Tertiary drainages (Kern 2007). In the Albany hinterland, palaeochannels are present in the King River and Manypeaks areas where basement erosion is deeper than 0 m AHD.

In the Kalgan River area, the Pallinup Formation is the outcropping formation and is sandy through much of the area. It forms the Pallinup aquifer and provides a local groundwater supply to farmers. It is the watertable aquifer and is connected to the Kalgan River and its tributaries.

In the Nanarup area, several bores confirm the presence of two aquifers: a minor local, unconfined aquifer in the Nanarup Limestone and a palaeochannel infilled by sand of the Werillup Formation, forming the Werillup aquifer. The unconfined aquifer is not monitored and its potential as a groundwater resource is unknown.

A detailed description of how the AEM data was used to develop a depth to basement layer is presented in Appendix A. The depth to basement layer identifies areas of pre-Tertiary erosion in the basement, and where palaeochannels have most likely formed. This layer is available from the department as an ArcGIS raster file. A table summarising details of all bores is given in Appendix B. Bore information is available from the Water Information Reporting (WIR) tool on the Department of Water and Environmental Regulation website at www.dwer.wa.gov.au.

Table 1 Stratigraphy and aquifers in the Albany hinterland

	Geology		**Hydrogeology**	**Location**
Age	**Stratigraphic unit**	**Lithology**	**Hydrostratigraphy**	
Eocene	**Pallinup Formation**	Silt, sand and clay	Pallinup aquifer, minor/local, low productivity	King River, Kalgan River, Manypeaks
	Werillup Formation			
	Nanarup Limestone Member	Limestone, clay	Aquifer, minor/local	Nanarup
	Clay (informal member)	Clay, silt and sand	Impervious (aquitard), no groundwater resources	All
	Sand (informal member)	Sand and lignite	Werillup aquifer, highly productive	King River, Manypeaks,
Proterozoic	*Nornalup Complex*	Clay, gravel, sand (weathered bedrock)	Aquitard – local aquifer where sandy	All
		Granite, mafic gneiss (bedrock)	Impervious, no groundwater resources (aquitard)	All

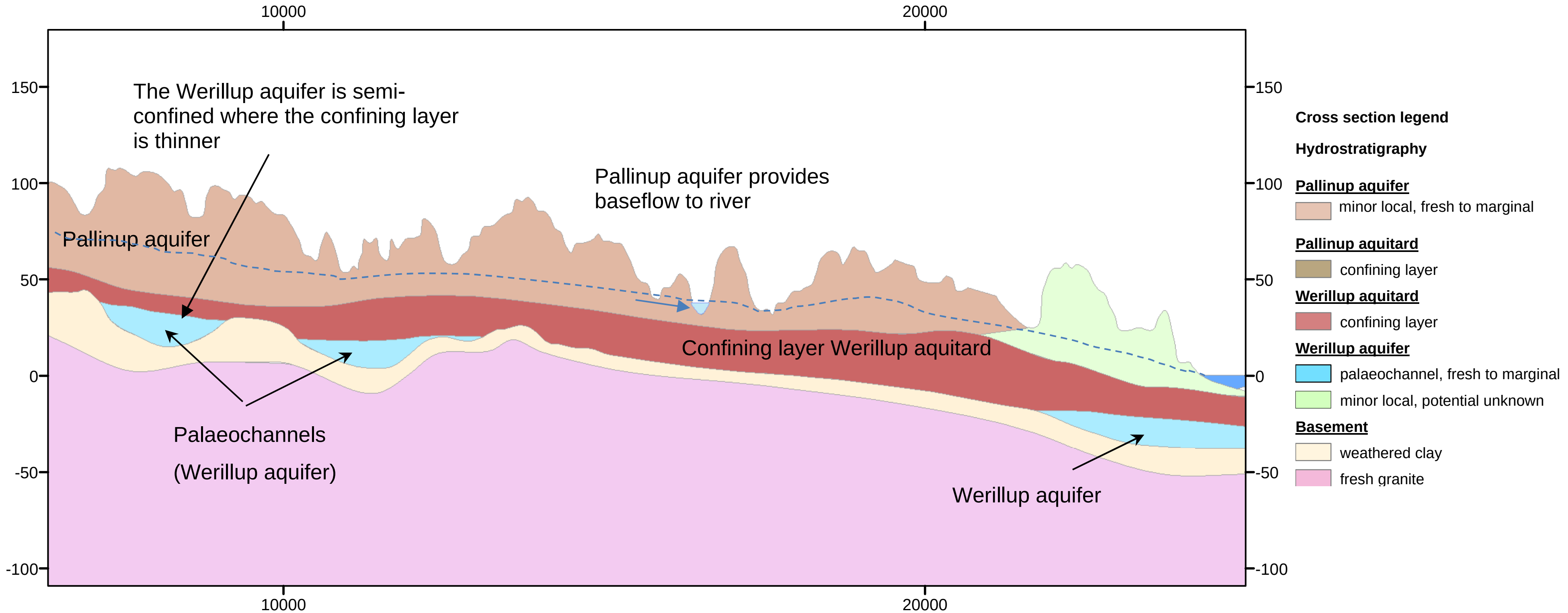


Figure 2 Generalised cross-section of the Albany hinterland

2.1 Groundwater salinity

Each prospective groundwater resource area has been subdivided into zones based on salinity categories. The department categorises salinity into five broad ranges, shown in Table 2, that indicate suitability for various generalised uses. Higher salinity water can often be used if appropriate technologies, crop selection and farming techniques are applied. The salinity categories are based on categories developed by Hem (1970) and are explained in greater detail in the department's *Water Resource Inventory 2014* (DoW 2014b). Most resources in the Albany hinterland are within the fresh to brackish categories.

Where possible, groundwater salinity values are derived from laboratory analysis and are expressed as total dissolved solids (TDS). Where that information is not available, salinity has been estimated from field electrical conductivity (EC) measurements based on Equation 1 (Freeze & Cherry 1979):

$$TDS = A \; x \; C \qquad \text{(Equation 1)}$$

Where:

TDS = salinity expressed as Total Dissolved Solids (mg/L)

A = specific conductance conversion factor (0.55)

C = conductance $(\mu s/cm)$

Table 2 Salinity categories and generalised uses

	Fresh **0–500 mg/L TDS**	**Marginal** **500–1000 mg/L TDS**	**Brackish** **1000–3000 mg/L TDS**	**Saline** **3000–35 000 mg/L TDS**	**Hypersaline** **>35 000 mg/L TDS**
Potable water – desirable					
Potable water – acceptable					
Irrigation					
Industry					

2.2 Groundwater recharge

Groundwater recharge refers to the amount of water that enters an aquifer and is an important factor in determining the quantity of groundwater potentially available for abstraction. For the Albany hinterland groundwater resources, recharge was considered to derive predominantly from rainfall and thus estimated as a proportion of mean annual rainfall. The recharge quantity is expressed in gigalitres per year (GL/yr) in this publication, where one gigalitre is the equivalent to 1 000 000 000 litres or 1 000 000 kilolitres.

Groundwater recharge is presented as a range of values for each groundwater area zone shown on the map. The range is determined from the minimum and maximum concentration of chloride ions in groundwater proportional to the concentration in rainfall.

Analysis for the nearby Albany Groundwater Area (GWA) demonstrates a declining total annual rainfall trend, with a reduction of about 13% observed over the 1969 – 2015 period (Ryan et al 2017). Mean annual rainfall calculated over the 1995 – 2015 period was chosen as representative of current conditions for the estimation of recharge volumes in this study area. Future climate analysis for the Albany GWA projects continuing rainfall decline and recent analysis of the relationship between rainfall and recharge (Ryan et al. 2017) shows that for every unit decline in rainfall, the reduction in recharge can double. Recharge estimates should be considered as indicative only due to the variability of climate and the uncertainties in estimation techniques.

Table 3 summarises groundwater recharge for each resource zone defined on the map. The full methodology used to calculate recharge and storage, along with the uncertainties in the calculations and methodology used, is described in Appendix B — Groundwater recharge methodology.

Table 3 Groundwater recharge estimates

Prospective groundwater resource	Area (km^2)	Mean annual rainfall 1995–2015 (mm)	Recharge (% of annual rainfall)	Recharge range (GL/yr)
King River zone 1	50	795	3.9–14.2	1.5–5.6
King River zone 2 (north)	15	750	2.0–10.6	0.1–1.2
King River zone 2 (south)	12	795	2.0–10.6	0.1–1.0
King River zone 3	16	750	1.4–3.2	0.1–0.4
King River zone 4	1	795	2.0–3.0	0.0–0.02
King River area total	**94**			**1.8–8.2**
Kalgan River zone 1	48	725	1.0–2.0	0.1–0.7
Kalgan River zone 2	6	725	1.0–2.0	0.0–0.1
Kalgan River zone 3	11	725	1.0–2.0	0.0–0.2
Kalgan River zone 4	10	725	3.0–5.0	0.1–0.4
Kalgan River area total	**75**			**0.2–1.3**
Manypeaks area total	**20**	700	5.0–9.0	**0.7–1.3**
Nanarup area total	**30**	755	5.0–8.0	**1.2–1.7**

2.3 Groundwater storage

Groundwater storage refers to the total volume of water stored in an aquifer. It does not reflect the amount of water available for sustainable abstraction.

