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

Securing Western Australia's water future

Northern Perth Basin: Geology, hydrogeology and groundwater resources

Department of Water
Hydrogeological bulletin series
Report no. HB1
January 2017

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For more information about this report, contact Manager, Water Resource Assessment Branch.

Cover photo: Ellendale Pool, a groundwater dependent waterhole, on the Greenough River, with outcrop of mid-Jurassic sandstone (equivalent to the Cattamarra Coal Measures and Cadda Formation), 35 km east of Geraldton (photo Alex Kern).

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Summary

The substantial groundwater resources of the northern Perth Basin have been known since the late nineteenth century. Since then, a wealth of hydrogeological information and knowledge has been progressively collected from the basin and its surrounds. This bulletin represents the first compilation and analysis of all the available information on the groundwater resources of the northern Perth Basin in one document. With this publication, the Department of Water provides a technical resource for groundwater professionals, and a complete source of information for current and potential groundwater users and the general public.

The geographical scope of this bulletin extends from Gingin Brook in the south to the Murchison River in the north and from the Indian Ocean in the west to the western edge of the Darling Plateau in the east. The coastal region between Gingin and Geraldton is dominated by the Swan Coastal Plain, a low-lying, gently undulating plain with numerous wetlands and coastal sand dunes. The Swan Coastal Plain is bound to the east by the Gingin Scarp which defines the western edge of the elevated Dandaragan Plateau and Arrowsmith region. This bulletin also includes the southernmost portion of the Carnarvon Basin and the Northampton Inlier that are present adjacent to the northernmost extent of the Perth Basin.

This bulletin is considered a companion document to previously published reports on the hydrogeology of the Perth Basin in the Perth region (Davidson 1995) and the southern Perth Basin (DoW in prep.). Collectively, these three publications provide a full description of the geology and hydrogeology of the entire Perth Basin.

The northern Perth Basin makes up the northern half of the Perth Basin, which is a north to north–northwest trending, onshore and offshore sedimentary basin extending about 1300 km along the southwestern margin of the Australian continent. The northern Perth Basin contains up to 12 km of sediments onshore. Our understanding of the groundwater resources of the northern Perth Basin have been developed through over 30 separate, government-funded hydrogeological investigations, surface water – groundwater interaction studies and numerous investigations by other agencies and private companies for mining, irrigated agriculture and geological purposes.

The northern Perth Basin spans an area of highly variable climate and hydrology and the economic development of the region is reliant on continued access to reliable, good quality groundwater resources. The aquifers of the northern Perth Basin currently supply about 95 per cent of all water used for town water supply, irrigated agricultural enterprises, mines and industries across the region. These aquifers also support many groundwater-dependent wetlands, watercourses, vegetation associations, and cave and aquifer ecosystems. These groundwater-dependent ecosystems (GDEs) support a variety of habitats for plants and animals and, in doing so, provide a range of amenities to people.

The largest fresh groundwater resources within the northern Perth Basin are in the Superficial, Leederville, Leederville–Parmelia and Yarragadee aquifers. There are also three secondary aquifers: the Mirrabooka, Cattamarra and Eneabba–Lesueur aquifers. In addition to these groundwater resources, there are minor shallow and fractured-rock aquifers that are

locally significant sources of water. Hydraulic connection between aquifers is often impeded across faults and low permeability units, both within and between aquifers.

This bulletin summarises the known distribution and structure of the major geological formations, and the hydrogeological features of each aquifer, presenting over 100 maps and figures. Aquifer test results that provide valuable hydraulic parameters for the main aquifers are discussed in the text and reported in full in the appendices. These data underpinned the development of a numerical groundwater model of the northern Perth Basin between Guilderton to the south and Geraldton to the north, known as the Gingin Arrowsmith Regional Aquifer Modelling System (GARAMS).

The Department of Water has a network of over 700 monitoring bores in the northern Perth Basin, which show that in some places the depth to watertable has risen in response to extensive clearing of native vegetation. Elsewhere, it has declined in response to the abstraction of groundwater resources and a drying climate. The climate is predicted to continue drying into the future and this is likely to present challenges in managing the region’s groundwater resources.

Water availability and the relatively low cost of groundwater source development will mean that groundwater will remain the major source of water supply in the northern Perth Basin for the foreseeable future. As the population of the region grows, and mining and other developments expand into more remote areas of the state, available fresh–marginal, or brackish–saline groundwater resources will be increasingly used. However, the potential for groundwater resources to meet future water demand in the northern Perth Basin is not just a function of the hydrogeological characteristics of the aquifers. There is also a complex array of community, economic and environmental factors that influence how much groundwater is available for abstraction, and how that water can be taken and used.

The Department of Water has a legislative responsibility to take these factors into account when managing the availability of, and access to, groundwater across the northern Perth Basin. Groundwater development proposals are assessed against appropriate groundwater level and quality objectives, which need to be determined for individual proposals, and must take into account potential effects on other groundwater users and the environment. This bulletin concludes with a discussion of the relevant resource and regulatory considerations to guide future groundwater users in designing viable, approvals-ready proposals for groundwater development within the northern Perth Basin.

1 Introduction

The substantial groundwater resources of the northern Perth Basin have been known since the late nineteenth century, when government geologist Andrew Gibb Maitland highlighted the need for further investigations to meet the demand for information.

> The favourable results which have accrued by the sinking of artesian wells in that tract of country adjacent to the Indian Ocean which may be called the Great Coastal Plain, and the possible amelioration of some of the conditions of life in the arid portions of the Colony, has led to applications from the Departments of Works and Lands for geological advice in connection with the question. The demands for such advice far exceed the limits of the accumulating supply of information. (Maitland 1898)

Since Maitland published his report 118 years ago, a wealth of hydrogeological information and knowledge has been progressively collected across the northern Perth Basin and surrounds. Until now, this information, which represents an investment of over $100 million in real terms, has been stored among private bore records, government databases, geological reports and unpublished hydrogeological reports.

The Department of Water is Western Australia's lead water agency, responsible for managing the state's vast groundwater resources. The department is custodian of all northern Perth Basin data, comprising geological logs, drillers' logs, water levels, aquifer test results and water quality. This bulletin represents the first compilation and analysis of all available information on the groundwater resources of the basin in one document. The area covered by this bulletin also includes the southernmost portion of the Carnarvon Basin and the Northampton Inlier that are adjacent to the northernmost extent of the Perth Basin.

This publication is colloquially referred to as the 'northern Perth Basin bulletin' and it provides not only a technical resource for groundwater professionals but also a complete source of information for current and potential groundwater users and the general public.

The geographical scope of this bulletin extends from Gingin Brook in the south to the Murchison River in the north and from the Indian Ocean in the west to the western edge of the Darling Plateau in the east (Figure 1).

The geological sequence of this region records over 500 million years of Earth's history. The sediments of the entire Perth Basin have been deposited within relatively low-lying topography created by rifting during the breakup of Gondwana some 300 million years ago. It is these sediments, up to 12 km thick and now filled with water from rainfall past and present, that provide most of the water resources to the region. Some of the geological formations within the Perth Basin have analogues within the southern Carnarvon Basin that were deposited at the same time, under similar environmental conditions. For completeness, these formations are also described in this bulletin.

This bulletin is considered a companion document to previously published reports on the hydrogeology of the Perth Basin in the Perth region (Davidson 1995) and the southern Perth Basin (DoW in prep.). Collectively, these three publications provide a full description of the geology and hydrogeology of the entire Perth Basin. For further information on the Carnarvon

Basin, readers are referred to Hocking et al. (1987), which describes the geology of the Carnarvon Basin, and Allen (1987), which describes the hydrogeology of the Carnarvon Basin north of the Murchison River.

This bulletin contains six chapters and a series of appendices. After this introduction, Chapter 2 presents an historical overview of our understanding of the groundwater resources of the northern Perth Basin, including hydrogeological investigations, groundwater model development and ecohydrological investigations. Chapter 3 summarises the environmental setting of the groundwater system, describing the climate, land use, catchment hydrology, ecosystems and geological setting. Chapter 4 presents detailed stratigraphic and lithologic descriptions of the geological formations of the region. Chapter 5 summarises the current state of knowledge of the aquifers in the region, with a focus on the aquifers of the northern Perth Basin, but also includes the southern Carnarvon Basin, and the Northampton and Mullingara inliers. Chapters 4 and 5 of this bulletin are based on a preliminary report produced for the Department of Water by Pennington Scott (2010), with modifications and additions. Finally, Chapter 6 focuses on the management of groundwater resources, including current use and future potential demand.

Groundwater concepts and terminology that might not be common knowledge are explained in the glossary, along with a list of abbreviations and a reference list containing all relevant publications and sources of data. The appendices present data from aquifer tests and the estimated aquifer properties.

This bulletin contains over 100 figures that include geological and hydrogeological maps, cross-sections, diagrammatic sections, geophysical logs, hydrographs and climate data. Maps are drawn on a regional scale based on the interpretation of available data and are valid at the scale presented. Digital spatial data can be accessed at spatial.data@water.wa.gov.au by quoting the datasets and the relevant figure number.

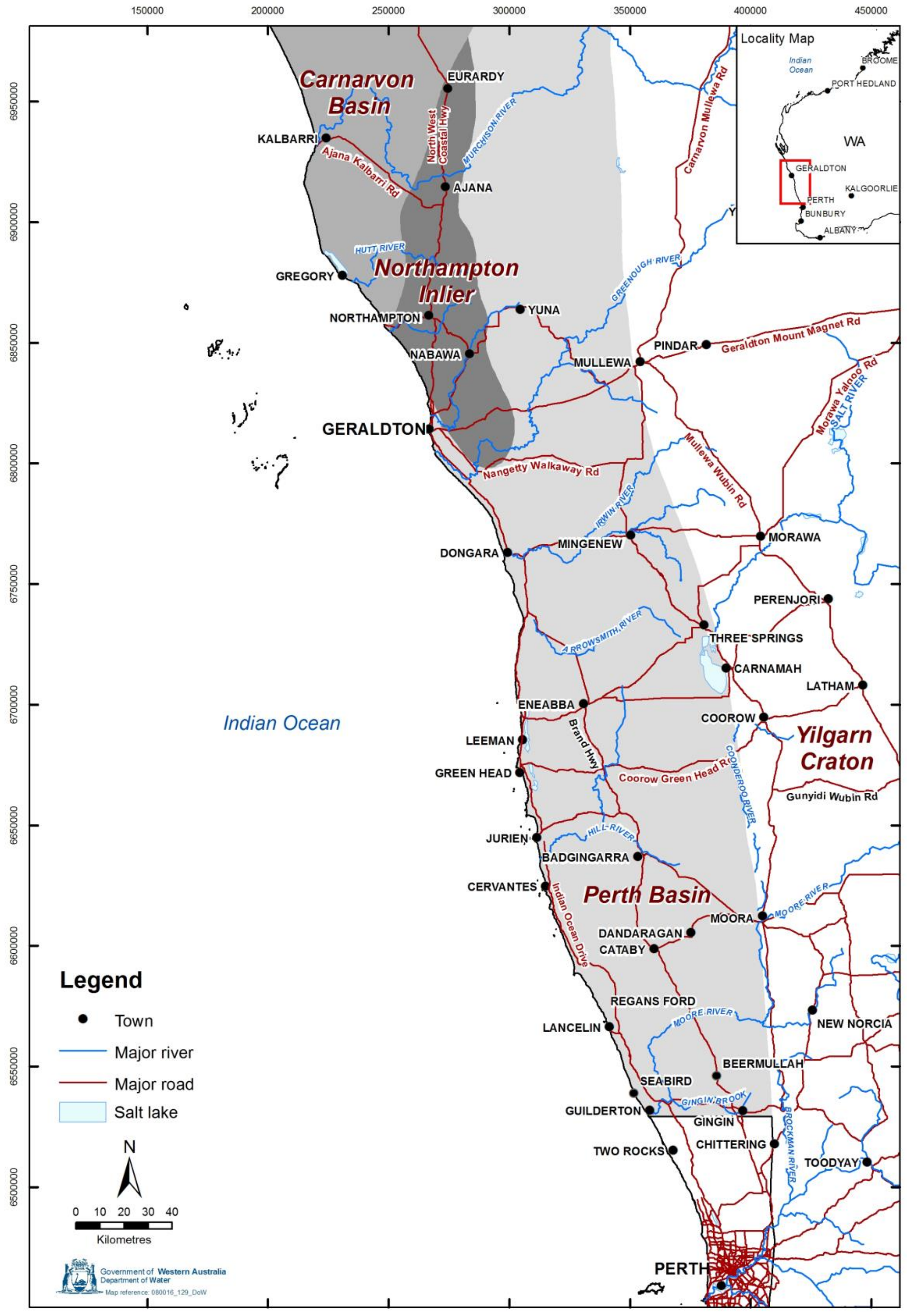


Figure 1 Geographical area covered by the northern Perth Basin bulletin

2 Developing an understanding of the groundwater system

The two sections of this chapter summarise the major investigations and publications related to the groundwater systems of the northern Perth Basin (Figure 2). The first section summarises the findings of over 30 separate, government-funded hydrogeological investigations conducted over the past 100 or so years, and the main investigations undertaken by other agencies and private companies for mining, irrigated agriculture and geological purposes. The second section summarises surface water – groundwater interaction studies, including groundwater-dependent ecosystems (GDEs), wetlands, river baseflow and cave ecohydrology. Collectively, the publications referenced in this chapter capture the current state of knowledge of the groundwater systems of the northern Perth Basin.

2.1 Hydrogeological investigations

The groundwater resource potential of the northern Perth Basin was first recognised in the late nineteenth century and government investigations commenced early in the following century. The state government drilled exploratory bores for water and coal in the townships of Mullewa, Eradu, Mingenew, Geraldton, Dongara, Moora and Yardarino (Campbell 1910; Maitland 1913; Connolly 1954; Allen 1997). During World War II, the Royal Australian Engineers drilled water supply bores for army camps and airfields throughout the basin at Dandaragan, Gingin, Mingenew, Moora and Morawa (Allen 1997). Significant groundwater development began in the 1950s when new land was released under the War Service Land Settlement Scheme and drilling for stock and domestic supplies increased (Mory 1995a, 1995b). These bores, some of which were as much as 150 m deep in the Badgingarra–Eneabba area, were equipped with windpumps.

Prospects for farm water supplies, particularly in the northern part of the basin where groundwater salinity is relatively high, have been reported by the Geological Survey of Western Australia (GSWA) in both published (e.g. Berliat 1966) and unpublished (e.g. Laws 1980) hydrogeology reports. Groundwater salinity in this region was found to generally increase from west to east, and to be controlled by rock types, and partly by faults and topography. Town water supply development and private investigations by mining companies and agricultural developers have also contributed significantly to the hydrogeological knowledge of the northern Perth Basin.

The potential groundwater availability in the northern Perth Basin demonstrated by the early drilling investigations led to a period of systematic investigation conducted by the GSWA from 1963 to 1994, initially under the Federal Water Resources Assessment Program. Since 1995 groundwater investigations have been carried out successively by the former Water and Rivers Commission, the Department of Environment, and the Department of Water. These investigations, summarised in Table 1 and Figure 3, comprise a range of investigations that include:

- six major deep east–west borehole lines spaced about 50 km apart between Guilderton and Dongara

- one ‘infill’ deep regional investigation in the Swan Coastal Plain between Guilderton and Cervantes
- five shallow regional investigations covering the full extent of the Swan Coastal Plain from Gingin to Geraldton
- local investigations for various purposes, including those carried out jointly with the former Public Works Department and also former Water Authority of Western Australia focusing on town water supply development in strategic areas (Wicherina, Allanooka and Irwin View, Arrowsmith, Agaton and Jurien Bay)
- local investigations focused on surface water – groundwater interaction in the northern Perth Basin.

From these investigations, 709 monitoring bores were constructed in the northern Perth Basin and a subset are monitored at least twice a year for water levels. They can also be used for monitoring changes in salinity and hydrochemistry.

Collectively, these investigations have provided a broad baseline understanding of aquifer extents and thickness, depth to groundwater, groundwater recharge, flow and discharge, aquifer salinity, hydrochemistry, groundwater age and in some cases surface water – groundwater interaction and GDEs. This wealth of information has been captured in reports and has vastly improved the sustainable management of groundwater resources in the region.

Deep regional investigations

The GSWA commenced a systematic drilling program to investigate the stratigraphy and map the hydrogeology of the northern Perth Basin, and provide an ongoing regional assessment of available groundwater resources as early as 1963.

A total of six deep east–west borehole lines were drilled in the northern Perth Basin about 50 km apart to depths of up to 800 m. These are, in order from north to south: the Dongara Line, Eneabba Line, Watheroo Line, Moora Line, Gillingarra Line and the Gingin Line (Figure 2). Boreholes were completed for long-term water level and salinity monitoring where possible, and many sites included multiple bores screened at different depths and in different aquifers.

The first borehole line in the northern Perth Basin was the Gingin Line, drilled in 1965–66. The project drilled 11 bores and confirmed that the multilayered aquifer system previously mapped from Mandurah to Bullsbrook extended as far north as the Gingin area. An ‘abundance’ of domestic quality groundwater was found within the Upper Jurassic – Lower Cretaceous aquifers up to depth of 150 m (Sanders 1967a, 1967b).

Drilling of the Watheroo Line commenced in 1967 and was completed in 1972, consisting of 11 bore sites and 23 bores up to 762 m depth, from near Watheroo in the east to Jurien Bay in the west (Harley 1974). Drilling of the Watheroo Line restarted in 1971 and was completed in 1972. This drilling program proved up the presence of large fresh groundwater resources in the Superficial, Leederville–Parmelia, Yarragadee and Eneabba–Lesueur aquifers. The investigation also discovered that the Otorowiri Formation forms an important confining unit. In addition, the potentiometric surface can be deep beneath parts of the Dandaragan Plateau, as much as 113 m bgl (below ground level) in Watheroo Line bore WL4.

The Eneabba Line to the north was drilled between 1972 and 1974 and comprised 28 bores at 11 sites to a maximum depth of 800 m. The drilling program discovered very large fresh groundwater resources in the Yarragadee and Leederville–Parmelia aquifers (Commander 1978). It found that the Cattamarra and Eneabba–Lesueur aquifers contain large reserves of fresh to brackish groundwater. It also found a high geothermal gradient in the west of up to 5.5 ^{o}C per 100 m but lower gradients to the east.

The Eneabba Line investigation was followed by drilling of the Moora Line, which started in 1974. The Moora Line runs from Moora to the coast and consists of 19 bores of up to 801 m depth (Briese 1979). Soon after, the Gillingarra Line between Lancelin and Mogumber was drilled between 1981 and 1986. Twenty bores were drilled at eight sites to a maximum depth of 1200 m (Moncrieff 1989). These drilling programs demonstrated the presence of large fresh groundwater resources in the southern portion of the northern Perth Basin, principally beneath the Swan Coastal Plain and the western part of the Dandaragan Plateau.

The Dongara Line, extending east from Dongara, was completed in 1995 (Groves 1995; Irwin 2007). This investigation confirmed the Yarragadee aquifer as a major groundwater resource in the area, but also identified salinity increases with depth and near the coast where there is mixing with seawater. The investigation also found that the potentiometric surface can be very deep in the area, as much as 181 m bgl in Dongara Line bore DL4B. Also, the Leederville–Parmelia aquifer was identified east of the Dandaragan Scarp, where it yields fresh groundwater and the water levels are increasing as a result of land clearing in the region.

More recently, between 2013 and 2015, a series of four deep bore lines were drilled across the Swan Coastal Plain between Guilderton and Wedge Island to the west and the Gingin Scarp to the east. A total of 29 bores were installed at 12 sites to a maximum depth of 1022 m. This drilling program focused on the Leederville and Yarragadee aquifers, improving groundwater monitoring and refining the hydrogeological conceptualisation between the Gingin, Gillingarra and Moora lines. Significant fresh groundwater resources were confirmed in the Leederville and Yarragadee aquifers (Tuffs 2016).

Department of Water reports can be accessed at www.water.wa.gov.au or at www.wir.water.wa.gov.au.

Geological Survey of Western Australia reports can be accessed at http://geodocs.dmp.wa.gov.au/

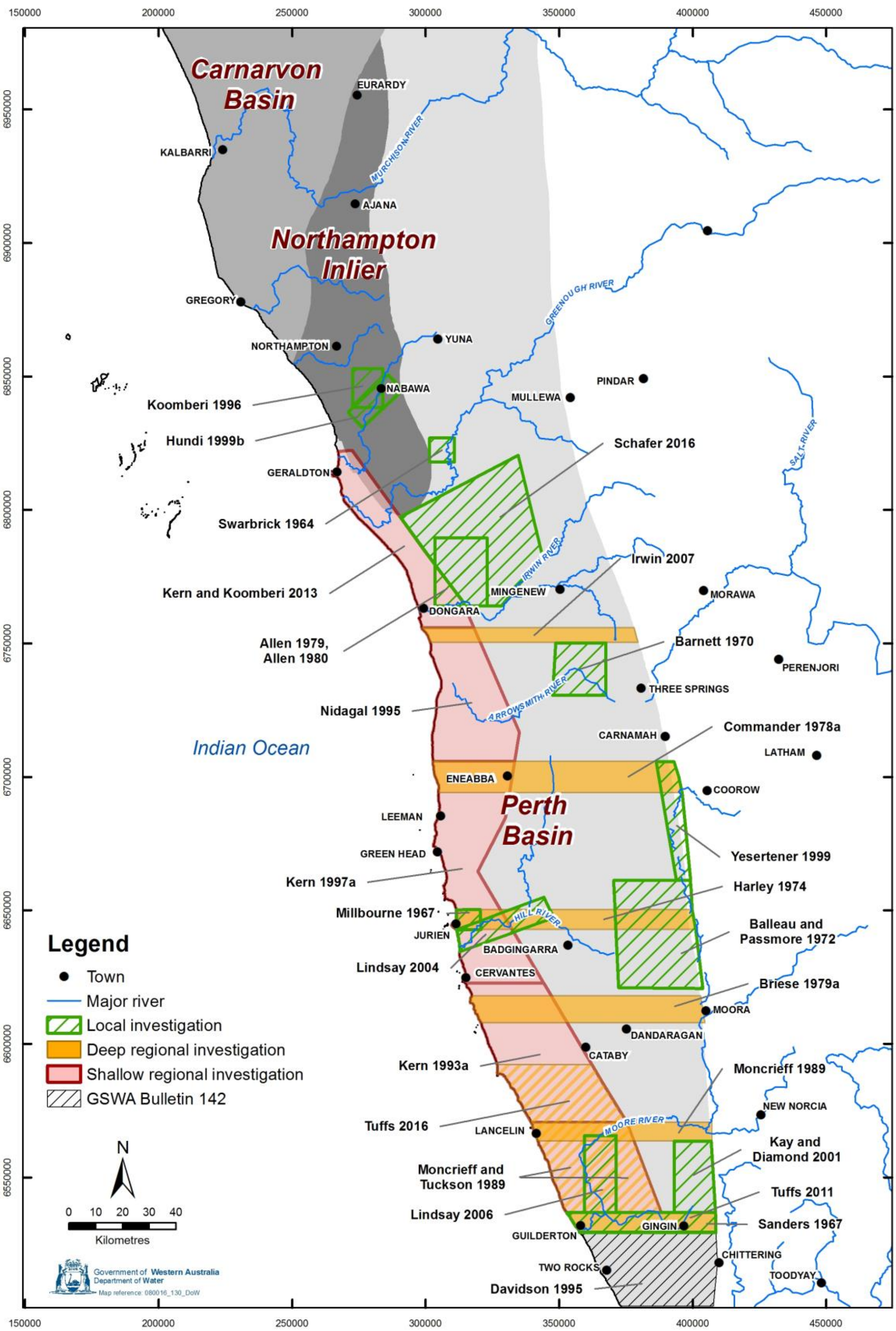


Figure 2 *Northern Perth Basin bulletin study area and the main hydrogeological investigations compiled in the bulletin*

Table 1 State government groundwater investigation programs in the northern Perth Basin

Program	Prefix	Sites	Bores	Year	Reference
Deep regional investigations					
Gingin Brook Line	GB	5	6	1965–66	Sanders 1967a
Watheroo Line	WL	12	23	1967–72	Harley 1974
Eneabba Line	EL	11	28	1972–76	Commander 1978a, b
Moora Line	ML	9	19	1974–77	Briese 1979a, b
Gillingarra Line	GL	8	20	1981–86	Moncrieff 1989
Dongara Line	DL	5	10	1990–95	Groves 1995; Irwin 2007
North Gingin	NGG	12	29	2013–15	Tuffs 2016
Shallow regional investigations					
Gingin	GG	11	11	1973	Allen 1975
Salvado	S	22	31	1976–80	Moncrieff & Tuckson 1989
Cataby Shallow	CS	35	65	1985–87	Kern 1988
Leeman Shallow	LS	34	68	1990–93	Nidagal 1994; Kern 1997
Greenough Shallow	GS	19	25	1994	Kern & Koomberi 2013
Mid West GDEs	Various	10	38	2009–12	Boniecki & Ryan 2010; Ryan 2012b
Local investigations					
Arrowsmith	AR	54	54	1963–67	Barnett 1969
Wicherina	–	5	5	1964	Swarbrick 1964b
Jurien Bay	JB	12	12	1965–66	Milbourne 1967
Allanooka	A	90	90	1965–98	Allen 1980
Agaton	A	16	18	1967–69	Balleau & Passmore 1972
Irwin View	IV	24	24	1974–77	Allen 1980

Program	Prefix	Sites	Bores	Year	Reference
Mt Hill	–	6	6	1977–96	Allen 1980
Nabawa	NAB	10	10	1994–95	Koomberi 1995
Chapman Valley	WRC	14	14	1998	Hundi 1999a, b
Yarra Yarra Lakes	YR	5	28	1999	Yesertener 1999a, b
Red Gully	RG	3	3	2000	Diamond 2000
Hill River	HRM	2	2	2004	Lindsay 2004
Gingin Superficial (Cowalla)	GS	10	10	2006	Lindsay 2006
Gingin Brook	GGB	16	32	2008	Tuffs 2011
Allanooka–Casuarinas	AC	17	28	2010–11	Schafer 2016

Shallow regional investigations

In the 1970s investigations began into the shallow aquifers of the Swan Coastal Plain between Guilderton in the south and Geraldton in the north. These investigations installed 200 monitoring bores (Figure 4). The first shallow drilling program to install monitoring bores in the Superficial aquifer was conducted in 1973 on the northern Gnangara Mound by the Metropolitan Water Authority. This program constructed 11 monitoring bores between Gingin and Guilderton (GG series). This was followed by the installation of the GB series of monitoring bores in 1977.

The first systematic investigation by the GSWA was the Salvado project between 1976 and 1980, consisting of 31 bores drilled across the Swan Coastal Plain between Guilderton and Lancelin (Moncrieff & Tuckson 1989).

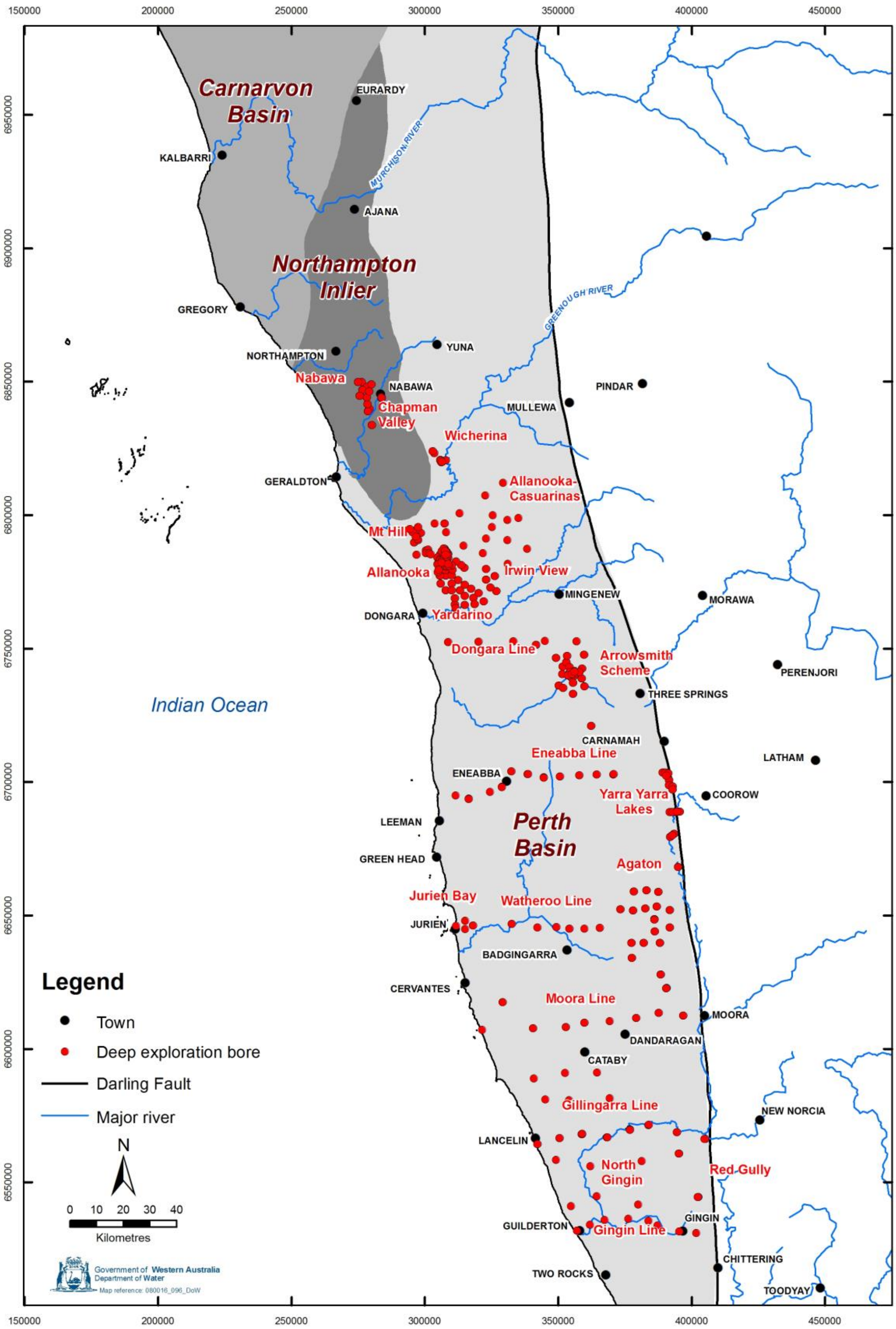


Figure 3 Deep exploration bores

The Cataby Shallow project extended the bore network to the north from Lancelin to Cervantes. This is the largest shallow investigation to date, comprising 68 bores at 35 sites (Kern 1988). Both the Cataby Shallow and Salvado projects confirmed the presence of a large fresh groundwater resource, up to 60 m thick, in the Superficial aquifer that could be used for irrigated agriculture and town water supply.

The Leeman Shallow project extended the network to Dongara, with 64 bores drilled between Leeman and Dongara (Nidagal 1994; Kern 1997). Major freshwater resources were found in the Yarragadee and Lesueur Sandstone component of the Eneabba–Lesueur aquifers. This investigation determined the saturated thickness of the Superficial aquifer as generally less than 20 m with groundwater salinity increasing to the north. It also confirmed that groundwater is generally brackish to saline in the Cattamarra aquifer and Eneabba Sandstone component of the Eneabba–Lesueur aquifer.

The Greenough Shallow project was completed in 1994, with 26 shallow bores installed between Dongara and Geraldton (Koomberi 1994b; Kern & Koomberi 2013). This investigation found that groundwater in all aquifers was generally brackish to saline, except in the eastern portion of the coastal plain where fresh groundwater can occur locally in the Superficial and Yarragadee aquifers.

Local-scale investigations

Town water supply investigations

Numerous investigations have been undertaken as part of town water supply development. Drilling and monitoring information on each of these sources has been collected by the Water Corporation and its predecessors (Public Works Department and Water Authority of Western Australia).

The Arrowsmith investigation in the Parmelia aquifer commenced in 1963 to identify suitable water supplies for towns located on the eastern edge of the basin and adjacent Yilgarn Craton (Barnett 1969). The investigation drilled 54 bores in the Arrowsmith River region, 10 km west of Arrino, resulting in the development of the Arrowsmith Scheme that supplies water to Mingenew, Arrino, Morawa and Perenjori.

Investigations for the Agaton project in the Leederville–Parmelia aquifer in the late 1960s were undertaken as part of the Northern Comprehensive Water Supply Scheme, which aimed to develop an integrated piped water supply scheme through much of the state’s northern agricultural area and Goldfields region (Balleau & Passmore 1972). Although significant groundwater resources were discovered, the area was never developed as an integrated water supply scheme.

Investigations for Geraldton’s town water supply were conducted as early as 1927 (Swarbrick 1964b), resulting in the development of the Wicherina borefield. Following increased demand and declining water quality in the Wicherina borefield, the Allanooka, Irwin River and Mount Hill investigations were initiated in the late 1960s to identify a suitable replacement water source (Allen 1964, 1965). Over 100 bores were drilled at the Allanooka, Mount Hill and Wye Springs borefields. Abstraction from the Allanooka borefield commenced in 1967, with the scheme supplying Geraldton, Dongara, Port Denison, Walkaway, Narngulu, Mullewa and

Eradu. A further 17 bores were drilled between 1974 and 1977 to augment the scheme (Allen 1979, 1980). Since then, the Water Corporation has installed additional monitoring and production bores. Further investigation drilling has been conducted by the Department of Water in the Casuarinas area to the north and east of Allanooka (Schafer 2016).

The Water Corporation recently conducted investigations of the Superficial and Eneabba–Lesueur aquifers near Jurien Bay to expand the town water supply. This included drilling 40 new bores (Baddock & Lach 2003) and investigating potential environmental impacts of groundwater abstraction (Froend et al. 2002).

Several smaller investigations to improve hydrogeological understanding and identify new water sources have taken place at Nabawa and Chapman Valley north of Geraldton (Koomberi 1995; Hundi 1999a, b), in the Yarra Yarra region (Yesertener 1999 a, b), and in the Gingin area (Diamond 2000; Tuffs 2011).

For more information on groundwater use for town water supply, including the locations of water supply wells and pipelines, refer to Section 6.2.

Environmental hydrogeology investigations

Investigations to assist managing agricultural land include a review of the impacts of rising groundwater levels and development of secondary salinity on biodiversity and agriculture in the West Midlands region (Carter & Deshon 2002). McConnell (2000) carried out an investigation of the Nebru catchment in the upper Arrowsmith River. This work concluded that the Urella Fault might act as a groundwater barrier and therefore reduce the risk of saline groundwater leakage from the Nebru catchment into the Perth Basin.

Studies of waterlogging due to rising groundwater and increased runoff from extensive clearing have also been undertaken in the Moora Group at Moora townsite (Deshon 2001) and in the Jingemai Dolomite, 28 km east of Mingenew (Speed et al. 2004). The Department of Agriculture and Food, Western Australia (DAFWA) carried out a hydrogeological assessment of rising groundwater levels in the Tumblagooda aquifer and potential saline land degradation near Adjana (Speed 2003).

Drilling and aerial electromagnetic survey have been conducted in the Gillingarra – West Koojan area for the Moore Catchment Council (Moore Catchment Council 2008). More recently, DAFWA carried out local drilling near lakes Indoon and Logue in 1999 as part of their long-term monitoring program (R Speed 2016 pers. comm.). There have also been drilling programs focused on surface water – groundwater interactions, including the characterisation of GDEs (Stelfox 2001; Lindsay 2004; Tuffs 2011; Ryan 2012a).

Other groundwater investigations

Groundwater investigations by mining companies for irrigated agriculture and geological studies have also contributed significantly to the hydrogeological knowledge of the northern Perth Basin. The information from many of these investigations is synthesised in this bulletin, and the main references are outlined here.

The mineral sands deposits at Eneabba and Cataby and their water requirements have driven a number of groundwater investigations (Baxter 1977). Water supply drilling for the Eneabba area began in 1971, with more than 40 production bores constructed in the

Superficial, Yarragadee, Cattamarra and Eneabba–Lesueur aquifers (e.g. AGC 1974, 1975; Rockwater 1977, 1980b, 1995; Commander 1980).

Similar investigations were carried out in the Cataby area in the 1980s and 1990s for the Cooljarloo mineral sands deposit, with over 30 bores drilled in the Superficial and Yarragadee aquifers (Rockwater 1992; AGC 1989b). Other significant investigations for mineral sands projects have also been conducted near Jurien Bay (AGC 1975; McPhar Geophysics Pty Ltd 1975).

In the 1980s an investigation in the Hill River area was undertaken to prove groundwater resources for a proposed coal-fired power station (AGC 1989b). While the power station was never constructed, the three production bores with aquifer test data and nine monitoring bores contributed significantly to the understanding of the hydrogeology of the Hill River area. More recently, investigations have been undertaken for a proposed coalmine in the Cattamarra Coal Measures, west of Eneabba (Rockwater 2009), which included drilling and aquifer tests of four production bores and construction of 16 monitoring bores.

Groundwater supplies have been investigated by two magnetite mining projects with several investigation bores constructed in both the Leederville–Parmelia and Yarragadee aquifers in the Arrowsmith River and Mingenew areas to assess groundwater resources for process and slurry transport (Aquaterra 2005; Rockwater 2008).

Since the 1990s large irrigated agriculture projects have also undertaken significant investigations to assess groundwater resources. Several horticultural operations in the Dinner Hill area have undertaken localised investigations of the Leederville–Parmelia aquifer to prove up the resource (Woodward Clyde 2000a; ERM 2001a; Water Direct 2004; Aquaterra 2004; Pennington Scott 2006). Irrigated fodder crop operations have also installed several deep Yarragadee bores north of Eneabba (Worley 2004); near Badgingarra (Pennington Scott 2009b); in the Cataby area (Pennington Scott 2009c); as well as in the Eneabba–Lesueur aquifer west of Eneabba (GRC–Dames & Moore 1990). Most recently an investigation for an irrigated almond project included the drilling of five deep bores in the Yarragadee aquifer and three bores in the Leederville–Parmelia aquifer near Eneabba (Pennington Scott 2007, 2008b, 2009a, 2009b).

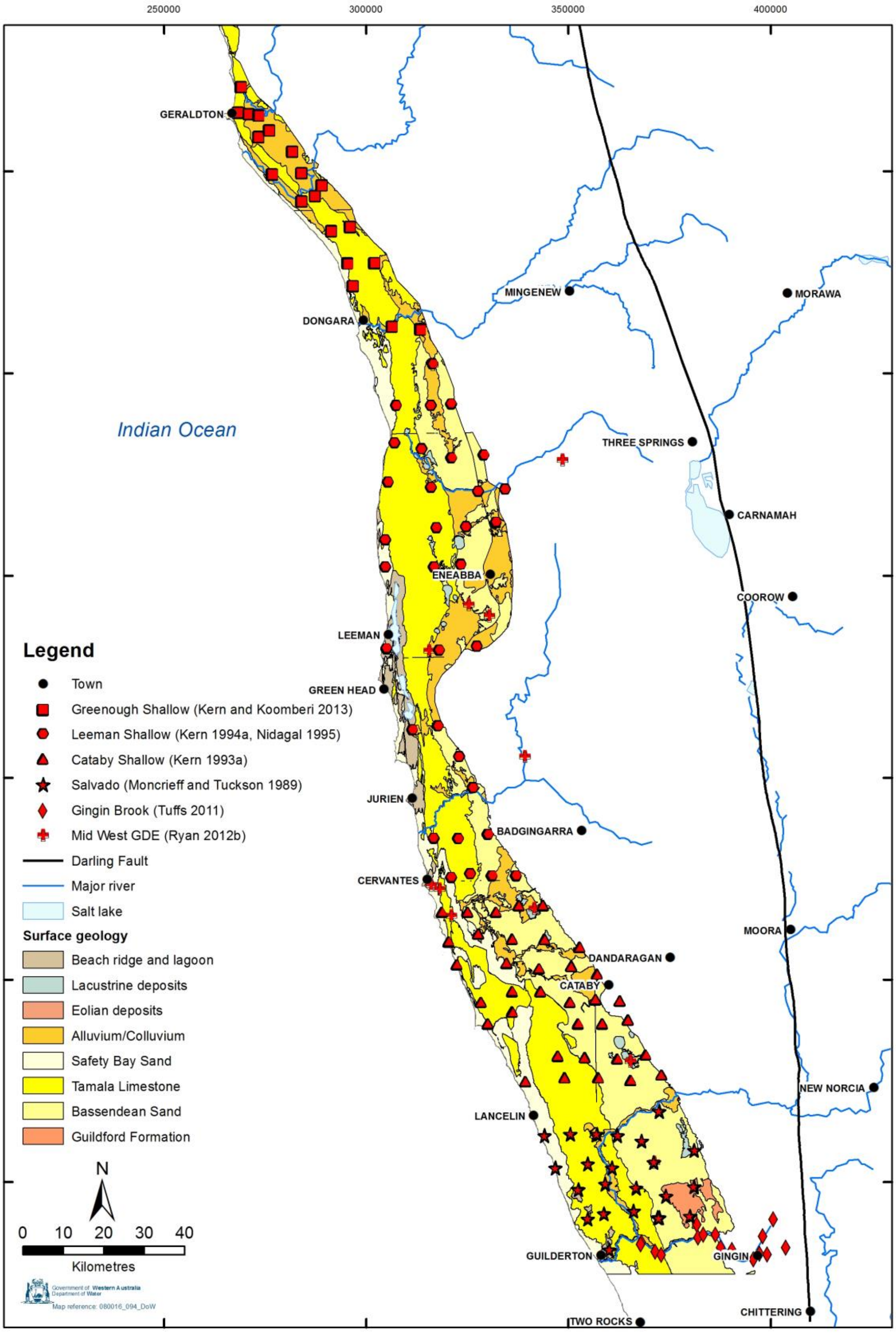


Figure 4 Shallow regional investigations

2.2 Environmental water investigations

Numerous investigations into environmental water requirements and GDEs across the northern Perth Basin have been published since 1995. The major findings of many of these studies are summarised in the department's HG11 report (Rutherford et al. 2005).

Groundwater-dependent ecosystem studies

V & C Semeniuk Research Group (2001) and PPK (2001) studied GDEs of the northern Perth Basin. These studies mapped potential groundwater-dependent wetlands, vegetation and caves. To do the latter, PPK (2001) considered both depth to groundwater and Normalised Difference Vegetation Index (vegetation 'greenness') of satellite imagery.

Following these studies were several studies of ecological and social water requirements of the Moore River (Strategen 2005, 2006) and ecological water requirements of the Hill River (Wetland Research and Management 2005).

Rutherford et al. (2005) generated a depth-to-groundwater contour map of the northern Perth Basin based on data from the state monitoring network, along with interpretations by PPK (2001) and Davidson et al. (2004). They produced conceptual models of 98 potential GDEs, and mapped remnant vegetation over shallow groundwater.

In 2007 the Northern Agricultural Catchments Council and the Department of Water consulted the northern Perth Basin community on their visions and desires for groundwater (Northern Agricultural Catchments Council 2007). The report documents consultation with representatives of the Noongar and Yamatji Indigenous groups, including information on the relevance and history of specific GDEs, and songlines in general, many of which are strongly defined by water in the landscape.

The GDE Vulnerability in the Mid West project (2009–12) drilled monitoring bores, analysed lithology, groundwater and acid sulfate potential (Boniecki & Ryan 2010, Ryan 2012b), characterised ecosystems (Casson 2012; Pinder & Quinlan 2015; Susac 2012) and conducted aerial electromagnetic surveys (GroundProbe Geophysics 2011a; 2011b) at 10 representative GDEs between the Moore and Irwin rivers. The study confirmed the importance of confined aquifers to ecosystems of high conservation priority. It also noted that while risk to ecosystems from abstraction is commonly attributable to drawdown, abstraction might also present a water quality risk to ecosystems, for example through inducing movement of saltwater–freshwater boundaries (Lam 2013), or through generation of acid sulfate soils.

Wetland studies

The V & C Semeniuk Research Group (1994) evaluated wetlands between Lancelin and Dongara to support nomination of individual wetlands to the Register of the National Estate. Their approach was to identify the natural groupings of wetlands and to assign them to a type, or consanguineous suite. This was to support selecting a variety of wetland types for recognition for their conservation significance.

Bennelongia Environmental Consultants (2010) completed a 'snapshot' literature review of wetlands between the Moore and Murchison rivers. They identified significant wetlands and watercourses, along with their ecological communities, flora and fauna. Some references relevant to the northern Perth Basin's GDEs include volumes of the 1993–96 series *Wetlands of the Swan Coastal Plain* (e.g. Hill et al. 1996, which formed the basis for the Geomorphic Wetlands Swan Coastal Plain spatial dataset); surveys of lake geomorphology and salinity management in the Yarra Yarra catchment (Boggs et al. 2007; GHD 2006), surveys of the Hutt River catchment (Quinlan et al. 2009); and plant, animal and water quality surveys on parts of the Murchison River (Gibson et al. 2000; Halse et al. 2000).

River baseflow studies

Four major river baseflow studies have characterised how rivers traversing the northern Perth Basin gain from, and lose to, various aquifers along their lengths (Johnson 2000; Stelfox 2001; Lindsay 2004; Tuffs 2011). The rivers of the northern Perth Basin can therefore be conceptualised as a series of connected yet distinct GDEs, with a variety of conceptual models applying along their lengths.

Stelfox (2001) assessed the groundwater–river interactions of the Coonderoo and Moore rivers in the context of concerns around secondary salinity and its potential impacts on groundwater quality. Saline river water was found to recharge the aquifer on the Swan Coastal Plain. Groundwater south of Gingin Brook was found to have elevated nutrient concentrations, with potential implications for the health of Gingin Brook and the lower Moore River and its estuary. There has also been investigation of the hydrodynamics of the Moore River estuary in relation to variable patterns of groundwater, marine water and surface water contributions over time (Cousins 2003).