Total groundwater storage for each resource is listed in Table 4 and is expressed as gigalitres (GL). The aquifer storage volumes were estimated by considering the total area and average saturated thickness of the aquifer units, multiplied by an estimated specific yield value ranging from 0.1 to 0.2. Specific yields are based on specific yield values for similar units in the Perth Basin (De Silva et al. 2013). Aquifers with higher clay or silt content or finer grained sediments have a lower specific yield.

Table 4 Groundwater storage estimates

Prospective groundwater resource	Area (km^2)	Saturated thickness (m)	Specific yield	Storage (GL)
King River zone 1	50	19	0.20	190
King River zone 2 (north)	15	20	0.20	60
King River zone 2 (south)	12	7	0.20	17
King River zone 3	16	11	0.20	35
King River zone 4	1	15	0.20	3
King River (total)	**94**			**305**
Kalgan River zone 1	48	15	0.10	72
Kalgan River zone 2	6	15	0.10	9
Kalgan River zone 3	11	15	0.10	17
Kalgan River zone 4	10	15	0.10	15
Kalgan River (total)	**75**			**113**
Manypeaks area (total)	**20**	**35**	**0.15**	**105**
Nanarup area (total)	**30**	**8**	**0.20**	**48**

3 Prospective groundwater resources

This section discusses area-specific information including our understanding of the geology and conceptual hydrogeology, estimated yields, water quality and what to expect when drilling.

3.1 King River area

Summary

The King River groundwater resource area is located in the western half of the investigation area (Figure 3). Its main groundwater resources are found in a palaeochannel that runs north-east to south-west. The palaeochannel, containing the Werillup aquifer, extends from the northern boundary into the Albany GWA, where the channel outflows to the ocean and is overlain by the Pallinup aquifer. Cross-sections A–A' and B–B' show the distribution and hydrogeology of the Pallinup and Werillup aquifers. More than 50 bores have been drilled across the area, confirming the distribution and hydrogeology.

The Pallinup aquifer is the watertable aquifer and is separated from the underlying Werillup aquifer by a layer of black clay of the Werillup Formation. The Pallinup aquifer is low yielding; however, where it is sandy enough, it may be suitable for small-scale abstraction.

The Werillup aquifer is the main target aquifer for this area and contains fresh to brackish groundwater. Potential water supply from the Werillup aquifer ranges from 1.8 to 8.2 GL/yr.

Pallinup aquifer

In the King River area, the Pallinup Formation is an unconfined aquifer of low permeability. It consists of unconsolidated silts interbedded with very fine- to fine-grained sand beds and discontinuous clay layers. At the surface, sediments are lateritic with minor sands and clays. Thicknesses range from 7 to 40 m, with an average thickness of 15 m. The formation is thin where depressions in the landscape occur and thinnest to the north-west of Phillips Brook.

The Pallinup aquifer has low permeability and may potentially provide a small groundwater supply, but only locally due to the aquifer's irregular nature. Data on the aquifer's properties is limited and no storage estimates have been made. Where a suitable supply has been determined, bores have been successfully constructed with yields ranging from 4 kL/d (< 0.1 L/s) to 130 kL/d (1.5 L/s). Water quality is marginal to brackish, with salinities ranging from 920 to 2900 mg/L TDS.

Werillup aquifer

The Werillup aquifer is a confined/semi-confined aquifer of moderate permeability, and is the most prospective aquifer in the King River area. The aquifer is overlain by a black carbonaceous clay of the Werillup Formation and is underlain by clayey weathered rock from the granitic basement. The Werillup aquifer consists of a grey to dark grey, fine to very coarsely grained sand with minor lignite and pyrite.

The aquifer is thickest in the central part of the palaeochannel with a maximum intersected thickness of 24 m. Clay content increases along the edges of the palaeochannel, as the channel sands become thinner.

The Werillup aquifer has the potential to provide an annual groundwater supply between 1.8 to 8.2 GL/yr. Airlift yields vary from 40 kL/d (0.5 L/s) along the channel edges to more than 1000 kL/d (> 12 L/s) in the central channel. Groundwater is fresh in the west of zone 1 where the overlying clay is thin and has a higher silt/sand to clay ratio, allowing greater leakage from the overlying Pallinup Formation. In the north, the Werillup aquifer is confined and has lower transmissivity, resulting in higher groundwater salinities and lower airlift yields. Water quality is freshest in the south (Werillup area zone 1) where the overlying clay is thinner, allowing higher recharge. The groundwater quality is marginal to brackish across the remaining zones.

In the north-west, a potential tributary of the palaeochannel has been interpreted from the AEM where the depth to basement is deeper than 0 m AHD. As no bore information is available in this area, the potential for fresh groundwater supply is unknown.

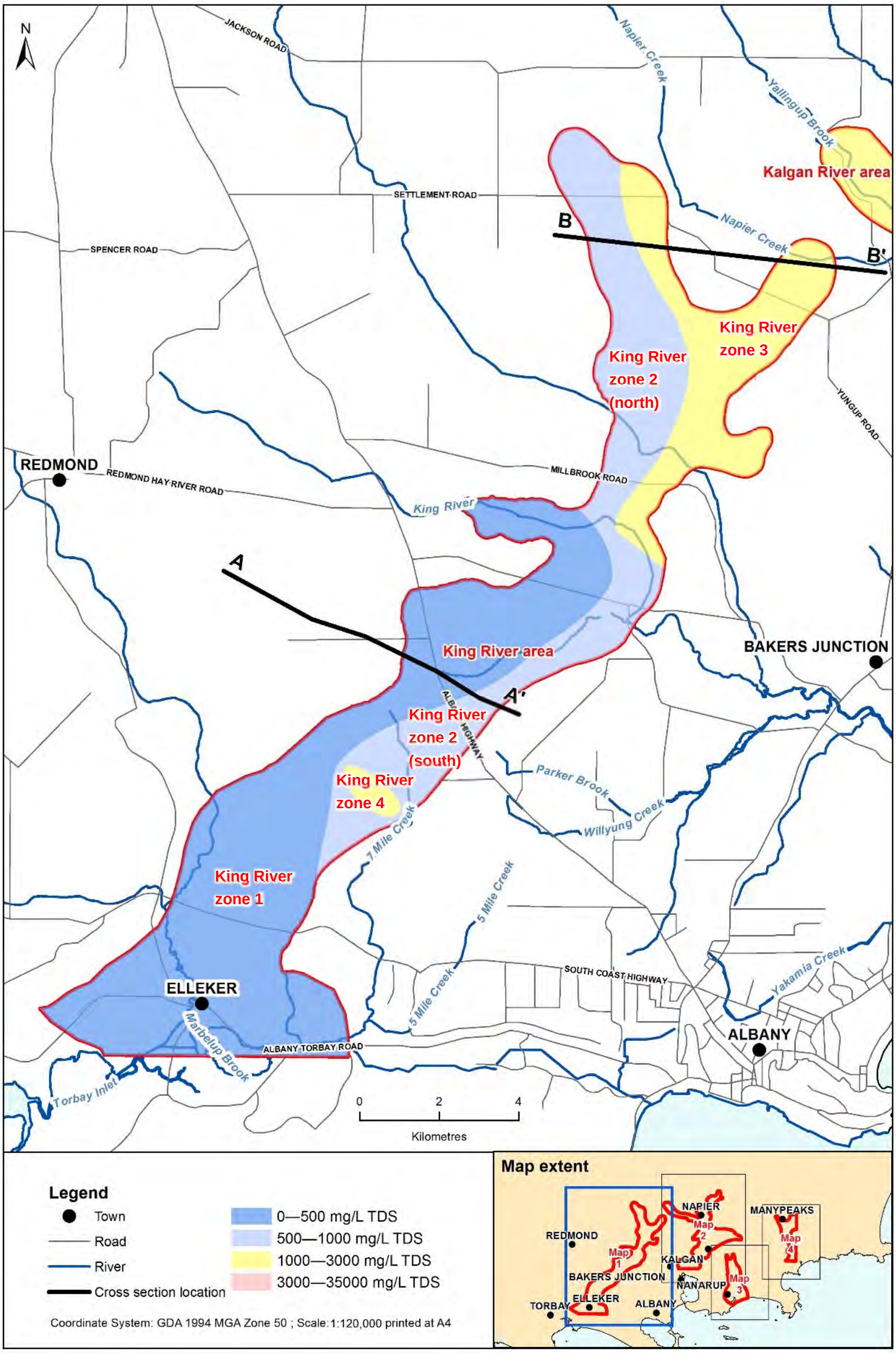


Figure 3 King River area location map

3.2 Kalgan River area

Summary

The Kalgan River groundwater resource area is located in the centre of the investigation area. Its groundwater resources are found within the Pallinup aquifer and follow the Kalgan River and its tributaries from the northern study area boundary to where the river terminates at Oyster Harbour (Figure 4). Cross-sections C–C' and D–D' show the distribution and hydrogeology of the Pallinup aquifer. There is minimal drilling in the area.

The Pallinup aquifer is the watertable aquifer and the target aquifer for this area. It is generally low yielding, however along the Kalgan River and its tributaries the Pallinup aquifer is sandier than in other areas of the hinterland, and may be suitable for small- to moderate-scale abstraction. It contains fresh to saline groundwater and potential water supply ranges from 0.2 to 1.3 GL/yr.

Sands from the Werillup Formation are present, but drilling indicates they are very thin (< 5 m thick) with no flows recorded. The Werillup Formation is not considered an aquifer in this area.

Pallinup aquifer

In the Kalgan River area the Pallinup Formation forms an unconfined aquifer of low permeability. The aquifer consists of unconsolidated silts interbedded with very fine- to fine-grained sands with discontinuous clay layers and infrequent fine- to medium-grained sandstones. Thicknesses range from 5 to 50 m, with the thinnest sequence underlying the river's main tributary. Sediment thickness is controlled by the current landscape, with sediments located alongside and underneath current drainage lines forming only a thin veneer (< 20 m thick). Where the Pallinup Formation outcrops, the sediments are lateritic with minor sands and clays. It is underlain by a black carbonaceous clay of the Werillup Formation, or is directly underlain by weathered or unweathered granitic bedrock.

The Pallinup aquifer has the potential to provide 0.2 to 1.3 GL/yr, although water quality may be highly variable. Where the Pallinup aquifer is strongly connected to the Kalgan River (Kalgan River zones 1 and 2), streamflow may recharge groundwater in some reaches and water quality is expected to be brackish to saline. Salinity in the Kalgan River varies seasonally but it is largely saline; salinity of more than 10 000 mg/L TDS is recorded during the summer months.

The Pallinup aquifer discharges to the Napier Creek where the groundwater and surface water systems are connected in Kalgan River zone 3. The Pallinup aquifer groundwater quality is expected to be marginal to brackish, similar to the Napier Creek salinity range of 1000 to 2000 mg/L.

There are few known bores in the Kalgan River area. In the east, several attempts to construct bores into the Pallinup aquifer have been made. Airlift measurements could not be attained at some drill sites due to insufficient flows. Where airlift yields could be measured they were about 40 kL/d (0.5 L/s). Groundwater is fresh to marginal, with salinity around 1100 mg/L TDS calculated from EC measurements.

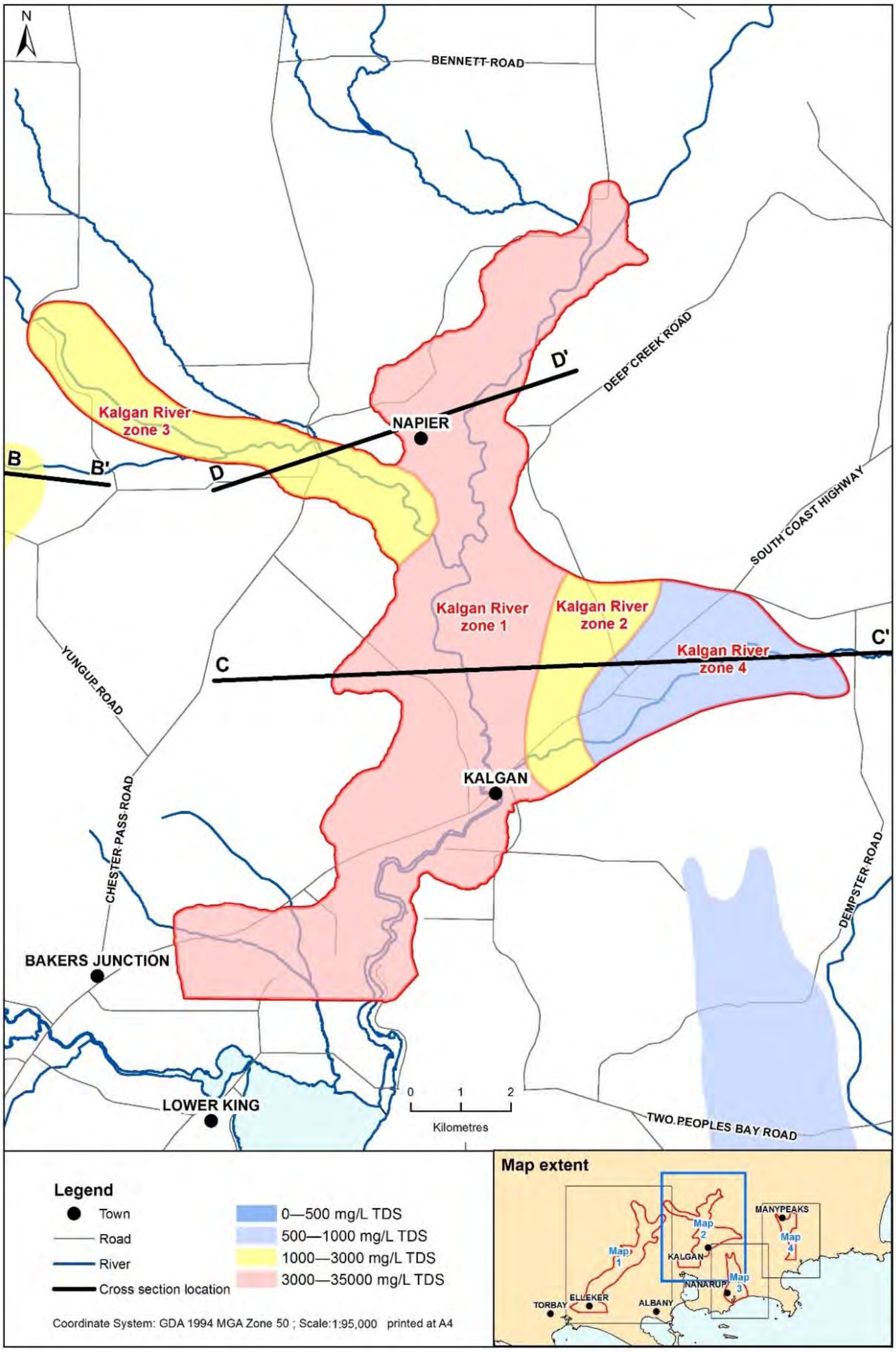


Figure 4 Kalgan River area location map

3.3 Manypeaks area

Summary

The Manypeaks groundwater resource area is located at the eastern extent of the investigation area (Figure 5). Its groundwater resources are found in the Werillup and Pallinup aquifers in a palaeochannel located south of the Manypeaks townsite. Only the western extent of the palaeochannel falls within the investigation area, however the depth to basement data indicates the palaeochannel may meander from the north to the south-east, possibly terminating at the coastline either near Normans Beach or where King Creek meets the coastline. Further work is required to define the palaeochannel extent. Cross-section E–E' shows the distribution and hydrogeology of the Pallinup and Werillup aquifers.

The Pallinup aquifer is semi-confined and connected to the underlying Werillup aquifer. For the purposes of this map, it has been treated as one resource and is referred to as the Werillup aquifer.

The Werillup aquifer is the main resource in this area and contains fresh to marginal groundwater. It is a moderate- to high-yielding aquifer with a potential water supply estimate of 0.7 to 1.3 GL/yr, based on the currently mapped extent.

Pallinup aquifer

In the Manypeaks area, the Pallinup Formation forms a semi-confined aquifer of low to moderate permeability. It consists of silty clays and siltstones overlying a locally clayey, fine- to coarse-grained pale brown lateritised sandstone, which forms the Pallinup aquifer. Laterite is common at the top where the sediments are above the watertable. Thicknesses range from 39 to 53 m, with an average thickness of 46 m. The clay and siltstone is generally around 30 m thick, with the base of the clay at about 60 m AHD. The sandstone is coarser and less clayey in the centre of the palaeochannel.

The Pallinup aquifer is connected to the underlying Werillup aquifer.

Flows of approximately 86 kL/d (1 L/s) were recorded during exploratory drilling, and the groundwater increases in salinity with depth, ranging from fresh to brackish.

Potential water supply and storage estimates for the Pallinup aquifer have been combined with estimates for the Werillup aquifer, given they are considered to be the same resource in this area.