Lindsay (2004) assessed the relationship between the Hill River and groundwater. Over its course, the river traverses aquifers that are in places artesian, supplying water to the river via springs and seeps. The effect of rising groundwater levels on baseflow was noted, with this effect attributed to land clearing.

Tuffs (2011) drilled monitoring bores and analysed lithology and groundwater to investigate surface water – groundwater interaction along Gingin Brook, confirming the various contributing aquifers. The report noted the potential for groundwater and surface water abstraction to impact baseflows, as well as drying climate. This study followed work by Johnson (2000) that assessed the hydrogeology of five perennial brooks of the Dandaragan Plateau (Gingin, Lennard, Nulila, Breera and Yalyal brooks) as primarily fed by springs and seeps along the stream banks. The report noted landholder observations of declines in stream flow over 1992–2000, as well as substantial groundwater level declines in one contributing aquifer, attributable primarily to abstraction.

Cave studies

V & C Semeniuk Research Group (2001) and PPK (2001) both reported on caves of the northern Perth Basin. PPK (2001) mapped caves between Geraldton and Cervantes, and the V & C Semeniuk Research Group (2001) reported that there were no recorded caves between Grey and Yanchep, but this might be through lack of knowledge as opposed to their confirmed absence, given the existence of karst.

Susac (2009) produced a comprehensive literature review and report on karst biodiversity, palaeontology and hydrology of the Northern Agricultural region, for the Northern Agricultural Catchments Council. The report provides information on individual caves, in the context of a literature review on how selected caves interact with aquifers and surface water. Susac (2012) nominated one high value representative of each of seven subterranean ecosystem types, based on available information and expert cave knowledge.

3 Biogeophysical setting

Groundwater systems are fundamentally linked to their environmental setting. The groundwater system resides within a geological framework that has developed over millennia. Topography, climate, land use, catchment hydrology and ecosystems are all interlinked with the processes of groundwater recharge and discharge.

This section describes the environmental setting of the northern Perth Basin, providing the essential context for understanding and managing the groundwater system. Subsections include physiography, climate, catchment hydrology, GDEs and regional geological setting. The subsection on GDEs provides an overview of the distribution of GDEs within the northern Perth Basin region. Descriptions and conceptual diagrams of individual GDEs, and management considerations, are presented in Chapter 6. The geological setting subsection includes information on the depositional history and structural geology in the northern Perth Basin. For detailed stratigraphy and lithologic descriptions, refer to Chapter 4 of this bulletin.

3.1 Physiography and topography

The physiographic regions of the northern Perth Basin are shown in Figure 5. These correspond broadly to those described by Finkl and Churchward (1973) and Playford et al. (1976).

The coastal region between Gingin and Geraldton is covered by the Swan Coastal Plain (Saint-Smith 1912). The plain is low-lying, gently undulating and covered by Quaternary coastal dunes, marine shoreline deposits, and numerous wetlands further inland. The 40 km-wide plain is bound by the Indian Ocean to the west and Gingin Scarp to the east that is a steep slope resulting from the erosion of the elevated Dandaragan Plateau and Arrowsmith region to the east (Playford et al. 1976). The plain is developed upon a marine erosional surface over the underlying Mesozoic rocks that are covered by late Pliocene–Holocene sediments. Its western margin contains the coastal belt with a series of low dune systems comprising the Bassendean, Spearwood and Quindalup dunes that have formed parallel to the coast (McArthur & Bettenay 1960). The dune systems extend up to 20 km inland, and increase in width and age eastward. A number of these shorelines have economic significance owing to the occurrence of heavy mineral sands (Baxter 1977). The eastern margin of the coastal plain hosts the flat Pinjarra and Eneabba plains.

The Arrowsmith region is undulating and sandy with hills of Triassic and Jurassic sediments commonly capped by laterite (Playford et al. 1976). The Dandaragan and Gingin scarps represent the eastern and western boundaries of the Arrowsmith region, respectively. Some of the hills are flat topped, but many laterite outcrops slope towards present drainage lines, forming breakaways where they are eroded along the valley flanks (Playford et al. 1976; Mory 1994b). The area is drained by the Arrowsmith, Irwin and Hill rivers and numerous creeks. Many of these watercourses do not reach the coast, terminating into swamps, lakes and sinkholes along the Swan Coastal Plain (Rutherford et al. 2005). The Irwin and Hill rivers discharge at the coast.

The Dandaragan Plateau is a sand- and laterite-capped, gently undulating plateau that overlies Cretaceous sediments, with elevation ranging from 140 to 300 m AHD (Australian

Height Datum) (Gentilli & Fairbridge 1951; McArthur & Bettenay 1960). It is bound by the Dandaragan and Gingin scarps to the west and southwest respectively, and the Yarra Yarra region to the east. The Gingin Scarp is a fairly prominent topographic feature up to 75 m high, while the Dandaragan Scarp reaches up to 90 m high. The Gingin Scarp might represent a period of marine erosion associated with higher sea levels in the early Pleistocene or late Tertiary (Playford et al. 1976). Valleys within the Dandaragan Plateau are infilled with deep yellow sands that capture most rainfall, causing streams to be highly ephemeral (Playford et al. 1976; Commander 1981). The plateau is characterised by ephemeral streams and swamps (Rutherford et al. 2005), and flat-bottomed valleys that flood after exceptionally heavy rains (Earth Tech Engineering 2002). Along the western edge of the Dandaragan Scarp, the Otorowiri Member of the Parmelia Group outcrops and a line of springs and groundwater discharge into the downstream Gingin and Lennard brooks (Mory & Iasky 1996), and the Arrowsmith and Moore rivers (Rutherford et al. 2005).

The Victoria Plateau is a large, gently undulating sandplain overlying a laterite cap to the north of the Irwin River and having an elevation of about 250 m AHD (Johnson et al. 1951; Johnson et al. 1954). The plateau is generally undissected except at breakaway edges and in areas where the sand has been eroded. Other major incisions to the Victoria Plateau were cut by the Greenough and Murchison rivers where the river valley has exposed the laterite cap overlying the Tertiary, Jurassic and Permian sediments (Playford 1954; Playford et al. 1976). Apart from the Greenough and Murchison rivers, the Victoria Plateau has little surface drainage with most rainfall being captured by surface sands (Playford et al. 1970). Playford (1954) also suggested that uplift of the Victoria Plateau during the Tertiary might have contributed to the rejuvenation of the rivers, and likely predates lateritisation of the Victoria Plateau (Playford 1954).

The Lockier region is of low relief with generally clayey soils overlying Permian and Proterozoic sediments, and Proterozoic granitic rocks (Playford et al. 1976). The granitic rocks form a line of rounded hills known as the Mullingara Inlier. Flat-topped outliers of the Victoria and Dandaragan plateaus are present in the region. These are capped by laterite and sand, in contrast to clayey soils in the centre of the region. The Lockier region is drained by the upstream sections of the Irwin, Lockier and Arrowsmith rivers.

The Yarra Yarra region is narrow and low lying, and straddles the basin boundary along the Darling Fault (Playford et al. 1976). It comprises Proterozoic, Permian, Jurassic and Cretaceous sediments that are extensively lateritised, and have clayey to sandy soils. Average elevation is about 200 m AHD decreasing to the south. Internal drainage between the Darling and Dandaragan plateaus is poor with intermittent streams feeding into numerous swamps and salt lakes, the most prominent being the Yarra Yarra Lakes, a series of terminal salt lakes that receive runoff from the Darling Plateau to the east (Playford et al. 1976). Chains of these lakes and water bodies connect following heavy rains to form broad streams within the Coonderoo River that periodically discharges into the Moore River.

The Chapman region comprises moderately dissected Proterozoic, Triassic and Jurassic sediments with small flat-topped remnants of the Victoria Plateau characterised by laterite capping Jurassic sediments (Playford et al. 1976; Hocking et al. 1987). Limestone along the coast is associated with the Pleistocene Tamala Limestone. Precambrian rocks form rounded hills surrounded by residual clayey and sandy soils derived from the Northampton Inlier. Major drainage lines include the Greenough and Chapman rivers.

The Wittecarra region is moderately dissected with discontinuously preserved lateritic duricrust (Hocking et al. 1987). Calcrete-capped remnants of the Pillawarra Plateau (Menarra Hill) form elevated features. The topography gradually slopes downward to the coast at Kalbarri. The coastal dune belt obstructs palaeodrainage lines and there are no significant river systems. The Wittecarra region is geologically younger than the Pillawarra Plateau, but it was formed about the same time as the main incision of the Murchison River Gorge (Hocking et al. 1987).

The Murchison Gorge region relates to the deep gorge cut by the Murchison River through Silurian sandstone and Proterozoic granitic rocks of the Northampton Inlier.

3.2 Vegetation and land use

Large swathes of botanically diverse sandplain heathland, or kwongan, cover the northern Perth Basin (Beard 1984). Kwongan is typically found as low heath and scrubheath covering most of the Dandaragan Plateau, Arrowsmith region, Swan Coastal Plain, Victoria Plateau and Chapman region (Beard 1981). Banksia woodland is more common in the southern half of the Swan Coastal Plain and Dandaragan Plateau, while the Arrowsmith region supports marri woodland in the south between the Moore River and Badgingarra. Acacia thickets are found throughout the coastal plain (Beard & Parker 1976; Beard et al. 1976; Beard 1979a, 1979b). As well as supporting kwongan in higher areas in the landscape, the Chapman region and the Victoria Plateau support acacia (jam) scrub with scattered York gums, and thickets of melaleuca–hakea (Chapman region) or acacia–casuarina (Victoria Plateau), and samphire flats (Victoria Plateau).

Watercourses support taller vegetation than the surrounding landscape, including woodlands or scattered individuals of river gums with paperbarks, wandoos and York gums. Casuarinas are often found bordering saline watercourses and wetlands. Wetlands of the Swan Coastal Plain are commonly vegetated, and typically support swamp heath, tea-tree thickets or paperbark thickets. The wetlands are found in depressions at the base of the Gingin Scarp, and in interdunal swales further west (Beard & Parker 1976; Beard et al. 1976; Beard 1979a, 1979b).

Before European settlement, the Noongar people occupied and maintained land in the northern Perth Basin. The Amangu, Yued and Whadjuk groups travelled with the seasons, depending on the availability of food. The songlines (oral maps of the landscape) in the area of the Perth Basin related to water features connected to groundwater, and the people who used these were distinct from the ‘rock-hole’ people further inland. Aboriginal peoples used fire as a land management tool, which influenced the structure of the vegetation (Enright & Thomas 2008).

Clearing of land for agriculture in the northern Perth Basin commenced as early as the 1850s, generally in areas like Dandaragan with more clayey soil types that were most conducive to farming. Significant clearing of sandplain areas started with the War Service Land Settlement Scheme in the 1950s and 1960s. The government bought, improved and subdivided fully and partially developed farms, then sold them to returned soldiers. By 1958 demand for land by ex-service personnel had declined, but the scheme had been so successful that the government opened it up to general applicants. This policy continued until 1969 and is largely responsible for the pattern of present land use (Jarvis 1979).

About 70 per cent of the natural vegetation has been removed through land clearing. Areas of remnant native vegetation are shown in Figure 6. The Swan Coastal Plain has retained up to 40 per cent native vegetation but only about 25 per cent native vegetation remains in other areas underlain by the Perth Basin. Uncleared areas tend to be sandy, rocky or waterlogged, and therefore not preferred for agricultural development.

Broadacre agriculture for cereals and pasture is widespread in the region. Other industries include mineral sand mining at Eneabba and Cataby, commercial fishing from coastal settlements, and gas and oil production near Dongara. Most recently, large horticultural developments (such as vegetables, grapes and olives) and tree plantations have expanded.

Coastal towns, including Seabird, Lancelin, Cervantes, Jurien, Green Head, Leeman, Dongara and Kalbarri, are centres for the rock lobster industry and tourism. Inland towns such as Badgingarra, Eneabba and Mingenew are farming centres that are also supported by tourism, particularly during the wildflower season. Geraldton is a major regional centre supporting agriculture and mining activities throughout the Mid West.

The state government manages conservation areas across the northern Perth Basin, most of which lie on the Swan Coastal Plain. These include a number of national parks (Drovers Cave, Lesueur, Nambung, Badgingarra and Watheroo), the large coastal Beekeepers Nature Reserve and many smaller nature reserves.

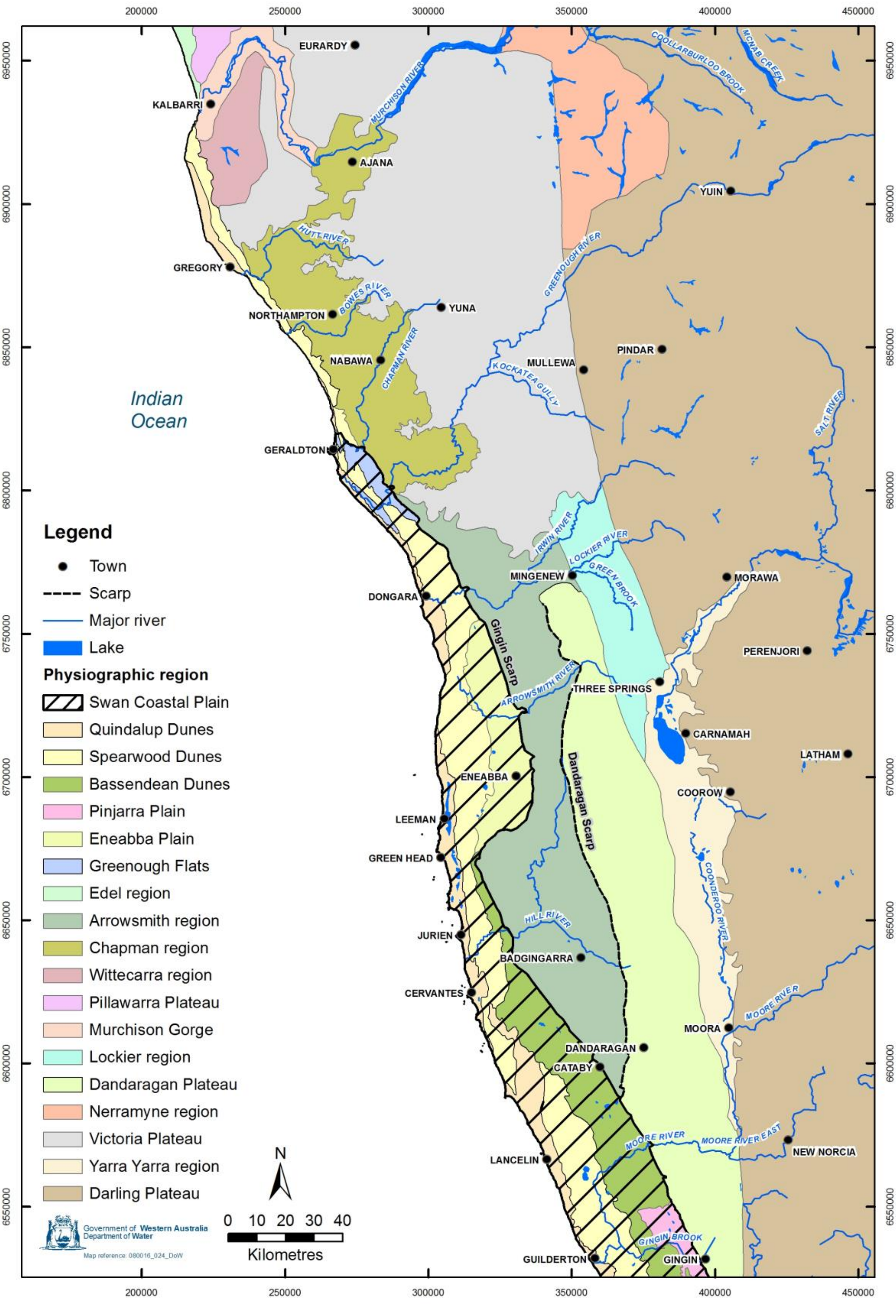


Figure 5 Physiography and topography of the northern Perth Basin

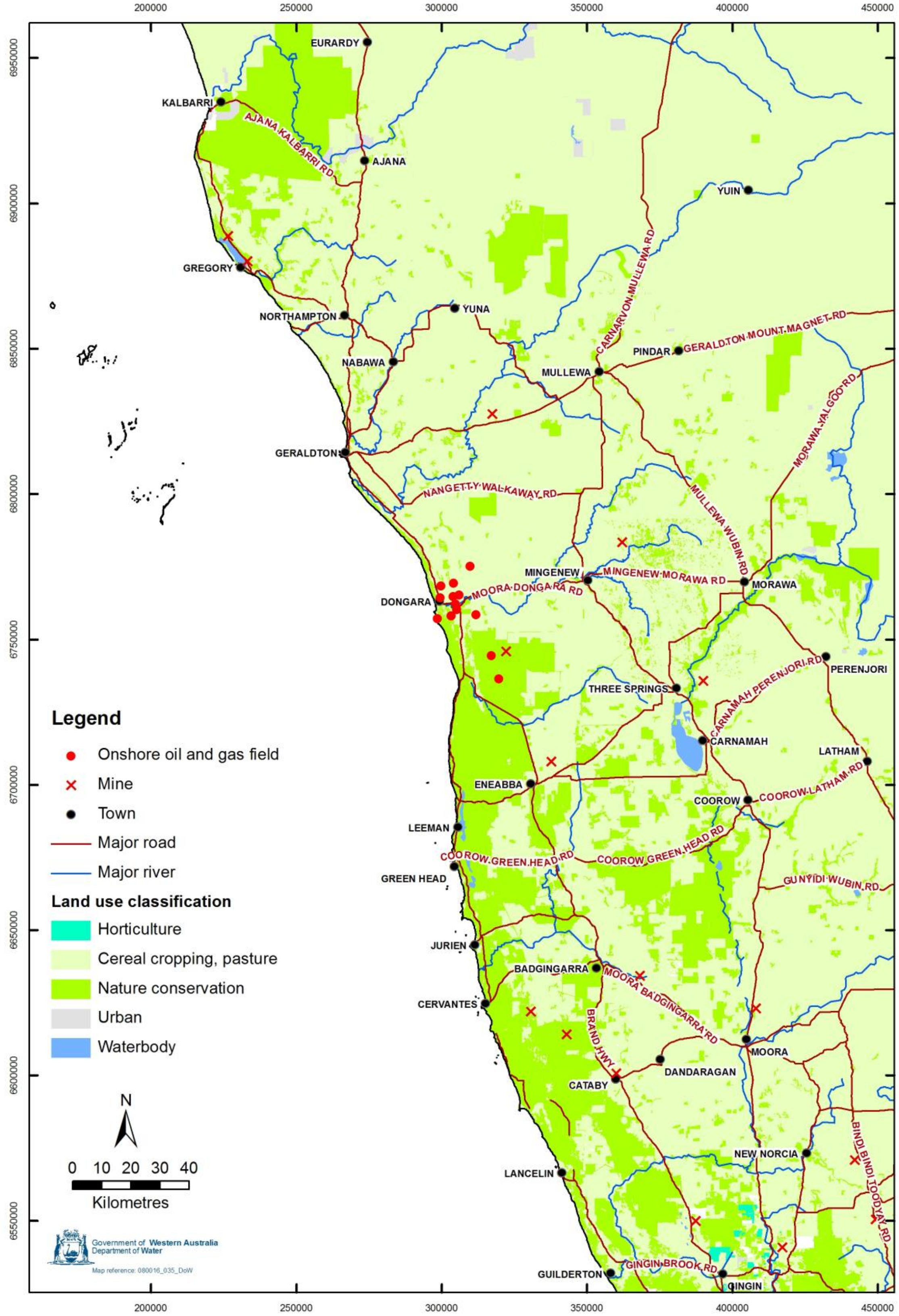


Figure 6 *Land use*

3.3 Climate: past, present and future

The northern Perth Basin has a subtropical climate (based on the Köppen classification scheme) with mild, marked wet winters and hot, distinctly dry summers (BOM 2006). Hotter days in summer are characterised by the flow of warm north-easterly winds from the interior of the continent, controlled by the west coast trough, while wet winter days are associated with cold fronts originating in the Southern Ocean. The subtropical ridge, a band of high pressure that extends west to east, impacts how far north rain-bearing storms and frontal systems extend. The subtropical ridge has a seasonal north–south transition and is generally located to the south of Australia in summer and then moves northward during winter to be located over central Australia. As a result, the southern half of the northern Perth Basin receives higher average winter rainfall. Summer rainfall can be from thunderstorms and ex-tropical cyclones, which can often produce significant event-based rainfall, skewing the annual totals.

The south-west of Western Australia, which includes the northern Perth Basin, has experienced declining annual average rainfall from the 1970s, accompanied by rising average temperatures (CSIRO & BOM 2007; Indian Ocean Climate Initiative 2012; Hope et al. 2015; DoW 2015a; BOM 2013a). A shift in atmospheric circulation patterns caused by changes in global heat distribution means that rain-bearing fronts crossing the south-west are weaker and less frequent (Frederiksen et al. 2012). This also means that the magnitude of the declining trend observed over the past 30 years in the northern half of the northern Perth Basin is less than the decline in the lower half of the Basin and lower south-west of the state (DoW 2015a).

The Bureau of Meteorology (BOM) commenced recording rainfall in the area in 1877 with the opening of a station in Geraldton (BOM ref. 008050). Long-term trends for Geraldton indicate a decline in rainfall and increase in temperature (Figure 7). From 1900 to 1974 the average rainfall was 465 mm/year while for 1975–2015 the average was only 408 mm/year, a drop of 12 per cent. Average annual evapotranspiration for 1975–2015 is estimated at 1576 mm, almost four times the average rainfall. These rainfall trends are consistent with observations at other meteorological sites in the basin. Declines are more pronounced in the southern and coastal parts of the basin, compared to inland and northern locations.

The climate is highly variable and droughts, or extended sequences of low rainfall, can be common in the northern part of the basin as indicated by the large range in maximum and minimum annual rainfall. For Geraldton, the largest observed annual rainfall, of 855 mm, was measured at the gauge in 1917. The lowest observed annual rainfall was in 2006 when only 192 mm was recorded. The largest rainfall year in recent times was 1999, when Tropical Cyclone Elaine crossed the coast between Geraldton and Kalbarri as a tropical low. Flood events cause large flows and severe flooding in surface water catchments in the area and subsequently large volumes of groundwater recharge.

A monthly breakdown of the rainfall at Geraldton shows the highly seasonal nature of the rainfall (Figure 8). This wet winter rainfall pattern is consistent with observations at other meteorological sites in the basin where typically on average, about 70–80 per cent of total annual rainfall is received over the May to September period. The area is water-limited from

September/October to April, when evaporation exceeds rainfall. Evaporation exhibits a northward increasing trend across the area (Figure 8).

There is a strong average rainfall gradient across the region; rainfall decreases with distance from the coast and from south to north (Figure 9). Average annual rainfall over the 1975 to 2015 period ranges from 585 mm at Lancelin (the southern end of the basin extent) to 343 mm at Kalbarri (the northern extent). Inland at Carnamah, average rainfall is 337 mm per annum.

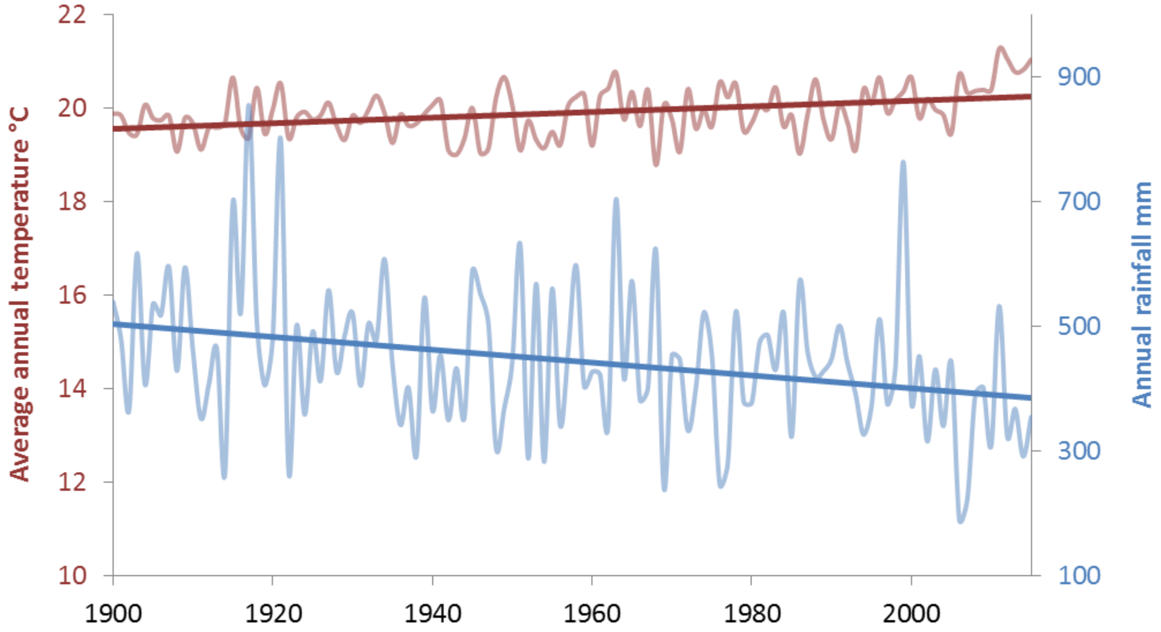
Climate change is projected to result in increased temperature and evaporation throughout Western Australia, coupled with a decline in winter and spring rainfall in the south-west. There is high confidence in these climate projections as there is a good understanding of the atmospheric circulation patterns that drive the climate in south-west Western Australia and there is strong agreement on the direction and magnitude of change among global climate models (CSIRO & BOM 2015). Based on the most recent global climate models, increased intensity of extreme rainfall events are more likely into the future (CSIRO & BOM 2015).

The Department of Water uses the results from global climate models in water resource assessments and planning in the south-west of the state (DoW 2015a). For the northern Perth Basin area, future changes in rainfall under a dry scenario 2030 climate range from a decline of 3 per cent at Geraldton to a decline of 14 per cent at Eneabba compared to the 1975–2015 averages (Table *2*).

Department of Water's 2015a report can be accessed at www.water.wa.gov.au.

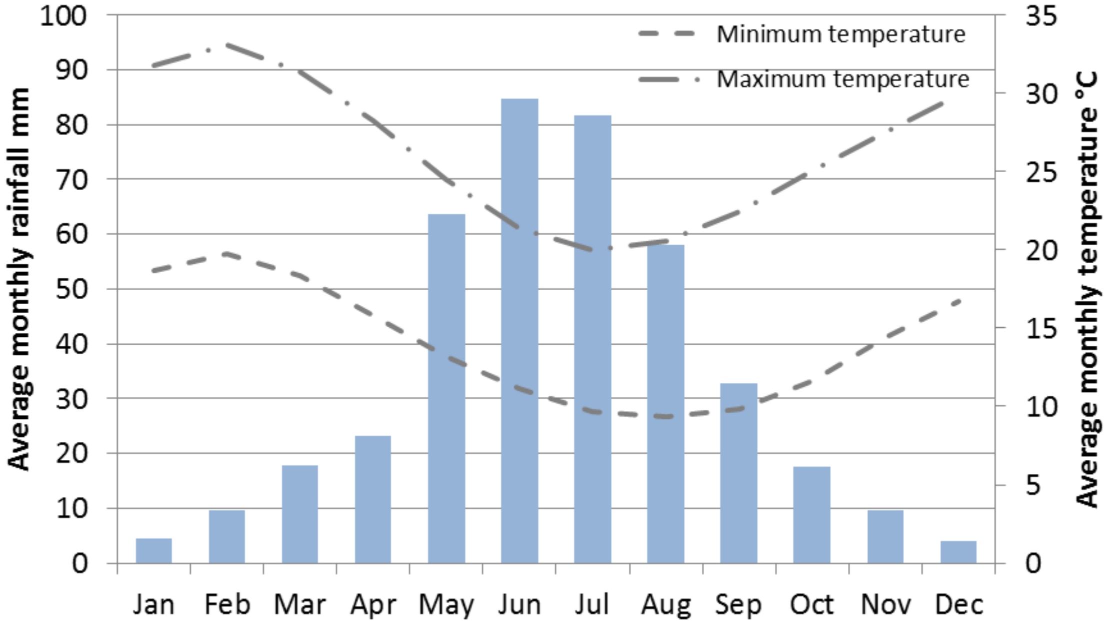
More information on climate change can be found at:

- Climate Change in Australia – resource of climate projections and climate science www.climatechangeinaustralia.gov.au
- BOM – seasonal forecasting and historical climate data and trends www.bom.gov.au
- Intergovernmental Panel on Climate Change – international source of climate science www.ipcc.ch.



(BOM ref. 008050); sourced from the Bureau of Meteorology (2005) and Department of Science, Information Technology and Innovation (2015)

Figure 7 Long-term rainfall and temperature trends at Geraldton



(BOM ref. 008050) for 1975–2015; sourced from the Bureau of Meteorology (2005) and Department of Science, Information Technology and Innovation (2015)

Figure 8 Mean monthly rainfall and minimum and maximum temperature averages for Geraldton

Table 2 Mean annual rainfall projections with a 2030 future climate at four meteorological sites in the northern Perth Basin (DoW 2015a)

	Mean annual rainfall (mm) 1975–2015	Mean annual rainfall (mm) 1961–1990	Wet scenario 2030	Median scenario 2030	Dry scenario 2030
Carnamah future climate mean annual rainfall	337	369	357	348	312
% change compared to 1975–2015 period			6%	3%	–7%
% change compared to the 1961–1990 period			–3%	–6%	–15%
Eneabba future climate mean annual rainfall	476	527	508	486	440
% change compared to 1975–2015 period			7%	2%	–8%
% change compared to the 1961–1990 period			–4%	–8%	–16%
Lancelin future climate mean annual rainfall	585	660	636	602	559
% change compared to 1975–2015 period			9%	3%	-4%
% change compared to the 1961–1990 period			–4%	–9%	–15%
Geraldton future climate mean annual rainfall	408	475	458	446	399
% change compared to 1975–2015 period			12%	9%	–2%
% change compared to the 1961–1990 period			–4%	–6%	–16%

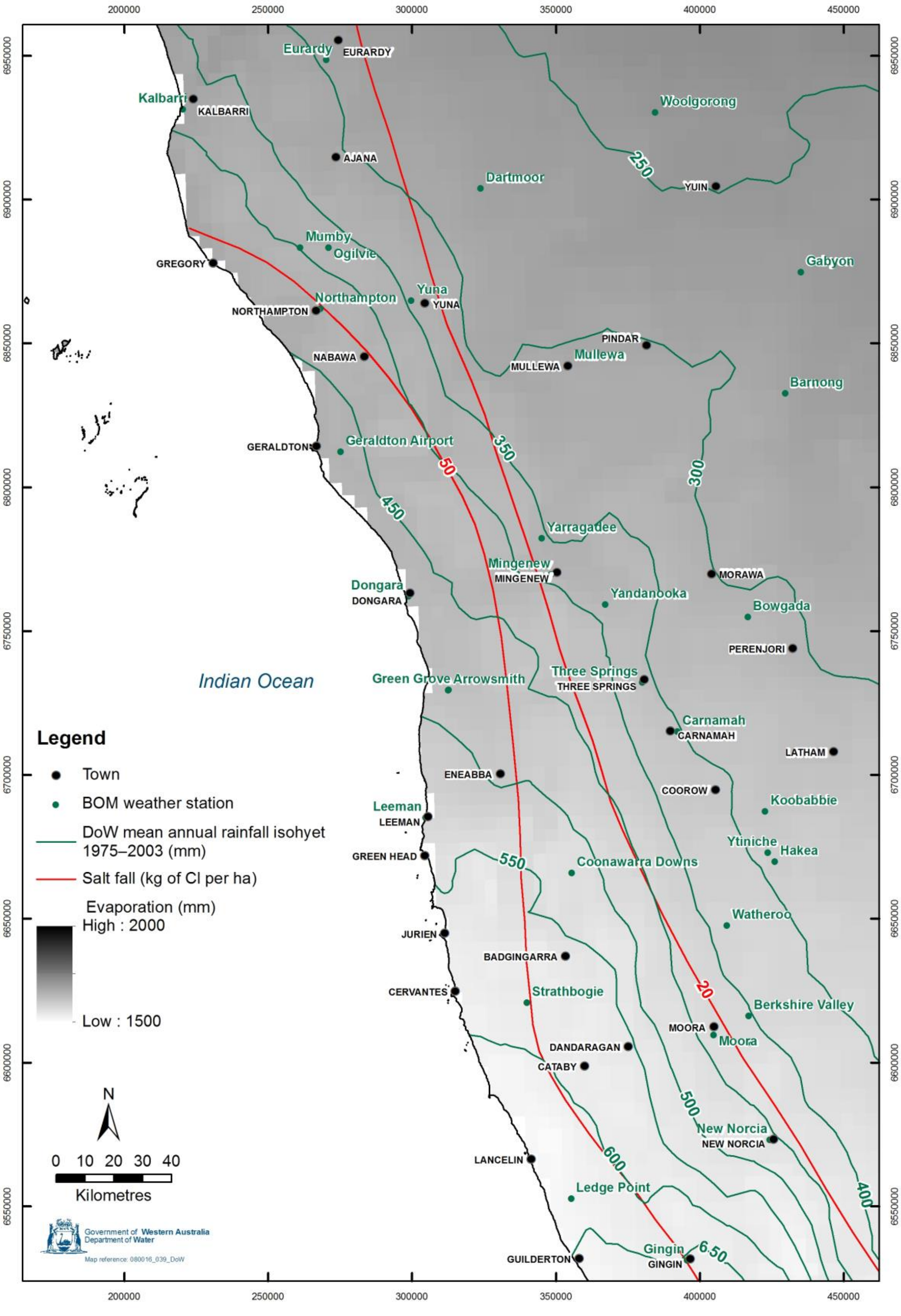


Figure 9 Climate of the northern Perth Basin

3.4 Catchment hydrology

The northern Perth Basin extends from Gingin Brook in the south to the Murchison River in the north, encompassing portions of 18 surface water catchments (Figure 10). Of these catchments, the Murchison River is the largest, extending beyond the northern and eastern extent of the basin towards Meekatharra. The Murchison, Greenough, Irwin and Moore rivers originate on the Yilgarn Plateau before descending onto the coastal plain. There are five internally draining catchments (with no outlet to the ocean): the Arrowsmith River, Indoon–Logue, Cockleshell Gully, Nambung River and Cataby – Caren Caren catchments.

The Department of Water has operated 40 streamflow monitoring sites within the surface water catchments that cover the northern Perth Basin, and as at 2016, 27 are operating. Table 3 lists the catchment area, mean annual flow and stream salinity for the surface water catchments.

Real-time information and the latest surface water data can be obtained from the Department of Water's Water Information Reporting website www.wir.water.wa.gov.au.

Streamflow in the northern Perth Basin transitions from reliable winter flows in the south and coastal areas to large episodic events and extended dry periods that characterise the northern and inland catchment flows. This reflects the seasonal climate pattern where the southern and coastal catchments in the northern Perth Basin are more influenced by winter frontal systems. The northern and inland areas are more strongly influenced by ex-tropical cyclones and summer thunderstorm events than winter rainfall.

Many of the watercourses in the northern Perth Basin cease to flow for part of each year (particularly during summer months). However, groundwater discharge maintains year-round flow in some reaches of the Irwin, Hill and Moore rivers and Gingin Brook. Surface water can also infiltrate into aquifers, recharging groundwater resources. Many of the larger rivers have extensive floodplains and significant recharge results from these major flood events. Major flooding can occur at any time within the year but the larger events are more common during summer in the northern catchments (Table 4).

Rivers, lakes or wetlands that receive groundwater discharge are characterised as gaining systems (Winter et al. 1998). Surface water features that contribute to recharge of aquifers are referred to as losing systems. In some cases, groundwater discharges on the up-hydraulic gradient side of a surface water body and recharges on the down-hydraulic gradient side. These systems are called throughflow (or flow through) systems. Alternatively, there might be no hydraulic connection between the surface water and the aquifer, often termed a disconnected (or perched) system (Brunner et al. 2010).

Figure 11 shows likely areas of connectivity between rivers and groundwater as identified in selected previous studies (Allen 1979; Commander 1981; Lindsay 2004; Stelfox 2001; Swarbrick 1964a). As hydraulic connectivity is not fixed (it can vary seasonally or with groundwater and surface water use, for instance), this figure is presented to highlight the interconnected nature of the two resources and should only be used as a guide. Sections 3.5 and 6.4 and Figure 98 of this bulletin provide further information on groundwater-dependent features in watercourses, such as baseflow, in-stream and offline springs, river pools and fringing groundwater-dependent vegetation.

A description of each of the major surface water catchments is provided below.

Murchison River catchment

The Murchison River is the largest surface water system in the region and the second longest river in Western Australia. The catchment is 103 768 km^2 and the river is over 700 km long. Beginning inland beyond Meekatharra on the Yilgarn Plateau, the river flows west to the coast at Kalbarri. Major features of the river include Woonana and Wilgiamia pools and Murchison Gorge, west of the North West Coastal Highway. To the east of the highway there are numerous wells and erosional flood plain areas (WRC 1998a).

The river is generally saline with salt lakes in the eastern parts of the catchment and can become fresher after major rainfall events (DoW 2014). The catchment is largely (95%) uncleared land used for open-range pastoral grazing.

The river flows intermittently after rainfall events. Groundwater from underlying aquifers discharges to the system upstream of the Northampton Inlier. The river discharges into the Tumblagooda Sandstone downstream of the Northampton Inlier. The presence of semi-permanent pools in the Tumblagooda Sandstone suggests local groundwater discharge (A Kern 2016, pers. comm.).

There has been one gauging station operating in the catchment since 1967. Emu Springs station, located near the base of the catchment, collects runoff from an area of 101 080 km2. The annual flow varies widely from year to year; no flow was measured in 2013 and 1806 GL was recorded in 2006 following Cyclone Emma (Figure 12). The 2006 flow has a significant influence on this average; the longer term average from 1967 to 2015 is about 25 per cent lower.

As the majority of the catchment extends inland, the monthly flow distribution shows patterns similar to that of the rainfall at Meekatharra where most rainfall falls between December and April. Monthly streamflow is highly variable, as evident in the large difference between the mean and median monthly flow values. For instance, on average, around 13 per cent of annual flow is in December; however, there was no flow in December in 12 of the last 16 years. This shows the significance of the infrequent large flow events.

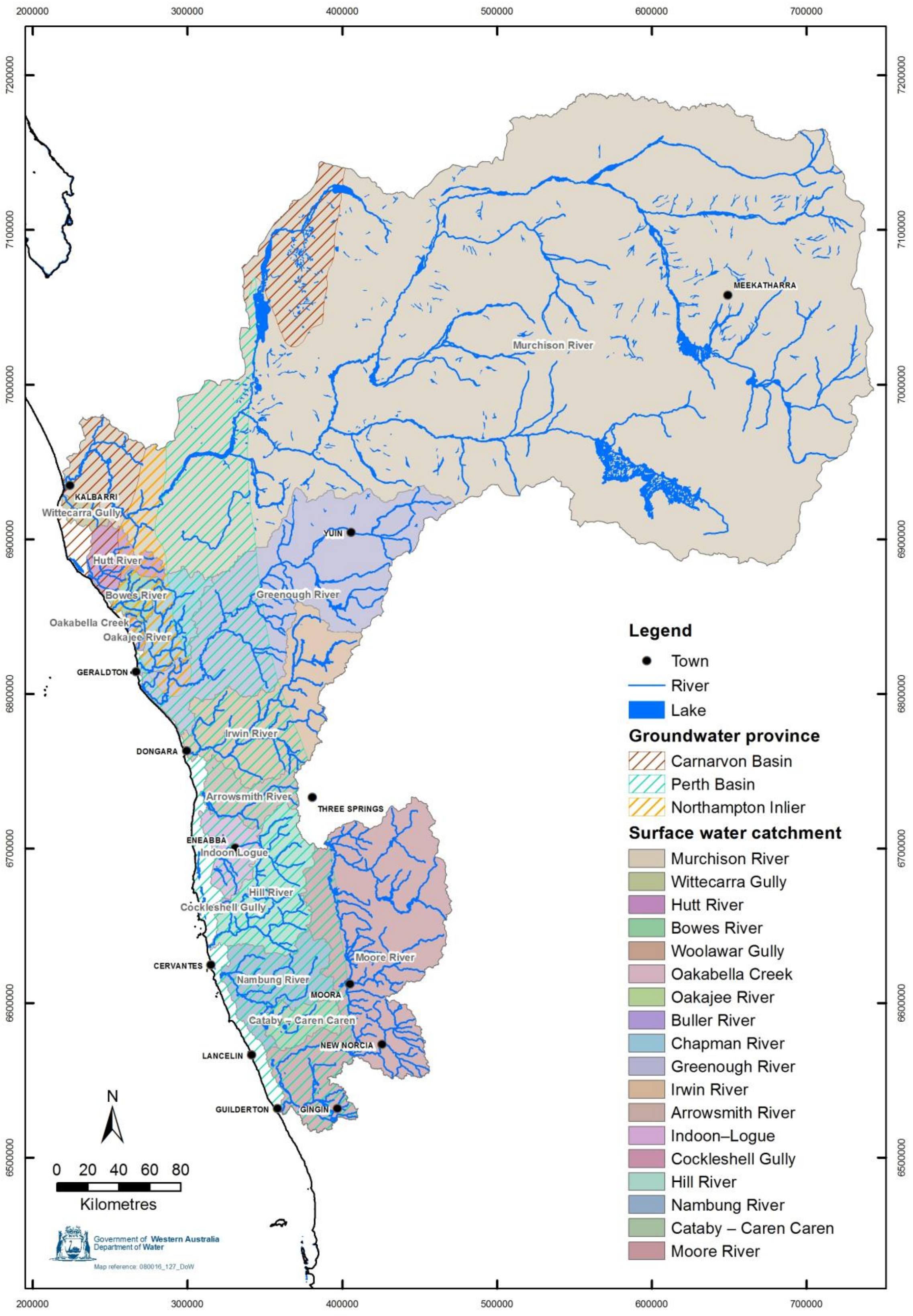


Figure 10 Surface water catchments

Table 3 Surface water catchment, flow and salinity characteristics

River system	Catchment area (km^2)	Streamflow gauge (AWRC reference)	Streamflow gauge catchment area (km^2)	Mean annual flow 2000–15 (GL/a)	Average stream salinity[1] (mg/L TDS)	Stream salinity class
Murchison	103 768	Emu Springs (702001)	101 080	247	3000–35 000	Saline
Wittecarra	478	–	–	–	3000–35 000	Saline
Hutt	1280	Yerina (701010)	1104	5	1000–3000	Brackish
Bowes	715	–	–	–	1000–3000	Brackish
Woolawar	41	–	–	–	3000–35 000	Saline
Oakabella	57	–	–	–	3000–35 000	Saline
Oakajee	49	–	–	–	3000–35 000	Saline
Buller	37	Buller[a] (701006)	34	0.7[a]	3000–35 000	Saline
Chapman	1903	Utakarra (701007)	1836	4	3000–35 000	Saline
Greenough	12 560	Eradu (701011)	10 794	23	3000–35 000	Saline
Irwin	6071	Mountain Bridge (701009)	5264	16	3000–35 000	Saline
Arrowsmith	1604	Robb Crossing[b] (701005)	810	5[b]	3000–35 000	Saline
Indoon–Logue	1374	–	–	–	1000–3000	Brackish
Cockleshell	63	–	–	–	1000–3000	Brackish
Hill	3704	Ardross (617017)	3702	5	1000–3000	Brackish
Nambung	2956	–	–	–	1000–3000	Brackish
Cataby – Caren Caren	1089	–	–	–	1000–3000	Brackish
Moore	13 608	Quinns Ford (617001)	11 423	33	3000–35 000	Saline

[a] Buller gauging station data, 1974–2000.

[b] Robb Crossing gauging station data, 1973–2000.

Note: All streams exhibit varying salinity along their length, due to factors such as land clearing and groundwater discharge. Salinity classifications have been taken from Mayer et al. 2005.

Table 4 Summary of major flood events in the northern Perth Basin

Moore River	Greenough River	Chapman River	Murchison River
July 1983	February 1888	March 1971	Feb 1960
July 1995	March 1953	July 1996	March 1975
March 1999	March 1971	May 1999	March 2006
May 1999	May 1988		March 2011
	May 1999		
	January 2006		
	February 2011		

Hutt River catchment

The Hutt River catchment is 1280 km^2 of farmland within the Victorian Plateau and Chapman regions. The river is about 60 km long. It originates 25 km north of Northampton and discharges to the ocean south of Port Gregory. The Yerina gauging station (701010) is located 10 km upstream of the Hutt River mouth, with a catchment area of 1104 km. The station has been operating since 1981. Mean annual flow recorded between 2000 and 2015 was 5 GL/a (Figure 12). Including the large flows observed during the 1990s (Figure 12), gives a mean annual flow of 9 GL/a for the period 1993 to 2015.

Most streamflow is during winter, with 70 per cent of mean annual flow occurring between June and September.

The upper reaches of the Hutt River are ephemeral, while tributaries in the middle and lower reaches are mostly perennial. Perennial flows are maintained by local sandplain seeps (Department of Environment 2005). Water quality data is limited; however, data collected at Yerina indicates an average salinity of 2900 mg/L TDS (total dissolved solids) (Department of Environment 2005).