Werillup aquifer

The Werillup aquifer is a semi-confined aquifer of moderate permeability and is overlain by the Pallinup aquifer. It consists of a basal fine- to coarse-grained black friable sandstone with minor silt. Pyrite and lignite are common. The aquifer is underlain by the black carbonaceous clay typically associated with the Werillup

Formation. A fine- to coarse-grained silty sand layer directly underlies the clay and in places is connected to a sandy saprolitic layer of weathered basement. When combined with the overlying Pallinup aquifer, saturated thicknesses are around 35 m in the central channel.

The Werillup aquifer has the potential to provide an annual groundwater supply of 0.7 to 1.3 GL/yr. Airlift yields increase with depth, varying from 34 kL/d (0.4 L/s) at shallower depths to 302 kL/d (3.5 L/s) near the base of the aquifer. Groundwater quality is generally in the marginal (500–1000 mg/L TDS) category, and becomes more saline with depth (up to 1500 mg/L TDS).

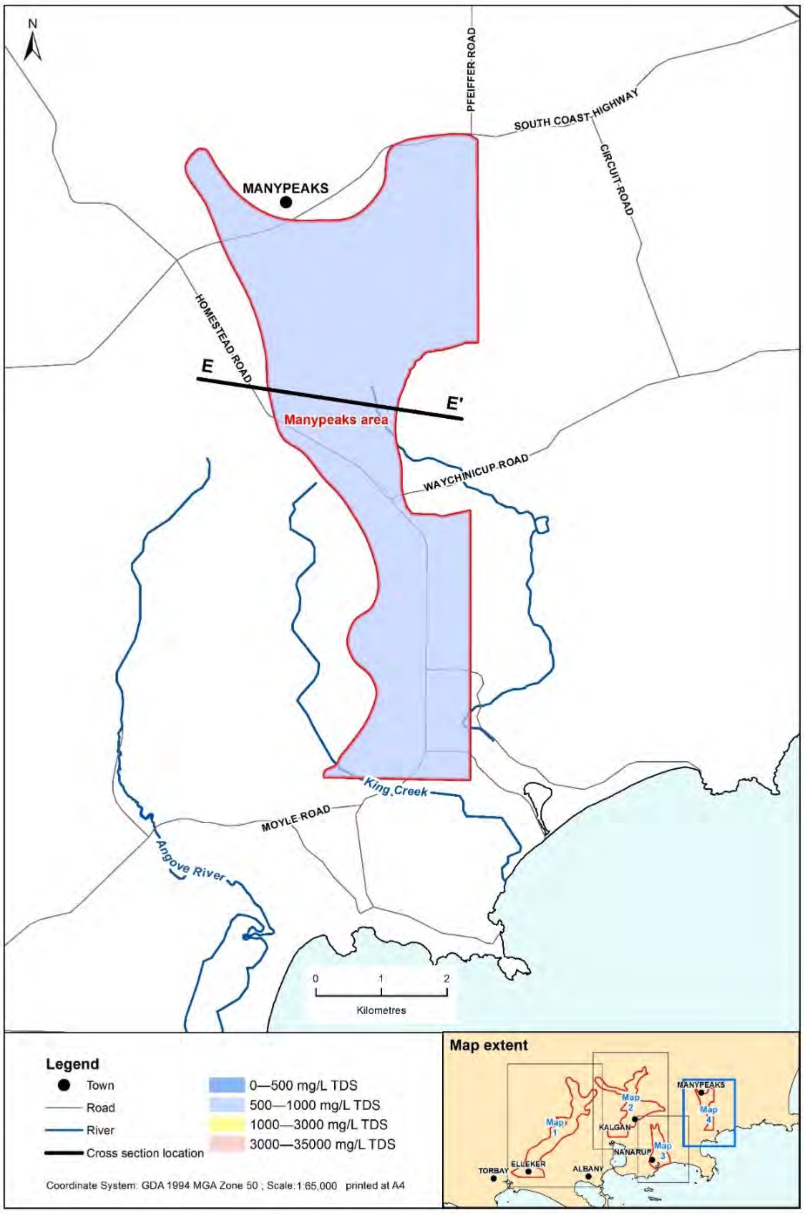


Figure 5 Manypeaks area location map

3.4 Nanarup area

Summary

The Nanarup groundwater resource area is located along the southern coastline of the investigation area east of Oyster Harbour (Figure 6). Cross section F-F’ shows the distribution and hydrogeology of the Werillup aquifer. Drilling confirms the Werillup aquifer is present within the palaeochannel beneath the clay of the Werillup Formation, though a thinner aquifer also associated with the Werillup Formation is present above the clay.

An outcropping limestone unit identified as the Nanarup Limestone Member of the Werillup Formation (Quilty 1969,1981) and a thin black sandstone make up the watertable aquifer. This aquifer is separated from the lower confined Werillup aquifer by a black clay layer. There is limited bore information available for this watertable aquifer and no estimates have been made during this investigation on the viability of this layer as a groundwater resource.

Groundwater is confined in the palaeochannel and it is the target aquifer in this area. The aquifer is less than 10 m thick, contains fresh to marginal groundwater and has the potential to produce 1.2 to 1.7 GL/yr.

Werillup aquifer

The Werillup aquifer is a semi-confined to confined low-yielding aquifer. It consists of interbedded finely grained black sands, silty sands and silts. The aquifer is overlain by the black carbonaceous clay typically associated with the Werillup Formation. The aquifer is thin, ranging in thickness from 5 to 10 m, with an average thickness of 8 m. It is underlain by a saprolitic silt layer on a granite basement.

The Werillup aquifer has the potential to provide an annual groundwater supply of 1.2 to 2.7 GL/yr. However, airlift yields from bores that have been drilled to date are low, varying from 34 kL/d (0.4 L/s) to 190 kL/d (2.2 L/s). Groundwater is generally marginal (500–1000 mg/L TDS), but locally it can be fresh (< 500 mg/L TDS). The aquifer may be suitable for local supply.

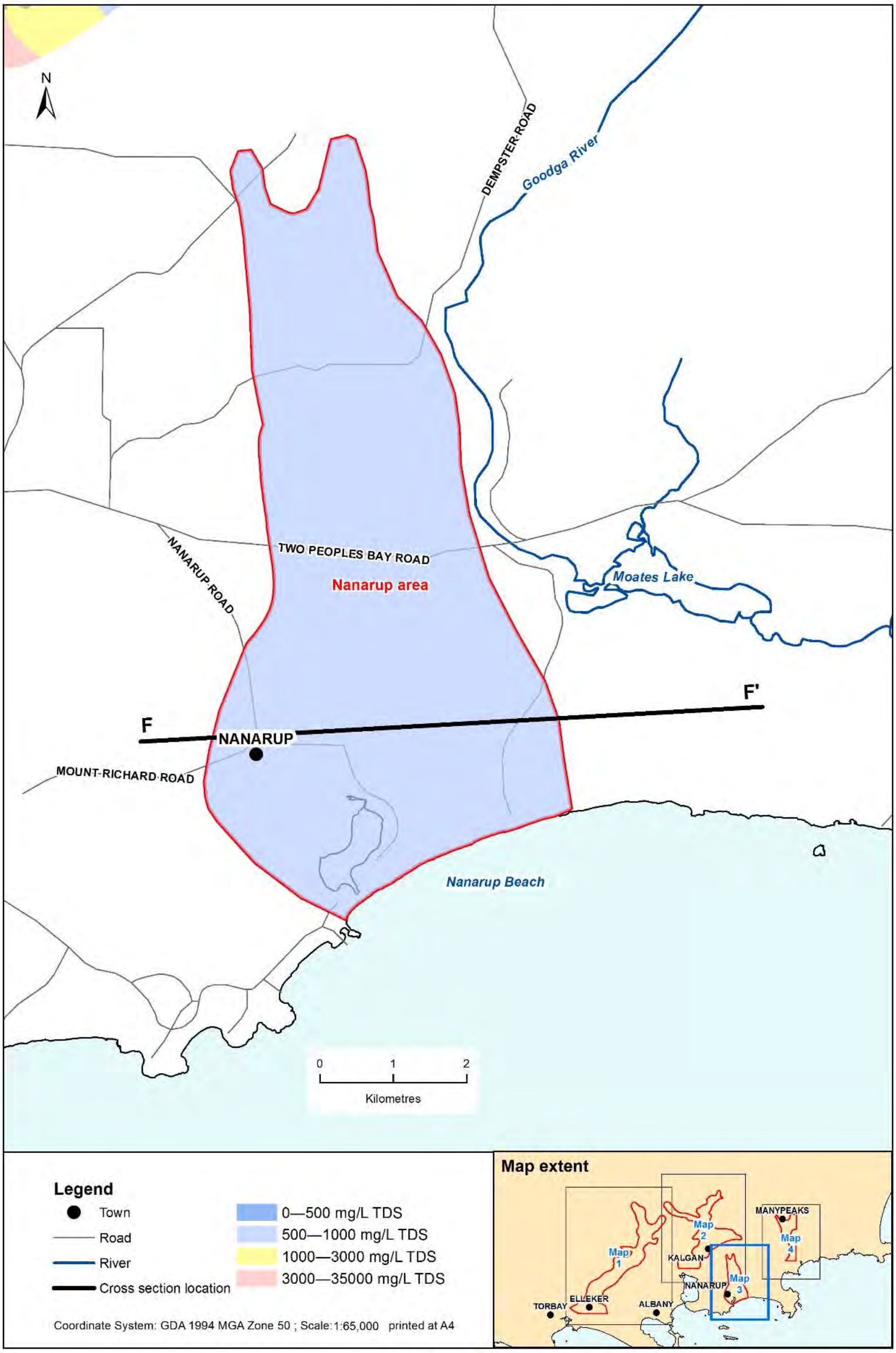


Figure 6 Nanarup area location map

Appendices

Appendix A — Depth to basement mapping

In 2013 an AEM survey was carried out using the TEMPEST system (Fugro 2013). The survey's aim was to identify potential water resources by determining the depth to basement and locating high conductivity units representing a confining clay layer in the channels. A total of 2137 km was flown in 178 lines covering an area of 8810 km^2. The survey was conducted at a line spacing of 600 m over the hinterland and 300 m over the Albany GWA, where higher resolution was required (Fugro 2013).

An initial inversion of the raw AEM data carried out by Geoscience Australia indicated several potential channel areas (Figure A1). However, due to the limited drilling data and the clayey nature of both the Pallinup and Werillup formations, it was difficult to interpret the geometry of the resources. Following on from this, in November 2014 the department conducted a groundwater investigation program across 16 sites in the prospective groundwater areas identified by the AEM survey.

By mapping out the depth to basement from the AEM, palaeochannels formed by pre-Tertiary erosion could be identified.

In 2016, Mira Geoscience was commissioned to carry out a second geologically constrained inversion of the data incorporating the results from the 2014 drilling program and the revised stratigraphic model of the area. The results showed that the top unsaturated Pallinup sediments were generally resistive (<10 mS/m). A more conductive unit directly underlying this (50–>150 mS/m) correlated well with the clay member of the Werillup Formation. Bedrock/basement had a low resistivity, averaging 1.2 mS/m.

A depth to basement layer covering the northern domain was developed by doing an unconstrained layered earth inversion on the initial data from the TEMPEST AEM survey (Figure A2). The geologically constrained inversions were unsuccessful due to the highly heterogeneous nature of the sediments and produced geologically implausible models. Instead a manual interpretation of the depth to basement from the VPem1D model has been used to develop the final layer (Figure A3).

The full methodology and results are documented in the *Interpretation of TEMPEST airborne electromagnetic data from the Albany hinterland, Western Australia* (Mira Geoscience 2016).

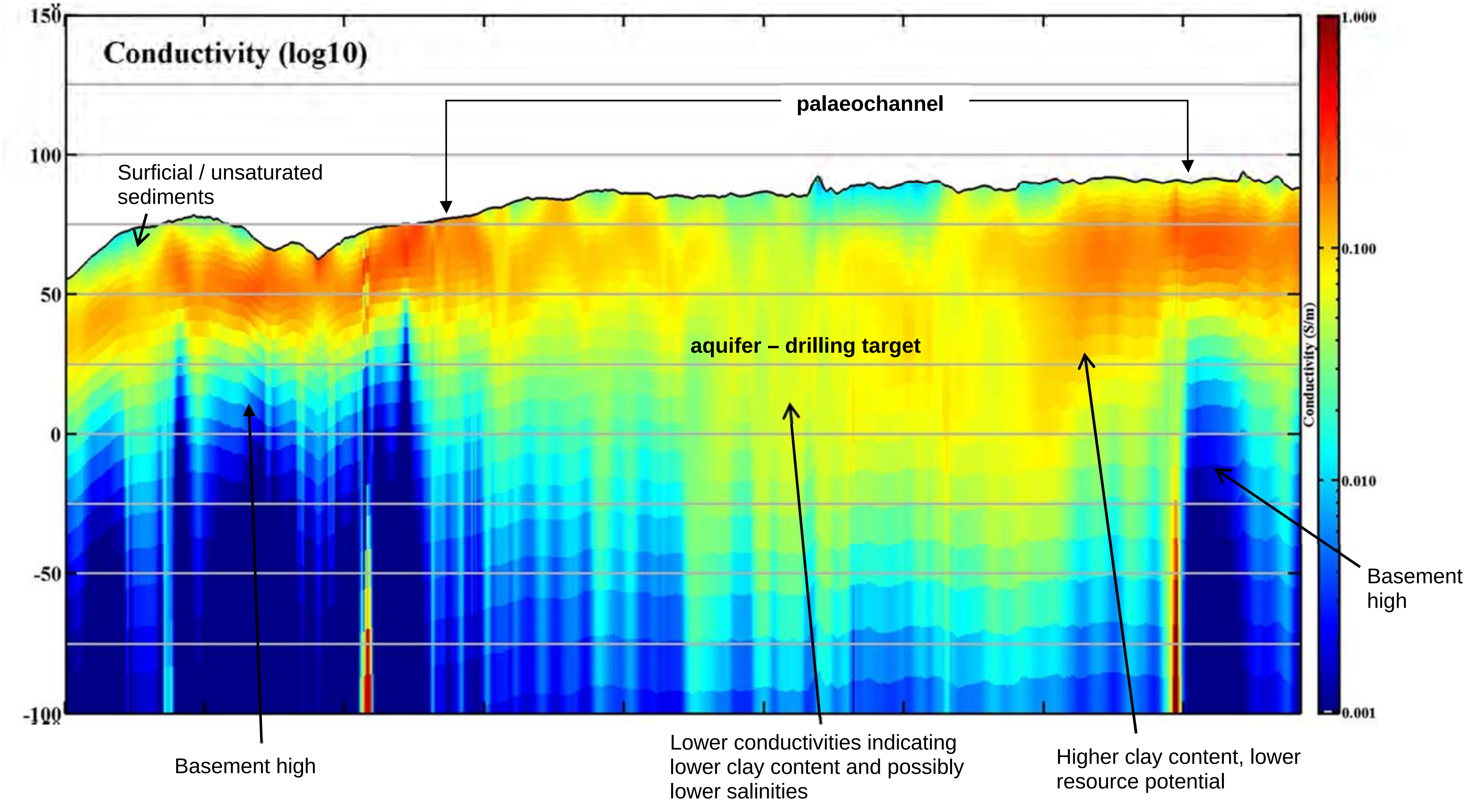
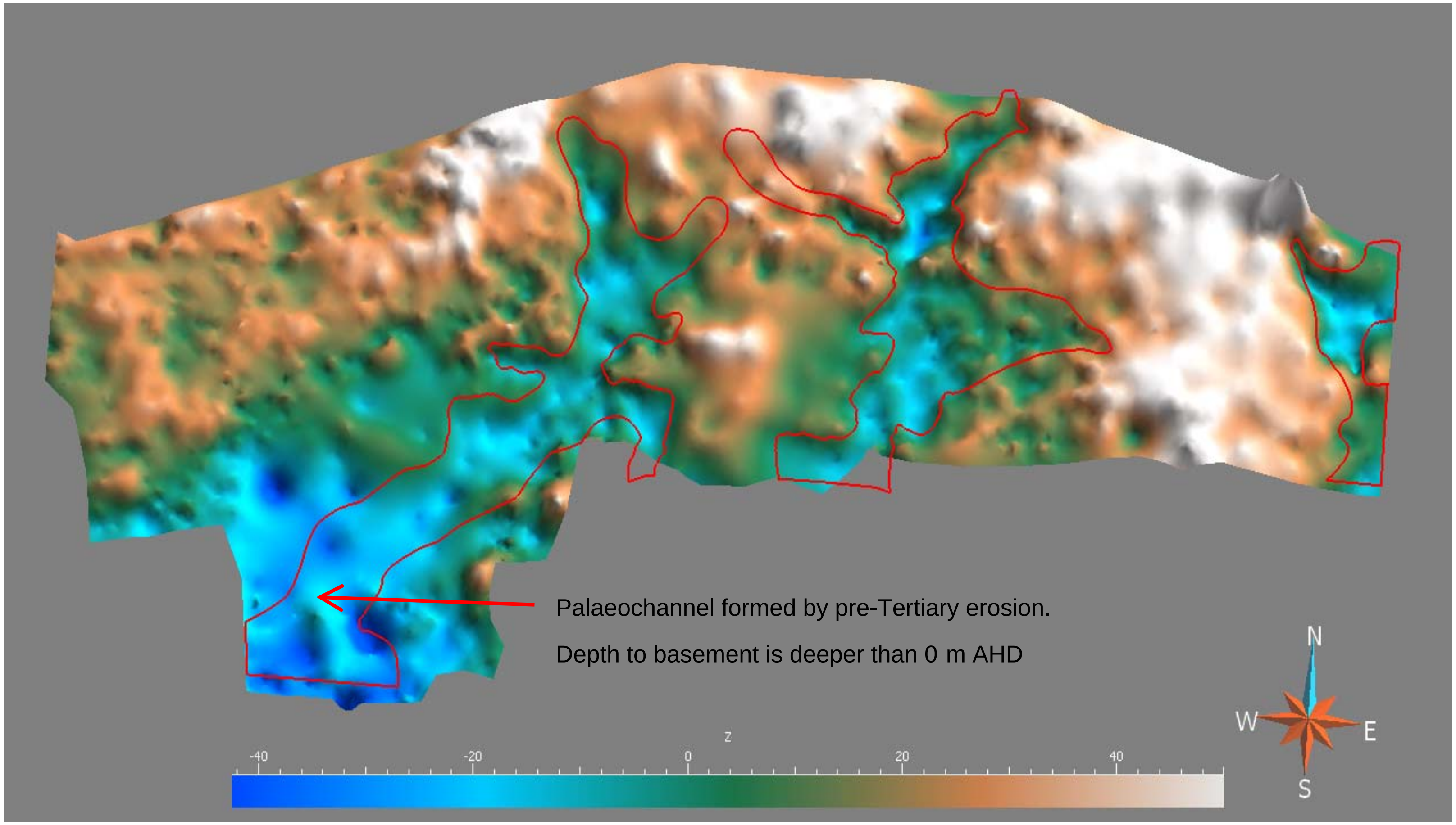