Bowes River catchment

The Bowes River catchment is 715 km^2 of farmland within the Victorian Plateau and Chapman regions. The river is 40 km long, originating 15 km east of Northampton. It flows south and then west before discharging to the ocean through an inlet, the Bowes River mouth, between Port Gregory and Geraldton. The sandbar at the mouth only opens to the ocean after periods of heavy rainfall.

The Wearbe gauging station (701601) operated in the catchment between 1971 and 1998 on a very small tributary of the Bowes River. The data shows a similar seasonal pattern to the Hutt River catchment to the north.

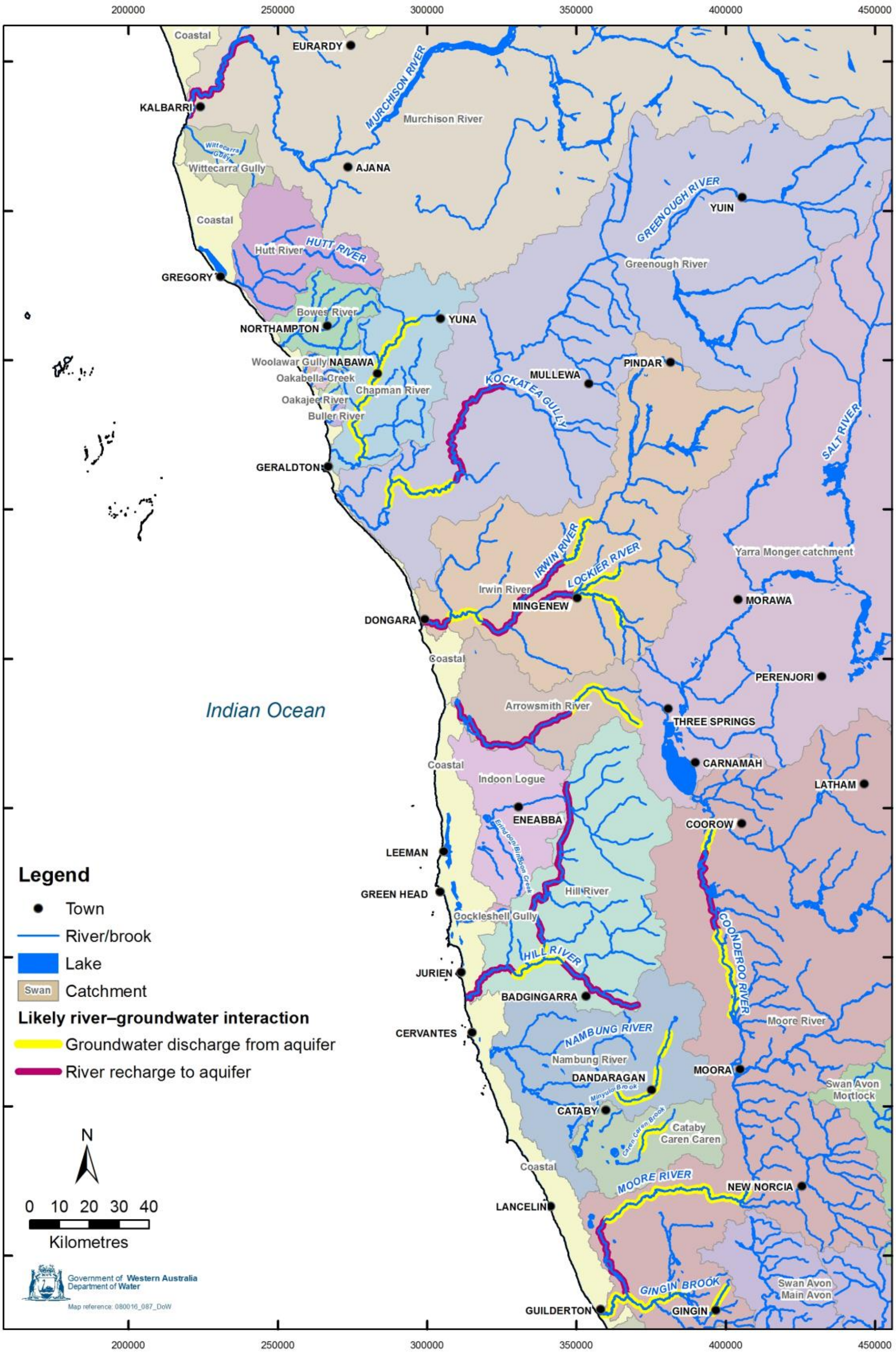


Figure 11 Surface water catchments and likely river–groundwater interaction

Chapman River catchment

The Chapman River catchment is 1903 km^2 of farmland near the Waterloo Range and Chapman Valley (Mayer et al. 2005). The river begins at Yuna, about 60 km north-east of Geraldton. It is about 80 km long, and flows through the sandplains of the northern Perth Basin, to granite and alluvium of the Northampton Block, before moving across the Moresby Range to its mouth at Sunset Beach, Geraldton (WRC 1998a). There has been extensive clearing in the catchment; in 1996 the catchment was 90 per cent cleared (Mayer et al 2005). The river is moderately saline with a mean salinity (between 1993 and 2002) of 2900 mg/L TDS (Mayer et al. 2005).

Two streamflow gauging stations have operated in the Chapman River catchment; the Narra Tarra Homestead (701004) on the Chapman River East tributary (operational from 1971 to 1986), and the Utakarra gauging station (701007), which has been operating since 1976. Utakarra has a catchment area of 1836 km^2 and is located about 9 km from the Chapman River mouth.

Annual streamflow is highly variable as evident in Figure 12. There have been no major flood events since 1999 and the mean annual flow between 2000 and 2015 is 4 GL/a. Similar to the Hutt River, a number of large flows were recorded in the 1990s, which increases the longer term mean (1976–2015) to well above that for the 2000 to 2015 period (~16 GL).

Flow during this 2000–15 period was highly seasonal in the Chapman River, with around 76 per cent of mean annual flow occurring between July and September. The river can also flow during summer; however, there has only been three years where flow has been recorded between January and April over the last 16 years.

Greenough River catchment

The Greenough River is about 340 km long, originating in the Yilgarn Plateau and flowing south-westerly through sand plains before passing through hilly terrain. It turns north-westerly through the Greenough Flats area and discharges to the ocean through an inlet at the Greenough River mouth, 10 km south of Geraldton. A sandbar blocks the river mouth, only breaking in periods of strong flow. Once broken, the river mouth usually remains open for several months. In major flows, the river breaks its banks and floods large areas behind the coastal dunes.

There are four gauging stations operating in the Greenough River catchment. Eradu station (701011) has a catchment area of 10 794 km^2 and has been operating since 1998. Annual streamflow is highly variable as illustrated by the highest flow of 92 GL recorded in 2006 being followed by no flow in 2007. The mean annual flow (2000–15) is 23 GL/a (Figure 12).

The monthly flow distribution for the Greenough River shows how infrequent major summer rainfall events in the inland portion of the catchment have a major influence on the streamflow. High mean monthly flows between January and March are associated with major summer flood events in 2006, 2008 and 2011. However, the median monthly flow (zero in these months) highlights that in most years the river would not be flowing at this time. By contrast, July to September is the only period where median monthly flow is greater than zero, illustrating that flow is generated from regular winter rainfall. However, the mean winter monthly flow between June and October is only about 10% of the annual mean streamflow.

In summer, the Greenough River becomes a series of partially connected pools where the channel has incised below the watertable. This is mainly upstream of Ellendale Crossing (Allen 1980). The hydraulic connection to underlying aquifers varies along the length of the river (Figure 11). Downstream of the confluence with Kockatea Gully, the river recharges the Permian aquifers (Swarbrick 1964b). Upstream of Ellendale Pool, groundwater discharges into the river. Across the coastal plain, the river recharges groundwater until it reaches its outlet with the sea. The water is moderately saline.

Irwin River catchment

The Irwin River originates to the east of Mullewa, flowing south-west through sandy and erosional plains. The river flows in a southerly direction between Geraldton, Mount Magnet Road and the Mullewa – Wubin Road, where it expands into a relatively wide river. It then turns south-westerly and constricts as it passes through hilly terrain before flowing into Arurine Bay near Dongara.

The Irwin River catchment is 6071 km^2. As at 2016, there are six operational streamflow gauging stations in the catchment, with the first opening in 1970. Mountain Bridge gauging station, with a catchment area of 5264 km^2, has a mean annual flow recorded since 2000 of 16 GL/a.

High mean monthly flow between February and March, coupled with much lower median flows during this period, highlight the effect of infrequent high-intensity summer rainfall events on streamflow (Figure 13). However, unlike the other large catchments further north in the basin (Greenough and Murchison rivers) the regular winter flows in the Irwin River provide a much higher proportion of the annual mean streamflow. The mean June to October flows are almost 40 per cent of the mean annual flow. The relatively consistent mean and median monthly flows in the Irwin River catchment mark the transition from the winter dominated streamflow of the southern catchments to the periodic summer event dominant streamflow systems in the north of Basin.

Permanent summer baseflow is maintained by groundwater discharge from the Yarragadee aquifer between the Strawberry Bridge and Mountain Bridge gauging stations (Allen 1980; Commander 1996; Schafer 2016). The river recharges the Yarragadee aquifer between Mingenew and Irwin as well as the Tamala Limestone on the coastal plain (Figure 11).

The river is moderately saline and becomes increasingly more so where saline groundwater discharges from Permian aquifers east of Mingenew (Mayer et al. 2005). The river is less saline in areas where it or its tributaries receives fresh groundwater discharge from the Yarragadee aquifer (e.g. Springy Creek).

Arrowsmith River catchment

The Arrowsmith River drains a catchment of 1604 km^2. It originates in hilly terrain near Arrino on The Midlands Road, east of Three Springs. The river flows west-southwesterly from the hilly terrain of the Dandaragan Plateau onto sand plains. To the west of the Brand Highway, the river flows north-westerly through coastal plains. The river has no defined ocean outlet. It terminates in Arrowsmith Lake and flows into caves in the Tamala Limestone, 9 km inland from Cliff Head.

One streamflow gauging station, Robb Crossing (701005), operated in the catchment between 1972 and 2000. Annual streamflow during this period ranged from a minimum annual flow of 0.1 GL in 1976 to 24 GL in 1999 (Figure 13) with a mean of 5 GL. Monthly streamflow distribution shows a general winter flow pattern with very little to no summer flow.

Springs and permanent baseflow in the Arrowsmith River correspond with outcropping Otorowiri Siltstone at the Dandaragan Scarp (Barnett 1969). Elsewhere, the river typically flows between June and September (Barnett 1969) and can cease to flow over summer. Downstream of the Dandaragan Scarp, the river discharges into the Yarragadee and Superficial aquifers (Commander 1981).

The Arrowsmith River is moderately saline from the catchment area on Permian sediments. However, the river receives fresh groundwater discharge from the Parmelia aquifer on the Dandaragan Plateau (Mayer et al. 2005).

Hill River catchment

The Hill River has a catchment area of 3704 km^2. The river rises along the Dandaragan Scarp about 8 km east of Badgingarra, before flowing across the Arrowsmith region and Swan Coastal Plain. The river discharges into the Indian Ocean about 9 km south of Jurien Bay.

There has been two streamflow monitoring stations that have operated on the Hill River, with the most downstream site at Ardross operating since 1999. Annual streamflow ranges from 0.9 GL to 23 GL over the period 2000 to 2015 and the mean is 5 GL/a (Figure 13). Streamflow is highly seasonal, with over 95 per cent of flow occurring over winter from June to October.

The Hill River seasonally recharges the underlying Yarragadee aquifer in the eastern part of the catchment (Carter & Deshon 2002). It receives groundwater discharge from the Yarragadee aquifer upstream of Hill River Spring to Conover Pool, and recharges the Superficial aquifer near the coast, south of Jurien Bay (Commander 1981; Lindsay 2004). The downstream river reach contains numerous perennial seeps and permanent pools (WRC 2005) that are isolated in summer due to a lack of connected flow, but become connected during higher flow periods in winter (Lindsay 2004).

The salinity ranges from fresh upstream in areas overlying the Yarragadee aquifer through to marginal and brackish where associated with the Cattamarra Coal Measures (Commander 1981).

Moore River catchment

The Moore River drains a large catchment of 13 550 km^2 in the Moore – Hill Rivers Basin. The north branch originates east of Moora, then flows south at the base of the Darling Scarp where it merges with the East Branch at Gillingarra before flowing west across the Dandaragan Plateau. The river diverts southward and flows over the Swan Coastal Plain, forming overflow lakes at Karakin Lakes. Gingin Brook joins the river about 15 km upstream of the river mouth. There is usually a sandbar over the river mouth at Guilderton during summer months.

Quinn's Ford streamflow gauging station has been operating on the Moore River since 1969. The catchment area to this station is 11 423 km^2. Since 2000 the average annual streamflow has been 34 GL/a (Figure 13). There have been no major flows since 2000 and the longer term mean (1970 to 2015) is significantly higher at over 55 GL/a. Streamflow is mainly during the winter months (this pattern is evident in both the mean and median monthly flow) with over 85 per cent of mean monthly flow occurring between June and October.

Streamflow occurs all year round at Quinn's Ford, indicating that groundwater might be discharging into the river at this point (Figure 11 and Figure 13). Groundwater has been shown to discharge into the stretch of river on the Dandaragan Plateau, on the Swan Coastal Plain east of the Tamala Limestone, and between the Gingin Brook confluence and the ocean. The river recharges the Superficial aquifer system downstream of Karrakin Lakes (between Cowalla Bridge and Waterville Road) (Stelfox 2001).

Early explorers found the Moore River to be fresh and suitable for drinking. However, land clearing for agriculture in the upper catchment has increased river salinity since the 1850s and the river is mostly brackish to saline now (Stelfox 2001). Stream salinity is somewhat diluted by fresher groundwater discharge from the Leederville–Parmelia and Superficial aquifers downstream of Gillingarra (Stelfox 2001). Salinity is also diluted downstream of the confluence with Gingin Brook (which stays fresh throughout the year) (Mayer et al. 2005; Tuffs 2011).

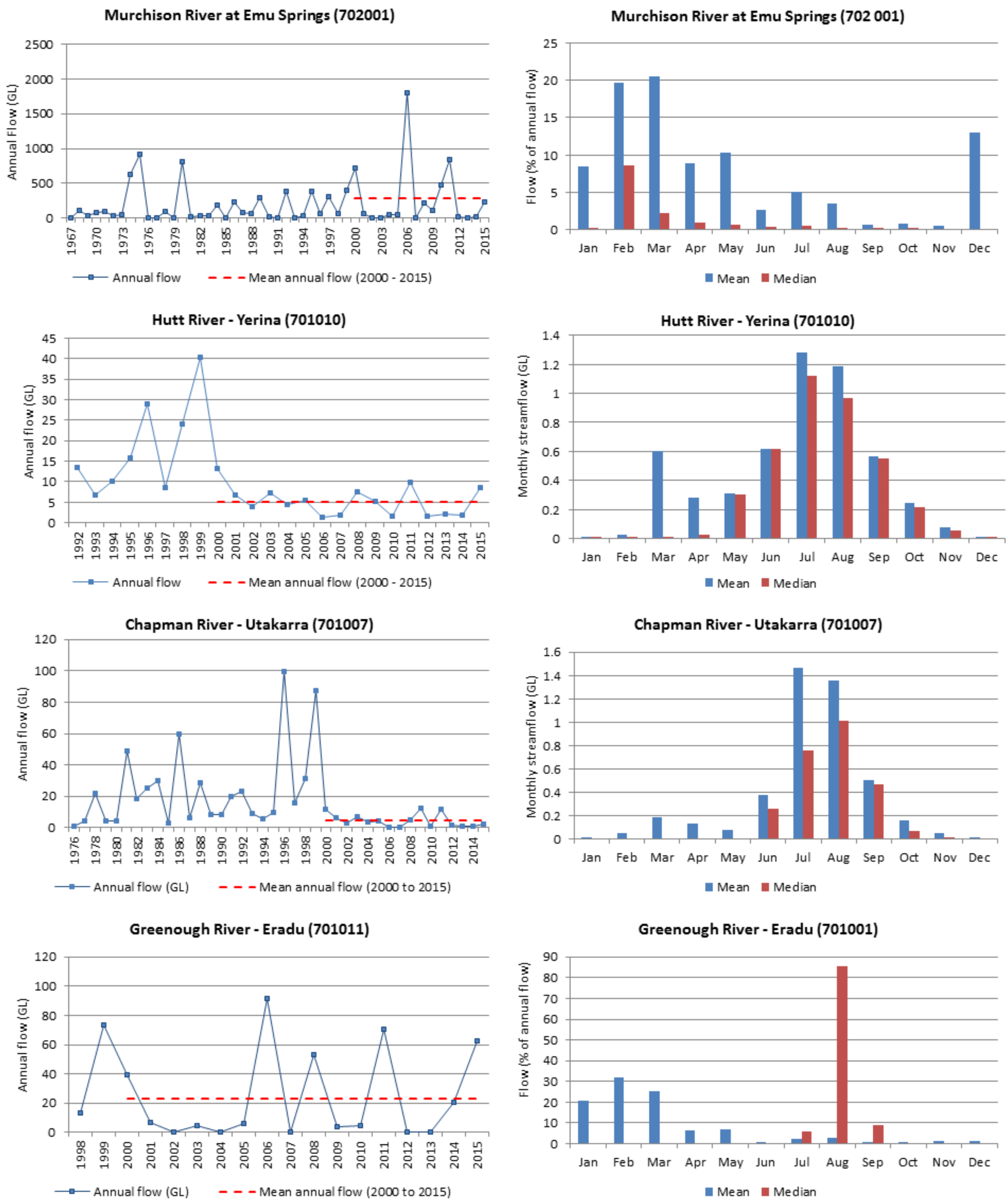


Figure 12 Annual and monthly streamflow distribution – Murchison, Hutt, Chapman and Greenough rivers

Figure 13 Annual and monthly streamflow distribution – Irwin, Arrowsmith, Hill and Moore rivers

3.5 Groundwater-dependent ecosystems

Many of the wetlands, watercourses, vegetation associations, cave ecosystems and aquifer ecosystems across the northern Perth Basin are groundwater dependent. These GDEs support a variety of habitats for plants and animals, and in doing so, provide a range of services to people.

Aquatic ecosystems (wetlands and rivers) that form where groundwater discharges support native aquatic animals like fish, amphibians (e.g. frogs), reptiles (e.g. oblong turtles), mammals (e.g. rakali or water rat), wetland birds, crustaceans (e.g. marron) and mussels (Morgan et al. 2000; Turtle Oblonga Rescue & Rehabilitation Network Inc. 2016; Trocini 2015; DEC 2009; Department of Environment 2005). The water in wetlands and rivers also supports insects that control crop pests and bees that pollinate crops. Land-dwelling animals, like kangaroos, emus and stock, gather around wetlands and rivers to drink.

Wetland and riverine plants that grow around the northern Perth Basin's aquatic GDEs typically have roots that extend to the watertable, as deep as 15 m (N Lauritsen 2013, pers. comm.). This allows them to grow taller and more quickly than plants in the broader landscape. Tall trees, like flooded gums, river gums and paperbarks, provide shelter for stock, kangaroos and emus, and nesting trees for eagles, cockatoos and possums. Wetland sedges and grasses provide food for herbivores.

In dryland areas where groundwater is shallow, overstorey trees growing above heathland might also have roots that extend to the watertable. Banksia woodland is an ecologically significant ecosystem type that reaches its northern extent through the northern Perth Basin, with the banksias opportunistically using groundwater where it is within reach of the roots (Zencich et al. 2002). Both tuart trees and marri trees also reach the northern extent of their range in the northern Perth Basin (DEC 2003; Western Australian Herbarium 1998), where they are typically found in sites over shallow groundwater. These are developed as rest areas for travellers, such as Tuarts Reserve and Wilbinga Grove.

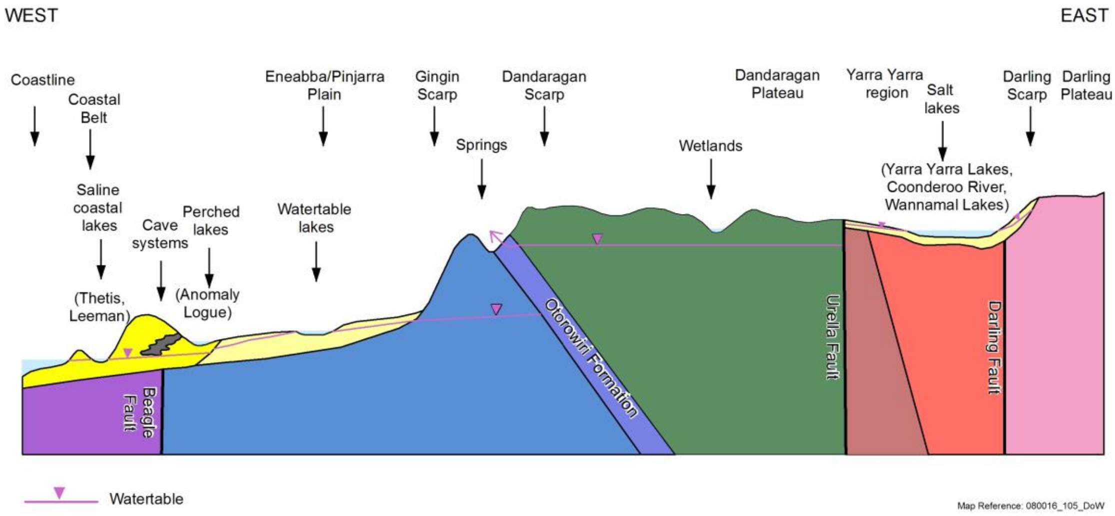
Caves in karstic limestone along the coast support a range of cave-dwelling fauna that depend on groundwater. Aquatic crustaceans live in cave pools in the dark zone, and humid cave entrances form roosting sites for bats and nesting sites for swallows (Susac 2009, 2012). Karstic aquifers support stygofauna, including aquatic crustaceans, and are of great interest to caving enthusiasts (Susac 2009).

Some aquatic GDEs support recreation and tourism (e.g. Ellendale Pool, Lake Thetis and the Moore River estuary). Picturesque sites where tall trees provide shelter at wetlands are developed as picnic or camping areas for locals and visitors, such as Regans Ford, Lake Indoon and Little Three Springs.

Watering sites along the North West Stock Route that was used to move stock from Geraldton to Fremantle are also GDEs (Heritage Council of Western Australia 2003).

Groundwater supports significant places for Indigenous people, who used the food resources of coastal lakes and maintained groundwater wells throughout the landscape (Department of Conservation and Land Management 1998).

The distribution of GDEs across the northern Perth Basin can be summarised according to physiographic features within the landscape, as shown in Figure 14.



(see figures 19 and 51 for legend)

Figure 14 Schematic east–west section showing position of groundwater-dependent ecosystems

At the western edge of the Swan Coastal Plain, fresh groundwater discharges through karstic limestone into shallow coastal marine environments where seagrass meadows grow, near Cervantes (Passfield 1988). This same karstic limestone contains the northern Perth Basin's cave and aquifer ecosystems. Estuaries of major rivers are found in the karst, and form sites where groundwater, seawater and surface water interact. Along their courses, several significant rivers receive baseflow from groundwater as they cross the karst (Lindsay 2004). Others become losing streams as they reach the karst (Stelfox 2001), with some even disappearing into caves (Susac 2009).

Within the dunes along the coastline, groundwater-dependent vegetation is common because groundwater is typically shallow (Figure 14). Various fresh and saline coastal wetland types can also be found, including an extensive linear chain of salt lakes between Cervantes and Coolimba. Freshwater springs punctuate the eastern margin of these salt lakes, and similar freshwater coastal springs are known from as far south as Wedge Island (Panoramio 2014), some of which formed the town of Cervantes' first water supply (Barnett 1969). Lake Thetis is a deep, permanent, hypersaline wetland in this landscape position, and supports a threatened ecological community of microbialites (DEC 2012).

East of the coastal cave and dune systems, lakes and wetlands that intersect the watertable are common on the Bassendean Dune System and the Eneabba and Pinjarra plains (Figure 14). Groundwater-dependent vegetation is found in interdunal swales and surrounding wetlands and watercourses. The Banksia woodland of the Bassendean Dune System (Beard & Parker 1976) contains overstorey species that are opportunistically groundwater-dependent, where the watertable is within reach. Drainage lines through the

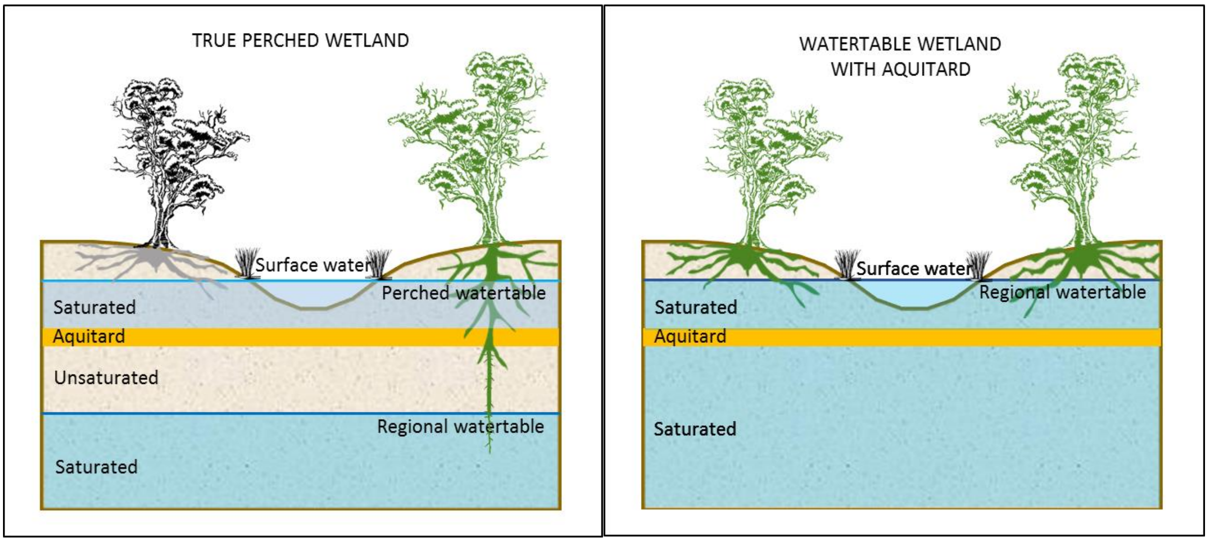
Banksia woodland might also support groundwater-dependent flooded gums (Beard 1979b). At the eastern extent of the Swan Coastal Plain, near the base of the Gingin Scarp, groundwater supports baseflow in rivers, as well as extensive chains of lakes, wetlands, waterlogged flats and groundwater-dependent vegetation. These are often over clay or laterite layers but are rarely truly perched (Figure 15).

Within the Arrowsmith region, ecosystems supported by shallow groundwater and groundwater discharge are found in topographic depressions, in locations where watercourses have eroded the land surface towards the potentiometric surface. These sites are an important source of water and shelter for both stock and native animals.

Along the western and northern boundaries of the Dandaragan Plateau, springs and watercourses with perennial baseflow are common, from Mingenew to south of Gingin (Rutherford et al. 2005). This groundwater discharge supports tall, flourishing groundwater-dependent trees and regionally-rare permanent aquatic habitats of high ecological value. There are two recognised threatened ecological communities associated with this discharge (Hamilton-Brown et al. 2004; Rees & Broun 2005). In the south of the Dandaragan Plateau, wetlands and GDEs are also found in the centre of the plateau as well as along the western edge, mostly associated with watercourses.

Along and near the western boundary of the Lockier region are groundwater springs that support aquatic ecosystems, farm water supplies and groundwater-dependent vegetation. Groundwater over much of the Yarra Yarra region is very shallow and salty and supports the saline Yarra Yarra Lakes. The lakes are a stopover for migratory birds, and form foraging habitat for black swans, pelicans and banded stilts (Northern Agricultural Catchments Council 2014).

Various wetlands and watercourses east of the Gingin Scarp have clayey or lateritic beds that delay the infiltration of rain-derived water in winter (Jacobs 2015). In some of these wetlands, the aquatic habitat is supported by perched groundwater (unsaturated zone below the perched aquifer), but groundwater is commonly shallow in this landscape position, and the fringing or riparian vegetation might be dependent on regional groundwater. Other wetlands have saturated sediments adjoining the base of the aquitard and are not truly perched, so that the wetland and its fringing vegetation will be dependent on regional groundwater (Figure 15).



(after Richardson et al. 2011)

Figure 15 Perched and non-perched wetlands

3.6 Regional geological setting

This section summarises the regional geology of the onshore portion of the Perth Basin north of the Moore River and Gingin Brook, referred to as the northern Perth Basin. The description also includes the southernmost portion of the Carnarvon Basin south of the Murchison River, the Proterozoic Northampton and Mullingarra inliers as well as the metasedimentary rocks of the Pinjarra Orogen along the eastern margin of the northern Perth Basin. Further detail on the tectonic framework of the greater Perth Basin can be found in Thomas (2014).

The northern Perth Basin stretches about 450 km from north to south and up to 90 km from west to east. The basin covers about 35 000 km^2, making up three-quarters of the onshore Perth Basin. The northern Perth Basin is bound in the east by the Darling Fault where it abuts Archean rocks of the Yilgarn Craton. Crystalline basement beneath the Perth Basin comprises Proterozoic igneous and metamorphic rocks of the Pinjarra Orogen, which formed as an intercontinental mobile belt between the Australian and Indian parts of eastern Gondwana.

Sedimentation of the Perth Basin commenced with rifting of a pull-apart basin in the Late Ordovician or Early Silurian, and fluvial deposition (Tumblagooda Sandstone). Rifting extended southward into the basin during the Early Permian, continuing into the Early Cretaceous and culminating with the separation of Greater India from Gondwana during the final stage of continental breakup. The pre-breakup sedimentary sequences are extensively faulted, and are overlain by relatively undeformed sediments deposited after continental separation.

Throughout the basin, a number of major structural units are recognised (Figure 16, Table 5). These structurally-controlled subdivisions have been described and progressively revised by Playford et al. (1976), Hocking et al. (1987), Hocking (1994), Crostella (1995) and Mory and Iasky (1996). The most recent refinement of the geological structure is included in the tectonic units mapping in Western Australia (Department of Mines and Petroleum 2015), and an adaptation of this has been used in this bulletin.

The major north–northwest-trending faults that formed during the formation of the basin are normal faults and these have been grouped into three fault systems (Mory & Iasky 1996). From east to west, these are: the Darling Fault system (Darling, Urella and Muchea faults), the Eneabba Fault system (Eneabba and Coomallo faults), and the Beagle Fault system (Beagle, Mountain Bridge and Beharra Springs faults). As these regional faults form long linear features, a component of strike-slip movement can be implied (Lowell 1985; Middleton 1991; Crostella 1995).

The Darling Fault is about 1000 km long with a maximum vertical displacement of possibly up to 15 000 m (Playford et al. 1976). About half of the throw of the Darling Fault north of the Barberton Terrace has been relayed to the Muchea Fault (Mory & Iasky 1996). The throw on the Darling Fault decreases north of the Abrolhos Transfer Fault, which is compensated by an increased throw on the parallel Urella Fault (Mory & Iasky 1996). The Eneabba Fault has a throw of several hundred metres at its northern limit, decreasing towards the south (Crostella 1995). The Coomallo Fault reaches a maximum displacement of 3000 m (Mory & Iasky 1996). The Beagle Fault system is relatively steeply dipping and downthrown to the east (Mory & Iasky 1996). The Allanooka Fault that occurs near Dongara is one of only a few easterly striking faults, and is steeply dipping.

A series of northwest-striking transfer faults that were initiated at breakup cross the northern Perth Basin (Mory & Iasky 1996) with apparent sinistral horizontal displacement (left lateral movement). The two largest transfer faults are the Abrolhos and Cervantes transfer faults. The Abrolhos Transfer Fault is believed to have a horizontal displacement of several kilometres (Mory & Iasky 1996), with a significant change in throw along the fault.

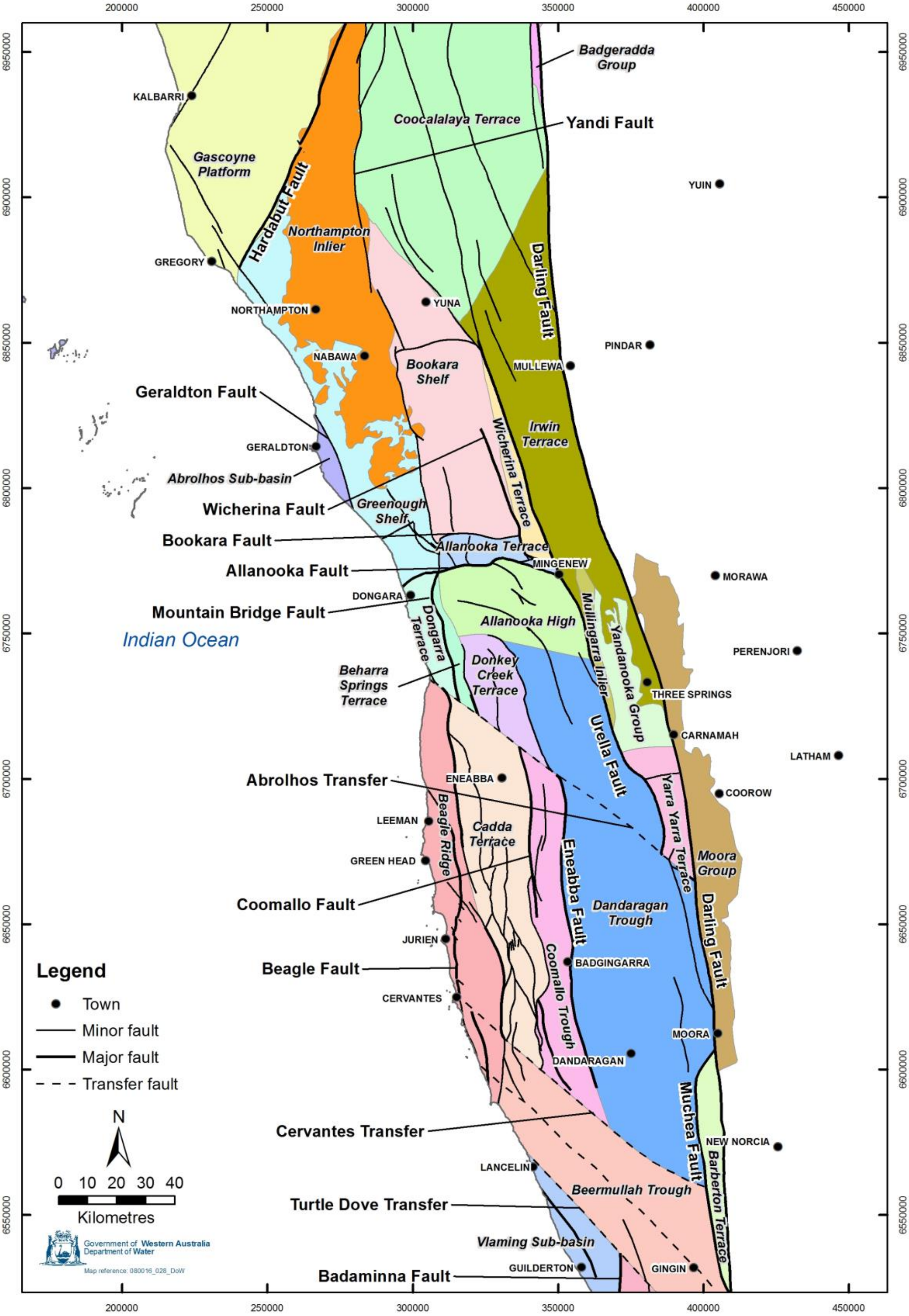
The thickest sediments of the northern Perth Basin are found in the Dandaragan Trough, a large syncline between the Darling Fault (or Urella Fault at its northern maximum) and the Eneabba Fault (Crostella 1995), where the depth to basement is up to 15 000 m (Figure 17). The Dandaragan Trough becomes shallower to the north due to thinning of the Cretaceous and Jurassic sediments, and post-Jurassic erosion (Mory & Iasky 1996). Although significant faulting is not mapped within the Dandaragan Trough, unmapped faults are probably present.

The sedimentary sequence generally thins to the west, north and south of the Dandaragan Trough, reaching a minimum thickness of about 1000 m over the Beagle Ridge (Playford et al. 1976). The sediments of the Perth Basin become absent towards the northern margin of the basin at the Northampton Inlier. Sediments are also thin (less than 3000 m) along the eastern margin of the basin between the Urella and Darling faults over an elevated terrace comprising the Irwin Terrace and Yarra Yarra Terrace. These terraces are separated by outcropping Proterozoic Mullingarra Inlier (Mory & Iasky 1996).

Table 5 Structural units (from south to north) as mapped on Figure 16

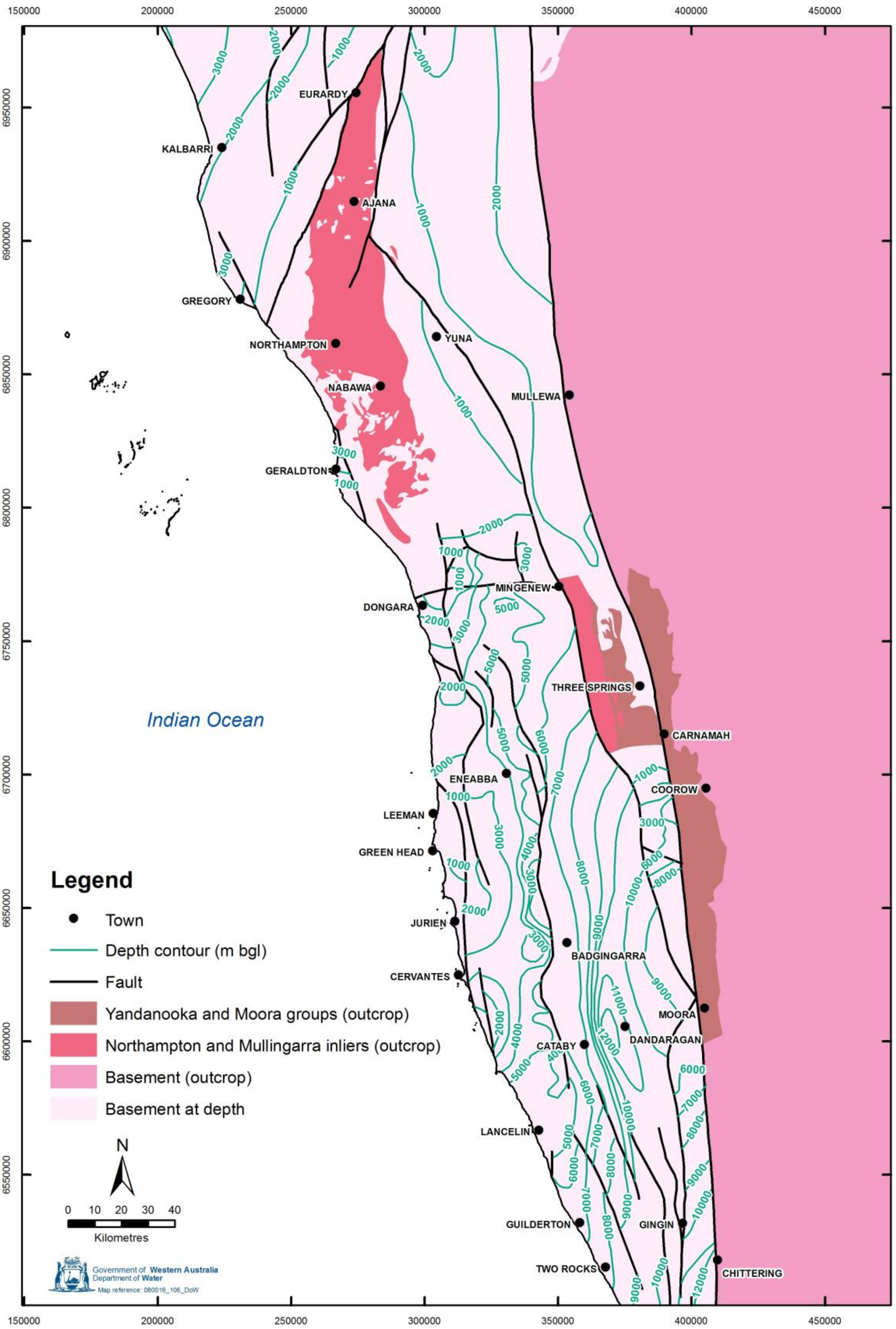
Structural unit	Description
Vlaming Sub-basin	Found mostly offshore, but is onshore south of the Turtle Dove Transfer Fault and west of the Badaminna Fault System. Contains up to 15 km of mostly Lower Cretaceous sediments.
Mandurah Terrace	Situated south of the Turtle Dove Transfer Fault and between the Badaminna Fault System and Darling Fault. Shallows southward.
Barberton Terrace	A block of shallower basement between the Darling and Muchea faults, containing about 6–7 km of sediments.
Beermullah Trough	Situated between the Cervantes and Turtle Dove transfer faults, east of Beagle Ridge. Contains up to 15 km of sediments.
Dandaragan Trough	Contains up to 12 km of sediments within the eastern portion of the basin east of the Eneabba Fault. Bound in the east by the Darling Fault or, in the northern portion, the Urella Fault.
Coomallo Trough	Elongate depression bound in the north by the Abrolhos Transfer Fault, and the Eneabba and Coomallo faults. Merges with the Dandaragan/Beermullah Trough in the south about the Cervantes Transfer Fault. Contains a similar thickness of sediments as the Dandaragan Trough. North–northwest oriented folds present. Southern limit uncertain.
Cadda Terrace	Elevated basement, bound by the Beagle and Coomallo faults, south of the Abrolhos Transfer Fault, and extending approximately to the Cervantes Transfer Fault. Sediment thickness increases eastward, from 2 to 8 km. En echelon faults that progressively step down to the east and north–northwest oriented folds present. Southern limit uncertain.
Beagle Ridge	Mid-basin ridge between a southern extension of the Geraldton Fault and Beagle Fault System, south of the Abrolhos Transfer Fault, with a cover of 1–3 km of sedimentary rocks. Contains a number of anticlines (Crostella & Backhouse 2000). Triassic formations subcrop on the ridge.
Yarra Yarra Terrace	An elevated terrace between the Urella and Darling faults, south of the Abrolhos Transfer Fault, and containing up to 3 km of sediments. Previously part of the 'Irwin Sub-basin' (Playford et al. 1976).
Mullingarra Inlier	Outcrop of metamorphic basement rocks and mid-Proterozoic Yandanooka Group between the Urella and Darling faults (Baxter & Lipple 1985).
Irwin Terrace	An eastward-deepening, elevated terrace at the eastern margin of the basin with up to almost 2 km of Permian sediments. Transitional contact in the north with Coolcalalaya Terrace where Permian sediments thin and underlying Silurian–Ordovician sediments thicken (Hocking 1994).
Donkey Creek Terrace	A terrace north of the Abrolhos Transfer Fault between the Eneabba and Beharra Springs faults, with up to 6 km of sediments.
Beharra Springs Terrace	Terrace between the Mountain Bridge Fault and Beharra Springs Fault, north of the Abrolhos Transfer Fault, and containing 3–5 km of sediments.
Dongara Terrace	Terrace between the Abrolhos Transfer Fault and Allanooka Fault, and the Mountain Bridge Fault and Beagle Fault, with about 2 km of sedimentary cover, gradually deepening to the south.

Structural unit	Description
Allanooka High	Area of relatively elevated basement between the Urella Fault and Beharra Springs Fault, and south of the Allanooka Fault. Contains about 5.5 km of sediments, which shallow to the north.
Allanooka Terrace	Terrace bound by the Allanooka and Bookara faults, and Wicherina Fault in the east. Contains about 1500–3000 m of sediments. Previously defined as part of the Allanooka High (Crostella 1995).
Greenough Shelf	Shelf of shallow basement between the Geraldton and Mountain Bridge faults, and north of the Allanooka Fault to the Northampton Inlier that outcrops to the north. Contains up to 1.5 km of Palaeozoic and Mesozoic sediments, which shallow northward towards the Northampton Inlier.
Wicherina Terrace	A narrow terrace between the Urella and Wicherina faults, possibly with over 2 km of sediments. Merges with the Bookara Shelf to the north.
Bookara Shelf	North of the Bookara Fault between the Urella or Wicherina faults, and a series of faults along the abutting Greenough Shelf – Northampton Inlier. Up to about 2 km of sediments lie upon the shelf, thinning to the north and transition from Jurassic and Permian in the south to Ordovician–Silurian in the north. Previously defined as part of the Allanooka High.
Coolcalalaya Terrace	Situated between the Northampton Inlier – Gascoyne Platform and Yilgarn Craton. Might contain up to 5 km of Silurian–Ordovician sediments. North-easternmost tectonic unit of the Perth Basin. Separated from the Bookara Shelf in the south-west by a series of north-west trending faults. Bordered by the Byro Sub-basin of the Carnarvon Basin in the north.
Northampton Inlier	An inlier of outcropping high-grade metamorphic rocks between the northern Perth Basin and the southern Carnarvon Basin. Onlapped by sediments of the Greenough Shelf.
Gascoyne Platform (Carnarvon Basin)	Southernmost onshore tectonic unit of the southern Carnarvon Basin. Westward tilted, possibly containing up to 2 km of sediments south of the Murchison River. Bound in the south by the Hardabut Fault and in the east by a series of faults along the Ajana Ridge.