Figure A1 Example AEM depth slice in the Manypeaks area



Depth to basement scale. White represents basement highs and dark blue represents basement lows.

Figure A2 Depth to basement layer showing palaeochannel outlines

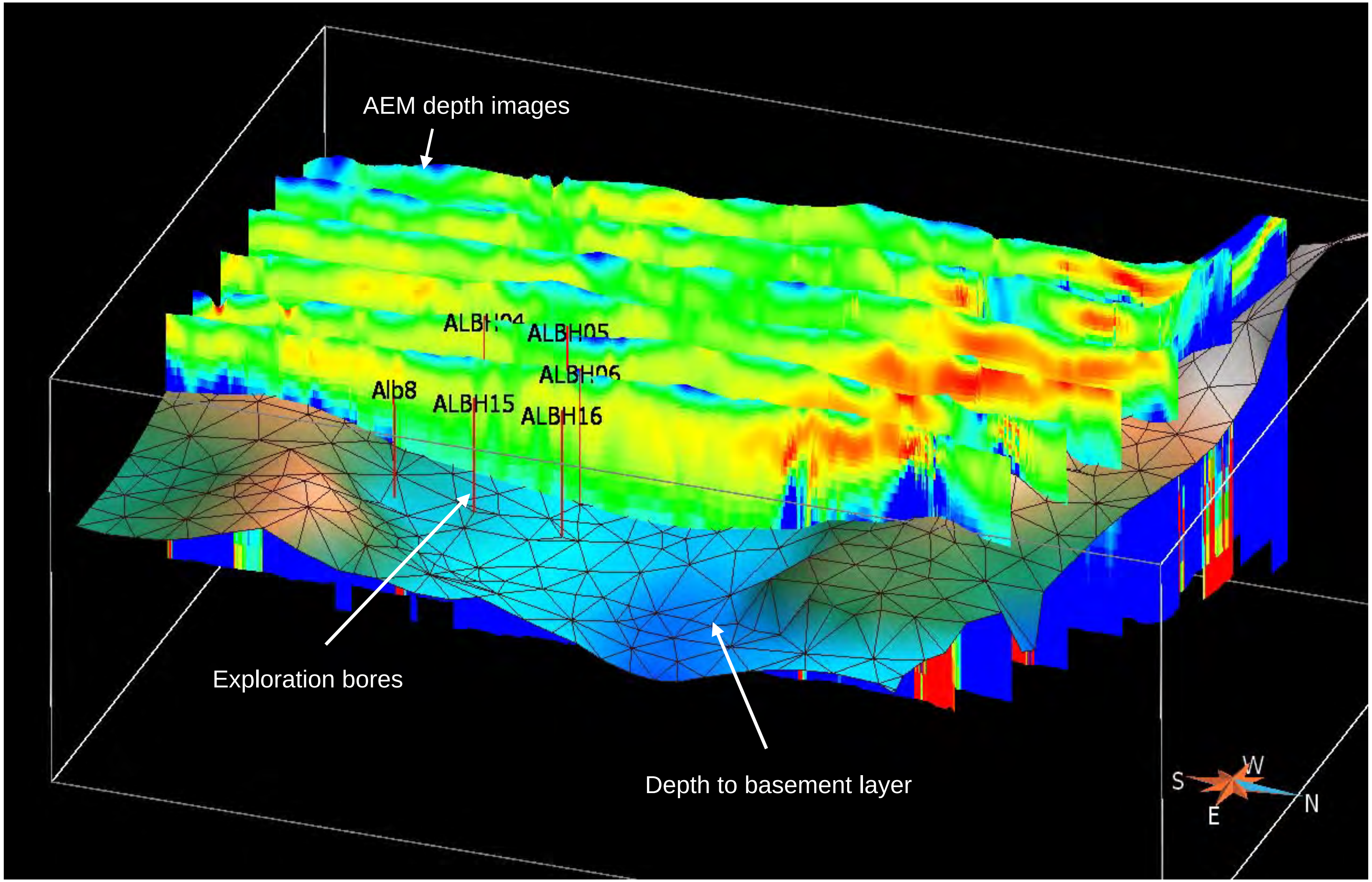


Figure A3 3D image of AEM survey with depth to basement layer and bore information in Manypeaks

Appendix B — Groundwater recharge methodology

Recharge calculations for the investigation were based on the chloride mass balance method (CMB). This method assumes chloride is highly soluble and is considered to be conservative so the only source of chloride in the groundwater is from rainfall deposition, chloride is not lost to evapotranspiration or precipitated to the aquifer material, and no chloride is gained through dissolution from the aquifer material. It is the most widely used method for estimating groundwater recharge in Australia and is well documented in the literature (Leany et al. 2011). The CMB method estimates net groundwater recharge and is applicable for steady-state conditions. The unknowns in the CMB equation are annual rainfall, chloride deposition rate at the ground surface and the chloride concentration of the groundwater, provided losses to surface runoff are insignificant, which has been assumed for this study. There was insufficient data for hydrograph analysis or other recharge calculation methods.

Rainfall chloride concentrations were estimated based on the spatial variation in rainfall chloride, with distance from the coastline, observed in rainfall chloride sampling undertaken at eight sites across the Albany GWA in 2013 (Table B1). This approach was supported by observation of Hingston and Gailitis (1976), demonstrating decreasing rainfall chloride deposition with increasing distance inland. Rainfall data was obtained from the SILO database (SILO 2016) for representative locations within the prospective groundwater areas.

Table B1 SILO rainfall locations and 1990–2015 average annual rainfall totals

Site	Easting	Northing	Average annual rainfall 1990–2015 (mm)	Rainfall Chloride (mg/L)
King River south-west	573047	6132210	795	17
King River north-east	577706	6143262	750	17
Kalgan	591419	6143135	725	17
Nanarup	595874	6131998	755	20
Manypeaks	609704	6142935	700	17

Equation 2 was used to calculate the chloride mass balance (Leaney et al. 2011). Chloride concentration data from bore chemistry samples were analysed for each zone and used to estimate recharge to the aquifers as a proportion of annual rainfall. Rainfall chloride concentration was estimated from samples collected in the Albany GWA in 2013, adjusted for each area based on distance from the coast.

$$R = P \times C_p / C_{gw} \qquad \text{Equation 2}$$

Where:
R = recharge rate (mm/yr)
P = average annual precipitation (mm/yr)
C_p = chloride concentration in rainfall (mg/L)
C_{gw} = chloride concentration in groundwater (mg/L)

Table B2 Rainfall depth, rainfall chloride concentration, groundwater chloride concentration and calculated estimated recharge based on CMB

Resource area	Average annual rainfall (P) (mm)	Rainfall chloride concentration (mg/L)	Bore AWRC* number	Bore site name	Chloride concentration (mg/L)	Recharge (mm)	Recharge % as proportion of P
King	750	17	60212736	RWB3	320	39.84	5.31
			60200176	RWB8	180	70.83	9.44
			60212742	RWB12	200	63.75	8.50
			60210010	RWB13	360	35.42	4.72
			60300019	RWB15	440	28.98	3.86
			60300024	RWB20	430	29.65	3.95
			60212647	RWB21	190	67.11	8.95
			60200202	RWB22	210	60.71	8.10
			60200203	RWB23	120	106.25	14.17
			60200211	RWB31	160	79.69	10.63
			60200207	RWB27	860	14.83	1.98
			60200210	RWB30	1000	12.75	1.70
			60200214	RWB33	530	24.06	3.21
			60200220	RWB39	1100	11.59	1.55
			60212640	RWB40	1200	10.63	1.42
			60300023	RWB19	630	20.24	2.70
Kalgan	725	17	60218239	ALBH10	491	24.76	3.46
			60219103	ALB4A	355	34.24	4.79
Nanarup	755	20	60219101	ALB2B	259	58.30	7.72
			60218238	ALBH09	310	48.71	6.45
			60219102	ALB3	370	40.81	5.41
Manypeaks	700	17	60218234	ALBH05	337	44.81	5.93
			60218245	ALBH16	478	31.59	4.18
			60218233	ALBH04	501	30.14	3.99
			60219109	ALB8	595	25.38	3.36

AWRC* Australian Water Resources Council

The CMB recharge estimation method is most reliable when groundwater chloride samples are obtained from the watertable, and under steady state conditions, and this constraint could not be assured for all samples. Chemistry samples assessed were generally within resource boundaries, however given the sparse historical data it was decided that all available groundwater chloride data would be assessed and then the results would be interpreted with consideration of the limitations. Table B2 contains the rainfall depth and chloride concentration, groundwater chloride concentration data and range of estimated CMB recharge.

The four potential groundwater areas were subdivided into salinity class zones, based on available data, where values ranged greater than one salinity class. The Manypeaks and Nanarup areas have only one salinity zone and one rainfall station. King River has several salinity zones and a rainfall station in the north and south. Zoning in the Kalgan River area has been based on surface water salinity and two rainfall stations.

Recharge has been calculated for each salinity zone using Equation 3. The final recharge estimate value chosen for each zone or area was determined from assessment of how the available data was considered to be representative, or varied from the assumptions, for the CMB approach and with consideration of the salinity and hydrogeological processes in each area. In areas where several samples were available, the minimum and maximum chloride values were used to define a range of groundwater recharge as a proportion of rainfall for each resource zone. The ranges for each zone are outlined in Table B3 and the recharge ranges expressed in gigalitres per year are in Table in Section 2.2.

$$R = P_a \times A_f \times F \qquad \text{Equation 3}$$

Where

R = calculated groundwater recharge (kL/yr)

P_a = average annual rainfall (m/yr)

A_f = the surface area covered by the formation (m^2)

F = the recharge rate as a percentage of average annual rainfall (%)

Table B3 Rainfall recharge percentages for each resource zone

Zone	Min recharge as % rainfall	Max recharge as % rainfall	Median recharge as % rainfall	Mean recharge as % rainfall	Range % rainfall
King River Zone 1	3.9%	14.2%	8.1%	7.4%	3.9–14.2
King River Zone 2	2.0%	10.6%	6.3%	6.3%	2.0–10.6
King River Zone 3	1.4%	3.2%	1.6%	2.0%	1.4–3.2
King River Zone 4	2.7%	2.7%	2.7%	2.7%	2.0–3.0
Kalgan River zone 1	1%	2%	n/a	n/a	1.0–2.0
Kalgan River zone 2	1%	2%	n/a	n/a	1.0–2.0
Kalgan River zone 3	1%	2%	n/a	n/a	1.0–2.0
Kalgan River zone 4	3%	5%	4%	4%	3.0–5.0
Nanarup zone	5%	8%	7%	7%	5.0–8.0
Manypeaks zone	3%	5%	3%	4%	3.0–5.0

Appendix C — Bores in the Albany hinterland

The groundwater potential of the Albany hinterland has previously been investigated by Diamond (2001) and Kern (2007). The investigations were primarily desktop studies that collated known private and public bore data with older geophysical data obtained by the Geological Survey of Western Australia. While the studies were focused on a broader area than this investigation, the four areas outlined in this study were all identified as potential groundwater resources.

More than 170 bores associated with the Albany hinterland are found in the department's Water Information database (WIN/WIR). However, most of these bores do not have geological logs and are too shallow to provide enough information. Groundwater yield and salinity data is available for many bores, but for most bores it is uncertain which aquifer the information is referring to. Bores with geological logs and their locations are given in Table C1.

Table C1 Bores with geological logs in the Albany hinterland

AWRC* reference	Bore name	Easting	Northing		AWRC reference	Bore name	Easting	Northing
60310639	1965_03P	566790	6125517		**60210582**	641	577010.7	6129155
60318500	1976_01A	566625.6	6126139		**60210580**	611	577795	6127659
60318501	1977_01	567096.6	6129077		**60210120**	MHC11B	577006.6	6125392
60318502	1977_02C	567942.6	6129067		**60210122**	MHC12A	577007	6125392
60218002	1978_02	566202.6	6126297		**60210136**	MHC17A	577523.9	6126172
60318506	1978_04L	561669.6	6128546		**60210151**	MHC23A	578669	6125785
60310162	1978_05E	570691.6	6127247		**60210152**	MHC23B	578669	6125785
60310636	1978_06F	569129.6	6126364		**60210153**	MHC23C	578669	6125785
60310198	1978_07H	565993.6	6127547		**60210105**	MHC3A	577565	6125403
60310654	1978_08D	573167.7	6126877		**60210194**	MHC3B	577564	6125403
60310666	1978_09I	565568.6	6128377		**60212734**	RWB01	572119	6135760
60310667	1978_10J	565696.5	6129787		**60212735**	RWB02	570700.2	6135105
60318512	1978_19M	564158	6125903		**60212736**	RWB03	569378.3	6135537
60310164	1978_21	569134.6	6126848		**60212737**	RWB04	568113	6136191
60318513	1978_22	566891.6	6128324		**60200174**	RWB05	574181.6	6134688
60318514	1978_23	566121.6	6128267		**60212738**	RWB06	573581	6133547
60310123	1978_24	565407.6	6125857		**60200175**	RWB07	573159.2	6135912
60310124	1978_25	567135.6	6125577		**60200176**	RWB08	573458.2	6135059
60310199	1978_27	568592.6	6127647		**60212739**	RWB09	573882	6136832
60310163	1978_28	568765.6	6126825		**60212740**	RWB10	572817	6136934
60318516	1978_29	566621.6	6126139		**60212741**	RWB11	572149.6	6136765
60318517	1978_30	565932.6	6127698		**60212742**	RWB12	572491.2	6134220
60318518	1978_31	566885.6	6127523		**60210010**	RWB13	571718.2	6132566
60319479	1994_01	573866.5	6131452		**60300018**	RWB14	570354	6130627
60319478	1994_02	573135.1	6131457		**60300019**	RWB15	571482.4	6130642
60319475	1994_03	571892.9	6132203		**60300020**	RWB16	571815	6130634

AWRC* reference	Bore name	Easting	Northing		AWRC reference	Bore name	Easting	Northing
60319477	1994_04	571896.1	6131537		**60300021**	RWB17	571096	6130619
60319476	1994_05	571610.4	6131852		**60300022**	RWB18	570705	6130646
60219104	1994_05A	572016	6132855		**60300023**	RWB19	570745.6	6131562
60319470	1994_06	571896.4	6132199		**60300024**	RWB20	570657.2	6131912
60319467	1994_08	572508.8	6132551		**60212647**	RWB21	574538	6135599
60319464	1994_09	572777	6133575		**60200202**	RWB22	575289.1	6136296
60319468	1994_10	573188.7	6132810		**60200203**	RWB23	576071	6137132
60319472	1994_11	573487	6132268		**60200204**	RWB24	576967	6138247
60319471	1994_12	572741.6	6132146		**60200205**	RWB25	575623	6138443
60319463	1994_13	571902.6	6133583		**60200206**	RWB26	576213	6138378
60319462	1994_14	570666.5	6133602		**60200207**	RWB27	577594	6137901
60319465	1994_15	570659	6132820		**60200208**	RWB28	577545	6137122
60319491	1994_16	570654.8	6132154		**60200209**	RWB29	578146	6137278
60319473	1994_17	570879.4	6131557		**60200210**	RWB30	578298	6138947
60319474	1994_18	571203.1	6131553		**60200211**	RWB31	577151	6137290
60319480	1994_19	571223.6	6133883		**60200213**	RWB32	580598	6140518
60212260	Alb2	595300	6128800		**60200214**	RWB33	580434	6139498
60219102	Alb3	598380	6134770		**60200215**	RWB34	580365	6139273
60219103	Alb4	598400	6140300		**60200216**	RWB35	580493	6139699
60219104	Alb5	571980	6132806		**60200217**	RWB36	580552	6139909
60319481	Alb5	571980	6132806		**60200218**	RWB37	580606	6140091
60219109	Alb8	608550	6140550		**60200219**	RWB38	581665	6140082
60218232	ALBH01	563064	6141188		**60200220**	RWB39	579534	6140578
60310691	ALBH02	562975	6138788		**60212640**	RWB40	580349	6141803
60310692	ALBH03	564788	6132877		**60212648**	RWB40a	580347	6141803
60218233	ALBH04	607383	6140847		**60200221**	RWB41	584074	6138147
60218234	ALBH05	607382	6141513		**60200222**	RWB42	581192	6143112
60218235	ALBH06	607964	6141824		**60200223**	RWB43	581882	6144033
60218236	ALBH07	597096	6129065		**60200224**	RWB44	581591	6144465
60218237	ALBH08	597059	6130263		**60212649**	RWB45	581690	6144568
60218238	ALBH09	596467	6128876		**60212650**	RWB45a	581691	6144568
60218239	ALBH10	598969	6144848		**60200225**	RWB46	577158	6137755
60218240	ALBH11	597161	6143481		**60212651**	RWB46a	577158	6137755
60218241	ALBH12	594162	6140610		**60212652**	RWB47	577858	6136813
60218242	ALBH13	597199	6141404		**60212653**	RWB47a	577858	6136813
60218243	ALBH14	597196	6140848		**60212654**	RWB48	576314.8	6135278
60218244	ALBH15	608591	6141205		**60210581**	631	578209.7	6127611
60218245	ALBH16	608566	6141898		**60210579**	609	576686.6	6128703