(see Table 5)

Figure 16 Structural subdivisions



(after Mory & Iasky 1996)

Figure 17 Depth to basement

4 Stratigraphy and lithology of the northern Perth Basin

Accurate identification of aquifers and aquitards intersected during drilling or well installation is essential for effective management and use of groundwater resources. This is achieved by comparing lithologic features of drill cuttings with previously published lithologic descriptions within the context of regional geology. The geological setting of the northern Perth Basin was outlined in Section 3.7. This chapter describes the stratigraphic sequence of the basin (Table 6) and provides detailed lithological descriptions of each unit and their spatial relationships. A series of maps and cross-sections show regional distribution and depth contours of the main formations. Maps are drawn on a regional scale based on the interpretation of available data and are valid at the scale presented. Spatial datasets can be requested from spatial.data@water.wa.gov.au.

The stratigraphic terminology of the Perth Basin has evolved as our understanding of the geology has improved. Relationships between the current terminology used in this bulletin and the terminology from previous reports are presented in Table 7. Some of the geological formations of the Perth Basin extend into the southern Carnarvon Basin, and the stratigraphy of these formations, and their comparable units in the Perth Basin, is shown in Table 8. Stratigraphic picks from key bores are provided in Appendix A.

The distribution of outcrop or subcrop of pre-Cenozoic geological formations is shown in Figure 18. A series of east–west geological cross-sections across the region representing the geology along each of the deep borehole lines are shown in Figure 19. Detailed lithologic descriptions of each formation are presented, beginning with the oldest formations and moving to progressively younger formations.

Sedimentation of the Perth Basin commenced with fluvial deposition in the Late Ordovician or Early Silurian (Tumblagooda Sandstone). Basin subsidence in the Early Permian was accompanied by deposition of shale and silt in a glacial marine shelf environment (Nangetty Formation, Holmwood Shale, and Carynginia Formation/Mingenew Formation) together with sand, carbonaceous shale and coal during periods of marine regression (High Cliff Sandstone and Irwin River Coal Measures). In the Early Permian, various deltaic to fluvial facies were deposited. During the Late Permian, there was a period of uplift and erosion in the northern part of the basin.

In the Early Triassic, a marine transgression in the northern Perth Basin deposited a marine shale (Kockatea Shale) followed by fluvial deposition during a regression from the Late Triassic to Early Jurassic (Woodada Formation, Lesueur Sandstone and Eneabba Formation). Within the northern part of the basin, marginal marine sediments were deposited during the later Early Jurassic (Cattamarra Coal Measures) and Middle Jurassic (Cadda Formation). The onset of major rifting during the Middle Jurassic to Early Cretaceous deposited a great thickness of sediments (Scott 1991; Mory & Iasky 1996) comprising fluvial sand (Yarragadee Formation), and extensive lacustrine clay and silt in the later stages (Otorowiri Formation and Parmelia Group).

The entire basin was uplifted and eroded during the final stage of continental breakup in the Early Cretaceous (early Valanginian age). The resulting hiatus in the sedimentary succession is referred to as the 'Breakup Unconformity' (GSWA 1990).

Following continental breakup, tectonic activity abated and the basin subsided to form a passive continental margin with episodic deposition during the Early Cretaceous in prograding shallow marine and fluvial environments (Warnbro and Winning groups) and shallow marine environments (Coolyena Group and Tooloonga Calcilutite).

A marine transgression in the Early Pleistocene or Pliocene created a series of strandlines below the Gingin Scarp (Ascot and Yoganup formations), and was subsequently followed by fluvial and lacustrine sedimentation (Guildford Formation and Bassendean Sand). Extensive carbonate dunes (Tamala Limestone) developed in the Middle Pleistocene when the coastline retreated west of its current position. The Holocene is marked by deposition of lagoonal and dune sediments representing sea levels up to 2 m higher than current levels.

Table 6 Stratigraphic sequence of the Perth Basin

Era	Period	Epoch (Ma)	Stage	Stratigraphy			Max onshore thickness (m)	Lithology	Depositional environment
Cenozoic	Quaternary	Holocene Present0.01		Superficial formations	Alluvium, estuarine and swamp deposits		~5	Clay, sand and peat	Alluvial to estuarine
					Safety Bay Sand		100	Sand	Shoreline and dune
					Becher Sand		~2	Sand	Shallow marine to shoreline
		Pleistocene 0.01–2.6			Tamala Limestone		150	Calcareous arenite, limestone, sand and clay	Dune and shoreline
					Bassendean Sand		~40	Sand, minor silt and clay	Dune
					Muchea Limestone		~2	Limestone	Lacustrine
					Guildford Formation		~30	Clay and sandy clay	Fluvial to estuarine
	Neogene	Pliocene 2.6-5.3			Yoganup Formation		21	Sand	Shoreline
					Ascot Formation		31	Sand, clay and limestone	Shallow marine
	Unconformity								
Mesozoic	Cretaceous	Late 65.5-100.5	Maastrichtian	Coolyena Group	Lancelin Formation	Poison Hill Greensand	59-41	Sandstone, siltstone, clay and glauconitic	Near-shore shallow marine
			Campanian						
			Santonian			Gingin Chalk	18	Chalk, sandy and glauconitic	Shallow marine
			Coniacian			Molecap Greensand	102	Sandstone, glauconitic	Shallow marine
			Turonian						

			Cenomanian		Osborne Formation	*Mirrabooka Member*	40	Sandstone, glauconitic, with siltstone and shale	Shallow marine
		Early 100.5 - 145.5	Albian			*Kardinya Shale Member*	235	Siltstone and shale, minor sandstone	Marine
			Aptian – late			*Henley Sandstone Member*	48	Sandstone, minor siltstone and claystone	Shallow marine
			Unconformity						
			Aptian – earliest	Warnbro Group	Leederville Formation	*Pinjar Member*	182	Sandstone, siltstone and shale	Marine to non-marine
			Barremian			*Wanneroo Member*	390	Sandstone, with lesser siltstone and shale	Non-marine to marine
			Hauterivian Barremian			*Mariginiup Member*	205	Sandstone, siltstone and shale	Marine
					South Perth Shale		178	Siltstone and shale, minor sandstone	Marine
					Gage Sandstone		260	Sandstone, siltstone and shale	Marine
			Unconformity						
			Berriasian	Parmelia Group	'Undifferentiated' Parmelia Group		~300	Sandstone, siltstone and shale	Fluvial to lacustrine
						Carnac Formation	450	Siltstone and shale, minor sandstone	Lacustrine
	Jurassic	Late 145.5-163.5	Tithonian					Sandstone, siltstone and shale	Fluvial to lacustrine
					Otorowiri Formation		102	Shale and siltstone, minor sandstone	Lacustrine
				Yarragadee Formation	Unit D		1741	Shale, siltstone and clayey sandstone	Lacustrine
			Kimmeridgian		Unit C		719	Sandstone and clayey sandstone	Fluvial
			Oxfordian						
		Middle 163.5-174.1	Callovian						
			Bathonian		Unit B		967	Siltstone, shale and sandstone	Lacustrine with fluvial intervals
			Bajocian		Unit A		1095	Sandstone, siltstone and shale	Fluvial
			Aalenian	Cadda Formation			290	Sandstone, siltstone, claystone/shale and limestone	Marine to marginal marine
		Early 174.1-201.3	Toarcian	Cattamarra Coal Measures			1200	Sandstone, siltstone, shale and coal	Lacustrine to fluvial
			Pliensbachian						
			Sinemurian	Eneabba Formation			854	Sandstone, siltstone and claystone	Fluvial
			Hettangian						

	Triassic	Late 201.3-237.0	Rhaetian	Lesueur Sandstone	1202	Sandstone	Fluvial
	Triassic	Late 201.3-237.0	Norian	Lesueur Sandstone			
	Triassic	Late 201.3-237.0	Carnian	Lesueur Sandstone			
	Triassic	Middle 237.0-247.2	Ladinian	Lesueur Sandstone			
	Triassic	Middle 237.0-247.2	Anisian	Lesueur Sandstone			
	Triassic	Early 247.2-252.2	Anisian / Olenekian	Woodada Formation	276	Sandstone and siltstone	Marine deltaic
	Triassic	Early 247.2-252.2	Olenekian / Induan	Kockatea Shale *Bookara Sandstone Member*	1061	Shale, minor siltstone and sandstone	Marine
Paleozoic	Permian	Late 252.2-259.8	Changhsingian Wuchiapingian	Wagina Sandstone / Dongara Sandstone / Beekeeper Formation	243, 336, 155	Sandstone, clayey sandstone, mudstone/shale and limestone	Fluvial to marine
		Disconformity / Unconformity					
Paleozoic	Permian	Early 272.3- 298.9	Artinskian	Carynginia Formation / Mingenew Formation	337	Siltstone, claystone and sandstone	Cold shallow marine
Paleozoic	Permian	Early 272.3- 298.9	Artinskian	Irwin River Coal Measures	307	Sandstone, siltstone, shale and coal	Alluvial delta
Paleozoic	Permian	Early 272.3- 298.9	Artinskian	High Cliff Sandstone	150	Sandstone, minor siltstone	Marine deltaic to shoreline
Paleozoic	Permian	Early 272.3- 298.9	Sakmarian	Holmwood Shale *Fossil Cliff Member*	700	Shale, siltstone and calcarenite	Cold marine
Paleozoic	Permian	Early 272.3- 298.9	Asselian	Nangetty Formation *Wicherina Member*	1000	Sandy siltstone and mudstone; sandstone	Glacial to proglacial marine
	Unconformity						
Paleozoic	Silurian	Llandovery 433.5–443.8		Tumblagooda Sandstone	>1000	Sandstone	Fluvial to shallow marine
Paleozoic	Ordovician	Late 443.8–458.0		Tumblagooda Sandstone			
	Unconformity						
Precambrian	Proterozoic	541.0-2500.0		Moora Group		Metasedimentary rocks	
Precambrian	Proterozoic	541.0-2500.0		Yandanooka Group	>5000	Metasedimentary rocks	
			Unconformity				
Precambrian	Proterozoic	541.0-2500.0		Mulligarra Inlier		Gneissic rocks	
			Unconformity				
Precambrian	Proterozoic	541.0-2500.0		Northampton Inlier		Granulite, granite	

See Table 10 for surficial stratigraphy

Table 7 Stratigraphic terminology used in previous hydrogeological publications

Author	**Term**	**Current name**
Sanders (1967a, b)	Yarragadee Unit II	Warnbro Group
Sanders (1967)a, b	Yarragadee Unit I	Parmelia Group
Barnett (1969)	South Perth Formation	Parmelia and Yarragadee formations
Balleau and Passmore (1972)	Cretaceous Yarragadee Formation	Parmelia Group
Harley (1974)	Yarragadee III–VI	Parmelia Group
Playford et al. (1976)	Cockleshell Gully Formation	Eneabba Formation and Cattamarra Coal Measures
Mory (1995a)	Eneabba Member of Cockleshell Gully Formation	Eneabba Formation
Mory & Iasky (1996)	Cattamarra Coal Measures Member of Cockleshell Gully Formation	Cattamarra Coal Measures
This publication	Yarragadee Formation	Yarragadee Formation or Yarragadee units A, B, C and D
This publication	Parmelia Group	Undifferentiated Parmelia Group, Carnac and Otorowiri formations
Playford et al. (1976)	Otorowiri Siltstone Member of Yarragadee Formation	Otorowiri Formation
Playford et al. (1976)	Gage Sandstone Member of South Perth Shale	Gage Sandstone
Fairbridge (1953)	Dandaragan Sandstone	Henley Sandstone Member
Commander (1978)	Lower Yarragadee	Yarragadee Formation
Commander (1978)	Upper Yarragadee	Parmelia Group
Briese (1979a, b)	Otorowiri Siltstone Member of Yarragadee Formation	Carnac Formation
Backhouse (1984)	Parmelia Formation	Parmelia Group

Table 8 Nomenclature correlation for Cretaceous stratigraphy between the Carnarvon and Perth basins

<table>
<tr><th colspan="2">Age</th><th colspan="2">Carnarvon Basin</th><th colspan="3">Perth Basin</th></tr>
<tr><th colspan="2"></th><th colspan="2">Stratigraphy</th><th colspan="3">Stratigraphy</th></tr>
<tr><td>Maastrichtian</td><td></td><td rowspan="8"></td><td rowspan="2">Unconformity</td><td rowspan="12">Coolyena Group</td><td rowspan="8">Lancelin Formation</td><td rowspan="2">Poison Hill Greensand</td></tr>
<tr><td rowspan="2">Campanian</td><td>Late</td></tr>
<tr><td>Early</td><td rowspan="4">Toolonga calcilutite</td><td rowspan="2">Gingin Chalk</td></tr>
<tr><td rowspan="2">Santonian</td><td>Late</td></tr>
<tr><td>Early</td><td rowspan="4">Molecap Greensand</td></tr>
<tr><td rowspan="2">Coniacian</td><td>Late</td></tr>
<tr><td>Early</td><td>Unconformity</td></tr>
<tr><td>Turonian</td><td></td><td>Haycock Marl</td></tr>
<tr><td>Cenomanian</td><td></td><td rowspan="7">Winning Group</td><td>Gearle Siltstone</td><td rowspan="4">Osborne Formation</td><td>Mirrabooka Member</td></tr>
<tr><td rowspan="2">Albian</td><td>Late</td><td>Unconformity</td><td rowspan="2">Kardinya Shale Member</td></tr>
<tr><td>Early</td><td>Alinga Formation</td></tr>
<tr><td rowspan="3">Aptian</td><td>Late</td><td>Windalia Radiolarite
Windalia Sandstone Member</td><td>Henley Sandstone Member</td></tr>
<tr><td></td><td>Unconformity</td><td colspan="3">Unconformity</td></tr>
<tr><td>Earliest</td><td rowspan="2">Birdrong Sandstone</td><td rowspan="7">Warnbro Group</td><td rowspan="5">Leederville Formation</td><td>Pinjar Member</td></tr>
<tr><td rowspan="2">Barremian</td><td>Late</td><td rowspan="3">Wanneroo Member</td></tr>
<tr><td>Early</td><td rowspan="7"></td><td rowspan="7">Unconformity</td></tr>
<tr><td rowspan="4">Hauterivian–Barremian</td><td rowspan="4"></td></tr>
<tr><td>Mariginiup Member</td></tr>
<tr><td colspan="2">South Perth Shale</td></tr>
<tr><td colspan="2">Gage Sandstone</td></tr>
<tr><td>Valanginian</td><td></td><td colspan="3" rowspan="2">Unconformity</td></tr>
<tr><td>Berriasian</td><td></td></tr>
</table>

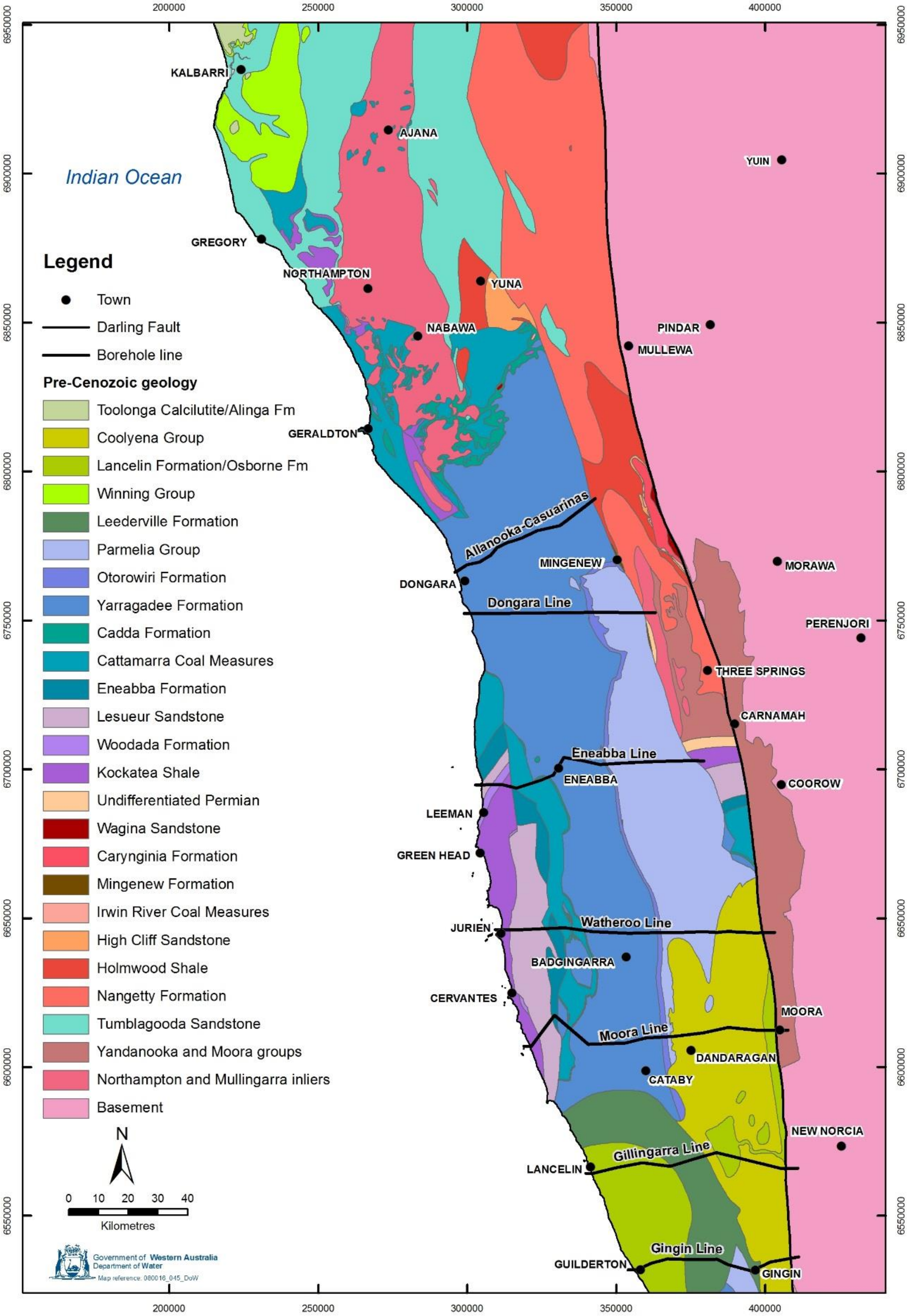


Figure 18 Regional pre-Cenozoic geology (in subcrop or outcrop)

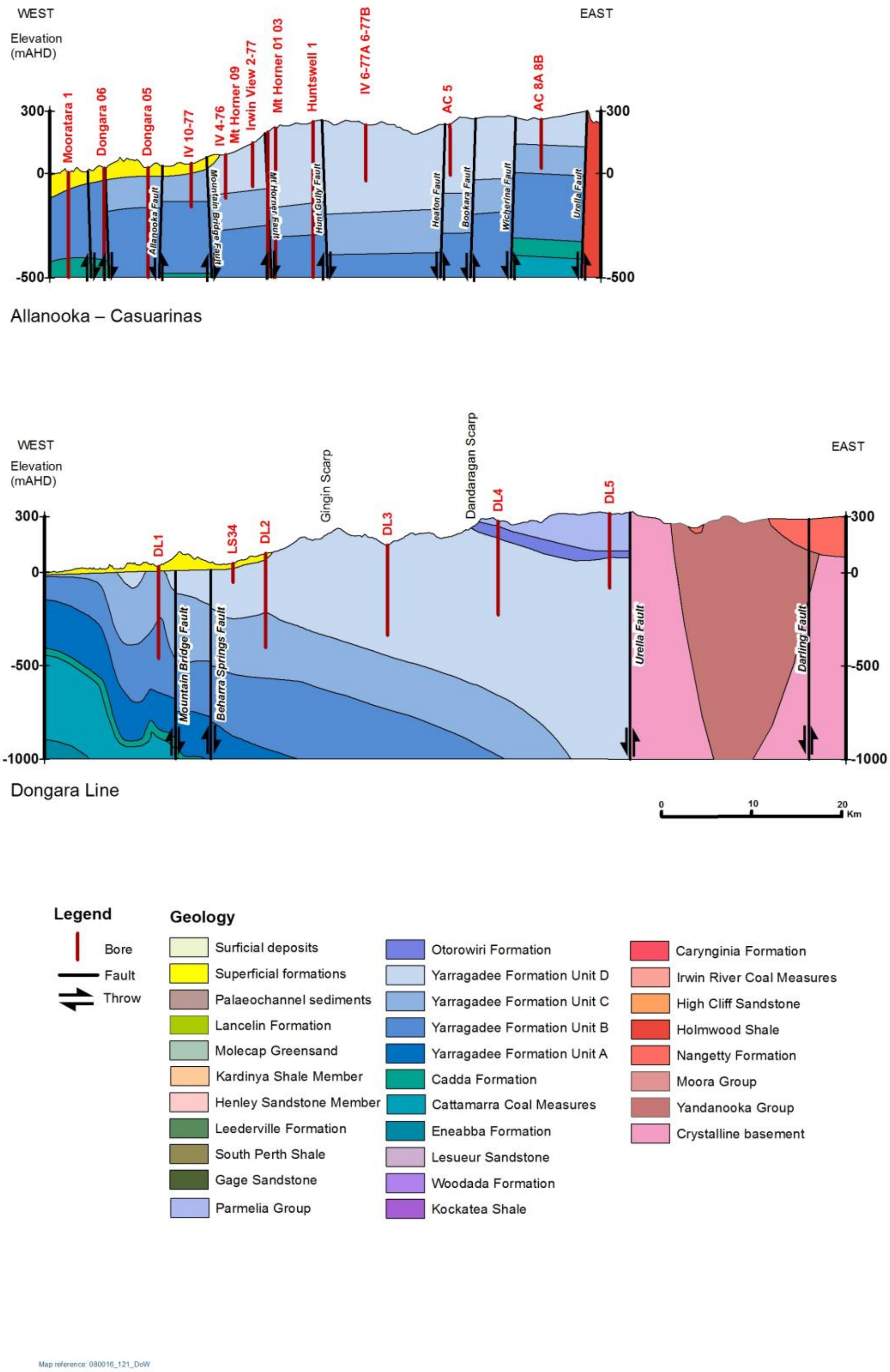


Figure 19 Geological cross-sections

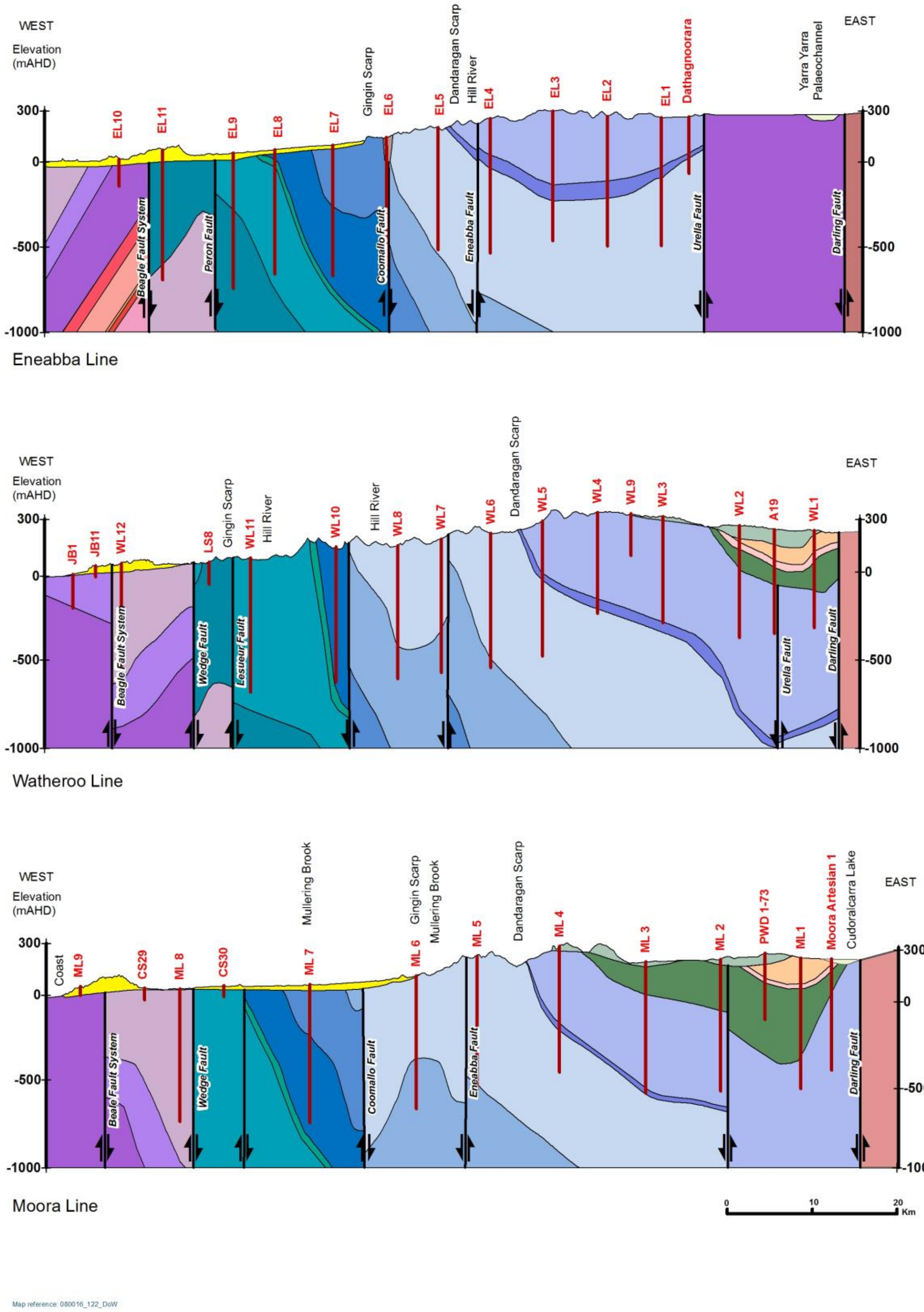


Figure 19 Geological cross-sections (continued)

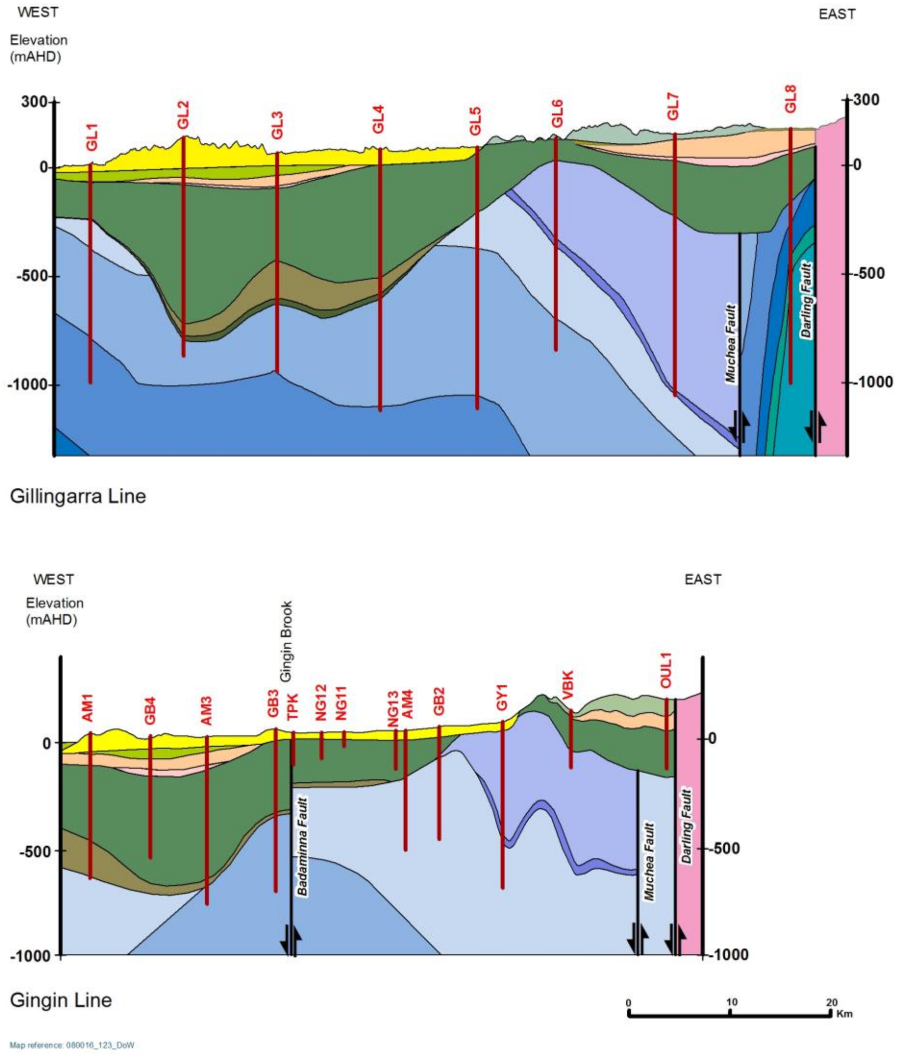


Figure 19 Geological cross-sections (continued)

4.1 Mullingarra and Northampton inliers

The Northampton Inlier was referred to as the ‘Greenough Block’ (Fairbridge 1951) before Hills (1965) established the term ‘Northampton Block’ (Daniels & Horwitz 1969). Subsequently, Myers (1990) introduced the name ‘Northampton Complex’. The GSWA has recently renamed this as the Northampton Inlier (A Mory 2016, pers. comm.). Therefore, this bulletin uses Northampton Inlier as the most recent name.

The geology of the Northampton Inlier was first described by Gregory and Gregory in 1848 (*in* Hocking et al. 1982) and, subsequently, Maitland completed systematic mapping of the Northampton Mineral Field in 1903. Jones and Noldart published a description of the regional geology in 1962 (Peers 1971). Detailed descriptions for the Northampton Inlier are contained in Playford et al. (1970) and Hocking et al. (1982).

The Northampton Inlier is a structural unit comprising Mesoproterozoic granulite and granite with migmatite along the granite–granulite contact of the Pinjarra Orogen (Peers 1971). The granulites are the oldest rocks of the Northampton Inlier and formed from regional metamorphism of sediments and gabbroic sills. The granulite has gneissic banding that varies in grain size and abundance of biotite and garnet (Peers 1971; Playford et al. 1970). These are interlayered with feldspathic quartzite and pegmatite (Peers 1971). Porphyritic granite with pink microcline phenocrysts intrudes the granulites and migmatite developed along the contact with the granulite. Proterozoic dolerite dyke swarms cut through the Northampton Inlier (Playford et al. 1970; Hocking et al. 1982). These are predominantly north-east trending. The dykes are vertical or very steep, are up to 25 m wide and might persist for 16 km (Playford et al. 1970). The Northampton Inlier is onlapped by Phanerozoic sediments where the Tumblagooda Sandstone and Kockatea Shale pinch out against the Northampton Inlier. Other parts of the inlier are overlain by flat-lying Jurassic sediments of the Cadda Formation and Cattamarra Coal Measures. Remnant Jurassic sediments occur as outliers upon the Northampton Inlier such as the Nabawa Sandplain (Koomberi 1995), forming flat-topped hills commonly capped by laterite. The north-western boundary is marked by the Hardabut Fault (Playford et al. 1976) and by the Yandi Fault to the east.

The Mullingarra Inlier, first described by Baxter and Lipple (1985), is a narrow inlier of Proterozoic gneissic rocks of the Pinjarra Orogen within the Perth Basin that is bound by the Urella Fault to the west. It comprises a series of pelitic, quartzo–feldspathic and semipelitic gneisses that are collectively referred to as the Mullingarra Gneiss. Lenses of quartzite and amphibolite are contained within the gneiss as are abundant veins of pegmatite. There is a small intrusion of porphyritic granite in the north-eastern part of the Ikewah Range. The Mullingarra Inlier is onlapped by Proterozoic sedimentary rocks of the Yandanooka Group to the east and overlain by Permian sediments in the north (Baxter & Lipple 1985). The inlier outcrops between the Irwin and Yarra Yarra terraces, and abuts the Parmelia Group along the Urella Fault (Mory & Iasky 1996).

4.2 Yandanooka and Moora groups

The Yandanooka and Moora groups are metasedimentary rocks of the Proterozoic Pinjarra Orogen preserved along the margin of the Perth Basin and Yilgarn Craton. For completeness, the Moora Group is included in this bulletin, as it is equivalent to part of the Yandanooka Group, although it lies entirely outside the Perth Basin (Figure 18).

The Yandanooka Group occupies the Irwin Terrace in a shallow north-plunging syncline, resting unconformably between the Darling Fault in the east and the gneissic rocks of the Mullingarra Inlier to the west. Its southern limit is near Lake Eganu, where it has a faulted boundary beneath Cretaceous sedimentary formations. Northward, it extends beneath the Permian Nangetty Formation (Low 1975; Muhling & Low 1977; Baxter & Lipple 1985). The Yandanooka Group outcrops between the Yarra Yarra Lakes northward to Corral Creek and between Three Springs and Yandanooka (Playford et al. 1976; Baxter & Lipple 1985).

The platform sequence of Proterozoic metasedimentary rocks between Moora and Carnamah on the adjoining Yilgarn Craton is assigned to the Moora Group, the lower subgroup of which (the Billeranga Subgroup) is recognised as being laterally equivalent to the Yandanooka Group (Baxter & Lipple 1985). The Moora Group has been described by Logan and Chase (1961), Playford et al. (1976), Carter and Lipple (1982), and Baxter and Lipple (1985).

Yandanooka Group

The Yandanooka Group was originally called the Yandanooka Beds by Woolnough and Somerville (1924) and subsequently renamed the Yandanooka Group by Johnson et al. (1954). Descriptions for the Yandanooka Group are detailed in Baxter and Lipple (1985), Low (1975) and Playford et al. (1976).

Baxter and Lipple (1985) describe the Yandanooka Group as a sequence of Proterozoic clastic sedimentary rocks possibly exceeding 5000 m in thickness. Five formations are recognised within the Yandanooka Group (Playford & Willmott *in* McWhae et al. 1958; Playford et al. 1976). These are (in order from the base) the Arrowsmith Sandstone, Arrino Siltstone, Beaconsfield Conglomerate, Enokurra Sandstone and Mount Scratch Siltstone (Low 1975). Brief descriptions of these formations are provided below.

The Arrowsmith Sandstone is a well-sorted and well-bedded feldspathic quartz sandstone. The type section is 335 m thick, located 6 km south-southeast of Arrino (MGA Zone 50, 367817 m E, 6736749 m N). It rests unconformably on an Archean gneiss unit of the Mullingarra Inlier, partially infills the irregular palaeotopography of this unit (Baxter & Lipple 1985; Low 1975) and pinches out against elevated basement in places (Low 1975).

The Arrino Siltstone is a dark reddish-brown, micaceous siltstone which lies conformably on the Arrowsmith Sandstone, except where the sandstone is absent, in which case it sits unconformably on the Archean gneiss. It is a uniform sequence that is poorly to well-bedded (Low 1975) and includes some sandy beds and layers of lenticular, conglomeratic sandstone, particularly towards the base of the unit (Baxter & Lipple 1985; Low 1975). The type section of the Arrino Siltstone is 509 m thick, and is 1.6 km east-northeast of Yandanooka (MGA Zone 50, 362168 m E, 6756078 m N) (Low 1975). Where it overlies the

Archean gneiss, 4.8 km north-northeast of Yandanooka, it is only 60 m thick (Playford & Willmott 1958; Low 1975).

The Beaconsfield Conglomerate consists of rounded to poorly-rounded cobbles with weak, imbricate fabric and layers of laminated, weakly cross-bedded grit (Baxter & Lipple 1985). The unit is an epiclastic deposit and is part of the substantial volcanic activity in the source area. It conformably overlies the Arrino Siltstone, and is overlain disconformably by the Enokurra Sandstone (Low 1975). The clasts comprise cobble-sized, black to dark red and yellow-grey vesicular dacite, andesite, porphyritic basalt and fine-grained dolerite. The matrix is unsorted, fine silt to a coarse-grained sand (Baxter & Lipple 1985; Low 1975). The type section is 40 m thick and is located on Beaconsfield Creek (MGA Zone 50, 363741 E, 6759852 N) (Low 1975).

Low (1975) describes the Enokurra Sandstone as a grey, yellow, brown and pink fine-grained to very coarse grained sandstone grading into fine conglomerate in places with quartz, quartzite, andesite and siltstone, with subangular to rounded pebbles and granules. Large-scale cross-bedding is also well developed. It overlies disconformably either the Beaconsfield Conglomerate or the Arrino Siltstone.

The Mount Scratch Siltstone conformably overlies the Enokurra Sandstone, and is overlain by the Lower Permian Nangetty Formation with an angular unconformity (Low 1975). Mount Scratch Siltstone comprises a thick sequence of reddish-brown, greenish-grey and grey micaceous siltstone between 7.6 and 9.0 km thick. The siltstone is well-bedded to fissile, commonly with well-developed cross-bedding and current ripple marks. Thinner beds of fine-grained sandstone and conglomerate are present, as are andesite and trachyte clasts and minor quartz grains and granite pebbles. The type section located at Mount Scratch is 896 m thick, and starts at 11 km east-northeast of Yandanooka (MGA Zone 50, 371433 m E, 6759819 m N) and continues to the east for 0.8 km (Low 1975).

Moora Group

The Moora Group comprises a thin remnant of a previously extensive platform sequence that unconformably overlies an irregular, locally rugged Archean basement topography. It is up to 15 km wide immediately to the east of the Darling Fault. It has undergone little deformation, and metamorphism is very low grade (Baxter & Lipple 1985). Blocks of chert in the Permian Nangetty Formation suggest that the subgroup was extensively eroded during Permian glaciation.

The lower Billeranga Subgroup comprises up to 400 m of weakly deformed immature fluviatile–alluvial, fan-basin margin sediments. It is disconformably overlain by the Coomberdale Subgroup comprising undeformed sandstone, siltstone, dolomite, and silicified dolomite up to 1500 m thick. The former Coomberdale Chert is now known as the Noondine Chert.

The basal Mokadine Formation of the Coomberdale Subgroup, as redefined by Baxter and Lipple (1985), conformably overlies the Dalaroo Siltstone of the Billeranga Subgroup. It grades upward into arkose and felspathic quartzite in the lower part of the formation, becoming siltstone, mudstone and minor chert in upper parts (Logan & Chase 1961).

The conformably overlying Noondine Chert comprises interbedded sandstone and algal–carbonate cycles of bedded chert, chert breccia, orthoquartzite, silicified limestone and dolomite with minor silicified siltstone and sandstone, and claystone (Carter & Lipple 1982). Although most of the carbonate units have been extensively silicified, minor dolomite is still preserved in several horizons, including exposures at Jingemia Cave (7 km north-west of Watheroo) defined as Jingemia Dolomite (Baxter & Lipple 1985). The dolomite has been steatised at the Three Springs talc mine. Locally, the Noingara Siltstone forms thin horizons of red-brown siltstone interbedded with sandstone of the Winemaya Quartzite (Baxter & Lipple 1985), which disconformably overlies the Dalaroo Siltstone.

4.3 Tumblagooda Sandstone

The Palaeozoic Tumblagooda Sandstone is the oldest formation in the Perth Basin, and outcrops on either side of the Northampton Inlier. It was named by Clarke and Teichert (1948), who described the sequence in the lower Murchison River. The type section, defined by Johnstone and Playford (*in* McWhae et al. 1958), extends for about 70 km of the Murchison River Gorge between Hardabut Pool and Second Gully.

The Tumblagooda Sandstone is a ‘red-bed’ sequence of predominantly hematitic, brownish-red to purplish-brown units of quartz and feldspathic fine- to coarse-grained sandstone with some granule to pebble conglomerate (Hocking 1991). A hematite–goethite coating of grains is responsible for the colouration of the sequence (Hocking et al. 1987). Pallid, light brown and yellow horizons are present in places and these tints are largely caused by deep weathering (Hocking 1991; Kern 1993b).

The sandstone is horizontally stratified, with small to large-scale cross-bedding, and frequent bioturbation of beds. Invertebrate trails and castings are also observed, as well as rare intercalations of greenish mudstone within the sandstone (Hocking 1991). The sandstone is hard and jointed below the weathering profile (Kern 1993b). At Kalbarri, north-northeast and north-west oriented joints are observed, as well as horizontal bedding plane partings (Barnett 1980).

In the southern Carnarvon Basin, the Tumblagooda Sandstone is at least 1000 m thick (Hocking 1987), although its full extent has not been penetrated. A stratigraphic thickness of about 1210 m is present at the type section (Hocking 1991) and a thickness greater than 2600 m has been encountered in offshore drilling (Hocking 1991). In the Perth Basin, petroleum exploration well Wendy 1, located 38 km east of Northampton upon the Bookara Shelf, intersected 1098 m of Tumblagooda Sandstone below 112 m depth (Victoria Petroleum NL 2004). Playford et al. (1970) considered the Tumblagooda Sandstone to be as much as 1500 m thick on the eastern side of the Northampton Inlier.

In the Palaeozoic, the Perth and Carnarvon basins formed a broad, north-opening trough within which the Tumblagooda Sandstone was continuously deposited (Hocking 1991). It was deposited in a braided, fluviatile environment, possibly with intertidal and tidally influenced shallow marine environments (Hocking et al. 1982).

The age of the Tumblagooda Sandstone is ambiguous. It was previously considered a Silurian deposit due to invertebrate trails and castings within the formation (Hocking et al.

1985) through to Upper Silurian age for the Dirk Hartog Group (Hocking 1982), which conformably overlies the Tumblagooda Sandstone in the central part of the Gascoyne Platform (Playford et al. 1975). It now appears that the Tumblagooda Sandstone age might extend from Cambrian to Early Silurian (Mory et al. 2003), based on fauna within the overlying Dirk Hartog Group being revised to Late Ordivician to early Silurian (Mory et al. 1998).

The Tumblagooda Sandstone is present through most of the Carnarvon Basin (Hocking 1991) and extends into the northernmost portion of the Perth Basin but not south of Geraldton. The Tumblagooda Sandstone unconformably overlies crystalline basement.

Within the central part of the Carnarvon Basin, the Tumblagooda Sandstone is overlain conformably or disconformably by the Dirk Hartog Group (Mory et al. 2003) but this group does not extend into the southern portion of the basin. South of the Murchison River, the Tumblagooda Sandstone is unconformably overlain by the Cretaceous Winning Group. Further south, near the south-western limit of the onshore Carnarvon Basin and into the Perth Basin, it is unconformably overlain by the Triassic Kockatea Shale or the Jurassic Cattamarra Coal Measures. In the Perth Basin, east of the Urella Fault on the Irwin and Coolcalalaya terraces, the Tumblagooda Sandstone is unconformably overlain by Carboniferous–Permian sediments of the Nangetty Formation.

The Tumblagooda Sandstone is concealed by a thin surficial cover to the east and west of the Northampton Inlier. Extensive outcrops are present within the Murchison River Gorge and as coastal cliffs south of Kalbarri. There are also small outcrops at the western and eastern margins of the Northampton Inlier as far south as Northern Gully near Wicherina, and east of the Urella Fault, near Bindoo Hill in the Perth Basin.

4.4 Nangetty Formation

The Nangetty Formation is a glacigene unit at the base of the Permian sequence, representing the start of continuing sedimentation in the Perth Basin through to the Late Cretaceous. The name was introduced by Clarke et al. (1951) as the ‘Nangetty Glacial Formation’, and amended by Playford and Willmott *in* McWhae et al. (1958) to the Nangetty Formation. The type area is located in the Nangetty Hills (MGA Zone 50, 348500 m E, 6791000 m N), 5 m between the Irwin River and Nangetty Creek about 20 km north of Mingenew. The formation outcrops across the Irwin Terrace (Mory & Iasky 1996) and Coolcalalaya Terrace (van de Graaff et al. 1980; Hocking et al. 1982) and the main exposures are within the Lockier and Irwin rivers. However, there is no specific type section because exposure is poor and discontinuous (Playford et al. 1976). Nangetty Formation lithostratigraphic equivalents are found over large parts of Gondwana. The formation is equivalent to the Shotts Formation in the Collie Basin (Le Blanc Smith & Mory 1995, Mory & Iasky 1996) and the Lyons Group in the Carnarvon Basin (Hocking et al. 1982).

The dominant lithology of the Nangetty Formation is pale greenish grey to blue-green laminated sandy siltstone and mudstone (Le Blanc Smith & Mory 1995; Mory & Iasky 1996). In outcrop, it is often weathered to a medium brown colour (Mory & Iasky 1996). Occasional erratic boulders up to 6 m diameter deposited by melting icebergs, and some large spherical limestone concretions are present (Playford et al. 1976; Le Blanc Smith & Mory 1995). The boulders comprise igneous, metamorphic, and sedimentary Archean and Proterozoic rocks, including rocks from the Yandanooka Group and Moora Group (Playford et al. 1976; Le Blanc Smith & Mory 1995). Some boulders show surface faceting and striations, indicating glacial deposition.

A sandstone bed, present at the base of the Nangetty Formation, has been formally defined as the Wicherina Sandstone Member (Mory & Iasky 1996). This comprises white, fine- to coarse-grained quartz sandstone with minor carbonaceous strips and some conglomerate (Mory 1995). The Wicherina Sandstone Member is tentatively correlated with the Harris Sandstone near the base of the Lyons Group in the Carnarvon Basin (Mory 1995). The designated type section is the interval member from 1308 to 1686 m bgl in petroleum well Wicherina 1 (Mory 1995). This is also the thickest section encountered. Representative downhole gamma-ray logs through the Nangetty Formation are shown in Figure 20 and Figure 21.

The Nangetty Formation was deposited in a glacial to proglacial marine shelf setting (Le Blanc Smith & Mory 1995). The sandstones of the Wicherina Member at the base of the formation represent continental moraine and high-energy fluvioglacial channel deposits (Baxter & Lipple 1985; Mory & Iasky 1996). The transition to the overlying siltstone and mudstone resulted from a transgression to lacustrine and probably marine conditions (Baxter & Lipple 1985). Palynomorphs from the upper Nangetty Formation and overlying Holmwood Shale are of Asselian age from the Early Permian (Backhouse 1992c, 1993a) placing the formation near the Carboniferous–Permian boundary.