AWRC* Australian Water Resources Council

Shortened forms

AEM	airborne electromagnetic (survey)
AHD	Australian Height Datum
AWRC	Australian Water Resources Council
bgl	below ground level
CMB	chloride mass balance
DoW	Department of Water
EC	electrical conductivity
SILO	Scientific Information for Land Owners
TDS	total dissolved solids
WIN	Water Information Database (Department of Water and Environmental Regulation)
WIR	Water Information Reporting tool (Department of Water and Environmental Regulation)

Glossary

AHD	Australian Height Datum; equivalent to Mean Sea Level
alluvium (alluvial)	detrital material that is transported by streams and rivers and deposited
aquifer	a geological formation or group of formations able to receive, store and transmit significant quantities of water
aquitard	a geologic formation, group of formations, or part of a formation with relatively low permeability which restricts groundwater movement
artesian aquifer (bore)	a confined aquifer under sufficient pressure that the water would rise in a bore above the ground surface
baseflow	the portion of river and stream flow coming from groundwater discharge
bore	small diameter well, usually drilled with machinery
confined aquifer	an aquifer lying between confining strata of low permeability so that the water in the aquifer cannot flow vertically
confining bed	sedimentary bed of very low hydraulic conductivity – see aquitard
estuary (estuarine)	the seaward or tidal mouth of a river where fresh water comes into contact with sea water
formation (geological)	a group of rocks or sediments that have certain characteristics in common and that were deposited about the same geological period, and constitute a convenient unit for description
gaining stream	a stream or reach of stream with flow being increased by inflow of groundwater
groundwater	water that occupies the pores and crevices of rock or soil beneath the land surface
groundwater flow	movement of water in the saturated zone
groundwater recharge	action of water percolating through the soil/ground to replenish an aquifer
lateritised (lateritic)	a surficially formed deposit consisting mostly or entirely of iron or aluminium oxides and hydroxides
lithology	description of the physical characteristics of a rock unit
losing stream	a stream that that loses water to (or recharging) the groundwater system as it flows downstream
member (geological)	minor rock stratigraphic unit comprising some portion of a formation

palaeochannel	a channel that is no longer part of the contemporary fluvial system, i.e. has been abandoned or buried
permeability	the property or capacity of a porous rock, sediment or soil for transmitting water
potentiometric surface	a surface of equal hydraulic heads or potentials, typically depicted by a map of equipotentials such as a map of watertable elevations
renewable resource (groundwater)	groundwater extracted from an aquifer that receives recharge from rivers, rainfall or from other aquifers
salinity	a measure of the concentration of total dissolved solids (TDS) in water (DoW 2014a) 0–500 mg/L, fresh 500–1000 mg/L, marginal 1000–3000 mg/L, brackish 3000–35 000 mg/L, saline >35 000 mg/L, hypersaline
seepage	water that seeped or leaked through a porous soil
semi-confined aquifer	an aquifer lying between strata of low permeability (aquitards) where the aquitards restrict, but don't prevent, groundwater movement
specific yield	the ratio of the volume of water that a given mass of saturated rock or soil yields by gravity to the volume of that mass (this ratio may be expressed as a percentage)
storage	the estimated volume of water contained in an aquifer
stratigraphy	the science of rock strata: concerned with original succession and age relations of rock strata and their form, distribution, lithology, fossils, geophysical and geochemical properties
subcrop	to lie directly beneath another geological unit
surface water	water flowing over the landscape, held in estuaries, rivers and wetlands or collected in a dam or reservoir
total dissolved solids	a term that expresses the quantity of dissolved material in water, usually determined by weighing the residue after evaporating a sample of known volume at 180^{o}C
unconfined aquifer	an aquifer with a free watertable or phreatic level at atmospheric pressure
watertable	the surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere
yield	sustainable rate at which a bore or well can be pumped

References

Clarke JDA, Gammon PR, Hou B & Gallagher SJ 2003, 'Middle to Upper Eocene stratigraphic nomenclature and deposition in the Eucla Basin', *Australian Journal of Earth Sciences*, vol. 50, pp231–248.

De Silva J, Wallace-Bell P, Yesertener C & Ryan S 2013, Perth regional aquifer modelling system (PRAMS) v 3.5 – conceptual model, Hydrogeological report series, HR334, Department of Water, Government of Western Australia, Perth (unpublished).

Department of Water (DoW) 2014a, *Great Southern regional water supply strategy,* Department of Water, Government of Western Australia, Perth.

Department of Water (DoW) 2014b, *Water Resources Inventory 2014,* Department of Water, Government of Western Australia, Perth.

Diamond RE 2001, Groundwater resource potential of the Albany hinterland, Department of Water, Hydrogeological record series, HR137, Government of Western Australia, Perth (unpublished).

Fugro Airborne Surveys 2013, South West Coastal Plain and South Coast, Western Australia TEMPEST airborne geophysical survey, acquisition and processing report for Geoscience Australia, report to the Department of Water (unpublished).

Gammon PR, James NP, Clarke JDA & Bone Y 2000, 'Sedimentology and lithostratigraphy of Upper Eocene sponge-rich sediments, southern Western Australia', *Australian Journal of Earth Sciences*, vol. 47, pp1087–1103.

Great Southern Development Commission (GSDC) 2014, *Great Southern regional blueprint,* Government of Western Australia, Perth.

Healy RW & Cook PG 2002, 'Using groundwater levels to estimate recharge', *Hydrogeology Journal,* vol. 10, Issue 1, pp91–109.

Hem JD 1970, 'Study and interpretation of the chemical characteristics of natural water', *Geological Survey Water Supply Paper*, 2254, US Geological Survey, Alexandria.

Hingston FJ & Gailitis V 1976, 'The geographic variation of salt precipitated over Western Australia'*, Australian Journal of Soil Research,* 14, pp319–35.

Kern, AM 2007, Hydrogeological assessment of the western South Coast region, Hydrogeological report series, HR260, Department of Water, Government of Western Australia, Perth (unpublished).

Leaney F, Crosbie R, O'Grady A, Jolly I, Gow L, Davies P, Wilford J & Kilgour P 2011, *Recharge and discharge estimation in data poor area,* Scientific reference guide, CSIRO Water for a Healthy Country National Research Flagship, Australia .

Mira Geoscience 2016, Interpretation of TEMPEST Airborne Electromagnetic Data from the Albany hinterland, Western Australia, report to the Department of Water (unpublished).

Quilty PG 1969, 'Upper Eocene planktonic Foraminifera from Albany, Western Australia', *Journal of the Royal Society of Western Australia,* vol. 52, pp41–58.

Quilty PG 1981, 'Late Eocene benthic Foraminifera, south coast, Western Australia', *Journal of the Royal Society of Western Australia*, vol. 64, pp79–100.

Ryan SA, Yesertener C & Maughan A 2017, Albany Aquifer Modelling System (AAMS) – conceptual model, Hydrogeological report series, HR377, Department of Water, Government of Western Australia, Perth (unpublished).

SILO 2016, SILO climate database, Queensland Government Department of Science, Information Technology and Innovation, retrieved 13 July 2016 from: https://www.longpaddock.qld.gov.au/silo/

Smith R 1997, *Hydrogeology of the Mount Barker–Albany 1:250:000 sheet,* Hydrogeological map explanatory notes series, HM1, Water and Rivers Commission, Government of Western Australia, Perth.

Yesertener C 2009, Assessment of net recharge rates changes to response of groundwater level within the Gnangara groundwater mound, Hydrogeological record series, HR269, Department of Water, Government of Western Australia, Perth (unpublished).

Department of Water and Environmental Regulation
Level 4 The Atrium 168 St Georges Terrace Perth WA
Postal: Locked Bag 33 Cloisters Square Perth WA 6850
Phone: 08 6364 7600
Fax: 08 6364 7601
National Relay Service 13 36 77
dwer.wa.gov.au
12709 00 0817