The Nangetty Formation is thickest in the east towards the Darling Fault, exceeding 1000 m upon the Irwin Terrace (Le Blanc Smith & Mory 1995). It thins to the west and south over the Allanooka High towards the Dongara Terrace and Greenough Shelf, and is absent over the Beagle Ridge and the western part of the Cadda Terrace (Mory & Iasky 1996). Within the Dandaragan Trough, the formation is too deep to have been intersected by drilling or identified on seismic profiles. However, within the Greenough Shelf, seismic profiles show that the Wicherina Member is about 250 m thick along the western side of the Dongara gas and oilfield, with a maximum intersected thickness of 378 m in petroleum well Wicherina 1 (Mory & Iasky 1996).

The Nangetty Formation unconformably overlies Proterozoic and Archean basement rocks, the Yandanooka Group and the Tumblagooda Sandstone. It is conformably overlain by the Holmwood Shale with an apparent gradational contact from pale greenish grey silts to blue-blackish shale, a decrease of erratics and the prevalence of mica in the shale (Le Blanc Smith & Mory 1995; Mory & Iasky 1996).

4.5 Holmwood Shale

The Holmwood Shale is an Early Permian siltstone and shale deposit comprising three members with thin beds of fossiliferous limestone named, in ascending order, the Beckett, Woolaga Creek Limestone and Fossil Cliff members (Playford et al. 1976; Le Blanc Smith & Mory 1995). Clarke et al. (1951) introduced the Holmwood Shale, named after the Holmwood homestead south of the Irwin River near the Darling Fault, and Playford and Willmott (*in* McWhae et al. 1958) nominated a type section nearby along Beckett Gully (MGA Zone 50, 356141 m E, 6789037 m N). The Fossil Cliff Member at the top of the formation was originally defined as a separate formation (Clarke et al. 1951), but was later incorporated as a member of the Holmwood Shale (Johnson et al. 1954; Playford et al. 1976) as it is not sufficiently distinct from the underlying siltstone and has restricted distribution.

The lower part of the Holmwood Shale comprises grey-green shale, and the upper portion is mainly grey to black clayey siltstone. Rare erratic boulders deposited by melting icebergs are often present within the basal portion (Le Blanc Smith & Mory 1995; Mory 1995b). Thin, brown, clayey limestone beds of the Beckett Member are present within the lower shaley portion of the formation. The upper clayey siltstone portion is well bedded with mica, jarosite (potassium and iron hydrous sulfate that is probably an oxidation product of pyrite) and gypsum (Le Blanc Smith & Mory 1995).

At the top of the Holmwood Shale, the Fossil Cliff Member is a mainly bioclastic calcarenite forming thin, lenticular beds within siltstone and shale becoming sandier in the east towards the Darling Fault (Le Blanc Smith & Mory 1995). A lower conspicuous fossiliferous limestone section, defined as the Woolaga Creek Limestone Member by Playford (1959), has been observed in the Woolaga Creek area near the Darling Fault east of Mingenew, but it has not been observed elsewhere.

Sandstone units are present in the upper formation in its north-eastern areas (Johnstone & Willmott 1966). These were intersected in petroleum wells Abbarwardoo 1 (279–333 m and 387–429 m), Wicherina 1 (953–1003 m) and Depot Hill 1 (1885–1920 m), and described in Abbarwardoo 1 (Burdett 1963) as a mainly fine-grained, friable quartz sand with minor clay matrix; however, this unit is coarse to very coarse grained in wells further to the south.

Downhole gamma-ray logs over the Holmwood Shale display a characteristically high gamma-ray count across the shale and clayey siltstone with low count associated with sandstone units (Figure 20, Figure 21 and Figure 22). In outcrop, the Holmwood Shale weathers to a white, yellow and pale to medium brown colour, and can appear very similar to weathered Nangetty Formation (Hocking et al. 1982; Le Blanc Smith & Mory 1995).

The Holmwood Shale was deposited in a cold-water marine environment under mainly reducing conditions, interpreted from the lack of benthic fauna (Playford et al. 1976). Rare, erratic boulders indicate occasional deposition from icebergs (Playford et al. 1976), and intervals of fossiliferous limestone suggest periods of well-aerated conditions that allowed benthic fauna to flourish (Playford et al. 1976). Palynological assemblages include some plant microfossils (Segroves 1971) and microfossils include mainly foraminifera (Crespin 1958) in shale. Most macrofossils are confined to the limestone beds, including pelecypods, gastropods, brachiopods, nautiloids, ostracods, coral, bryozoans and the ammonoid *Juresanites jacksoni* (Playford et al. 1976). The Fossil Cliff Member has a particularly abundant and large variety of benthic fauna fossils (Playford et al. 1976; Baxter & Lipple 1985). The formation lies mostly in the *Pseudoreticulatispora* confluence palynological zone, while at the top of the formation the Fossil Cliff Member belongs to the *P. pseudoreticulata* Zone, indicating an Asselian to Sakmarian age in the Early Permian (Backhouse 1993a).

The Holmwood Shale outcrops on the Irwin Terrace within watercourses. The main outcrops are in the Irwin and Lockier rivers (Playford et al. 1976, Mory & Iasky 1996). The northernmost outcrops are likely in the Murchison River valley, 13–25 km south of Bompas

Hill (Playford et al. 1976). The formation is found at considerable depth under most of the northern portion of the northern Perth Basin, including the Dandaragan Trough, the Cadda Terrace and the Beagle Ridge (Playford et al. 1976, Mory & Iasky 1996). It extends as far south as the petroleum well Cadda 1 and northward onto the Coolcalalaya Terrace (van de Graaff et al. 1980).

Like the Nangetty Formation, the Holmwood Shale is thickest in the east upon the Irwin Terrace (Mory & Iasky 1996), where it is between 400 and 700 m thick (Le Blanc Smith & Mory 1995). It thins westward across the Allanooka High. The type section of the formation is 566 m but, due to repetition from faulting, the true thickness might be closer to 450 m (Playford & Willmott *in* McWhae et al. 1958; Playford et al. 1976). Upon the eastern margin of the Allanooka Terrace, petroleum well Depot Hill 1 intersected 625 m of the Holmwood Shale (Mory 1995b). The Fossil Cliff Member has a maximum known thickness of 47.5 m at Beckett Gully (Muhling & Low 1977).

The Holmwood Shale was deposited conformably upon the Nangetty Formation, and is overlain with an apparent conformity by the High Cliff Sandstone (Le Blanc Smith & Mory 1995). On the Beagle Ridge and Greenough Shelf, the Holmwood Shale unconformably overlies basement rocks (Mory & Iasky 1996). The formation is equivalent to the Moorhead Formation in the Collie Basin (Le Blanc Smith & Mory 1995), and the Carrandibby and Callytharra formations of the Carnarvon Basin (van de Graaff et al. 1980).

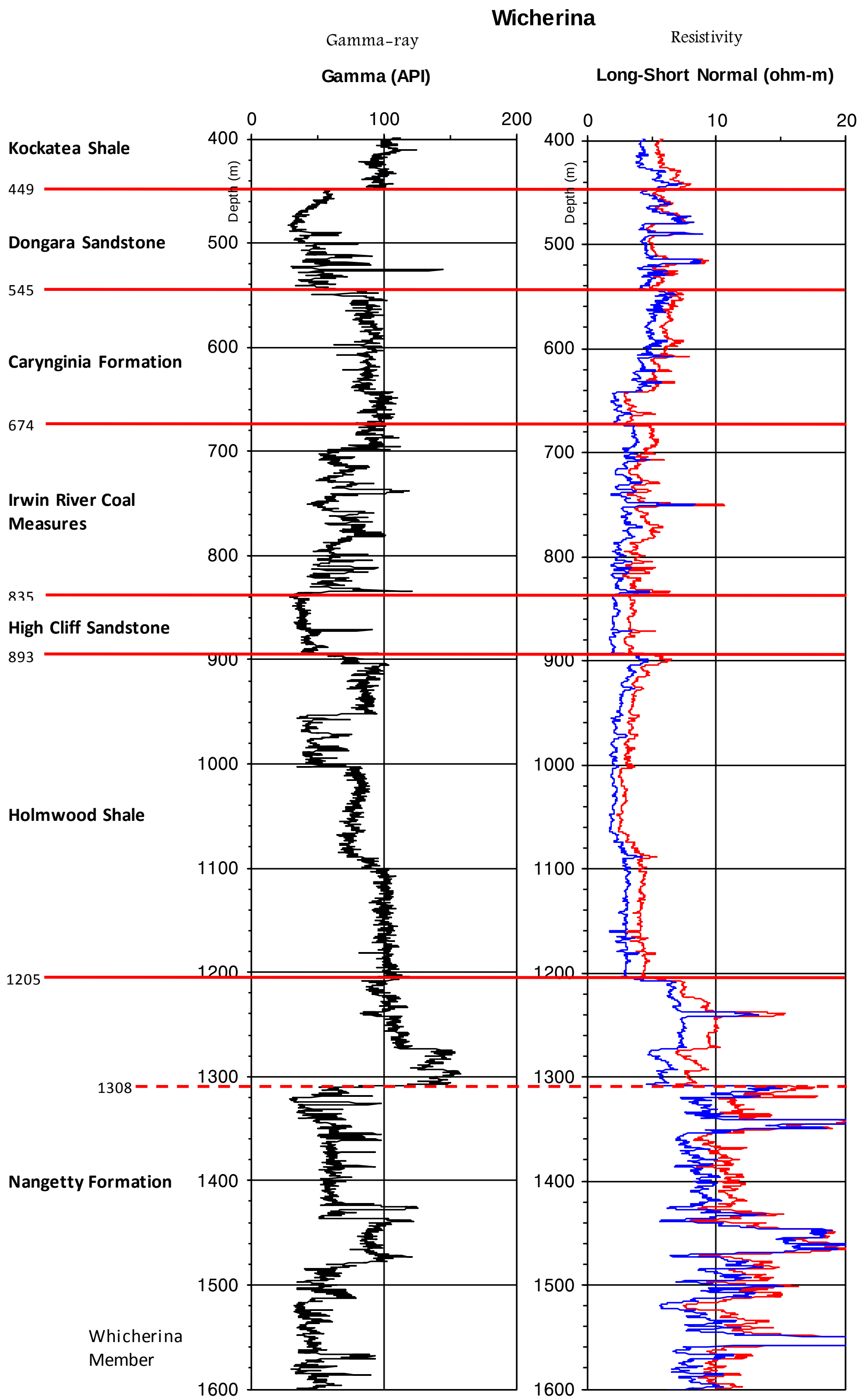


Figure 20 Downhole geophysical log from petroleum well Wicherina 1 (400–1600 m bgl) showing Permian formations

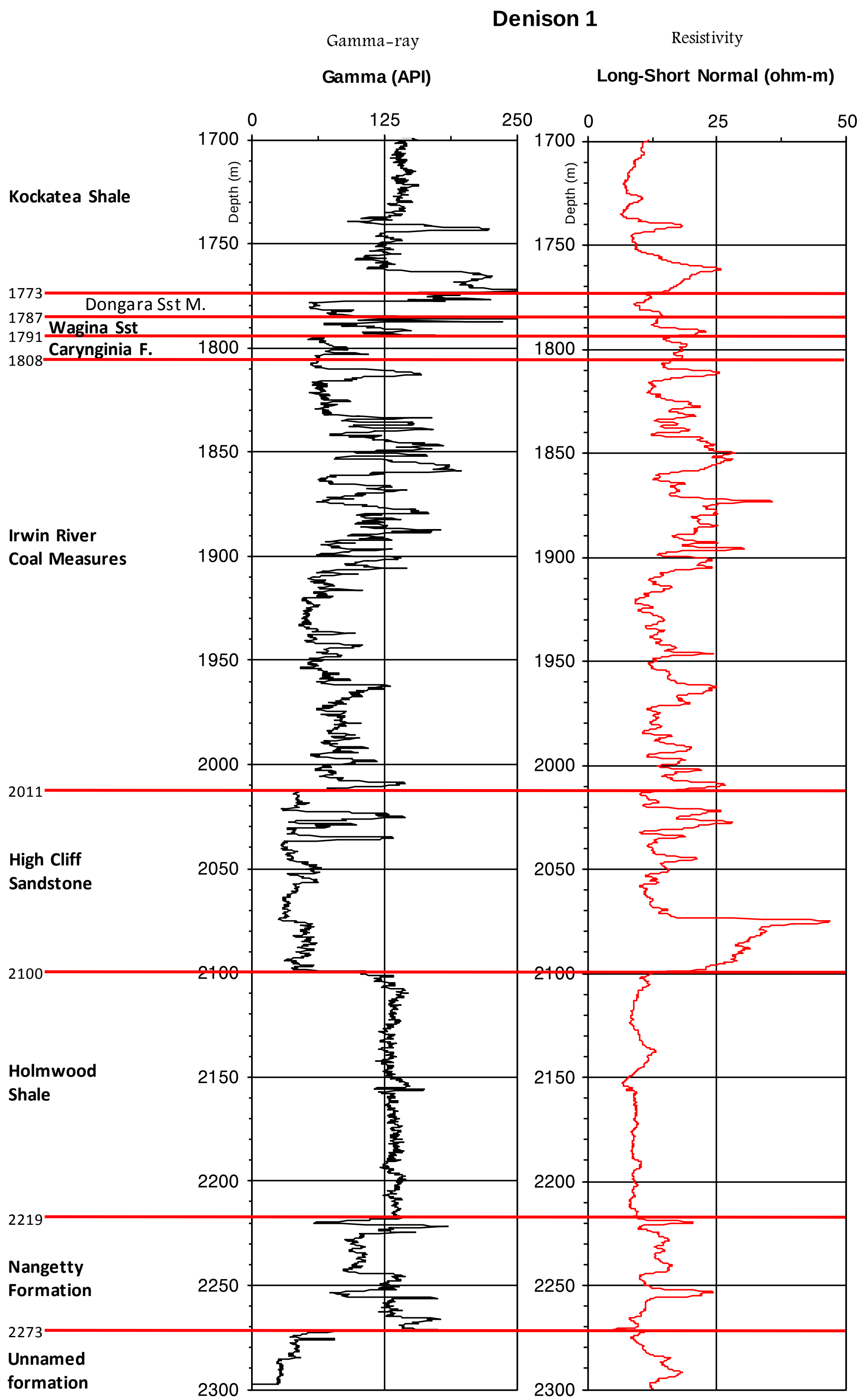


Figure 21 Downhole geophysical log from petroleum well Denison 1 (1700–2300 m bgl) showing the Permian formations

4.6 High Cliff Sandstone

The High Cliff Sandstone was introduced by Clarke et al. (1951) to represent an Early Permian sequence of interbedded sandstone, conglomerate and minor siltstone. The type section is located at High Cliff, on the south bank of the Irwin River north branch (MGA Zone 50, 358419 m E, 6797439 m N) on the Irwin Terrace where the formation is 26 m thick (Le Blanc Smith & Mory 1995). Outcrops of the High Cliff Sandstone are restricted to the Irwin Terrace, with the main exposures in the Irwin and Lockier rivers area. In exposure, the formation consists of a broadly upward-coarsening section of highly bioturbated, rippled, silty sandstone.

It has been suggested that the High Cliff Sandstone be redefined as a member unit of the Irwin River Coal Measures, as the contact can be gradational and the units difficult to distinguish (Le Blanc Smith & Mory 1995; Mory & Iasky 1996).

The High Cliff Sandstone comprises upward coarsening, white to medium grey, highly bioturbated, fine- to medium-grained silty sandstone, to coarse and very coarse grained sandstone and gravel. The coarse-grained sandstone is cross-bedded with thin pebble conglomerate beds (Le Blanc Smith & Mory 1995). The grain size of the sandstone appears to coarsen towards the Darling Fault, and possibly also towards the Urella Fault (Playford et al. 1976). Towards the base, the formation is more argillaceous with minor, thin interbedded siltstones that are medium to dark grey and carbonaceous. This part includes some angular to subangular erratic boulders up to 60 cm in diameter (Le Blanc Smith & Mory 1995).

Downhole geophysical logs through the formation typically have a low gamma-ray count, but often show a gradational contact with the overlying Irwin River Coal Measures (Figure 20 and Figure 21). Le Blanc Smith and Mory (1995) noted it can be difficult to distinguish the High Cliff Sandstone from the Irwin River Coal Measures in bores where the High Cliff Sandstone is thin and contains a similar proportion of siltstone to the overlying Irwin Coal Measures.

The High Cliff Sandstone was probably deposited in a delta front environment with shallow marine, lower deltaic and beach ridge elements (Playford et al. 1976; Baxter & Lipple 1985; Mory 1995b; Mory & Iasky 1996). This interpretation is supported by cross-stratification, wave ripples, sporadic conglomerate lenses, rippled siltstone drapes, and some marine fossils (Le Blanc Smith & Mory 1995). Erratic boulders suggest a proglacial setting (Le Blanc Smith & Mory 1995).

The depositional centre for the High Cliff Sandstone appears to be located on the Allanooka Terrace and Bookara Shelf (Mory & Iasky 1996), and it is thickest upon the Allanooka Terrace, where the maximum intersection of 150 m was in Mount Horner 1 (Mory & Iasky 1996). On the Irwin Terrace, the High Cliff Sandstone thickens from 26 m at the type section to 42 m to the south at Woolaga Creek (Playford et al. 1976). The formation thins to the west onto the Greenough Shelf and Dongara Terrace.

Normally the High Cliff Sandstone is unfossiliferous (Le Blanc Smith & Mory 1995; Mory & Iasky 1996). However, there is a marine fauna assemblage described at the base of the formation at Woolaga Creek that includes bivalves, gastropods and brachiopods, indicating an Artinskian age (Playford et al. 1976; Baxter & Lipple 1985). Although palynofloras have not been found in the sandstone, Backhouse (1993a) estimates that the High Cliff Sandstone is probably within the Artinskian *Striatopodocarpites fusus* Zone.

As with the other underlying Permian formations, the High Cliff Sandstone is present across the northern Perth Basin, extending from the Irwin Terrace west to the Greenough Shelf and Beagle Ridge. It also extends north, where it is recognised on the Coolcalalaya Terrace (van de Graaff et al. 1980) and is probably present at depth within the Dandaragan Trough. The formation is correlated with the Westralia Sandstone in the Collie Basin, and other units in the Wilga, Boyup and Southern Perth Basin (Le Blanc Smith 1993). There is a conformable, sharp contact between the High Cliff Sandstone and the underlying Holmwood Shale, while the contact with the overlying Irwin River Coal Measures is conformable and typically transitional.

4.7 Irwin River Coal Measures

The Irwin River Coal Measures were introduced by Clarke et al. (1951) as a coal bearing sequence of sandstone, siltstone and shale between the High Cliff Sandstone and the Carynginia Formation. The type section is located along the north branch of the Irwin River, from about 500 m upstream from High Cliff (MGA Zone 50, 358419 m E, 6797439 m N), where it is 55 m thick (Playford et al.,1976). The Irwin River Coal Measures consist of alternating beds of sandstone, siltstone with carbonaceous shale, coal seams and infrequent conglomerate and limestone (Le Blanc Smith & Mory 1995, Mory 1995b, Muhling & Low 1977). The sandstones are often strongly cross-bedded, with some current ripple marks, and are coloured white, red, yellow or brown (Playford et al. 1976). Le Blanc Smith (1993) correlated the Irwin River Coal Measures with the Ewington Coal Measures of the Collie Basin, and it can also be correlated with the Keogh and Billidee formations of the Carnarvon Basin, and even the Vryheid Formation in the Karoo Basin of southern Africa (Le Blanc Smith & Mory 1995).

The upper portion of the formation is dominated by siltstone and claystone with subordinate sandstone and minor coal. It is light to medium grey, and dark grey over the carbonaceous intervals. The siltstone is micaceous, and carbonised wood fragments are common within the claystone. Sandstone within the upper portion is mostly fine grained, and is massively bedded with common small-scale current bedding and slump structures (Playford et al. 1976). In parts, the sandstone is calcareous, grading into a sandy limestone.

The lower portion of the Irwin River Coal Measures is dominated by sandstone with interbedded siltstone and minor shale. The sandstone is white, light to medium grey, fine and coarse to very coarse grained, moderately sorted, kaolinitic, carbonaceous, micaceous and pyritic. Pebbles are often present within the coarse-grained sandstone, which sometimes grades into conglomerate lenses. The coarse-grained sandstone is typically poorly consolidated, while the fine-grained sandstone often has an argillaceous matrix and moderately to well-developed siliceous cementation. Cross-bedding and ripples are abundant in the sandstone, with wavy and flat lamination, rootlets and bioturbation (Le Blanc Smith & Mory 1995). A number of thin, lenticular, sub-bituminous coal seams are present within the lower part of the formation.

Downhole geophysical logs of the Irwin River Coal Measures typically show an irregular gamma-ray pattern with short intervals of high and low counts, normally containing one or two thicker intervals of low gamma-ray count corresponding to sandstone-dominated sections (Figure 20 and Figure 21).

The Irwin River Coal Measures were probably deposited on a lower delta plain formed from a series of coalesced alluvial deltas. This interpretation is supported by the lack of marine fossils and lenticular bedding (Le Blanc Smith & Mory 1995), and the presence of herbaceous flora (McLoughlin 1991). The upper portion of the formation grades into the overlying marine Carynginia Formation, coincident with a progressing cold-temperature, marginal marine embayment and fore-beach environment (Playford et al. 1976; Le Blanc Smith & Mory 1995).

Coalified plant remains, rootlets and bioturbation indicate an active faunal and floral presence (Mory & Iasky 1996). Palynological assemblages belong to the *Microbaculispora trisina* palynostratigraphic zone, with the *Striatopodocarpites fusus* Zone within the lower portion of formation (Backhouse 1993a) indicating an Artinskian (Early Permian) age. It is rich in the Permian flora *Glossopteris* (Rigby 1966) and contains abundant spores and pollen (Segroves 1969, 1970, 1971).

The Irwin River Coal Measures outcrop on the Irwin Terrace from the Greenough River to Woolaga Creek. In the subsurface, the Irwin River Coal Measures occur throughout much of the northern Perth Basin and thicken westward from the Irwin Terrace into a depositional centre probably across a broad north–south depression located over the western part of the Allanooka High and possibly extending into the Dandaragan Trough (Mory & Iasky 1996). The formation thins west onto the Beagle Ridge, while on the Greenough Shelf it has been eroded during a middle Permian erosion event so that the full sequence is not preserved (Mory & Iasky 1996). The maximum thickness of Irwin River Coal Measures intersected was 307 m in Arrowsmith 1 (Mory & Iasky 1996).

The Irwin River Coal Measures lie conformably between the High Cliff Sandstone and the Carynginia Formation. The lower boundary is defined as the lowest carbonaceous to coaly shale or siltstone overlying medium- to coarse-grained sandstone of the High Cliff Sandstone (Playford et al. 1976; Le Blanc Smith and Mory 1995). The upper boundary is at the base of the jarositic micaceous siltstone that is characteristic of the Carynginia Formation (Playford et al. 1976).

4.8 Carynginia Formation (including Mingenew Formation)

The Carynginia Formation is an Early Permian siltstone, claystone and sandstone sequence between the Irwin River Coal Measures and overlying Wagina Sandstone, Dongara Sandstone and Beekeeper Formation (Clarke et al. 1951; Playford & Willmott *in* McWhae et al. 1958). Carynginia Gully is the type locality, although the formation is discontinuous in this area. Playford and Willmott (1958) subsequently selected an exposure along Woolaga Creek as the main reference section (MGA Zone 50, 369692 m E, 6770482 m N).

The Carynginia Formation is similar to the Holmwood Shale and consists of black, grey and brown micaceous siltstone and claystone with grey to dark brown quartz sandstone containing thin, fine conglomerate beds (Le Blanc Smith & Mory 1995; Muhling & Low 1977; Mory 1995b). Within the formation, there are common yellow patches and layers of jarositic siltstone. The sandstone is predominantly fine to medium grained, forming lenticular beds with internal cross-laminae. Portions of sandstone have been reworked by wave and storm action leaving ripple and cross-stratification structures, and the sandstone content increases in the south and east (Le Blanc Smith & Mory 1995). In the lower portion of the formation there are boulder sized erratics of granitoid, gneiss and quartzite, attributed to proglacial ice-rafting processes (Playford et al. 1976). Descriptions from petroleum wells often identify four units comprising varying portions of claystone, siltstone and sandstone, commencing with a basal siltstone and claystone with minor sandstone.

Downhole geophysical logs through the Carynginia Formation show a relatively uniform and high gamma-ray count, with minor intervals of slightly low gamma-ray count possibly related to the presence of sandstone (Figure 20 and Figure 21).

The Carynginia Formation was deposited in a cold, shallow marine environment as indicated by the trace-fossil assemblages, common bioturbation, cross-stratification, wave ripples and conglomeratic lenses (Backhouse 1993). Glacial dropstones in the lower part of the formation suggest that icebergs dropped material onto the sea floor during the early stages of deposition. The increasing frequency of spinose acritarchs through the upper part of the formation indicates that open marine conditions became more prevalent in the later phase of deposition (Backhouse 1993). Spores and pollen are common in the Carynginia Formation (Segroves 1969, 1970, 1971), and are more prevalent than foraminifera (Crespin 1958). Backhouse (1993) recognised palynofloras from the *Praecolpatites sinuosus* Zone suggesting the Carynginia Formation is at Early Permian Artinskian age (Segroves 1971; Backhouse 1993b).

Outcrops of the Carynginia Formation are present across the Irwin Terrace, with the best exposures in the Irwin River and Woolaga Creek valleys. The formation extends at depth through most of the northern Perth Basin in the subsurface. At the reference section along Woolaga Creek, the formation is 236 m thick (Le Blanc Smith & Mory 1995). The formation thickens to the south, reaching a maximum of 337 m in well Erregulla 1 (Mory 1995b).

The contact between the Carynginia Formation and the underlying Irwin River Coal Measures is transitional and conformable. The upper contact with the overlying Wagina Sandstone, Dongara Sandstone or Beekeeper Formation is an angular unconformity (Playford et al. 1976; Mory & Iasky 1996).

The Carynginia Formation is correlated with the Allanson Sandstone and lower Premier Coal Measures in the Collie Basin (Le Blanc Smith 1993), and with the Byro Group in the Carnarvon Basin (Le Blanc Smith & Mory 1995).

A unit described as the Mingenew Formation along the Urella Fault System appears to be a local sandy, fossiliferous variation of the Carynginia Formation (Playford et al. 1976; Archbold 1988).

4.9 Wagina Sandstone, Dongara Sandstone and Beekeeper Formation

The Wagina Sandstone, Dongara Sandstone and Beekeeper Formation are the uppermost Permian formations recognised within the northern Perth Basin. They represent various facies of a deltaic system (Mory & Iasky 1996; Laker 2000). There is a facies change from the fluvial and deltaic plain deposits of the Wagina Sandstone, to the bioturbated delta front marine sands of the Dongara Sandstone, and the distal deltaic marine sequence of sandstone and limestone of the Beekeeper Formation (Mory 1995b, Mory & Iasky 1996). Late Permian palynoflora suggest that they are partly equivalent where the Wagina Sandstone interfingers with the Dongara Sandstone to the west, and further interfingers with the Beekeeper Formation to the south-west (Mory & Iasky 1996).

Laker (2000) suggests that these formations are diagenetically related, and should be grouped together as the Wagina Formation with two members: the Wagina Sandstone and Dongara Sandstone. As such, the terms Wagina and Dongara used by Laker (2000) refer to different portions of the succession than those used by Mory and Iasky (1996). The Wagina Sandstone Member of Laker (2000) largely corresponds to the Beekeeper Formation of Mory and Iasky (1996). The terminology used by Mory and Iasky (1996) is followed in this publication.

Wagina Sandstone

The Wagina Sandstone was named by Clarke et al. (1951) based on a type section at Wagina Well in the south branch of the Irwin River; however, exposures near the type section are limited. Playford and Willmott (*in* McWhae et al. 1958) proposed that the main reference section for the unit is near Woolaga Creek (MGA Zone 50, 370496 m E, 6771075 m N), Red Hill to near the Darling Fault. Mory and Iasky (1996) restricted the Wagina Sandstone to outcrops along the eastern part of the Irwin Terrace and northern Allanooka High, as to exclude the Dongara Sandstone.

The Wagina Sandstone consists mainly of white to medium grey, clayey sandstone, which is predominantly fine to medium grained with medium- to coarse-grained intervals, and minor beds of siltstone, claystone and low-grade coal (Playford et al. 1976; McTavish 1964; Mory & Iasky 1996; Laker 2000). The sand is angular to subrounded, poorly to well sorted and friable, and includes pebbly sandstone and lesser conglomerate beds (McTavish 1964; Gorter et al. 1984). Upward-fining cross-bedded sequences are present in the sand (Mory & Iasky 1996; Laker 2000). The siltstone is soft to firm, off-white, light grey and greenish, and micaceous, while the claystone is off-white to dark grey to black, slightly to moderately carbonaceous (Gorter et al. 1984).

Downhole gamma-ray logs have a low gamma-ray count with some peaks associated with clay and siltstone layers (Figure 21).

The Wagina Sandstone was deposited in a foreshore or delta (proximal delta front or delta top) setting with fluvial and tidal influences (Laker 2000). The coarse-grained sands were deposited by braided streams and sheet flow (Bergmark & Evans 1987). The interbedded siltstone and coal is associated with floodplain and swamp deposits over a delta plain (Le Blanc Smith & Mory 1995; Laker 2000).

Palynofloras encountered in the Wagina Sandstone include *Dulhuntyispora parvithola*, *Camptotriletes warchianus, Microreticulatisporites bitriangulatus, Verrucosisporites* sp. cf. *V. trisecatus and Triadispora* sp. cf. *T. epigona* (Mory & Iasky 1996). These are attributed to the *Microbaculispora* sp*.* A zone, indicating that the Wagina Sandstone is Late Permian (Playford et al. 1976; Le Blanc Smith & Mory 1995), possibly of Changhsingian age. Acritarch palynoflora and plant macrofossils are also present within the Wagina Sandstone (Mory & Iasky 1996). The formation correlates with the upper part of the Sue Coal Measures in the southern Perth Basin.

Deposition of the Wagina Sandstone took place in an alluvial fan delta centred at the Darling Fault (Bergmark & Evans 1987). On the Irwin Terrace, coal-forming swamps developed on the flanks of the main fan. West of the Urella Fault, the Wagina Sandstone interfingers and grades into the Dongara Sandstone. Outcrops are present at several locations adjacent to the Darling Fault about the Lockier and Irwin rivers, and along the Greenough River at Wicherina. A thickness of 243 m is estimated on the Irwin Terrace near the Woolaga Creek (Le Blanc Smith & Mory 1995) but might be thicker where it is truncated (Muhling & Low 1977; Le Blanc Smith & Mory 1995). Upon the Irwin Terrace, the Wagina Sandstone rests upon the Carynginia Formation with a low-angle unconformity (Mory & Iasky 1996) and its upper surface is truncated and overlain by a veneer of Cenozoic sediments. It is disconformably overlain by the Kockatea Shale near the Greenough River.

Dongara Sandstone

The Dongara Sandstone is a clean, bioturbated silty sandstone underlying the Kockatea Shale (Mory & Iasky 1996). The type section is in Dongara No. 11 (MGA Zone 50, 306686 m E, 6760842 m N) at depths of between 1682 and 1713 m (Mory & Iasky 1996). The upper portion was previously referred to as the 'Basal Triassic Sandstone' by Hosemann (1971), and in the Yardarino–Dongara area was attributed to the Yardarino Sandstone Member (Playford et al. 1976) for the upper 60 m of quartz sandstone.

The Dongara Sandstone is a marine sand comprising white to grey, friable, bioturbated medium- to coarse-grained sandstone with minor pebble bands, conglomerate, carbonaceous siltstone and shale. The sand is angular to subrounded but mostly subangular, moderately to well sorted, and can contain minor pyrite. Fine-grained intervals can have silica cementation with a trace of calcareous cementation (Discovery Petroleum 1995a). The sandstone has upward-coarsening sequences (Laker 2000). The upper portion has less clay and is coarser grained, with less bioturbation (Mory & Iasky 1996), and contains a significant portion of monazite (Rasmussen et al. 1989). Thin interbeds of limestone can be present near the base of the formation and towards its southern limit (Mory & Iasky 1996), suggesting that the unit interfingers with the Beekeeper Formation to the south.

Gamma-ray logs through the Dongara Sandstone show a low gamma-ray count associated with the sand lithology, with increases in gamma-ray count across siltstone and shale intervals (Figure 20 and Figure 21). The upper sand of the Dongara Sandstone is particularly pure with a consistently low gamma-ray count, resulting in a marked contrast between this sand and the high gamma-ray count of the overlying Kockatea Shale.

The Dongara Sandstone is a proximal fan to delta front deposit laid down during deltaic propagation (Mory & Iasky 1996; Laker 2000). The fluvial beach and littoral environments of the Dongara Sandstone transition into the marginal marine and shallow marine environments of the Beekeeper Formation (Tupper et al. 1994). The Dongara Sandstone contains palynofloras from the *Dulhuntyispora parvithola*, *D. dulhuntyi* and *D. ericians* zones (Backhouse 1992b), indicating that it was deposited in the Late Permian; however, it might extend into the earliest Triassic (Playford et al. 1976; Mory 1995b).

The Dongara Sandstone is located west of the Urella Fault, between the Wagina Sandstone on the Irwin Terrace and the Beekeeper Formation over the Beagle Ridge. It reaches a maximum thickness of 336 m in petroleum well Depot Hill 1, about 9 km west of the Urella Fault and decreases towards the south-west (Mory & Iasky 1996). The formation is less than 60 m thick in the Dongara gasfield and 31 m thick in petroleum well Dongara 11. The formation disconformably overlies the Carynginia Formation and is overlain by the Kockatea Shale, although it is uncertain whether this contact is conformable or disconformable (Mory 1995b; Mory & Iasky 1996). There is a gradual and often interfingering transition to the Beekeeper Formation to the south-west (Mory & Iasky 1996), and probably a similar contact with the Wagina Sandstone to the east.

Beekeeper Formation

The Beekeeper Formation was defined by Hall and Kneale (1992). It was previously recognised informally by Lane and Watson (1985) as the Carynginia Limestone and was subsequently incorporated as part of the 'Wagina Formation' by Tupper et al. (1994). It has also been named the Wagina Sandstone Member by Laker (2000). GSWA recognise it as a separate formation, with a type section for the Beekeeper Formation given as between 2239 and 2353 m depth in petroleum well Woodada No. 1 (MGA Zone 50, 320458 m E, 6702620 m N) (Hall & Kneale 1992).

The Beekeeper Formation consists of fine- to medium-grained sandstone with upward-fining sequences (Laker 2000) or medium- to coarse-grained sandstone (Mory & Iasky 1996), with intercalated beds of limestone, calcareous sandstone and mudstone/shale. In the north, the formation mainly consists of sandstone and dark grey mudstone, but limestone is dominant in the south (Mory & Iasky 1996; Laker 2000).

Gamma-ray logs through the Beekeeper Formation have a low to very low count associated with the sand and limestone lithologies. The Beekeeper Formation is distinguished from the Dongara Sandstone by the lack of peaks, which are observed across siltstone and shale intervals in the Dongara Sandstone. There is a marked contrast between the Beekeeper Formation and the high gamma-ray count of the overlying Kockatea Shale and the underlying Carynginia Formation.

The high portion of fossiliferous carbonate and abundant acritarchs indicate that an open marine depositional environment (Mory & Iasky 1996) developed at the distal margin of the delta system towards the offshore clastic shelf and delta front (Lane & Watson 1985; Laker 2000).

The limestone contains abundant macrofauna, including bryozoans, crinoids, brachiopods, bivalves and serpulids (Mory & Iasky 1996). The presence of *Dulhuntyspora* microflora suggests a late Wuchiapingian age (formerly Kazanian age), but might extend to the early Wuchiapingian of the Late Permian (Backhouse 1994).

The Beekeeper Formation does not outcrop but is widespread in the subsurface across the north-western part of the basin. It lies mostly upon the Beharra Springs Terrace and over the Beagle Ridge and Cadda Terrace, between Dongara and Cervantes. The most northern occurrence is in the Beharra Springs gasfield, about 30 km south-east of Dongara. The formation also extends south of Jurien Bay where it was intersected in petroleum well Cadda 1, 16 km east of the township (Crostella 1995). The Beekeeper Formation is 90 m thick in the Beharra Springs gasfield, increasing to a maximum intersected thickness of 134 m in petroleum well Point Louise No. 1 (Mory & Iasky 1996), about 10 km east of Green Head. The Beekeeper Formation lies disconformably on top of the Carynginia Formation (Mory & Iasky 1996) and underlies the Kockatea Shale, probably disconformably (Mory & Iasky 1996). It is partially coeval, and interfingers with the Dongara Sandstone to the north (Mory 1995b, Mory & Iasky 1996).

4.10 Kockatea Shale

The Kockatea Shale was first introduced by Playford and Willmott (*in* McWhae et al. 1958) based on a 12.5 m thick exposure near the Greenough River and Kockatea Creek junction (MGA Zone 50, 320897 E m, 6842040 m N) (Playford et al. 1970). The unit consists of light grey and greenish grey to black, micaceous shale, with minor siltstone and sandstone (Playford et al. 1976; Mory & Iasky 1996). In outcrop, the Kockatea Shale is bleached white or pale yellow, with red, purple and brown ferruginous beds and laminae. Distinct, lenticular sandstone and conglomerate beds are present in the lower part of the formation (Hosemann 1971; Playford et al. 1976).

Two sandy members are recognised in the Kockatea Shale within the northern portion of the basin: the Bookara Sandstone and Arranoo Members (Mory 1995b). The Bookara Sandstone Member is restricted to the northern portion of the basin within the lower Kockatea Shale (Mory & Iasky 1996). The Arranoo Member is a thinly bedded sandstone and siltstone sequence with minor limestone present in the upper portion of the Kockatea Shale in the Dongara – Mount Horner area (Mory 1995b). Mory and Iasky (1996) excluded the Dongara Sandstone (also known as 'basal Triassic Sandstone'), which had been previously included as a member of the Kockatea Shale (Playford et al. 1976).

The Kockatea Shale was deposited under shallow marine conditions, as suggested by a rich and varied fossil marine flora and fauna assemblage, including bivalves, conodonts, and microplankton (Playford et al. 1976). The sandstone beds in the lower part of the formation might represent strandline accumulations or possible offshore bars (Hosemann 1971). The palynomorph assemblage in the unit ranges from the *Kraeuselisporites saeptatus* Zone (Dolby & Balme 1976) up to *Triplexisporites playfordii* Zone indicating a Scythian (Early Triassic) age (Mory & Iasky 1996).

The Kockatea Shale is readily identified in gamma-ray geophysical logs by a consistently high gamma-ray count, which contrasts with the overlying transitional Woodada Formation and the underlying Permian Dongara Sandstone or Irwin River Coal Measures (Figure 20 and Figure 21). However, the basal Bookara Sandstone Member of the Kockatea Shale has a distinctive low gamma-ray response, similar to the Dongara Sandstone (Figure 20, Figure 21 and Figure 22).

The Kockatea Shale is up to 1061 m in petroleum well Woolmulla No. 1 near Dongara. The thickness generally increases to the south, possibly reaching about 1200 m thick at petroleum well Cadda 1 near Jurien Bay (Mory 1994).

The Kockatea Shale is widespread throughout the northern Perth Basin, extending as subcrop beneath the superficial formations along the coast, from Wedge Island in the south to Leeman in the north (the southernmost recorded intersection was in Cataby Shallow CS23). It was intersected in subsurface east of the Urella Fault adjacent to the Darling Fault on the Yarra Yarra Terrace (Ellis 1983). It is also present at shallower depths over the Beagle Ridge, and the northern portion of the Perth Basin on the Greenough and Bookara Shelves. It was intersected at Bookara in Greenough Shallow bores 13, 14 and 15. The Kockatea Shale outcrops adjacent to and on top of the Northampton Inlier (Figure 18).

In the northern part of the basin, the Kockatea Shale overlies the Dongara Sandstone, possibly conformably (Mory & Iasky 1996); elsewhere, it rests unconformably on the Permian Carynginia Formation. Adjacent to the Northampton Inlier it unconformably overlies the Tumblagooda Sandstone, while west of Mount Hill it overlies Proterozoic metasediments (Mory & Iasky 1996; Playford et al. 1976). It is conformably overlain by the Woodada Formation through most of the basin; however, in the very north of the basin, it is disconformably overlain by the Cattamarra Coal Measures, Eneabba Formation or Lesueur Sandstone (Mory & Iasky 1996).

The Wittecarra Sandstone of the Carnarvon Basin possibly correlates with the Bookara Sandstone Member, or at a slightly higher level, near the base of the Kockatea Shale, north of Dongara (Hocking & Mory 2006). The Wittecarra Sandstone is disconformable on the Tumblagooda Sandstone, and consists of a basal conglomerate, overlain by silty sandstone and siltstone, sandstone, conglomerate, and capped by sandstone with probable plant rootlets.

4.11 Woodada Formation

The Woodada Formation is a Triassic sandstone and siltstone sequence (Willmott and McTavish, *in* Willmott 1964). Its type section is shown in stratigraphic well BMR 10 (MGA Zone 50, 304473 m E, 6698778 m N) between 334 m and 610 m. Willmott (1964) also provided a reference section for the Woodada Formation in petroleum well Woolmulla 1 between 1012 and 1231 m.

The Woodada Formation comprises fine-grained sandstones and interbedded siltstone. The sandstone is light grey, moderately sorted, thin-bedded and kaolinitic. The siltstones are dark grey, carbonaceous, micaceous and finely laminated. The prevalence of siltstone increases with depth as the unit grades into the underlying Kockatea Shale (Playford et al. 1976).

The Woodada Formation represents a regressive depositional phase between the marine Kockatea Shale and the continental Lesueur Sandstone (Willmott & McTavish *in* Willmott 1964). Plant microfossils suggest that the Woodada Formation is a paralic deposit (Playford et al. 1976).

Downhole gamma-ray logs are transitional between the higher gamma-ray count of the underlying Kockatea Shale and the low gamma-ray count of the overlying Lesueur Sandstone (Figure 23).

Backhouse (1992b) identified palynoflora from the *Triplexisporites playfordii* floral zone within the unit, indicating an Early to Middle Triassic age between the Olenekian and Anisian ages, which supports the previous palynological analyses by Balme (1969).

The Woodada Formation is widespread in the subsurface of the northern Perth Basin, extending from just north of Dongara to Jurien Bay (Playford et al. 1976). It thickens to the south, reaching about 230 m in the Woodada gasfield, with a maximum known thickness of 276 m at BMR 10 stratigraphic well, 13 km north of Leeman.

Over most of the northern Perth Basin, the Woodada Formation is conformably overlain by the Lesueur Sandstone and conformably overlies the Kockatea Shale (Playford et al. 1976). North of the Allanooka Fault, it is disconformably overlain by the Eneabba Formation or Cattamarra Coal Measures, whereas on the Beagle Ridge, the Woodada Formation subcrops the superficial formations in a narrow zone extending north-east of Leeman, and a small zone about 4 km east of Cervantes (Mory 1995a). The formation is disconformably overlain by the superficial formations in two bores (JB1 and JB11) near Jurien Bay (Harley 1974); although subsequent drilling indicates that these bores are more likely to have intersected Kockatea Shale and Lesueur Sandstone (Baddock & Lach 2003).

4.12 Lesueur Sandstone

The Lesueur Sandstone was named by Willmott et al. (1964) to denote a coarse-grained sandstone that outcrops at Mt Lesueur. The type section, as modified by Mory and Iasky (1996), is between 429 and 1012 m depth in petroleum well Woolmulla No. 1 (MGA Zone 50, 325726 m E, 6677130 m N), between Green Head and Eneabba.

The Lesueur Sandstone consists of pale brown to grey, fine to very coarse grained quartz sand and granules, which are poorly to moderately sorted, angular to subrounded, and cross-bedded. Intergranular, white kaolin clay is common, and is probably derived from weathered feldspar. Minor black heavy minerals, pyrite and carbonaceous material are present both as bands and scattered particles in the sandstone (Briese 1979b; Harley 1970). Minor layers of siltstone and conglomerate (Playford et al. 1976; Mory & Iasky 1996), with grey clay and thin black or grey micaceous shale become more frequent towards the base of the unit (Briese 1979; Harley 1970).

Deposition in a fluvial (Mory 1994) and possibly alluvial fan environment (Mory & Iasky 1996) is indicated by coarse-grained sediments, high-energy cross-bedding structures, and the absence of marine fossils.

Downhole gamma-ray logs typically show a low gamma-ray count for the sandstone, punctuated by discreet zones of high gamma-ray count corresponding to mudstone layers (lower 173 m of a 1202 m thickness shown in Figure 23), giving the unit a characteristic blocky gamma-ray profile (Mory & Iasky 1996). The transition to the underlying Woodada Formation is characterised by a consistently higher gamma-ray count.

In the northern Perth Basin, spores and pollen from the *Triplexisporites playfordii*, *Staurosaccites quadrifidus*, *Samaropollenites speciosus* and *Minutosaccus crenulatus–Ashmoripollis reducta* zones of Helby et al. (1987) are identified in the Lesueur Sandstone (Backhouse 1992b). These assemblages indicate an age of Anisian (Middle Triassic) to Norian (Late Triassic), and possibly Hettangian (Early Jurassic) (Mory 1994; Mory & Iasky 1996).

The Lesueur Sandstone is present over much of the Perth Basin, extending from just north of Dongara to the southern margin of the basin at the Southern Ocean, near Augusta. There is a small outcrop of Lesueur Sandstone outcrop in the Mt Lesueur area (not shown in Figure 24), west of the Lesueur Fault (Mory 1994a). It is present at shallow depth beneath the superficial formations mainly upon the Beagle Ridge between Leeman and Wedge islands (Figure 24). Eastward of the Beagle Ridge, the formation becomes progressively deeper. There is also a small area of Lesueur Sandstone mapped upon the Yarra Yarra Terrace, west of Coorow (Mory & Iasky 1996).

The Lesueur Sandstone conformably overlies the Woodada Formation and is conformably overlain by the Eneabba Formation (Mory 1994). The thickest intersection of Lesueur Sandstone was 1202 m within petroleum well Cadda 1, 17 km east of Jurien Bay, which encountered a complete section of the formation (Mory 1994). Watheroo Line WL 12 intersected 608 m of the Lesueur Sandstone 6 km east of Jurien Bay (Harley 1975), and Moora Line ML8A, 16 km south-east of Cervantes, penetrated 617 m of the formation without reaching the base (Briese 1979a). Near the northern margin of the Lesueur Sandstone near Dongara, the formation is only about 100 m thick (Mory & Iasky 1996). The formation thickens to the south and has been interpreted to be almost 3000 m thick in petroleum well Barberton 1 on the Barberton Terrace south of Moora (Mory & Iasky 1996). However, this interpretation might include Jurassic formations that could not be distinguished due to the low-grade palynology of the sediments.

4.13 Eneabba Formation

The Eneabba Formation is an Early Jurassic, multicoloured sandstone, siltstone and claystone unit. The type section is in petroleum well Eneabba 1 (MGA Zone 50, 338589 m E, 6727778 m N) between 2320 and 2978 m depth (Playford & Low 1972). The unit was informally referred to as the ‘Multicoloured Member’ of the Cockleshell Gully Formation by West Australian Petroleum Pty Ltd (WAPET) reports and was also known as the Eneabba Member of the Cockleshell Gully Formation (Playford & Low 1972). The Eneabba Member now has formational status (Mory 1994a), and the use of the name ‘Cockleshell Gully Formation’ has been discontinued (Table 9). The Greenough Sandstone of the Chapman Group described by Arkell and Playford (1954), which was intersected in the Geraldton area and onlapping the Northampton Inlier (Playford et al. 1976), has been incorporated into the Eneabba Formation. The names ‘Chapman Group’ and ‘Greenough Sandstone’ are no longer in use.

The Eneabba Formation consists of sandstone with interbedded siltstone and claystone. The sandstone is predominantly light grey to white and light green in parts. It is fine to very coarse grained, subangular to subrounded, moderately sorted and feldspathic. It is predominantly friable and weakly cemented by kaolin clay. The coarse sand grades into conglomerate in parts (Pudovskis 1962). The claystone is mottled and multicoloured red-brown, brown, yellow, pink, green, purple, grey and white with minor grey carbonaceous shale and thin coal seams.

The Eneabba Formation lies conformably between the Lesueur Sandstone and Cattamarra Coal Measures (Mory 1995). In the Geraldton area, it is locally disconformable on top of the Kockatea Shale and Proterozoic basement (Playford et al. 1976). Downhole geophysical logs show a spiky gamma-ray pattern due to more interbedded sandstone with siltstone and claystone compared to the overlying Cattamarra Coal Measures (Figure 25 and Figure 26).

Deposition was in a fluvial setting with meandering rivers (Mory 1995), while the multicoloured claystone suggest periods of exposure to oxidising conditions in a continental low-energy environment (Mory & Iasky 1996). Palynomorphs belong to the *Corollina torosa* Zone (Backhouse 1992a, 1993b), which is Early Jurassic, probably of Hettangian to Pliensbachian age. The base of the Eneabba Formation appears to be diachronous across the Triassic and Jurassic boundary south of Eneabba (Mory & Iasky 1996). The sediments frequently lack microfossils, which were presumably weathered in a continental environment (Mory & Iasky 1996). The only macrofossils are bivalves and rare fossil wood.

The Eneabba Formation is present at depth through most of the northern Perth Basin. The formation outcrops between the Lesueur and Peron faults north of Jurien Road, and west of the Lesueur Fault in the Mintaja and Eragilga Hills south of Jurien Road (Mory 1994a) and subcrops beneath the superficial formations to the north of Coolimba (Figure 18). The Eneabba Formation is absent on the Beagle Ridge south of Coolimba in the west, and on the Irwin Terrace in the east due to either erosion or a period of non-deposition during Early Jurassic (Mory & Iasky 1996).

The Eneabba Formation reaches a maximum recorded thickness of 854 m in petroleum well Donkey Creek 1.22 km north–northeast of Eneabba (Mory & Iasky 1996) and probably thickens further to the south, but has not been fully penetrated. The Eneabba Formation shallows towards the northern extent, and westward onto the Cadda Terrace, Beharra Springs Terrace and Dongara Terrace. The Eneabba Formation is present on the Yarra Yarra Terrace, where it was intersected in the Yarra Yarra Lakes monitoring bores west of Coorow and north of Lake Eganu (Yesertener 1999a). It extends as far inland as 20 km north-east of Geraldton, between the Hutt and Greenough rivers (based on previous descriptions of the ‘Greenough Sandstone’).

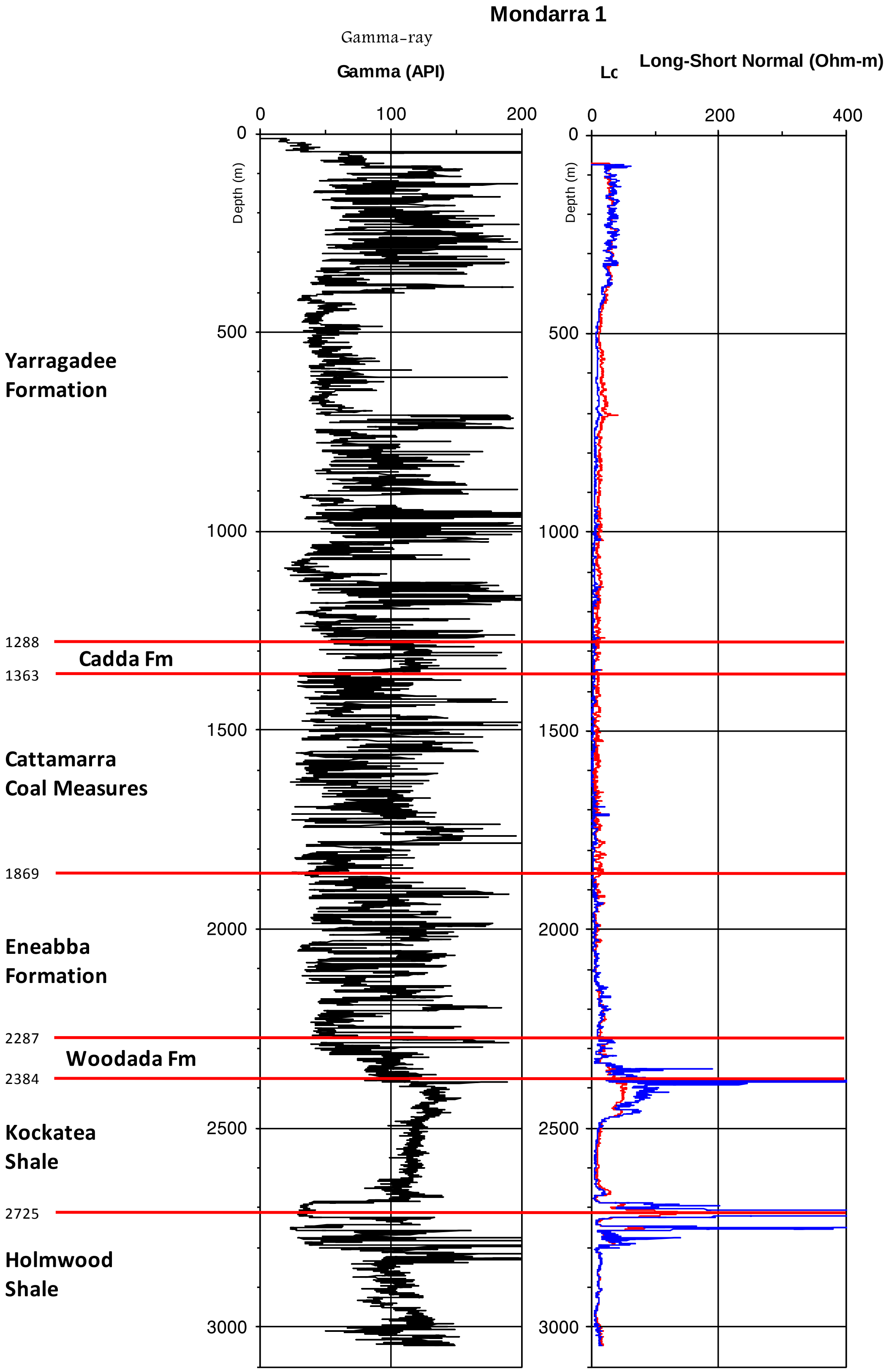


Figure 22 Downhole geophysical log from petroleum well Mondarra 1 (2384–2725 m bgl) showing the Kockatea Shale

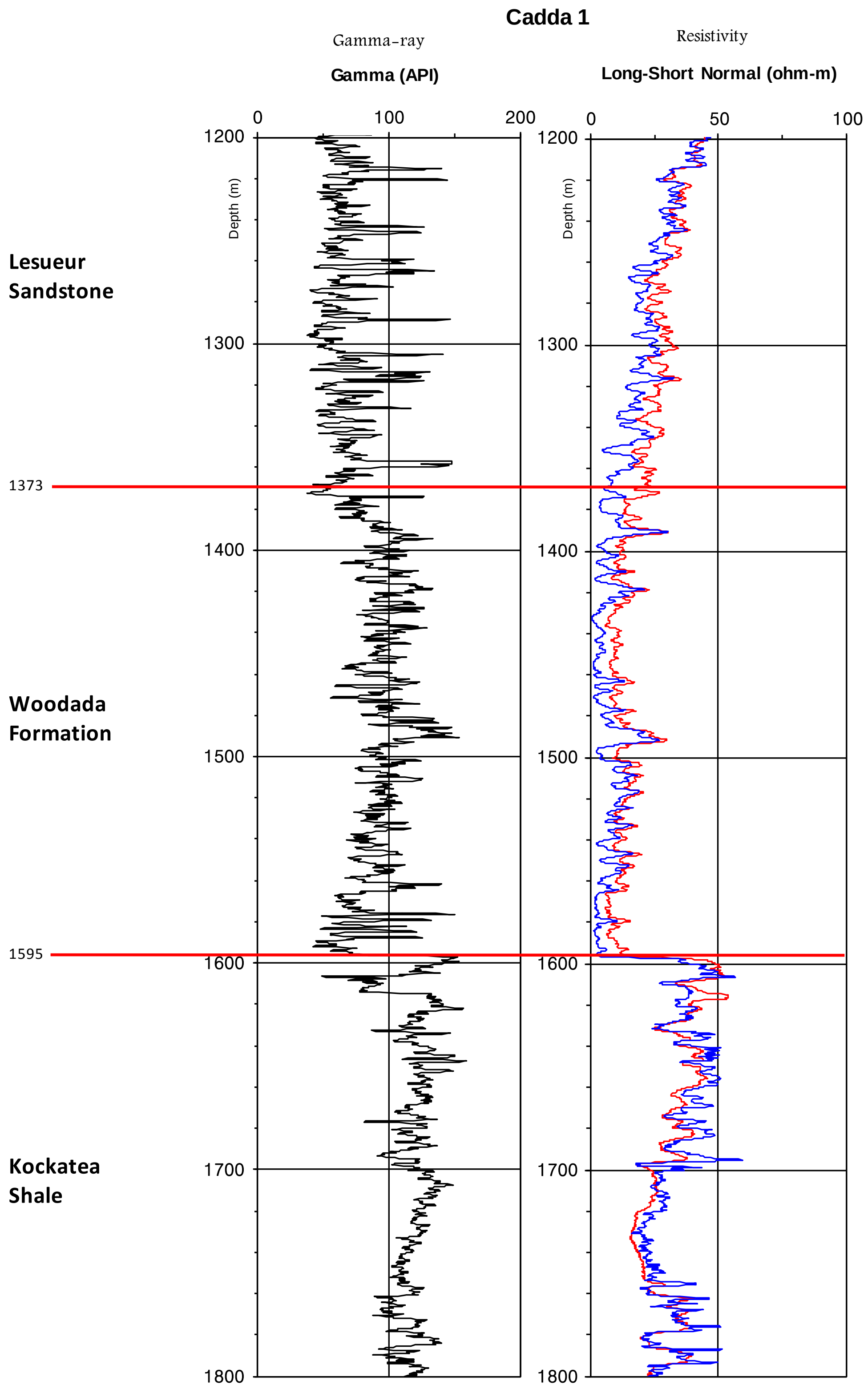


Figure 23 *Downhole geophysical log from petroleum well Cadda 1 (1200–1600 m bgl) showing the Woodada Formation*

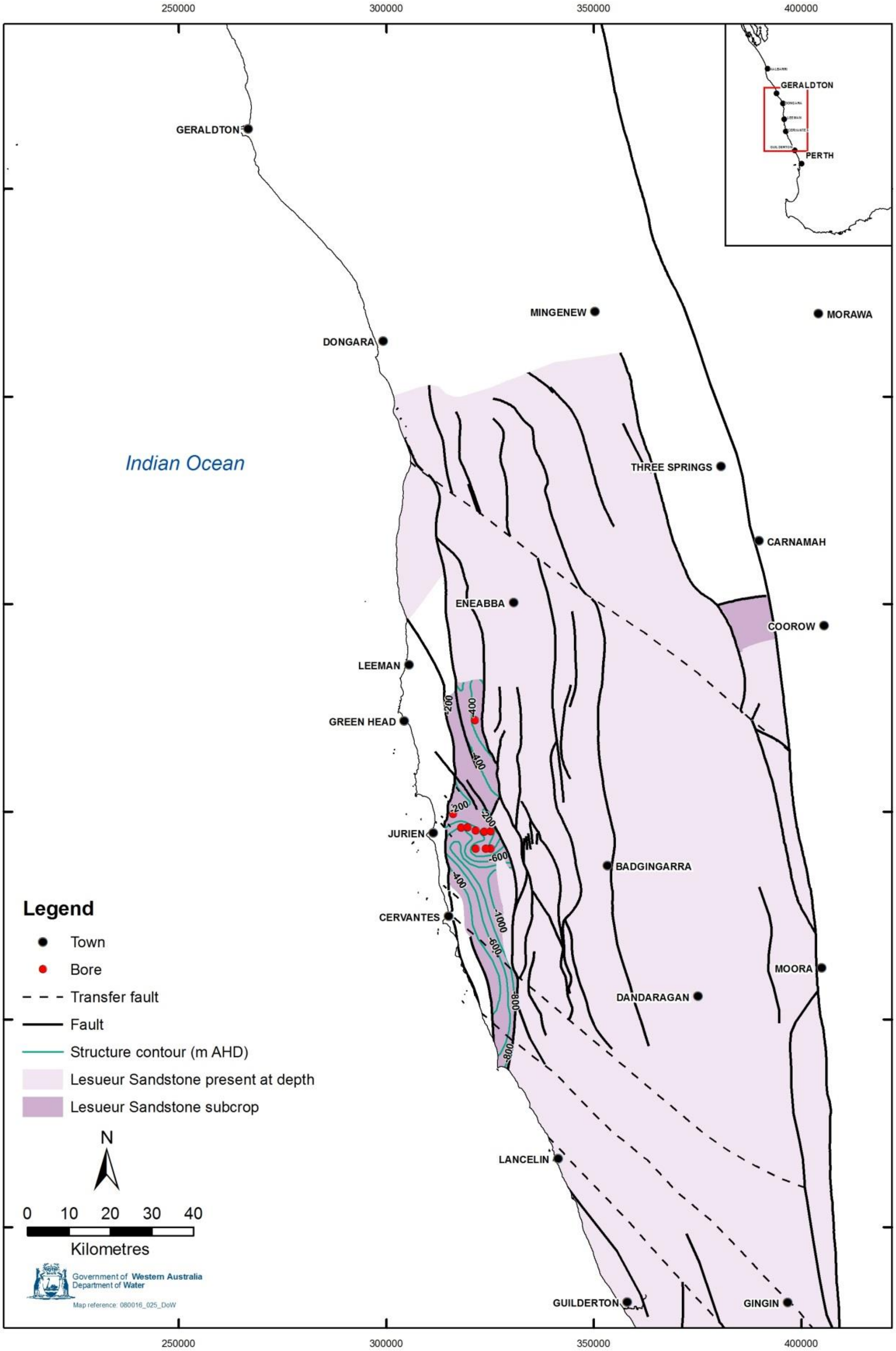


Figure 24 Lesueur Sandstone: contours on base of unit

Table 9 Nomenclature correlation for the Cadda Formation, Cattamarra Coal Measures and Eneabba Formation

<table>
<tr><th colspan="2">Overlying the Northampton Inlier</th><th colspan="2">Beagle Ridge</th><th>Dandaragan Trough</th></tr>
<tr><td colspan="2">Playford et al., 1976</td><td colspan="2">Playford et al., 1976</td><td>Mory & Iasky, 1994</td></tr>
<tr><td rowspan="4">Champion Bay Group</td><td>Kojarena Sandstone</td><td colspan="2" rowspan="4">Cadda Formation</td><td rowspan="4">Cadda Formation</td></tr>
<tr><td>Newmarracarra Limestone</td></tr>
<tr><td>Bringo Shale</td></tr>
<tr><td>Colalura Sandstone</td></tr>
<tr><td rowspan="3">Chapman Group</td><td>Moonyoonooka Sandstone</td><td rowspan="4">Cockleshell Gully Formation</td><td rowspan="2">Cattamarra Coal Measures Member</td><td rowspan="2">Cattamarra Coal Measures</td></tr>
<tr><td rowspan="2">Greenough Sandstone</td></tr>
<tr><td rowspan="2">Eneabba Member</td><td rowspan="2">Eneabba Formation</td></tr>
<tr><td colspan="2"></td></tr>
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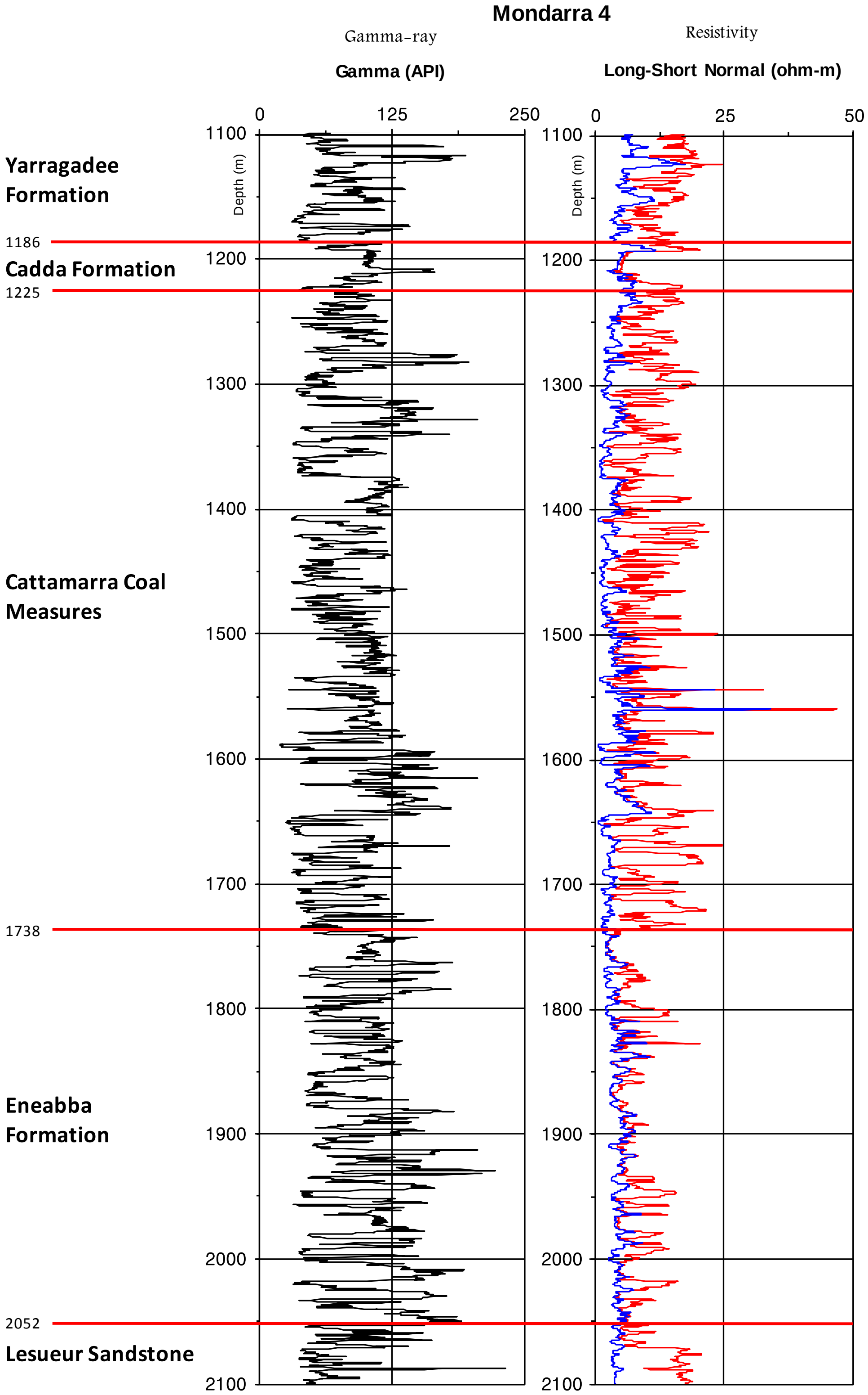


Figure 25 *Downhole geophysical log from petroleum well Mondarra 4 (1200–2200 m bgl) showing the Cattamarra Coal Measures and Eneabba Formation*

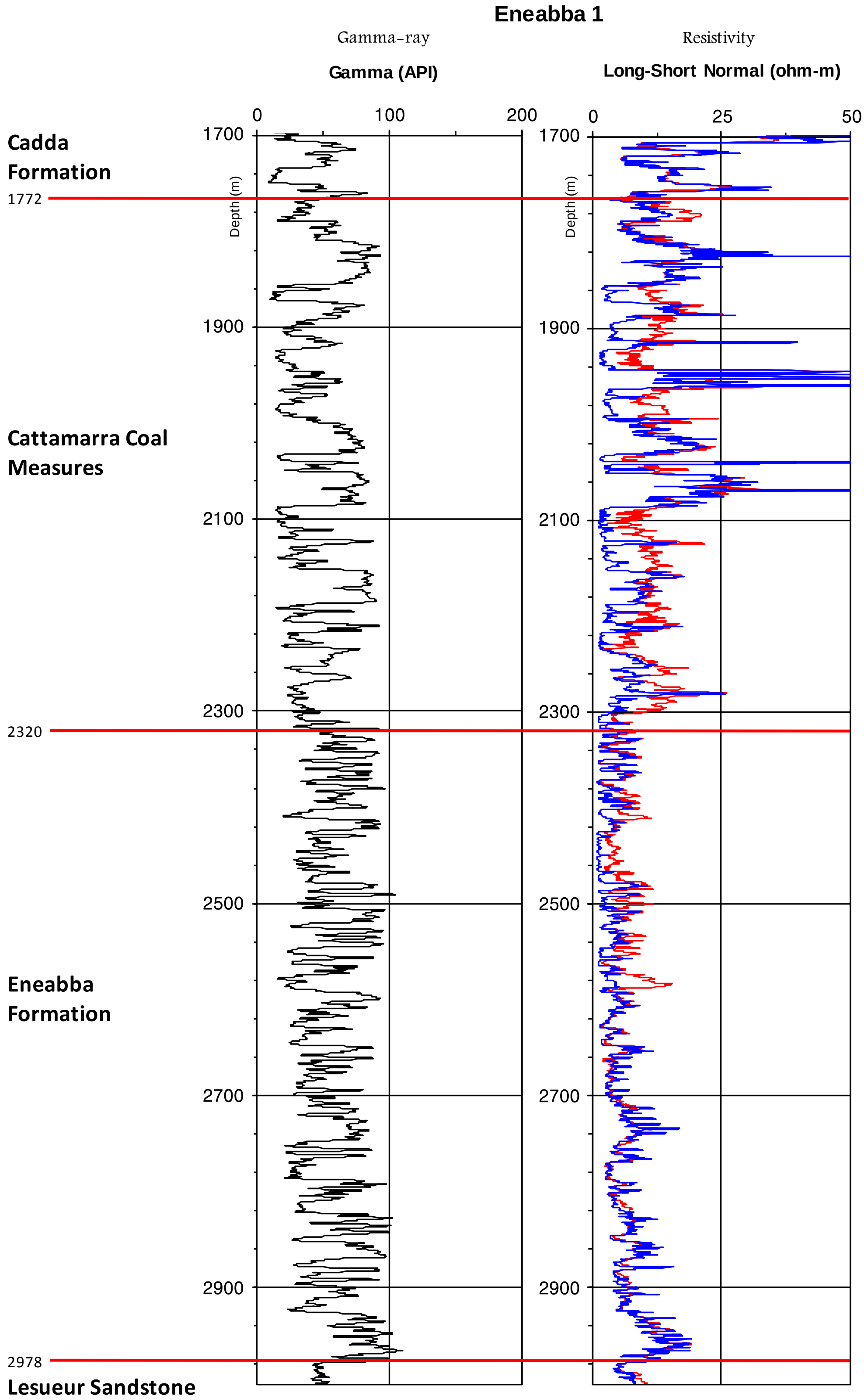


Figure 26 Downhole geophysical log from petroleum well Eneabba 1 (1700–3000 m bgl) showing the Cattamarra Coal Measures and Eneabba Formation

4.14 Cattamarra Coal Measures

The Cattamarra Coal Measures are Early Jurassic sandstones with dark carbonaceous siltstone and claystone interbeds, and coal seams. Playford and Low (1972) nominated the type section in petroleum well Eneabba 1 (MGA Zone 50, 338446 m E, 6727627 m N) from 1790 to 2302 m, and it was subsequently revised by Mory and Iasky (1996).

The Cattamarra Coal Measures were previously defined as the Cattamarra Coal Member (Willmott 1964) within the upper part of the Cockleshell Gully Formation (Table 9). The use of the name 'Cockleshell Gully Formation' was discontinued and the member reclassified as a formation (Mory 1994a). In the Geraldton area and over the Northampton Inlier, the Moonyoonooka Sandstone of the Chapman Group described by Arkell and Playford (1954) is largely equivalent to the Cattamarra Coal Measures (Playford et al. 1976). The use of the names 'Chapman Group' and 'Moonyoonooka Sandstone' is discontinued, and the Moonyoonooka Sandstone is now considered part of the Cattamarra Coal Measures. The Jurassic sediments below the Nabawa Sandplain (Koomberi 1995) are now correlated with the Cattamarra Coal Measures.

The Cattamarra Coal Measures consist of very fine to very coarse grained sandstone with thick beds of dark grey, carbonaceous siltstone, claystone, and coal seams of up to 11 m thickness (Playford et al. 1976; Mory & Iasky 1996). The sandstone is grey, very fine to very coarse grained, moderately to poorly sorted, subangular to subrounded, in parts pyritic, kaolinitic and feldspathic, and often clayey. However, in outcrop, coarse-grained sand units are interbedded with fine to very fine sandstone and siltstone, with cross-bedding (Mory 1995b). The siltstone, claystone and shale beds are medium to dark grey and brown-grey, often carbonaceous and laminated. In outcrop, the Cattamarra Coal Measures is generally weathered to a yellowish to red-brownish colour.

The Cattamarra Coal Measures lie conformably between the overlying Cadda or Yarragadee formations and underlying Eneabba Formation (Playford et al. 1976; Mory & Iasky 1996). Near the northern margins of the basin, the formation can unconformably overlie the Kockatea Shale, Woodada Formation, or Proterozoic granite and gneisses of the Northampton Inlier (Playford et al. 1970; Mory 1995b). The presence of thick, carbonaceous siltstone, claystone and shale units distinguish it from the underlying Eneabba Formation (Mory 1995; Mory & Iasky 1996) and these are evident on downhole gamma-ray logs as thick sections of high gamma count, interspersed with typically thinner intervals of low count over sandstone portions (Figure 25 and Figure 26) (Mory 1995). It can be difficult to identify the Cattamarra Coal Measures from the overlying Cadda Formation, unless the characteristic limestone of the Cadda Formation is present.

Deposition of the Cattamarra Coal Measures was in a non-marine, lacustrine deltaic to fluvial setting. The fine-grained siltstone and claystone, and coal seams, are local bay-filled deposits while the thicker sandstone beds, particularly those overlying the coal seams, are probably delta plain deposits (Mory & Iasky 1996). The depositional setting progressed from a near-source braided river to an estuarine/lacustrine meandering river from the south-east to north-west (Tarabbia 1991). Microplankton within the upper portion suggests some marine influences in the northern part of the basin (Young et al. 1974).

Palynomorph assemblages belong to the upper *Corollina torosa* and lower *Callialasporites turbatus* zones (Mory & Iasky 1996). They may also extend into the *Dictyophyllidites harrisii* miospore assemblage subzone or the lower *Dictyotosporites complex* miospore zone identified in Gillingarra Line GL8 (Moncrieff 1989). These assemblages suggest a Pliensbachian to Aalenian age (Early to Middle Jurassic) (Mory & Iasky 1996), possibly extending into the Bajocian. Fossil wood, leaves and rare bivalves, branchiopods and insects are present. Bioturbation of beds is also common (Mory 1994a).

The Cattamarra Coal Measures are widespread in the subsurface through most of the northern Perth Basin, extending offshore into the Vlaming and Abrolhos sub-basins (Crostella 2001). The formation outcrops on the Cadda Terrace and Greenough Shelf, and onlaps the Northampton Inlier where it was formerly known as the Chapman Group. The main exposures are near Geraldton (Allen 1980), on the Nabawa Sandplain (Koomberi 1995), at Mount Hill (Mory & Iasky 1996; Lowry 1974) and in the Hill River area (Playford et al. 1976). Outcrops are also at the southern onshore end of the Gascoyne Platform of the Carnarvon Basin. The formation subcrops the superficial formations between Cliff Head and Eneabba, and from Mt Hill to the Oakajee River, north of Geraldton (Figure 18). The formation is absent over the Irwin Terrace (including the Mullingarra Inlier) and Coolcalalaya Terrace in the east, and upon the Beagle Ridge south of about Coolimba in the west, where the formation was either not deposited or has been fully eroded.

Based on seismic and gravity data, the depth to the top of the Cattamarra Coal Measures reaches a maximum of 5600 m within the eastern Dandaragan Trough north-west of Moora and shallows to the west and in the more northern parts of the basin (Mory & Iasky 1996). The thickest sections of the Cattamarra Coal Measures are in the south, reaching almost 1200 m in petroleum well Cataby 1, although Mory and Iasky (1996) suggest it may be up to 1500 m thick at this location. The formation becomes thinner to the north and west, to be less than 200 m thick near Geraldton and about 35 m thick east of Geraldton (Mory 1995b; Mory & Iasky 1996).

4.15 Cadda Formation

The Cadda Formation, named by Playford and Willmott (1958) is a Middle Jurassic marine sequence of siltstone, sandstone, shale, claystone and fossiliferous limestone. The Champion Bay Group, described by Arkell and Playford (1954), present about the northern margin of the Perth Basin, and is considered as part of the Cadda Formation in this bulletin (Table 9). It is located 0.4 km west of Cadda Spring (MGA Zone 50, 333630 m E, 6635140 m N).

The Cadda Formation consists of sandstone, siltstone and shale, grading in places into sandy shelly limestone. The sandstone is white, pale grey and green-grey, fine to coarse grained, and contains some kaolin matrix. Interbeds of very fine to medium grained and moderately well-cemented sandstone are common. Sandstone in the middle to lower portion of the formation is fine to medium grained, friable to hard and contains glauconite with minor siliceous and calcite cementation. The siltstone is medium to dark grey, with some thin beds of very fine to fine-grained, white to green–grey micaceous sandstone. Minor coal and claystone is present within the upper part, while claystone, shale and siltstone are more abundant within the middle and lower parts of the formation. The claystone and shale is brown-grey and the lower part probably correlates to the Bringo Shale of the Champion Bay Group. Limestone beds are sometimes present in the upper part of the claystone and shale portion of the formation, and occasionally grade into calcareous sandstone (Playford et al. 1976; Mory & Iasky 1996). The limestone beds are yellow-brown and grey, firm to hard, and richly fossiliferous containing predominantly small bivalves (especially oysters) and some ammonites (Arkell & Playford 1954; Playford et al. 1976). The limestone becomes more conspicuous to the north, closer to the Northampton Inlier. In outcrop, the limestone is ferruginised and leached of carbonate with moulds of small molluscs. Fossiliferous beds are equivalent to the Newmarracarra Limestone within the Champion Bay Group (Arkell & Playford 1954).

The Cadda Formation lies conformably between the Cattamarra Coal Measures and the Yarragadee Formation (Playford et al. 1976). However, in the northern parts of the basin where the Cattamarra Coal Measures and Eneabba Formation are absent, the Cadda Formation disconformably overlies Kockatea Shale or Proterozoic basement. Downhole geophysical logs typically show a high gamma-ray count, distinguishing it from the overlying Yarragadee Formation (Figure 27). The gamma-ray count is often higher compared to shale of the underlying Cattamarra Coal Measures, due to the presence of glauconite (Mory & Iasky 1996), but resolving the contact with the Cattamarra Coal Measures is often difficult without palynological data.

The Cadda Formation was deposited in a marine to marginal marine setting (Playford et al. 1976). The sequence initially represents a marine transgression, progressing into an open shallow sea setting, and then prograding back to marginal marine conditions at the top of the sequence. Playford et al. (1976) described a similar succession of marine environments for the Champion Bay Group in the southern Carnarvon Basin where the basal Colalura Sandstone represents shallow-water deposits at the start of the marine transgression, followed by the Bringo Shale and Newmarracarra Limestone that were laid in a shallow sea environment with restricted circulation, and finally the top Kojarena Sandstone that was deposited in a shallow water to marginal marine environment.

Spores and pollen from the Cadda Formation belong to the *Dictyotosporites complex* and upper *Callialasporites turbatus* zones, and dinoflagellates are of the *Dissiliodinium caddaensis* Zone (Backhouse 1992a). Macrofossils and microfossils suggest Middle Jurassic, of Aalenian to Bajocian age (Playford et al. 1976; Backhouse 1992a).

The Cadda Formation is extensively distributed throughout the northern Perth Basin. The Cadda Formation outcrops upon the Cadda Terrace in the Gairdner Range near the Hill River and towards Eneabba. It also outcrops where it onlaps the Northampton Inlier and along the Greenough River as far east as the Urella Fault. There are minor outcrops at Enanty Hill near Mingenew and Mount Hill on the Greenough Shelf.

The formation has been encountered at depth on the Barberton Terrace in the Gillingarra Line GL8 (Moncrieff 1989) and extends into the Beermullah Trough (Crostella & Backhouse 2000). The Cadda Formation is absent on the Beagle Ridge south of Cliff Head, and over the Irwin and Coolcalalaya terraces.

The depositional centre of the Cadda Formation is in the central part of the onshore northern Perth Basin to the south of Eneabba (Mory & Iasky 1996). There is considerable uncertainty about the thickness of the Cadda Formation because the contact with the underlying Cattamarra Coal Measures is difficult to identify. Many reported intersections are likely to be overestimated. The maximum reported thickness is 290 m in petroleum well Mullering 1 and 288 m in petroleum well Ocean Hill 1 (Mory & Iasky 1996). The formation thins to less than 50 m north of Dongara (Mory & Iasky 1996).

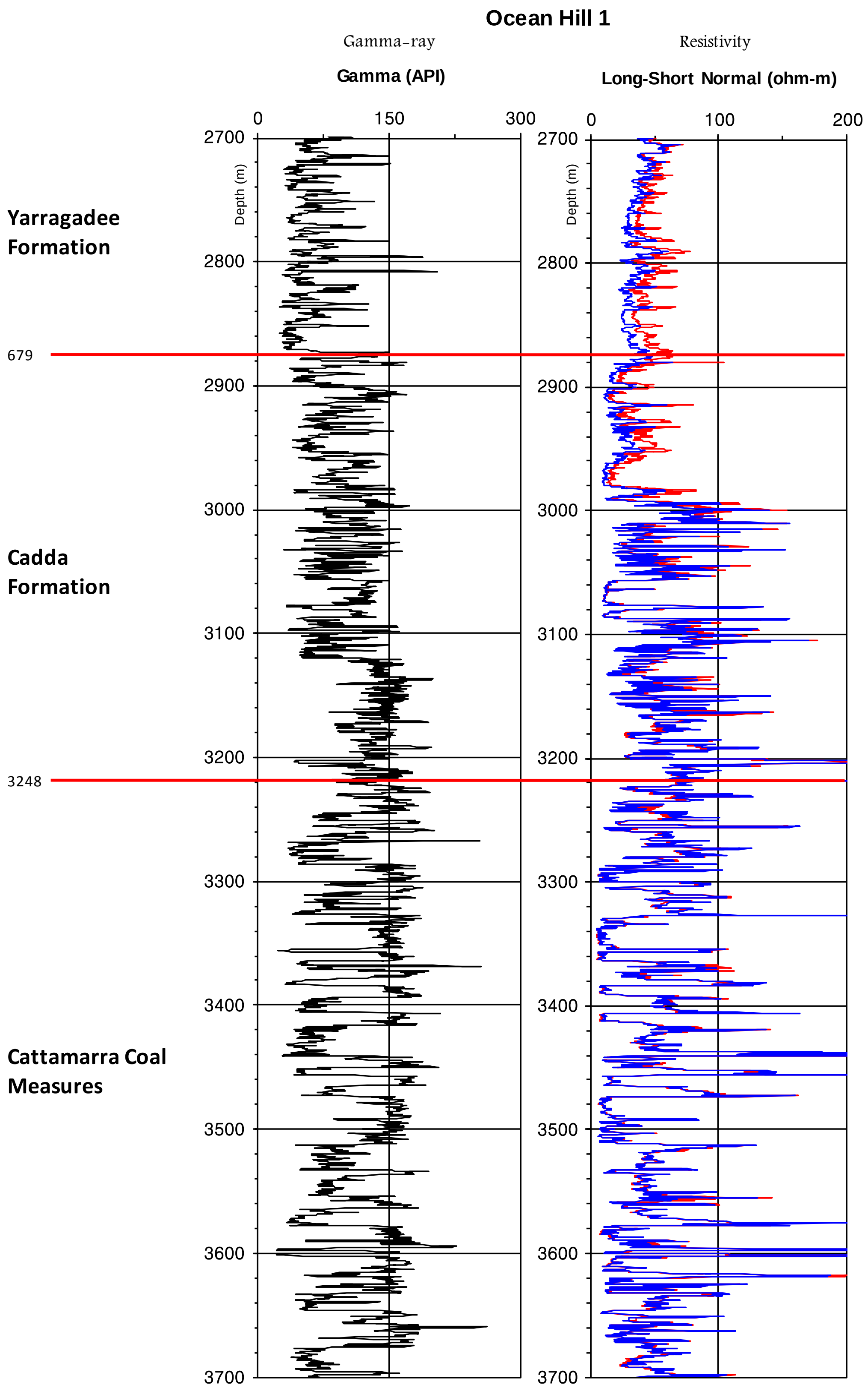


Figure 27 Downhole geophysical log of petroleum well Ocean Hill 1 (2700–3700 m bgl) showing the Cadda Formation

4.16 Yarragadee Formation

The Yarragadee Formation is a Middle to Late Jurassic, predominantly sand unit, which consists of interbedded sandstone, siltstone, shale and claystone beds with minor conglomerate. Sediments were deposited in a non-marine fluvial environment, with shale sections possibly representing a lacustrine or overbank setting (Mory & Iasky 1996). Facies analysis of petroleum well Gingin 1 near Gingin indicates that the Yarragadee sediments were deposited in a perennial braided river system with a high sediment load similar to the modern Brahmaputra River of Pakistan (McArthur 2009).

The name ‘Yarragadee Beds’ was introduced by Fairbridge (1953) for exposures of sandstone and siltstone on Yarragadee property, 12 km north of Mingenew. It was amended to Yarragadee Formation by Playford, Willmott and McKellar (*in* McWhae et al. 1958), and redefined by Backhouse (1984) to exclude the Parmelia Formation. A subsurface reference section was given in Gingin No. 1 well as 356–3315 m (Playford et al. 1976; amended Backhouse 1984). Previously, the portion below the Otorowiri Formation of the Yarragadee Formation was referred to as the Lower Yarragadee Formation (Commander 1978a, 1978b).

Sandstone beds in the Yarragadee Formation are typically thick and cross-bedded with thin lenticular clays and shale. Individual sand beds are typically discontinuous, and range in thickness to over 40 m (Nidagal 1995), but average about 10 m thick in the Allanooka area (Allen 1980). The sandstone beds consist of pale brown, pale grey to grey, very fine to very coarse grained and granular sand, variably feldspathic quartz sand, which is poorly to moderately sorted, angular to subrounded, and typically weakly cemented. It is often kaolinitic, particularly near the surface in outcrop areas (Irwin 2007). Lower portions of the formation contain minor mica, pyrite, garnet and heavy minerals, with garnet comprising up to 5 per cent in some beds (Moncrieff 1989). Thin layers of pyrite-cemented sandstone and thin laminae of coal are common.

The siltstone and shale beds are of similar thickness to the sandstone beds, usually laminated, and commonly sandy, pyritic and micaceous (Allen 1981). The siltstones are light to dark brown, grey and rarely green in colour. The shale beds are dark grey to black and carbonaceous, with thin coal beds of less than one metre thickness (Harley 1974).

In outcrop, the Yarragadee Formation is typically oxidised to considerable depths. Oxidation was observed as deep as 400 m below the surface along the Watheroo Line, between 100 and 200 m along the Eneabba and Dongara lines (Commander 1981; Irwin 2007), and to some distance below the watertable in the Allanooka area (Allen 1980). In the oxidised zone, the formation is white, cream, red or yellow-brown in colour. Feldspar within the weathered zone is altered to kaolin clay, pyrite is oxidised to ferruginous layers or nodules, and a laterite profile is often developed at the surface (Allen 1980).

The Yarragadee Formation is between 2000 m and 3700 m thick between Gingin and Mingenew except along the eastern margin of the basin, with the greatest thickness north-west of Moora where a maximum of 3693 m was intersected in petroleum well Warro 2. The Yarragadee Formation thins considerably to the west onto the Beagle Ridge, and north towards the Allanooka High. The Yarragadee Formation is absent north of the Greenough River.

Palynological assemblages within the Yarragadee Formation range from the miospore zonations *Dictyotosporites complex* Zone up to the *Aequitriradites acusus* miospore zone as defined by Backhouse (1988). These indicate a non-marine environment and a late Bajocian to Tithonian age. Sandy lithologies retain sparse palynological assemblages or are barren, but may contain wood fragments.

Several units are identifiable within the Yarragadee Formation based on lithology and palynology, and can be mapped throughout the northern Perth Basin. Craig (1990) recognised alternating fluvial and lacustrine sequences in petroleum wells Warro 1 and 2 that allowed its subdivision into units. Pennington Scott (2010) defined and informally referred to them as units A, B, C and D, in order of oldest to youngest. This classification has been adopted in this publication.

Units A and C contain predominantly sandstone sequences and are predominantly fluvial deposits. Unit A contains about 30 per cent siltstone and shale beds, but these are only minor in Unit C. Unit B contains 60–70 per cent siltstone and shale and are interpreted as lacustrine deposits. Unit D comprises up to 80 per cent fine-grained sediments that probably represent lacustrine deposits.

Representative downhole geophysical logs of the Yarragadee Formation from petroleum wells Warro 1 and Ocean Hill 1 are presented in Figure 28 and Figure 29 showing each of the units. High gamma-ray count associated with units B and D reflects the dominant clay lithology, and lower gamma-ray count against the A and C units suggests a sandier lithology. In general, the gamma-ray count in the Yarragadee Formation is lower than in the underlying Cadda Formation and Cattamarra Coal Measures where the gamma-ray count is more likely in the order of 100–150 API. However, the gamma-ray signature in the Gage Sandstone is often difficult to distinguish from the signature in the Yarragadee Formation because the Gage Sandstone represents an erosional surface of the Yarragadee Formation. Resistivity logs in the Yarragadee Formation are affected by the groundwater quality and is generally high, 50–100 Ωm, at the top of the formation where groundwater is generally fresh. However, the resistivity diminishes with depth while the salinity increases with depth and is it generally lowest in clayey strata.

The Yarragadee Formation is distributed throughout most of the northern Perth Basin (Figure 30, Figure 31, Figure 32 and Figure 33). The structural base elevation for the formation is equivalent to the base of Yarragadee Formation Unit A except in the northernmost parts of the Bookara Shelf where Unit A is likely absent and the base of Unit B forms the base of the Yarragadee Formation (Schafer 2016). The formation extends to about -4700 m AHD at its deepest within the eastern portion of the Dandaragan Trough, based on petroleum wells Warro 1 and 2 that fully penetrated the formation, as well as seismic interpretations and gravity data from Mory and Iasky (1996). The base of the formation rises to the west and north, reaching over 100 m AHD at its northern margin on the Wicherina Terrace, Bookara Shelf and Greenough Shelf. It is absent within the Beagle and Irwin terraces.

The Yarragadee Formation lies conformably upon the underlying Cadda Formation or Cattamarra Coal Measures, and is conformably overlain by the Otorowiri Formation of the Parmelia Group within the eastern Dandaragan Trough. It is unconformably overlain by the Warnbro Group in the south-west, by the superficial formations on the coastal plain north of

Eneabba, and in a small area in the south near Cataby. East of the Gingin Scarp, the Yarragadee Formation is exposed at the surface over the Arrowsmith region and Victoria Plateau, typically with a thin surficial cover and weathered profile. Upon the Cadda Terrace, the Yarragadee Formation abuts the Cattamarra Coal Measures along faulted contacts in the western portion of the terrace. Along the eastern boundary, the Yarragadee Formation abuts Archean crystalline rocks of the Yilgarn Craton at the Darling Fault, or Permian formations at the Urella Fault.

Unit A

Unit A of the Yarragadee Formation forms the basal portion of the formation. The reference section is between 3354 and 4331 m depth in petroleum well Warro 1 (MGA Zone 50, 378470 m E, 6662018 m N). Unit A comprises mainly medium- to coarse-grained, poorly to moderately sorted sandstone (about 70%), with beds of coarse to very coarse sandstones and very fine to fine sandstones. Unit A has moderate siliceous cementation and a kaolin matrix is common, although the clay is often not apparent in mud rotary drill samples. Some carbonate cementation is recorded toward the base (Young et al. 1978). Fine-grained sandstone beds are light grey, silty, kaolinitic, micaceous, friable, and often interlaminated with siltstone. The feldspar content of the sandstone is typically 20–25 per cent, but can reach 40 per cent of fresh and kaolinised feldspar over intervals (Pudovskis 1962). Unit A contains beds of siltstone and shale/claystone, up to about 20 m thick, which are light to dark grey-brown and grey-black, firm, silty, micaceous and carbonaceous. Unit A also contains occasional thin beds and laminations of very fine, silty sandstone.

Unit A is a fluvial deposit with sandstones forming stacked upward-fining sequences associated with channel deposits; and the siltstone and clay/shale intervals reflect overbank deposits. Palynological assemblages within Unit A belong to the *Dictyotosporites complex* Zone of Bajocian age.

The average thickness of Unit A intersected by fully penetrating drill holes is 387 m, with a maximum of 1095 m in petroleum well Gingin 1. Palynology data indicates that Yarragadee Unit A is either absent or very thin north of the Bookara Fault (Schafer 2016). The base elevation for Unit A, which forms the base of the Yarragadee Formation, is shown in Figure 30.

Downhole gamma-ray logs for Unit A have a diffused low gamma-ray count centred on 50 API, with interspersed peaks associated with shale/claystone horizons up to 150 API (Figure 28 and Figure 29). The high resistivity in Unit A in petroleum well Warro 1 between 3800 and 4300 m bgl is due to entrapped natural gas.

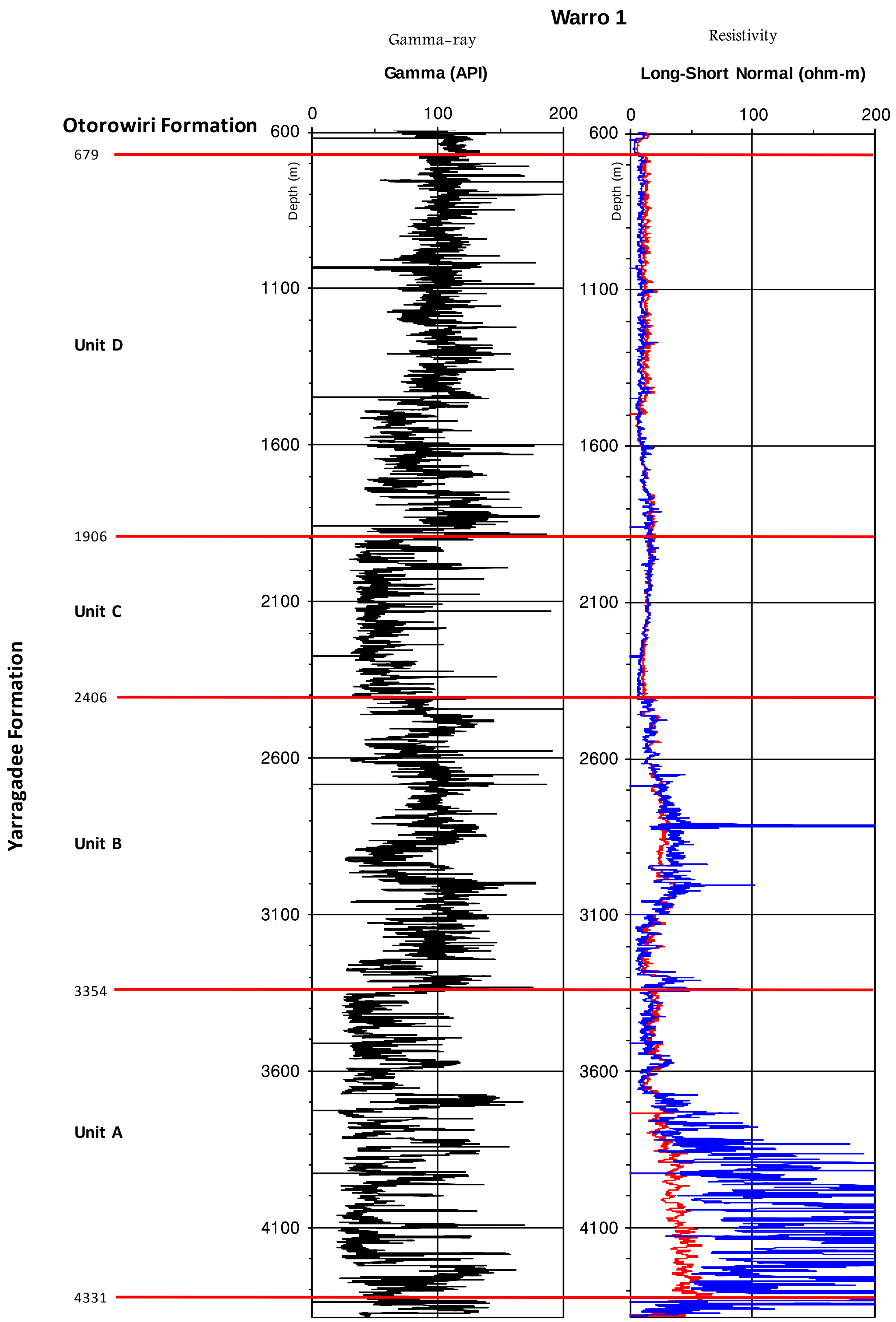


Figure 28 *Downhole geophysical log of petroleum well Warro 1 (600–4385 m bgl) showing the Yarragadee Formation*

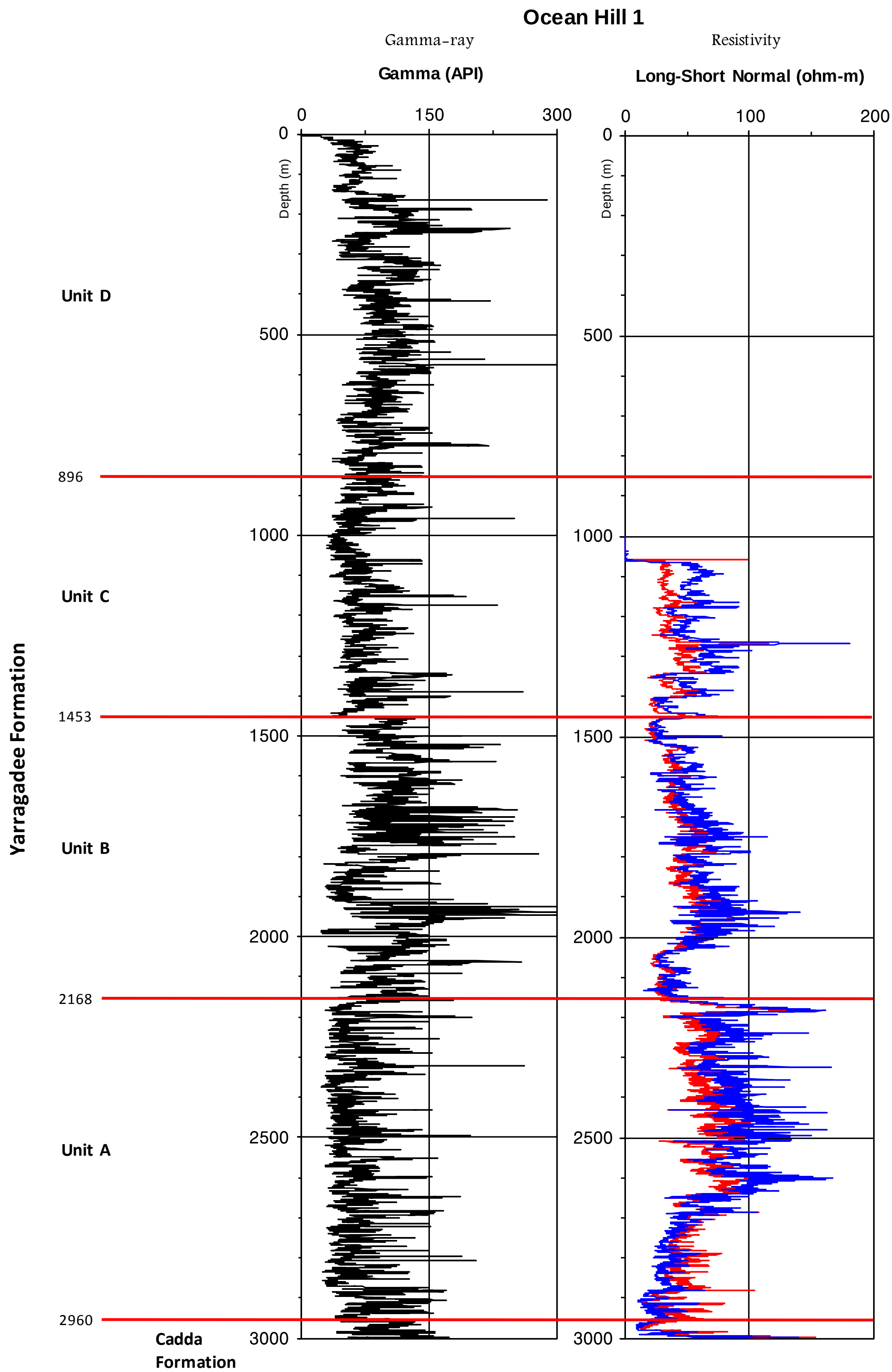


Figure 29 *Downhole geophysical log of petroleum well Ocean Hill 1 (0–3000 m bgl) showing the Yarragadee Formation*

Unit B

Unit B of the Yarragadee Formation, which overlies Unit A, is an argillaceous sequence containing about 60–70 per cent siltstone and shale/claystone layers. The reference section is within petroleum well Warro 1 between 2406 and 3354 m (MGA Zone 50, 378470 m E, 6662018 m N).

The siltstone in Unit B is grey with thin laminations of very fine, well-cemented, argillaceous sandstone (Johnson 1965) grading to claystone and shale that is dark brown-grey, micaceous, carbonaceous and pyritic that are up to about 20 m thick. The sandstone in Unit B is similar to that in units A and C; poorly to moderately sorted, angular to subangular, feldspathic with moderate development of siliceous cement. Kaolin clay is common, and is more abundant in the lower part of the unit. The sandstone also has coal laminae. A thicker sandstone interval is present within the central portion of the unit and is typically 100–200 m thick. This sandstone interval has been encountered in many petroleum wells in the central to southern Dandaragan Trough.

Unit B was deposited in lacustrine environments, with periods of deltaic and fluvial influence. Palynological assemblages within Unit B are from the *Contignisporites cooksoniae* miospore zone, indicating a Bathonian to early Callovian age.

Downhole gamma-ray logs show higher count over intervals dominated by shale and claystone with intermediate levels possibly representing siltstone and clayey sandstone (Figure 28 and Figure 29). There are also sections of low gamma-ray count associated with sand-dominated intervals that can contain substantial silt and kaolin clay. Overall, the gamma-ray signature in Unit B is tighter than in Unit A (below) and Unit C (above), and is centred on 100 API.

An average thickness of 350 m has been intersected by fully penetrating drill holes. The maximum thickness of 967 m was intersected in petroleum well Warro 2. Figure 31 shows the basal elevation for Unit B, which at its deepest reaches about –3700 m AHD at the eastern margin of the Dandaragan Trough, rising to the west. Recent investigations show Unit B is present north of the Bookara Fault, directly overlying the Cadda Formation, as Unit A is absent or very thin (Schafer 2016).

Unit C

Unit C is a distinctive, thick sandstone sequence that overlies the shale and claystone of Unit B. Unit C comprises about 80 per cent sand. The reference section is within petroleum well Warro 1 between 1906 and 2406 m depth below ground (MGA Zone 50, 378470 m E, 6662018 m N).

The sandstone is a light brown to light grey, medium to very coarse grained quartz sand with fine-grained intervals, with some gravel and pebbles and minor feldspar. It is poorly to well sorted (but mainly moderately sorted), subangular to subrounded, and mostly unconsolidated. There is minor kaolin clay in the matrix, minor siliceous cementation, and rare thin beds of grey to brown-grey, micaceous, slightly carbonaceous siltstone and black coal.

Unit C was deposited in a fluvial and alluvial setting during a tectonically active period accompanied by a large influx of sand (Craig 1990). The palynology belongs to the *Murospora florida* Zone, and ranges from Callovian to Kimmeridgian in age.

Downhole gamma-ray logs have a characteristic low count over the sequence, centred on 50 API, containing minor peaks corresponding to clay and siltstone intervals (Figure 28 and Figure 29). There is typically an abrupt contact with higher gamma-ray count of units B and D.

Unit C has an average thickness of 350 m and a maximum of 719 m (petroleum well Gingin 1). The deepest portion is about –2700 m AHD in the eastern Dandaragan Trough, shallowing to the west (Figure 32). Unit C is absent on the Cadda Terrace where this part of the Yarragadee Formation has been eroded (Schafer 2016).

Unit D

Unit D is a sequence of interbedded sandstone, claystone and siltstone overlying Unit C. The reference section is in petroleum well Warro 1 between 679 and 1906 m depth (MGA Zone 50, 378470 m E, 6662018 m N).

The sandstone within the upper portion of Unit D is white to light grey and pale greenish grey, silty to fine grained, friable to hard, silty in part, with a kaolin clay matrix. It is variably calcareous, rarely grading into light brown sandy limestone with occasional beds of loose, coarse to very coarse quartz sand.

Deeper in the unit, the sandstone is fine to very coarse grained, moderately to poorly sorted, subangular to subrounded, with some siliceous cement. Intervals of silty, fine-grained sand similar to the upper sandstone are also present. There is minor brown to black coal, and occasionally pyrite. Much of the deeper sandstone contains a portion of silt and kaolin clay that is not always apparent in mud rotary drill samples.

Interbedded siltstones are light to dark brown-grey, grading to dark brown-grey claystone that is soft to firm. Siltstone and claystone are dominant within the upper part of Unit D as far north as the Eneabba Line. The lower 150 m of Unit D south of petroleum well Yallalie 1 is mainly siltstone.

Unit D is a lacustrine deposit with fluvial interruptions. Palynological assemblages belong to the miospore zone *Retitriletes watherooensis* and the Tithonian age *Aequitriradites acusus* Zone. Downhole gamma-ray logs have a tight signature centred on 100 API and contrast with more diffused and lower gamma-ray counts in units A and C.

The full sequence of Unit D has been intersected beneath the Dandaragan Plateau with an average thickness of 930 m and a maximum of 1743 m in petroleum well Yallalie 1. Unit D has a maximum depth of about –2200 m AHD at the eastern margin of the Dandaragan Trough (Figure 33). The unit shallows to the west and extends into the Coomallo Trough and Allanooka High. Unit D is absent over the western onshore portion of the basin, where it has probably been fully eroded by the breakup unconformity.

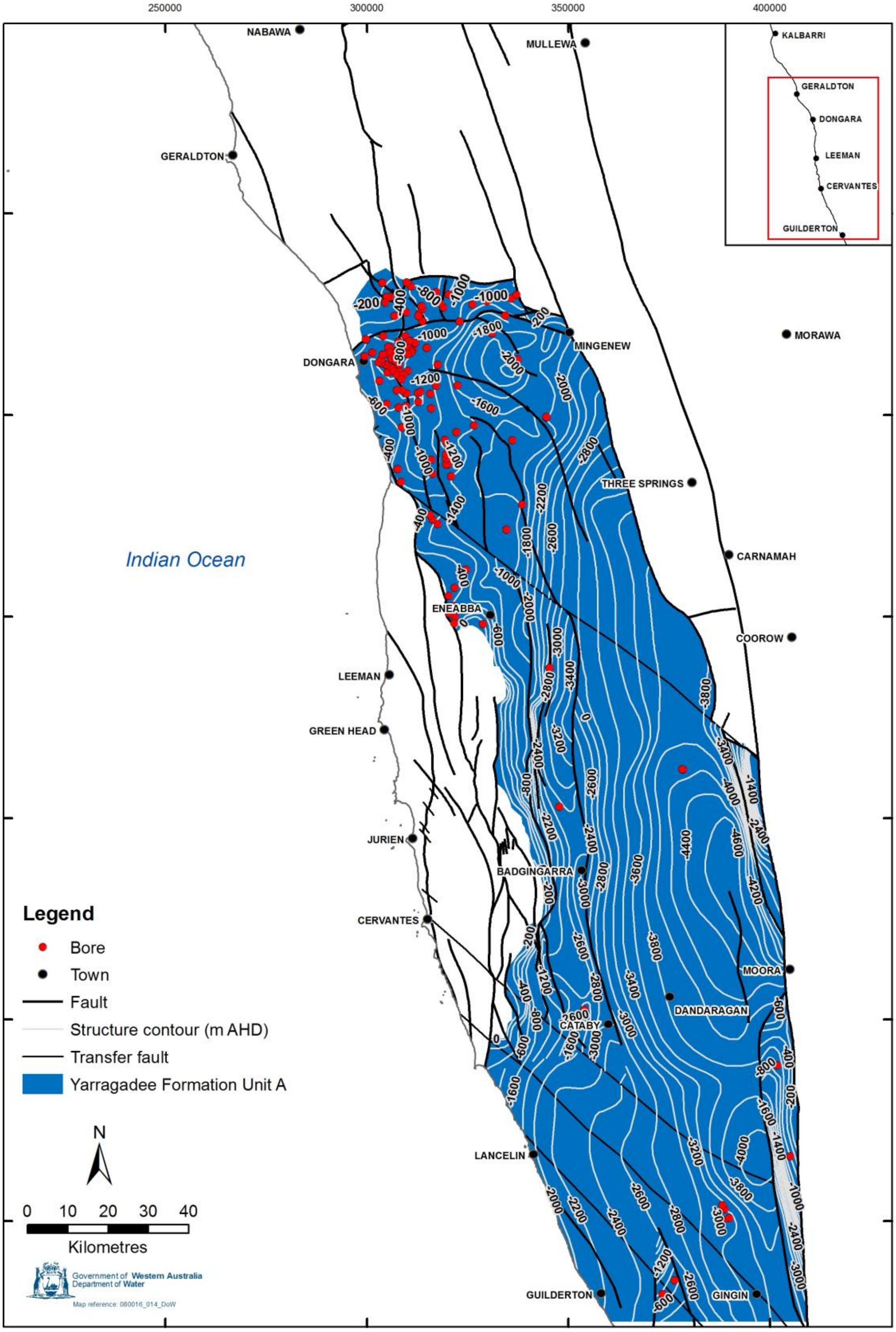


Figure 30 Yarragadee Formation Unit A: contours on base of unit

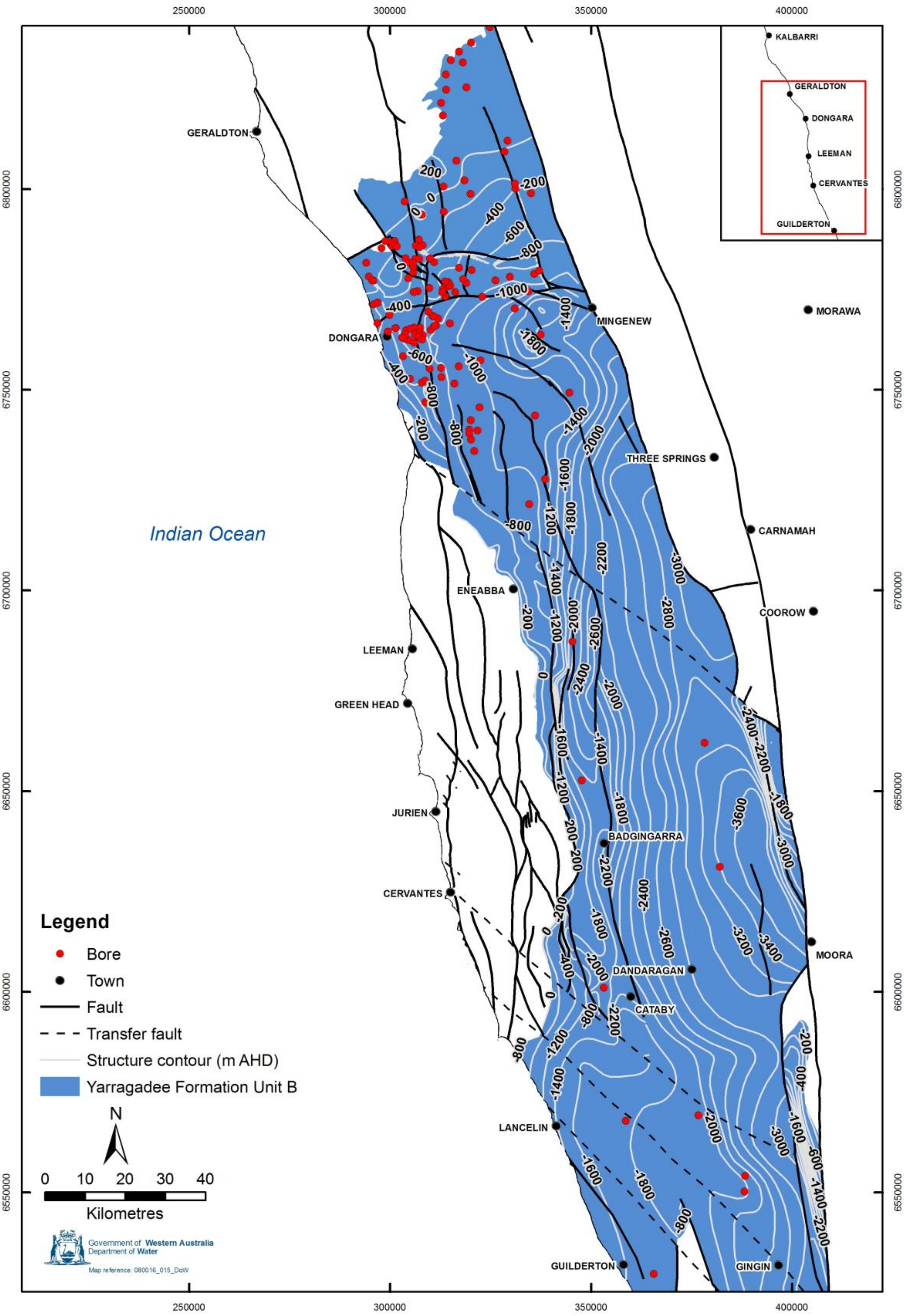


Figure 31 Yarragadee Formation Unit B: contours on base of unit

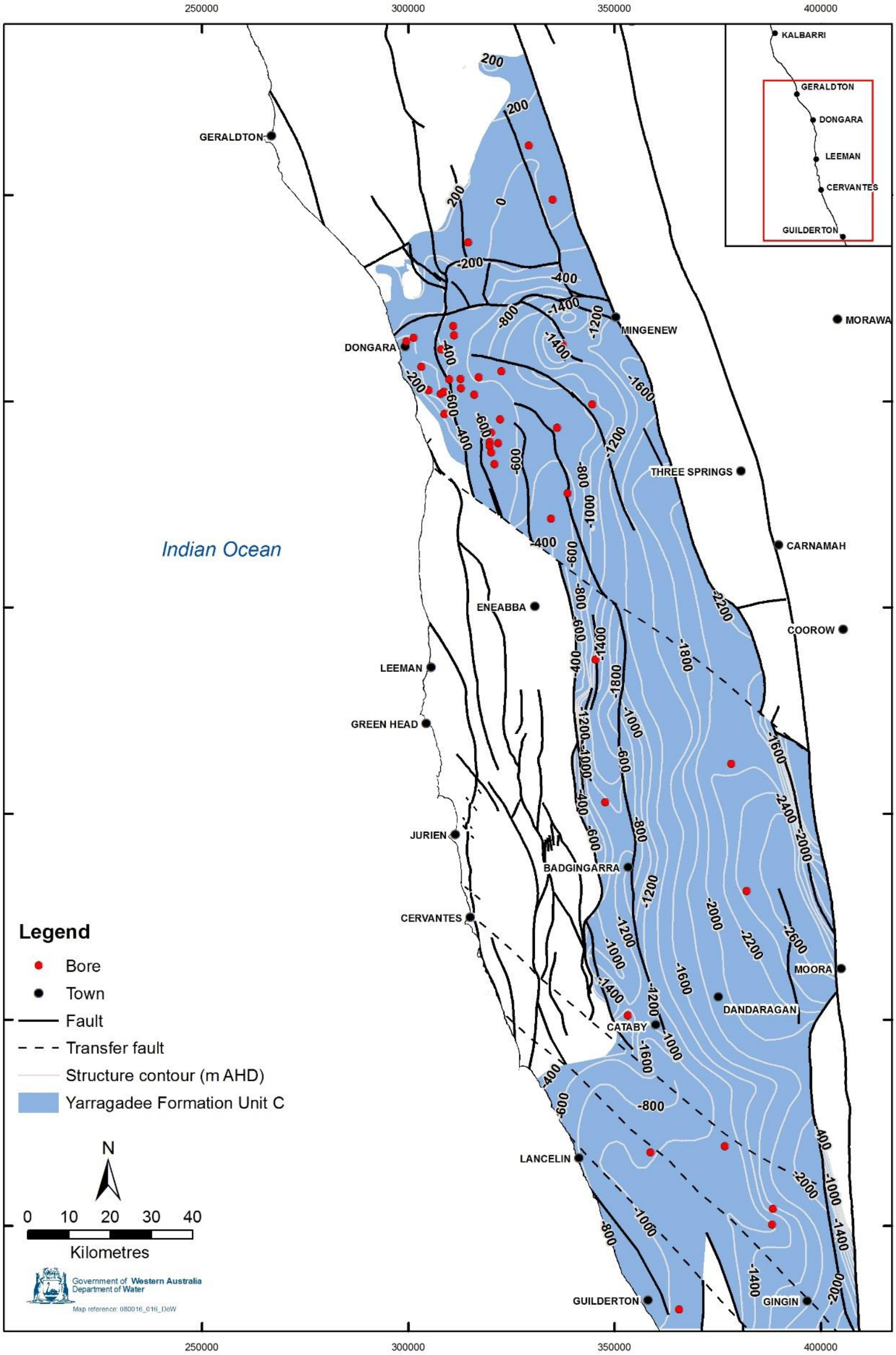


Figure 32 Yarragadee Formation Unit C: contours on base of unit

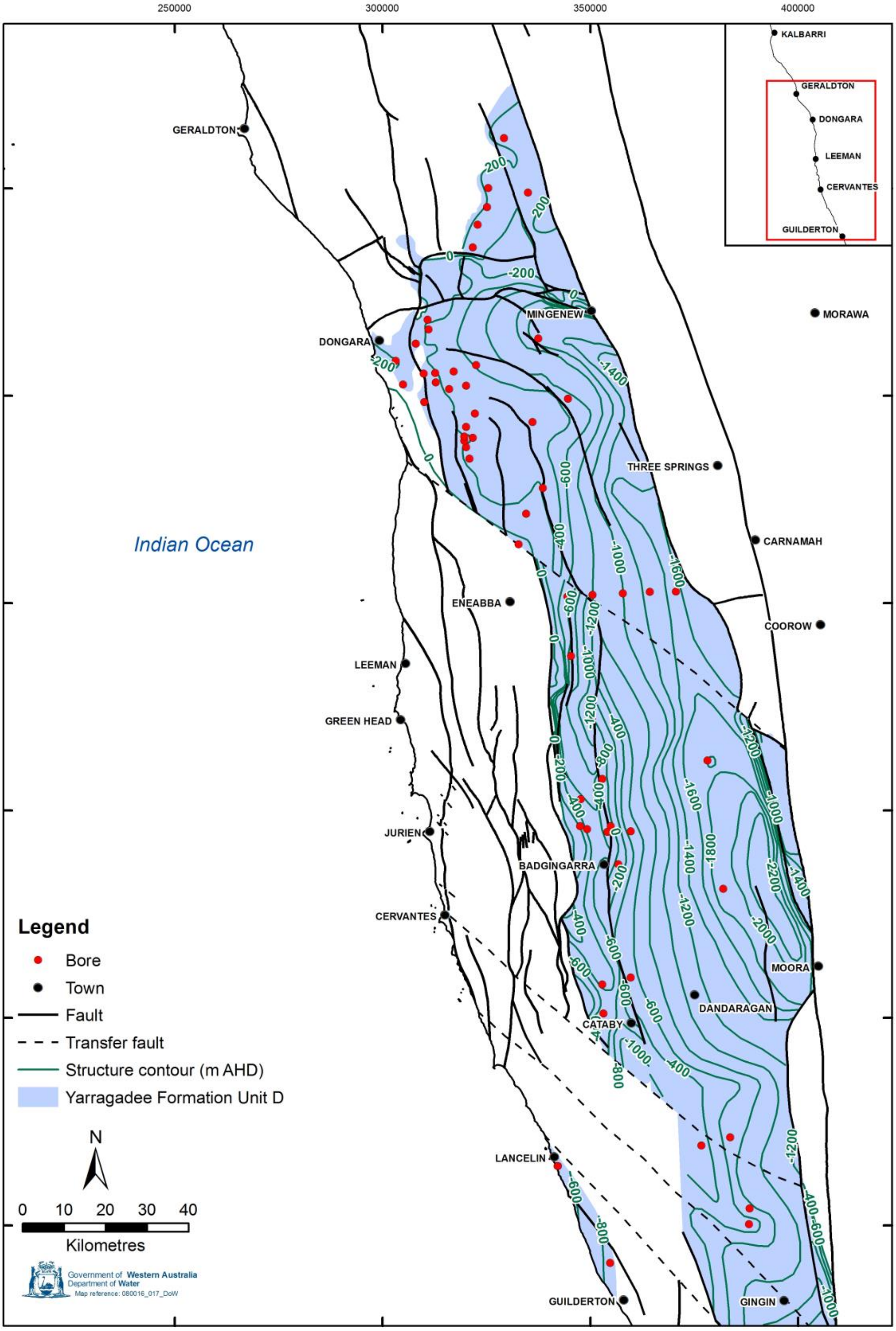


Figure 33 Yarragadee Formation Unit D: contours on base of unit

4.17 Parmelia Group

The Parmelia Group consists of sandstone, siltstone and shale that were deposited across the east of the northern Perth Basin in a fluvial to lacustrine environment during the Early Cretaceous. The name Parmelia Group was proposed by Crostella and Backhouse (2000), while previous member units of the Parmelia Formation, as defined by Backhouse (1988), were recognised as new formations. The group was previously described as part of the Yarragadee Formation (Playford et al. 1976). The formations within the Parmelia Group identified in offshore oil exploration wells are, in ascending order: the Otorowiri Formation, the Jervoise Sandstone, the Carnac Formation and the Charlotte Sandstone.

The Otorowiri Formation is the most widespread formation and forms the base of the Parmelia Group, and its outcrop can be traced from Mingenew to Dandaragan. In the south and centre of the area, the Otorowiri Formation is overlain by the shaley Carnac Formation. In the north and to the east, the Otorowiri Formation is overlain by an interbedded sand and subordinate shale, which is not found offshore. The Jervoise and Charlotte sandstones have not been recognised onshore. It is often difficult to distinguish the various formations above the Otorowiri Formation onshore, particularly in the Dandaragan and Beermullah troughs, and they are referred to as 'undifferentiated Parmelia Group' in this bulletin.

Sediments of the Parmelia Group were deposited within fluvio-deltaic and extensive lacustrine environments (Backhouse 1988). Based on palynological evidence, the siltstone and shale units that dominate the Otorowiri and Carnac formations are considered to be open, freshwater deposits (Backhouse 1988). In outcrop, the sediment beds are lenticular, variable in composition, and have limited lateral extent, with cross-bedding and slump structures evident.

Downhole gamma-ray logs through the Parmelia Group show distinctive fairly high count through the shaley Otorowiri and Carnac formations that distinguishes it from the more variable units above and below (Figure 34). The shale is notoriously prone to swelling, resulting in drilling problems.

The palynology of the Parmelia Group belongs to the *Biretisporites eneabbaensis* miospore zone and *Fusiformaccysta tuminda* microplankton zone (Backhouse 1988), which are Tithonian to Berriasian age of the upper Late Jurassic to lower Early Cretaceous. Dinoflagellate cysts are non-marine and associated with large lakes that were extensive across the Perth Basin at this time. Reworked Permian and Early Jurassic palynomorphs are also common.

Parmelia Group sedimentation was widespread within the Perth Basin, but much of the onshore portion was eroded during basin uplift in the final stage of continental breakup in the early Neocomian. The group is preserved within the eastern portion of the Dandaragan and Beermullah troughs and has a maximum known onshore thickness of 829 m in Gillingarra Line GL7 (Moncrieff 1989). The Parmelia Group is present over a large area offshore in the Vlaming Sub-basin where it can be over 2000 m thick and has been encountered in an onshore extension of the sub-basin at Guilderton within Artesian Monitoring AM1.

The Parmelia Group extends to a depth of –1400 m AHD at the eastern margin of the Dandaragan Trough, and rises to the western margin and within the northern area of its extent, reaching a maximum elevation of over 200 m AHD (Figure 35). The Parmelia Group subcrops beneath thin surficial deposits over the northern and western portions of the Dandaragan Plateau and outcrops along the Dandaragan Scarp (see Figure 18).

The Parmelia Group conformably overlies the Yarragadee Formation. It is disconformably overlain by the Warnbro Group and locally by the Coolyena Group in the south-west of the northern Perth Basin where the Warnbro Group is absent.

Otorowiri Formation

The Otorowiri Formation is characterised by shale and siltstone at the base of the Parmelia Group. It was first recognised in water bores in the Arrowsmith River area (Barnett 1970b). Ingram (1967) described it as the Otorowiri Siltstone Member of the Yarragadee Formation. The siltstone and shale unit was subsequently identified onshore within the Eneabba Line (Commander 1978a, 1978b) and extensively in offshore petroleum wells in the Vlaming Sub-basin. The type section is from 253 to 277 m depth in Arrowsmith River 25 (MGA Zone 50, 358301 m E, 6730642 m N) in the northern Dandaragan Trough. The Otorowiri Formation outcrops along the Dandaragan Scarp, which extends from Mingenew to Cataby.

The Otorowiri Formation comprises shale and siltstone with minor thin beds of fine-grained sandstone. The shale and siltstone is finely laminated, predominantly dark grey to greenish-grey, and micaceous, while the sand is glauconitic and pyritic (Playford, et al. 1976). In the Eneabba Line, there are two distinct siltstone beds separated by a thin sand horizon (Commander 1981).

Gamma-ray logs show a distinctive, fairly high count through the Otorowiri Formation that distinguishes it from the more variable units above and below (Figure 34). There is a corresponding low resistivity value within the formation. There is frequently a difference in resistivity between the upper and lower portions, with a slightly higher resistivity associated with increased siltstone and fine-grained sandstone.

The Otorowiri Formation was deposited during the Late Jurassic Tithonian age (Backhouse 1988). It was deposited in a lacustrine environment with some periods of marine lagoonal conditions as indicated by the presence of non-marine dinoflagellate cysts (Backhouse 1982) and marine dinoflagellates (Moncrieff 1989; Discovery Petroleum 1995b). Characteristically, there are some older microflora reworked from pre-existing formations.

The formation thickens southward from about 30 m near the Arrowsmith River (Barnett 1969) to 102 m in Eneabba Line EL2A. To the south of the Eneabba Line, the formation is less distinct and difficult to distinguish from overlying shale of the Carnac Formation. Contours on the base of the Otorowiri Formation are presented in Figure 35, which also represents the base of the Parmelia Group.

The Otorowiri Formation conformably overlies the Yarragadee Formation. It is overlain conformably by the Carnac Formation or ‘undifferentiated Parmelia Group’, and unconformably by the Warnbro Group between Moore River and Gingin Brook.

Carnac Formation

The Carnac Formation is a thick shale and siltstone sequence. It was originally defined as the Carnac Member of the Parmelia Formation by Backhouse (1984) and later elevated to formation status by Crostella and Backhouse (2000). Three members of the formation were described: the Stragglers, Mangles and Hawley members, in ascending order. Earlier descriptions of the formation referred to it as the Quinns Shale Member of the Yarragadee Formation (Bozanic 1969; Playford et al. 1976), but this terminology was abandoned by Backhouse (1984), who separated the Parmelia Formation from the Yarragadee Formation. The type section is between 2408 and 3064 m depth in offshore petroleum well Peel 1 (Backhouse 1984). Separate type sections are provided for the individual members in Crostella and Backhouse (2000).

The Carnac Formation comprises light to dark brownish grey, moderately consolidated siltstone, shale and claystone, with minor sandy layers. The sediments are slightly micaceous, with traces of pyrite and glauconite, and are laminated.

Within the Dandaragan Trough, the Carnac Formation was observed in the Gingin Brook and Moora lines (Moncrieff 1989). In Moora Line bores ML4 and ML3, the shale (including the basal Otorowiri Formation) is about 520 m thick. In Watheroo Line bore ML5, the shale sequence (termed Yarragadee Unit III) extends from the surface to 390 m depth (Harley 1975).

Along the Gillingarra Line, the sand content within the Carnac Formation increases eastward from about 20 per cent in GL6A to 50 per cent in GL7A (Moncrieff 1989), which may reflect proximity to provenance areas on the Yilgarn Craton. North of Agaton, the portion of sand increases to greater than 50 per cent of the formation with the sand being light grey to grey, fine to coarse grained and some gravel, poorly sorted, angular to subangular, feldspathic and clayey (Barnett 1970a). This lithology reaches a thickness of 435 m in Eneabba Line EL3 where the sequence is also more uniform (Commander 1978), and directly overlies the Otorowiri Formation. Conglomeratic layers are fairly common. The Carnac Formation is about 670 m thick in petroleum wells Warro 1 and 2, north-east of Badgingarra, and monitoring bore Agaton 15.

The Carnac Formation is a lacustrine deposit, possibly with some restricted marine elements as well as containing interspersed deltaic sediments (Backhouse 1986b; Crostella & Backhouse 2000). The sandy sequence is fluvial or deltaic.

The Carnac Formation either directly overlies the Otorowiri Formation, or is separated by a thin sequence of fine- to coarse-grained sandstone (Backhouse 1988), referred to onshore as ‘Undifferentiated Parmelia Group’. Offshore, this is probably the Jervoise Sandstone and it is overlain, possibly disconformably, by the Charlotte Sandstone that is a sequence of thick coarse-grained sand beds.

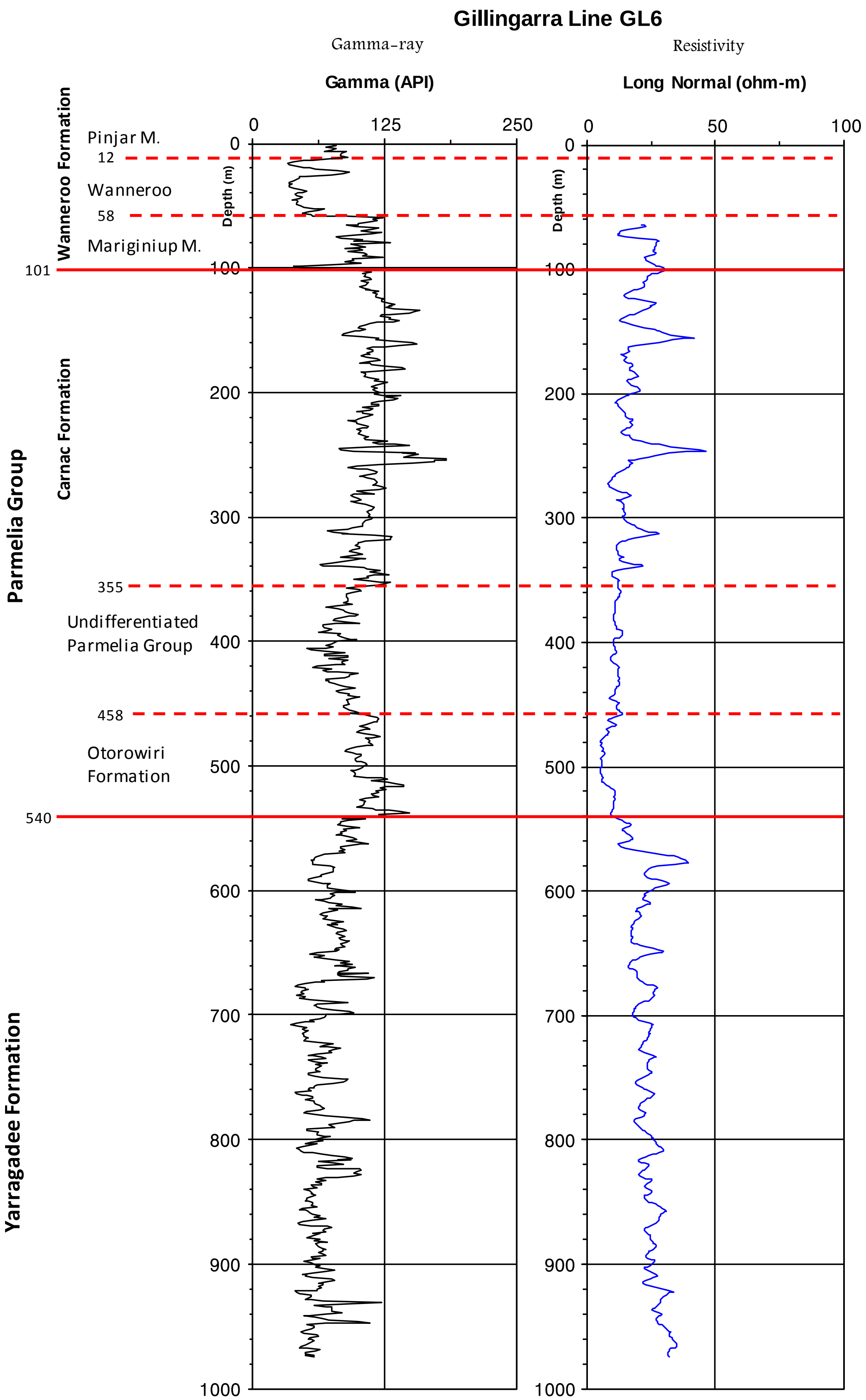


Figure 34 Downhole geophysical log from Gillingarra Line GL6 (0–975 m bgl) showing the Parmelia Group

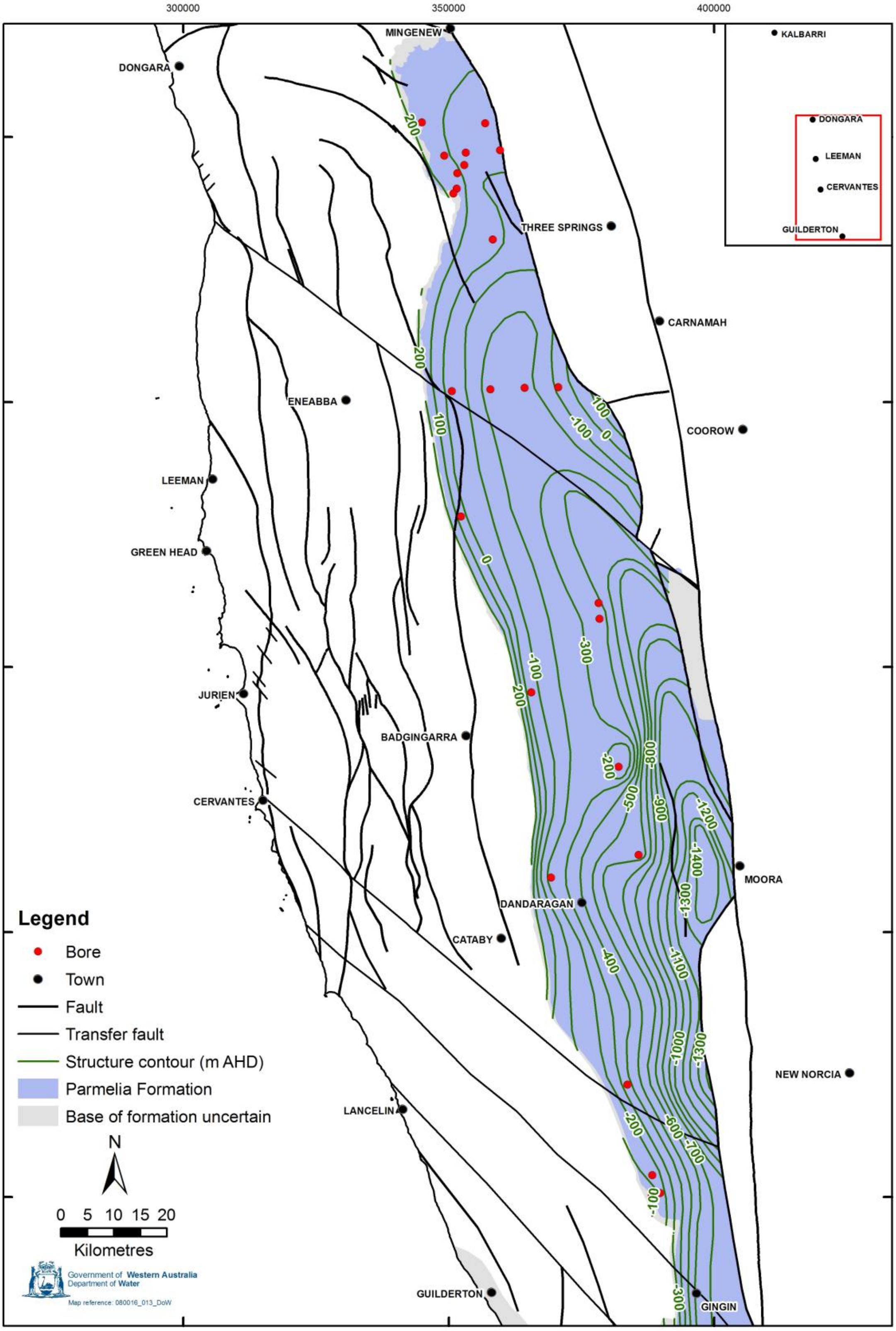


Figure 35 Parmelia Group: contours on base of unit

4.18 Warnbro Group

The Warnbro Group is made up of Early Cretaceous sediments that represent sedimentation following the final stage of continental separation from Greater India in the early Neocomian age (Cockbain & Playford 1973). The three formations within the group are the Gage Sandstone, South Perth Shale and Leederville Formation, in ascending order.

Sediments of the Warnbro Group were deposited in non-marine (mainly fluvial) and marine environments associated with a series of marine transgressions. Spring and Newell (1993) identified several depositional sequences in the offshore Vlaming Sub-basin, each representing a marine transgression and deltaic progradation producing a succession of sub-marine fan, deltaic/coastal, and fluvial deposits. Reworked Permian, Triassic and Jurassic palynomorphs are present in increasing abundance towards the west, suggesting rapid erosion of pre-existing strata and that the Beagle Ridge was a major source of sediment (Moncrieff 1989).

The Warnbro Group is present in the southern portion of the Perth Basin, extending northward beneath the coastal plain to near Cataby, and beneath the Dandaragan Plateau to the Watheroo National Park. The Warnbro Group was intersected in all bores of the Gillingarra Line (Moncrieff 1989) and Gingin Brook Line (Sanders 1967a, 1967b), and some bores of the Moora Line (Briese 1979) and Agaton Project (Balleau & Passmore 1972). The thickest intersection was 729 m in Gillingarra Line GL2B with its representative downhole geophysical log being presented in Figure 36. The geophysical log characteristics for each formation and member are discussed in more detail further in this section.

The maximum depth of the Warnbro Group is about –800 m AHD beneath the coastal plain, where it appears to form a north–south syncline east of Guilderton and Lancelin (Figure 37). A similar syncline where the Warnbro Group extends to –300 m AHD is also apparent beneath the Dandaragan Plateau extending north of Gingin. There are minor outcrops of the Warnbro Group in the Dandaragan area.

The Warnbro Group unconformably overlies the Parmelia Group or Yarragadee Formation and was deposited over an irregular pre-existing topography developed during the Neocomian continental breakup. Over most of the northern Perth Basin, the Warnbro Group is unconformably overlain by the mid-Cretaceous Coolyena Group, except in parts of the Swan Coastal Plain, where it is unconformably overlain by the superficial formations.

Gage Sandstone

The Gage Sandstone is the lowermost formation of the Warnbro Group, and was first recognised as a basal sand member of the South Perth Shale by Bozanic (1969). It was upgraded by Davidson (1995), who named it the Gage Formation, but it was subsequently renamed the Gage Sandstone by Crostella and Backhouse (2000) to reflect the arenaceous nature of the unit. The type section is between 1587 and 1704 m depth in petroleum well Gage Roads No. 1 within the Vlaming Sub-basin (MGA Zone 50, 346907 m E, 6463448 m N) (Crostella & Backhouse 2000).

The Gage Sandstone consists of sandstone interbedded with up to 50 per cent siltstone and shale. The sandstone is pale grey, fine grained to granular, poorly to well sorted, angular to subrounded quartz, and contains some feldspar, with minor pyrite and garnet. The shale and siltstone are pale grey, grey and grey brown, and can be micaceous. Deposition was in topographically low areas as basin fan deposits upon the breakup unconformity (Spring & Newell 1993) in a restricted marine environment (Crostella & Backhouse 2000). Microplankton palynology from the Gage Sandstone are of the *Gagiella mutabilis* miospore zone, which indicate a Valanginian age, possibly early Valanginian, of the Early Cretaceous epoch (Moncrieff 1989; Crostella & Backhouse 2000).

The formation unconformably overlies the Parmelia Group or Yarragadee Formation, and is overlain conformably by the South Perth Shale. Downhole gamma-ray logs over the formation show a low gamma-ray count through the sand units, and typically increasing resistivity values from below the South Perth Shale (Figure 36).

The Gage Sandstone has a maximum thickness of about 260 m in North Gingin borehole NGG1A north of Guilderton (Tuffs 2016). However, without palynology, the basal contact with the underlying Yarragadee Formation can be difficult to identify, given the similar lithology. The onshore portion of Gage Sandstone is restricted to beneath the coastal plain, extending north to near Namming Lake (Figure 38). The maximum depth of the Gage Sandstone is about –800 m AHD inland of Guilderton and Lancelin.

South Perth Shale

The South Perth Shale is dominantly marine shale and siltstone within the lower portion of the Warnbro Group (Playford et al. 1976). The type section is between 498 and 567 m depth in South Perth No. 1 (MGA Zone 50, 391492 m E, 6460971 m N).

The formation consists mainly of thinly bedded, grey, brown-black or black siltstone and shale, with minor thin sandy and calcareous beds. The formation is slightly micaceous, glauconitic in parts, and commonly contains minor pyrite (Allen 1978; Moncrieff 1989).

The South Perth Shale was deposited in a distal deltaic to shallow marine environment (Spring & Newell 1993). Palynological assemblages described within the South Perth Shale are assigned to the *G. mutabilis* to *Phoberocysta lowryi* microplankton zones and the *Balmeiopsis limbata* miospore zone (Moncrieff 1989), making it Valanginian to Hauterivian age (Moncrieff 1989; Cockbain 1990; Crostella & Backhouse 2000).

The South Perth Shale is present beneath the coastal plain south of Nilgen Swamp but does not appear to occur east of the Gingin Scarp (Figure 39). The average intersected thickness of the South Perth Shale in the northern Perth Basin is about 64 m, with a maximum of 178 m in Gillingarra Line bore GL3A. The maximum depth of the formation is about –780 m AHD within the north–south depression east of Guilderton and Lancelin, and it shallows towards its northern, western and eastern extent.

The South Perth Shale conformably overlies the Gage Sandstone, or unconformably overlies the Yarragadee Formation, and is overlain conformably by the Leederville Formation. Downhole gamma-ray logs of the formation have a distinctive, relatively uniform high count and corresponding low resistivity over the shale-dominated portions, while the siltstone portions have a higher resistivity.

Leederville Formation

The Leederville Formation is an Early Cretaceous non-marine and marine sequence of interbedded sand and shale overlying the South Perth Shale. The formation was originally introduced as the Leederville Sandstone (Fairbridge 1953) but later redefined as the Leederville Formation (Cockbain & Playford 1973). The type section is in the Leederville Valley (Redan Street) bore between 198 and 433 m depth (MGA Zone 50, 390044 m E, 6466222 m N). In the Perth region, three distinct member units have been defined within the Leederville Formation by Davidson (1995), which are, in ascending order, the Mariginiup, Wanneroo and Pinjar Members.

The Leederville Formation comprises discontinuous, interbedded shale, clayey sandstone and sandstone. The sandstone is light to medium grey, weakly to moderately consolidated, very fine to very coarse grained, angular to subangular, mostly poorly sorted, frequently clayey, and contains variable amounts of angular feldspar. Some intervals of predominantly sandstone are up to about 40 m thick, but they are generally less than 10 m thick. Siltstone, claystone and shales are laminated or thinly bedded, medium grey and brown-grey to black, weakly to well consolidated, and slightly micaceous. Glauconite is present within some marine beds, while there is minor pyrite, carbonaceous material and lignite with the non-marine beds (Cockbain & Playford 1973; Allen 1979; Moncrieff 1989). The bedding is lenticular so that correlation of beds between distant bores is not possible (Briese 1979).

Sediments of the Leederville Formation were deposited in a fluvio–deltaic environment, with shallow marine intervals. Palynological assemblages are from marine and non-marine (dominantly fluvial) environments. Spores and pollen belong to the *B. limbata* miospore zone (Backhouse 1988; Moncrieff 1989) and microplankton of the *Aprobolocysta alata*, *Batioladinium jaegeri*, and *Fromea monilifera* zones are frequently present (Backhouse 1988; Crostella & Backhouse 2000), indicating a Valanginian to earliest Aptian age (Moncrieff 1989).

The Leederville Formation is the most extensive formation of the Warnbro Group, extending beneath the Swan Coastal Plain almost as far north as Cataby, and beneath the Dandaragan Plateau as far north as the Watheroo area (Figure 40). The Leederville Formation has an average thickness of 235 m in fully penetrating drill holes. The greatest thickness of 640 m was intersected to the east of Lancelin in Gillingarra Line GL2B. There are only minor outcrops of the Leederville Formation along the Moore River near Gillingarra Line GL6. The sediments of the Leederville Formation onlap the Yilgarn Craton adjacent to the basin, where they overlie crystalline Archean–Proterozoic basement, and probably underlie the town of Moora (Deshon 2001).

The Leederville Formation conformably overlies the South Perth Shale or Gage Sandstone, or unconformably overlies the Parmelia Group or Yarragadee Formation. It is unconformably overlain by the Osborne Formation (Henley Sandstone and Kardinya Shale Members) or superficial formations (beneath the eastern portion of the coastal plain).

Mariginiup Member

The Mariginiup Member is the basal unit of the Leederville Formation, representing a transitional period between the South Perth Shale and Wanneroo Member. The type section is in Artesian Monitoring AM24 (MGA Zone 50, 389763 m E, 6491300 m N) in the Perth metropolitan area between 423 and 507 m depth (Davidson 1995).

The Mariginiup Member is predominantly of marine origin, and consists of thinly interbedded siltstones and shales with very thin beds of fine-grained sandstone (Davidson 1995). The fine-grained sandstone beds are commonly glauconitic and micaceous. A sandstone bed is apparent within the basal portion of the member that is about 40 m thick and possibly up to 100 m thick in Gillingarra Line GL2B. This sandstone bed consists of fine to very coarse grained sandstone and gravel with fine pebbles, poorly to well sorted, subangular to rounded, and feldspathic.

Microplankton ranging from the *G. mutabilis* to *Aprobolocysta* zones are present within the Mariginiup Member, suggesting Valanginian to early Barremian age (Backhouse 1980).

The Mariginiup Member is recognised in downhole geophysical logs as having a high gamma-ray count centred around 100–125 API with low gamma count intervals between 75 and 100 API corresponding with the sand beds (Figure 36). The basal portion has a predominantly low gamma-ray count corresponding to the basal sand. This provides a sharp contrast with the underlying high gamma-ray count of the South Perth Shale.

Wanneroo Member

The Wanneroo Member comprises a mainly non-marine sandstone sequence overlying the Mariginiup Member. The type section is within Artesian Monitoring AM24 (MGA Zone 50, 389763 m E, 6491300 m N) in the Perth metropolitan region from 223 to 423 m depth. The Wanneroo Member is late Neocomian to Aptian age (Backhouse 1980).

The Wanneroo Member contains weakly consolidated sandstone beds between 12 and 15 m thick with minor beds of siltstone and shale (Davidson 1995). The sandstone is pale grey and consists of fine to very coarse grained (predominantly coarse), poorly sorted, angular to subangular quartz grains. The siltstone and shale are grey and slightly micaceous. Granitic boulders are common near the Darling Scarp.

In downhole geophysical logs, the Wanneroo Member is characterised by a relatively low gamma-ray count of below 50 API over the sandstone beds.

Pinjar Member

The Pinjar Member is the uppermost unit of the Leederville Formation and consists of discontinuous, interbedded sandstone, siltstone and shale of marine and non-marine origin. The type section is from 157 to 223 m depth in Artesian Monitoring bore AM24 in the Perth metropolitan area (MGA Zone 50, 389763 m E, 6491300 m N) (Davidson 1995). The Pinjar Member extends northward to near Lancelin and has a maximum onshore thickness of about 150 m (Davidson 1995).

The Pinjar Member can comprise up to 50 per cent sandstone (Moncrieff 1989), with sandstone beds up to several metres thick. The sandstone is grey, weakly consolidated and consists of poorly sorted, fine to very coarse, subangular to subrounded quartz grains. The siltstone and shale are dark grey to black and micaceous, with thin laminations of fine-grained sandstone and minor lignite fragments. However, the upper 40 m of the Pinjar Member in the western portion of the Gillingarra Line (GL1, GL2, GL3) is characterised by a dark greenish grey to greenish black, slightly clayey, sandy, glauconitic siltstone and silty sandstone while the sand is very fine to fine grained, subrounded to rounded and well sorted.

In downhole geophysical logs, the Pinjar Member is characterised by a relatively high gamma-ray count centred around 100 API where it is shaley providing a contact with the lower count associated with the Wanneroo Member (Figure 36).

Downhole geophysical logs have thin zones of low gamma-ray count across sandstone intervals with higher counts in siltstone and shale beds.

The upper Pinjar Member within the western portion of the Gillingarra Line is a shallow marine deposit (Moncrieff 1989) corresponding to the *B. jaegeri* to *F. monilifera* zones, being late Neocomian to Aptian age (Backhouse 1980).

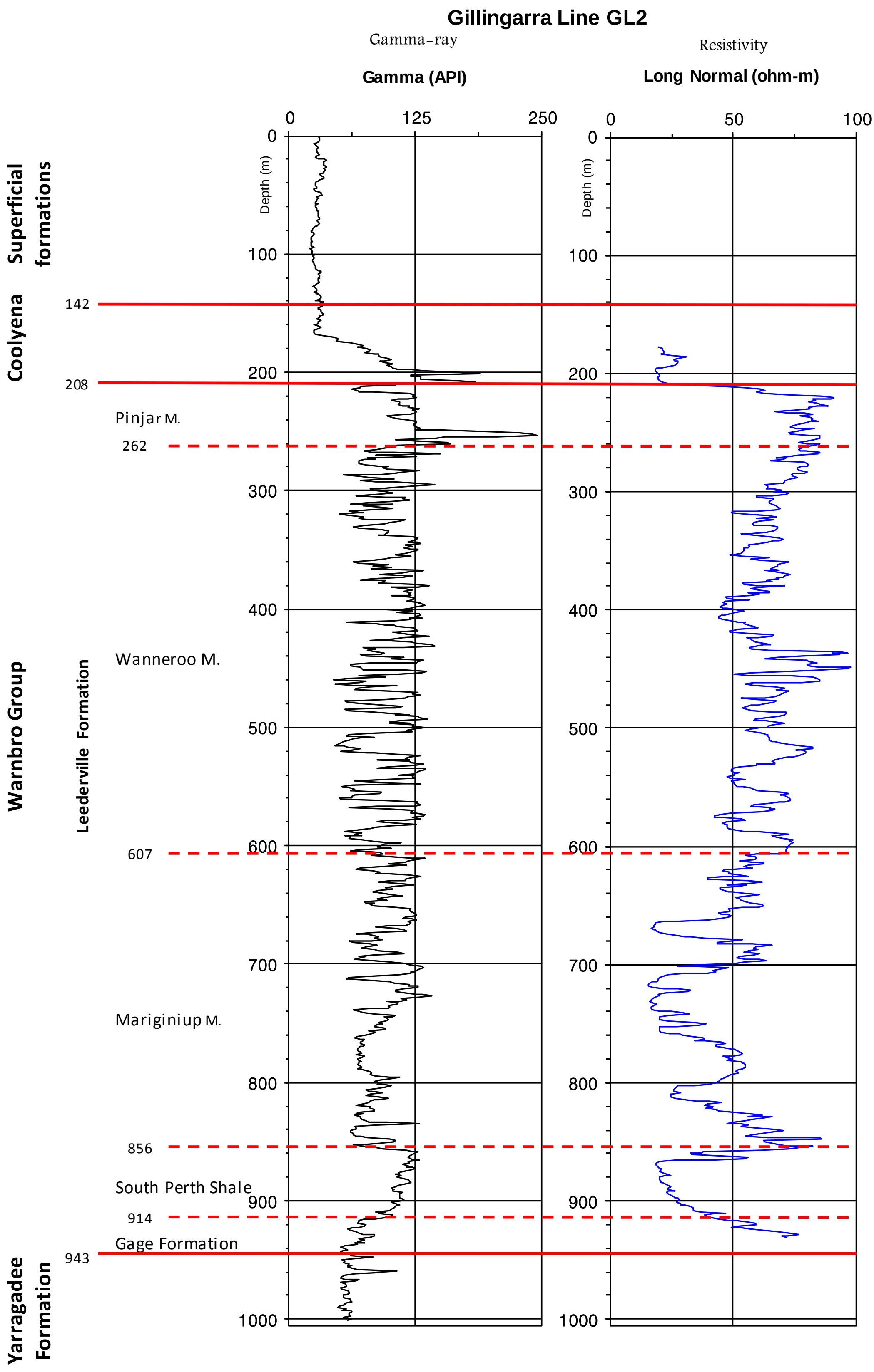


Figure 36 Downhole geophysical log from Gillingarra Line 2B (0–1000 m bgl) showing the Warnbro Group

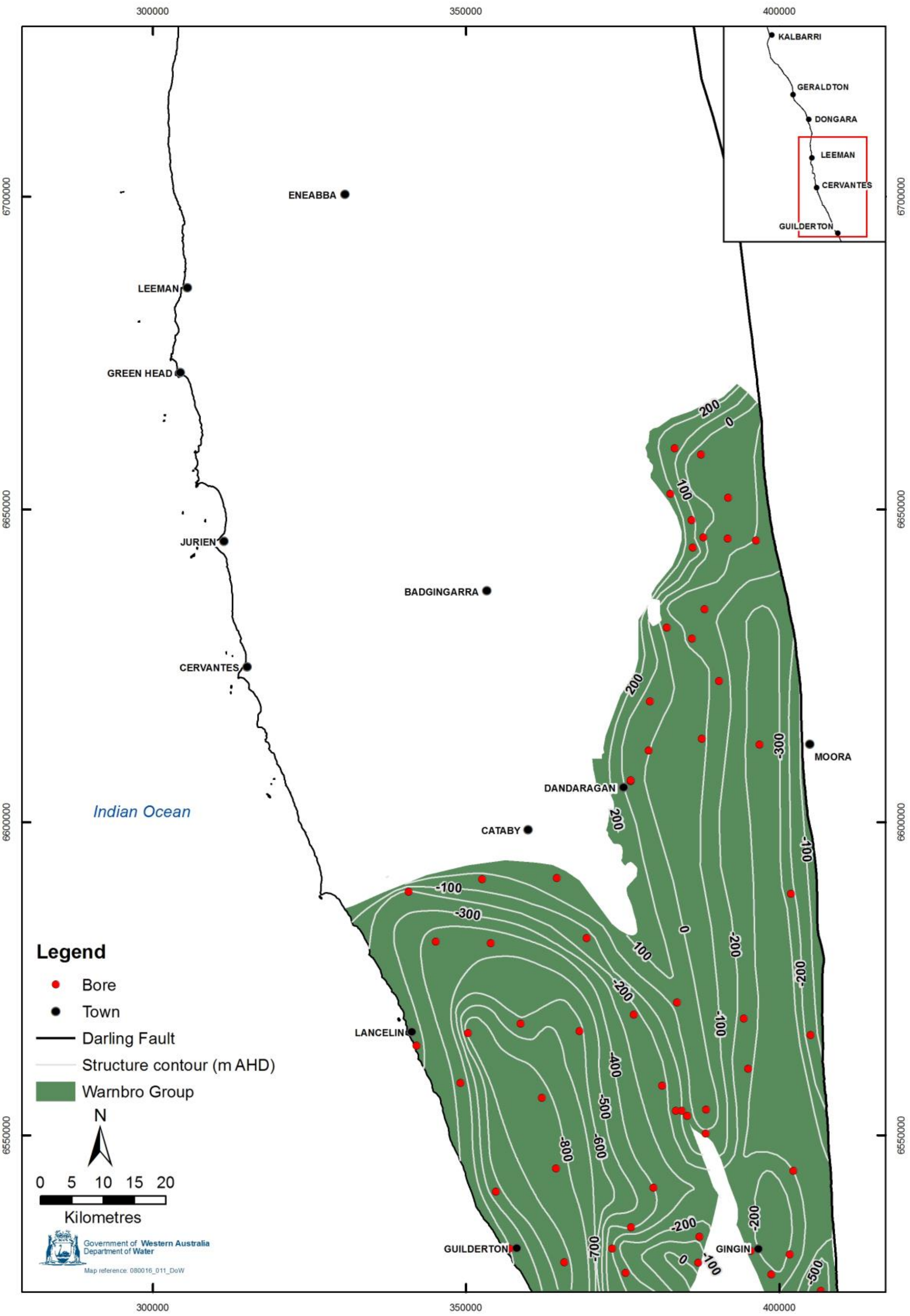


Figure 37 Warnbro Group: contours on base of unit

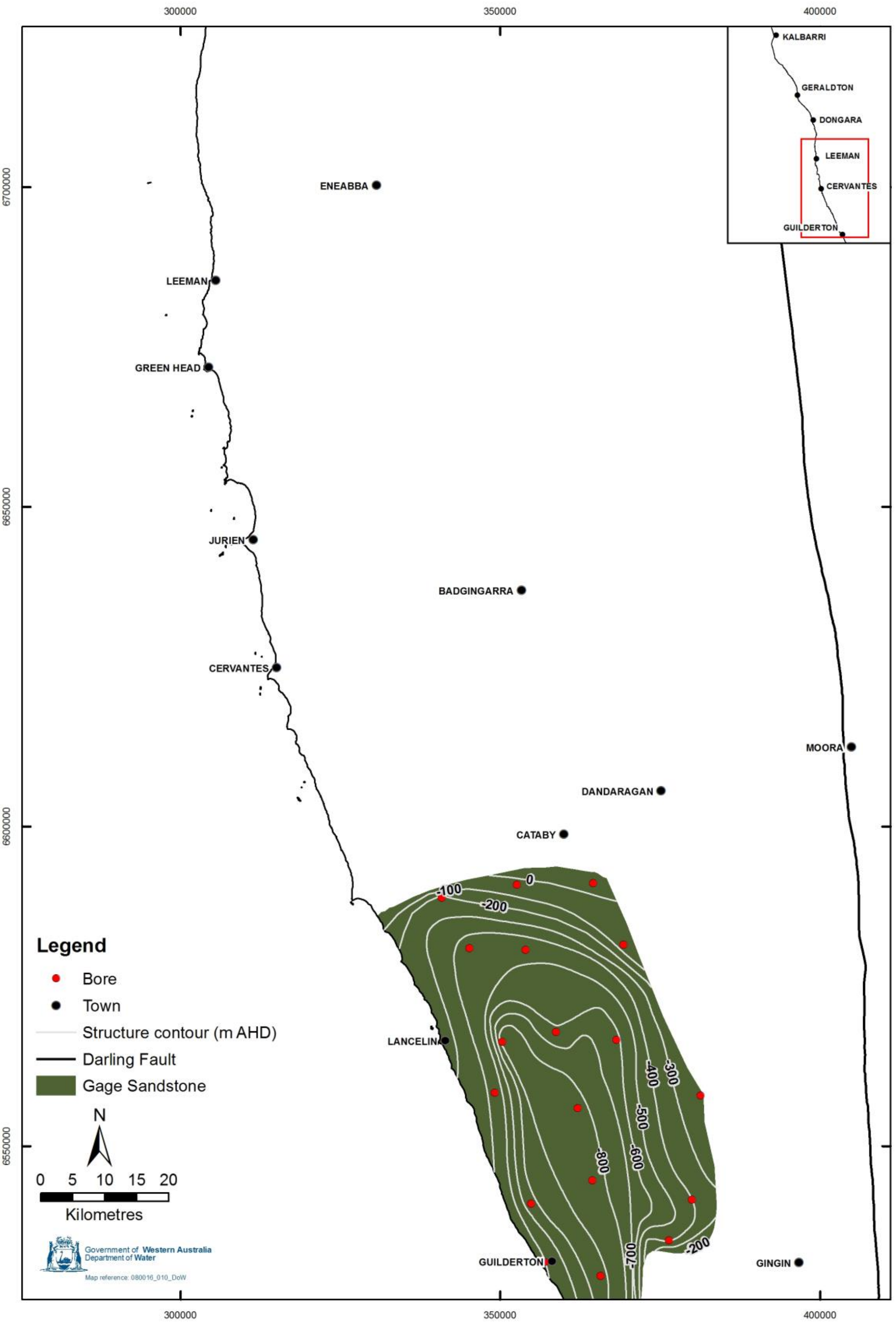


Figure 38 Gage Sandstone: contours on base of unit

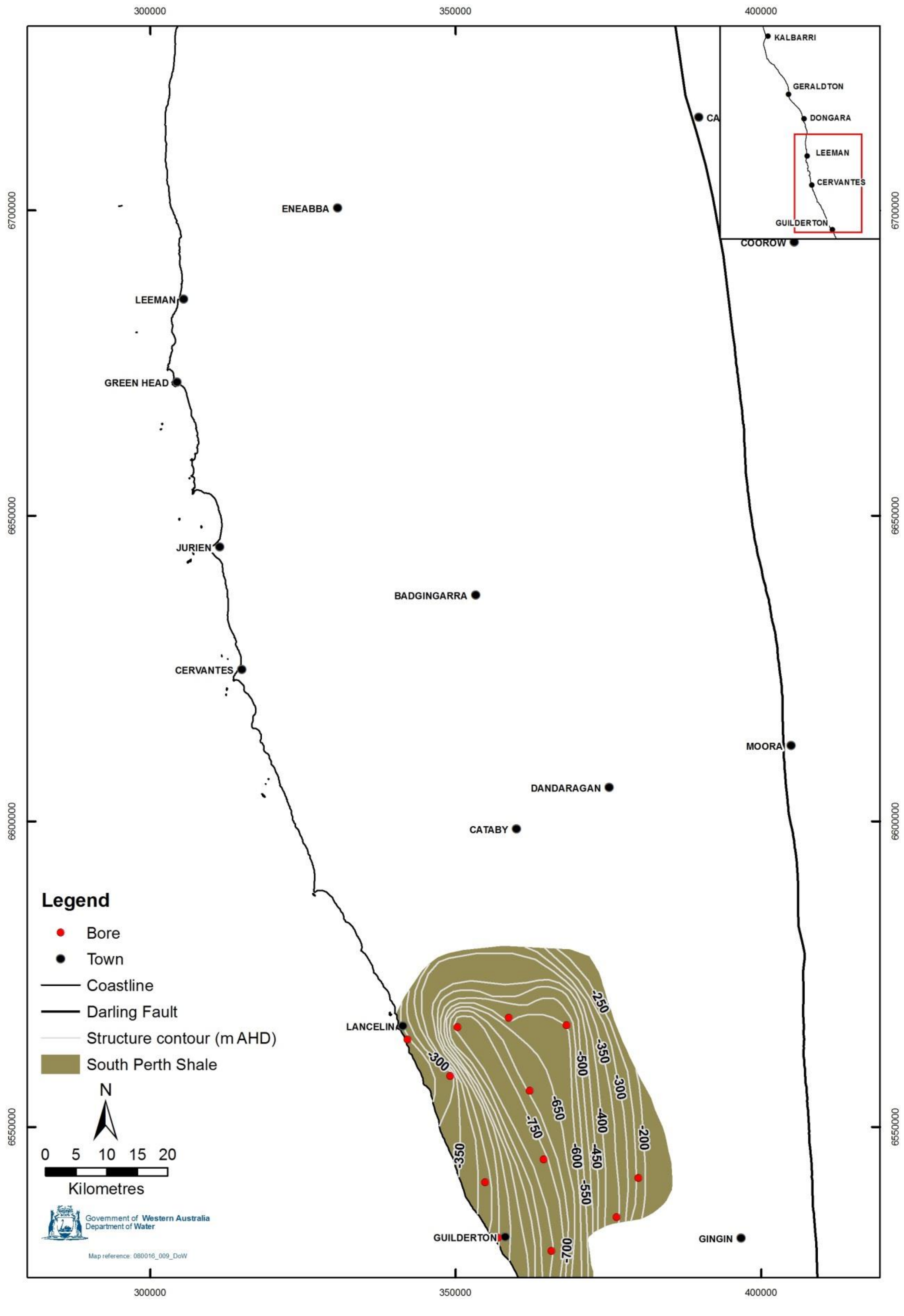


Figure 39 South Perth Shale: contours on base of unit

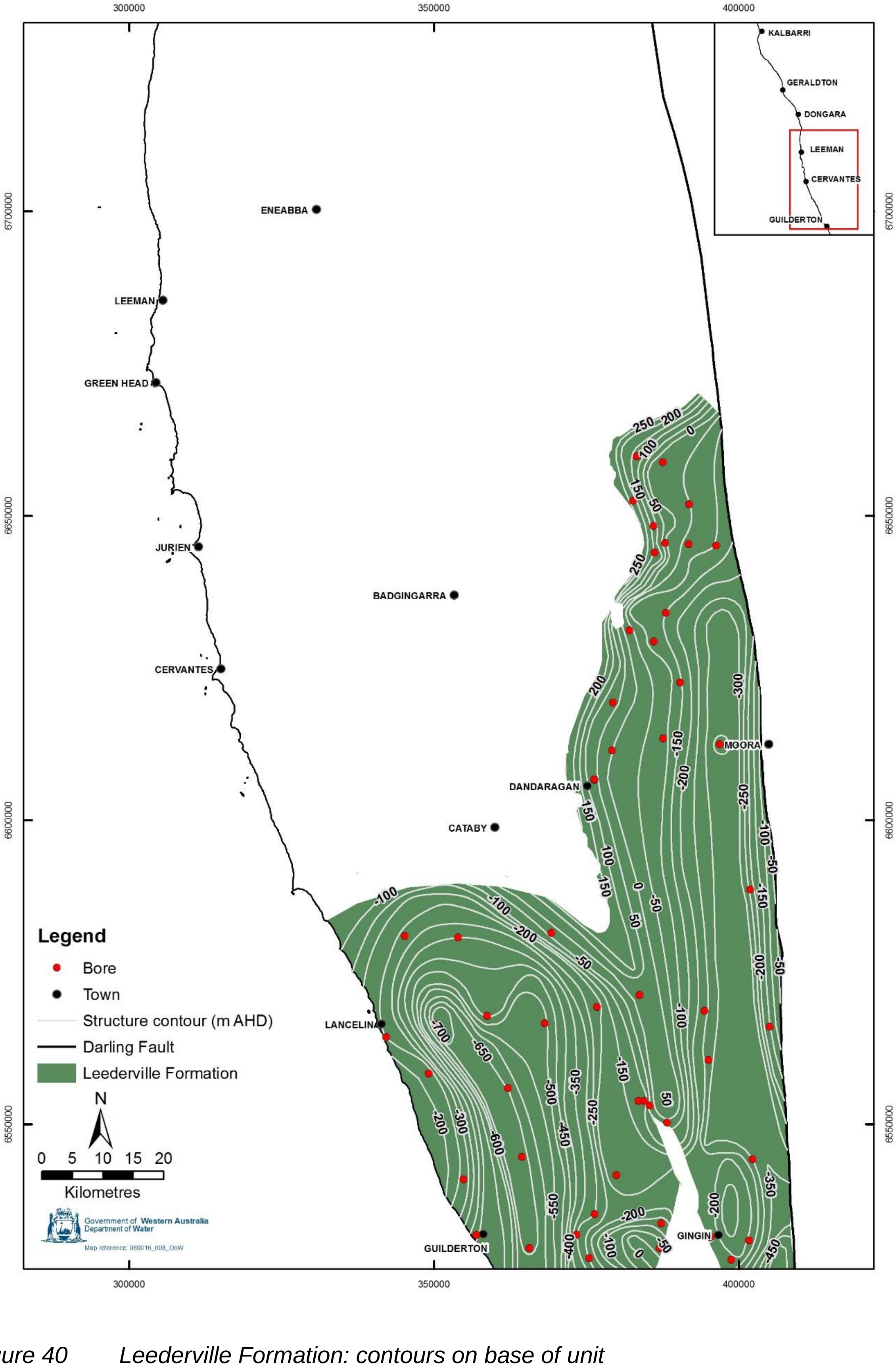


Figure 40 Leederville Formation: contours on base of unit

4.19 Winning Group

The Winning Group is a Cretaceous marine sequence within the Carnarvon Basin that was deposited during a major transgression throughout most of the Early Cretaceous, and is a time equivalent of the Warnbro Group. The Winning Group was originally named the 'Winning Series' by Raggat (1936), but was later amended to the 'Winning Group' by Fairbridge (1953). In the southern part of the Carnarvon Basin, the Winning Group consists of, in ascending order: the Birdrong Sandstone, Muderong Shale, Windalia Radiolarite, Alinga Formation and Gearle Siltstone (Mory et al. 2005; Hocking & Mory 2006) (see Table 8).

The Birdrong Sandstone is a basal sand facies comprising a fine to coarse grained, quartzose, commonly glauconitic, friable and often silty sandstone, with some silty claystone and shale. It is typically pale grey to white, and locally greenish. The Birdrong Sandstone is a coastal to near-shore deposit that was laid down with the marine transgression.

The Muderong Shale is an argillaceous sequence which lies conformably between the Birdrong Sandstone and the Windalia Radiolarite. The Windalia Sandstone Member was initially thought to occur within the Windalia Radiolarite, but is now recognised as belonging in the upper part of the Muderong Shale.

The Windalia Radiolarite is a radiolarian siltstone with a radiolarian content of up to 70 per cent. It lies conformably between the Muderong Shale below and Alinga Formation above.

The Alinga Formation is a glauconitic claystone and siltstone sequence, which outcrops near the lower Murchison Riverand and grades laterally into the Gearle Siltstone further north (Hocking et al. 1987). It rest conformably on the Windalia Radiolarite and is disconformably overlain by the Gearle Siltstone.

The Gearle Siltstone is a silty and clayey formation, with radiolarian siltstone, which unconformably overlies the Alinga Formation and is conformably overlain by the Haycock Marl.

The Winning Group has an outcrop area of about 900 km^2 south of the Murchison River and extends about 40 km south of Kalbarri. There is little borehole data available for the Winning Group, which has only been intersected in a few private bores. Drillers' logs from these bores indicate about 9 m of clay and 6 m of sand with an 'overburden' up to 27 m thick, which is likely to be weathered Winning Group. The lower sand unit may belong to the Birdrong Sandstone. The maximum thickness of the Winning Group south of the Murchison River is probably less than 100 m, preserved as remnant hills, and is typically less than 40 m thick.

The Winning Group unconformably overlies the Wittecarra Sandstone or Tumblagooda Sandstone to the south of the Murchison River. At its southern limit, the Cattamarra Coal Measures and Kockatea Shale may interfinger between the Winning Group and Tumblagooda Sandstone. The group has been fully eroded along the Murchison River, exposing the underlying Tumblagooda Sandstone. Minor patches of Toolonga Calcilutite overlie the Winning Group towards the west.

4.20 Coolyena Group

The Coolyena Group is a series of mid-Cretaceous marine formations comprising shale, glauconitic greensands and chalk. The Coolyena Group was originally defined by Cockbain and Playford (1973) and later extended by Davidson (1995). It includes, in ascending order: the Osborne Formation, Molecap Greensand, Gingin Chalk, and Poison Hill Greensand on the Dandaragan Plateau (Table 6). However, on the Swan Coastal Plain, the latter three formations are undistinguished and assigned to the Lancelin Formation. Three members are distinguished in the Osborne Formation and they are (in ascending order) the Hensley Sandstone, Kardinya Shale and Mirrabooka members.

The Coolyena Group was deposited under shallow marine conditions during a period of tectonic stability and is Albian to Maastrichtian in age (Early to Late Cretaceous period). The sediments comprise shale, greensand, and chalk and marl. The Coolyena Group has a maximum intersected thickness of 192 m within Agaton 13 (Balleau & Passmore 1972), but is generally less than 150 m thick (Moncrieff 1989).

In the northern Perth Basin, the extent of the Coolyena Group is restricted to two distinct areas: beneath the Swan Coastal Plain as far north as Lancelin, and beneath the Dandaragan Plateau extending north to the Watheroo National Park (Figure 42). The Coolyena Group unconformably overlies the Warnbro Group and is unconformably overlain by the superficial formations beneath the coastal plain. There are minor outcrops of the Coolyena Group in the Dandaragan area, east of the Dandaragan Scarp (Carter & Lipple 1982). Structure contours at the base of the Coolyena Group are presented in Figure 42.

The geophysical logs are highly variable in the Coolyena Group, with high gamma-ray counts in the shaley Kardinya Shale Member of the Osborne Formation and low gamma ray counts in the Henley Sandstone and Mirrabooka members (Figure 41). The geophysical log characteristics for each formation and relevant member are discussed in more detail further in this section.

Osborne Formation

The Osborne Formation comprises marine deposits of weakly to well consolidated, dark greenish grey, glauconitic shale, siltstone, and silty and clayey sandstone, and is the basal unit of the Coolyena Group (McWhae et al. 1958; Davidson 1995). The type section is between 37 and 133 m depth in King Edward Street bore in the Perth metropolitan area (MGA Zone 50 388242 m E, 6470176 m N). Three member units are recognised, which are, in ascending order: the Henley Sandstone Member (a basal sandstone sequence), the Kardinya Shale Member (a middle shale and siltstone unit) and the Mirrabooka Member (an upper, predominantly sandstone sequence).

The presence of glauconite and microplankton in the Osborne Formation indicate deposition in a near-shore, shallow-marine environment. Palynological assemblages belong to the *Pseudoceratium turneri* or *Odontochitina operculata* microplankton zones, and the *Endoceratim ludbrookiae 'c'* microplankton subzone (Moncrieff 1989), which are Late Aptian to Cenomanian age (Cookson & Eisenack 1958; Backhouse 1979, 1980b), equivalent to the Early to Late Cretaceous epoch.

The Osborne Formation is present over two areas, beneath the Swan Coastal Plain and beneath the Dandaragan Plateau. Beneath the western portion of the coastal plain between the Moore River and Eaglehawk Flats (about 13 km north-east of Lancelin), the Osborne Formation was intersected in Gillingarra Line GL2A and GL3A (Moncrieff 1989), and Gingin Brook Line 4 (Sanders 1967a). The formation is deepest in this part of the basin extending to –180 m AHD, and possibly reaching to 0 m AHD about its northern extent. Beneath the Dandaragan Plateau, the Osborne Formation extends as far north as the Watheroo National Park, west of Watheroo. The formation ranges in depth from about –80 m AHD south-east of Gingin to over 220 m AHD north-west of Moora. It was intersected in Gillingarra Line GL7A and GL8A, Moora Line ML1A, and in several of the Agaton bores. The Osborne Formation has been completely eroded between the western and eastern areas. It extends southward into the Perth metropolitan area (Davidson 1995).

The Osborne Formation unconformably overlies the Leederville Formation and is conformably or unconformably overlain by the Molecap Greensand in the east, and is disconformably overlain by the Lancelin Formation in the west. Beneath the central coastal plain, it is unconformably overlain by the superficial formations.

Henley Sandstone Member

The Henley Sandstone Member is the basal unit of the Osborne Formation. The type section is between 229 and 270 m depth in Artesian Monitoring bore AM11 in the Perth metropolitan area (MGA Zone 50, 406614 m E, 6525106 m N) (Davidson 1995). The Henley Sandstone Member was previously referred to as the Dandaragan Sandstone (McWhae et al. 1958) and attributed to the upper portion of the Warnbro Group (Playford et al. 1976), but was later named the Henley Sandstone Member of the Osborne Formation (Davidson 1995).

The Henley Sandstone Member consists of fine to very coarse grained quartz sandstone and fine conglomerate with minor siltstone and claystone. The sands are poorly to moderately sorted, angular to subrounded, and weakly consolidated. The Henley Sandstone Member is characteristically dark greenish brown and glauconitic, becoming feldspathic eastward towards the Yilgarn Craton. The Henley Sandstone Member can sometimes be difficult to distinguish lithologically from the underlying Leederville Formation. Deposition was probably in a high energy, shallow-marine environment (Moncrieff 1989).

In the northern Perth Basin, the Henley Sandstone Member is present beneath the south-western portion of the coastal plain, and beneath the eastern portion of the Dandaragan Plateau (Harley 1974; Briese 1979a; Moncrieff 1989). The basal elevation of the Henley Sandstone Member ranges from 0 to –280 m AHD (Figure 43). The average thickness is about 25 m, with a maximum thickness of 48 m intersected in Red Gully bore RG2A (Diamond 2000).

The Henley Sandstone Member at the base of the Osborne Formation is recognisable by a low gamma-ray count and higher resistivity when compared with the high gamma-ray and low resistivity values of the Kardinya Shale Member (see Figure 41). It can be difficult to distinguish the Henley Sandstone Member from the underlying Leederville Formation without palynology, although it can have a lower gamma-ray count and lack the distinct peaks of the Leederville Formation.

Kardinya Shale Member

The Kardinya Shale Member, a thick siltstone and shale horizon, is the major unit within the Osborne Formation. The type section is within Artesian Monitoring bore AM42 in the Perth metropolitan area between 28 and 167 m (MGA Zone 50, 388123 m E, 6452372 m N) (Davidson 1995). The Kardinya Shale Member outcrops along the Moore River for at least 5 km west of the Darling Fault.

The Kardinya Shale Member consists of moderately to tightly consolidated, interbedded siltstone and shale with minor thin interbeds of fine- to medium-grained sandstone (Diamond 2000). It is dark green to black, carbonaceous, micaceous and glauconitic, particularly towards the base. It contains rare to common pyrite, and is calcareous in parts. Nodules of phosphate were found at the base of the formation in Agaton bore A23 (Balleau & Passmore 1972).

The Kardinya Shale Member is present in the west beneath the coastal plain, and in the east adjacent to the Gingin Scarp (Figure 44). The deepest occurrences are in the western portion, with basal depths from –180 m AHD, rising to –25 m AHD in the north. Within the eastern portion, the basal depth ranges between –40 m AHD in the south to over 200 m AHD in the north. It occupies a north–south elongate trough stretching from Gingin to north of Moora that may represent a pre-existing valley at the time of deposition.

The average intersected thickness of Kardinya Shale Member within the northern Perth Basin is about 80 m, with the thickest intersection of 235 m in Glen Ruff bore GR1, 3 km north-west of Moora Line ML1

The Kardinya Shale Member is recognisable in geophysical logs by its very tight pattern of high gamma-ray count centred between 50 and 100 API and low resistivity due to the high shale content. These characteristic signatures provide sharp contrasts with the Henley Sandstone Member below and Mirrabooka Member above.

Mirrabooka Member

The Mirrabooka Member is a sandstone unit at the top of the Osborne Formation. The type section is between 34 and 199 m depth in Artesian Monitoring bore AM30Z (MGA Zone 50, 397699 m E, 6478981 m N) in the Perth metropolitan area (Davidson 1995). The unit was previously referred to informally as the ‘Channel Sand’ in the Mirrabooka area north-east of Perth (Allen 1977). In some areas, it may be a lateral equivalent of the Kardinya Shale Member (Kay & Diamond 2001), but this relationship is not well understood.

The Mirrabooka Member comprises dark greenish brown, weakly consolidated, fine to very coarse grained sand and gravel that is very poorly to moderately sorted and subangular to well rounded. It is silty and richly glauconitic, containing thin interbeds of dark green to black siltstone and shale. Within the weathering zone, the sandstone is limonitic.

The Mirrabooka Member has only been identified in a few drill holes in the eastern portion of the basin and north of the Moore River (Kay & Diamond 2001). The eastern margin of the Mirrabooka Member appears to have been truncated by the Molecap Greensand. The deepest occurrence is below 0 m AHD near Gingin Brook before rising to about 170 m AHD at its north-eastern limits. The Mirrabooka Member outcrops adjacent to the Darling Fault, west of Wannamal. The average thickness of the Mirrabooka Member is 15 m; however, it can be up to 50 m thick in West Koojan near Dandaragan (HydroConcept 2013) and 40 m thick in Gingin town water supply bore 1/75 (Figure 45).

In geophysical logs, the Mirrabooka Member contrasts with the underlying Kardinya Shale Member owing to its relatively low gamma-ray count and higher resistivity. The Mirrabooka Member is difficult to distinguish from the Molecap Greensand without palynological evidence.

Molecap Greensand, Gingin Chalk, Poison Hill Greensand and Lancelin Formation

The Molecap Greensand, Gingin Chalk, Poison Hill Greensand and Lancelin Formation form a sequence of Late Cretaceous shallow marine deposits comprising glauconitic sandstone with fossiliferous chalk and marl units. Moncrieff (1989) defined this sequence as the Lancelin Formation with each formation being member units; however, this nomenclature is not adopted in this bulletin because the Lancelin Formation, present in the west and central portion of the Swan Coastal Plain, is age equivalent to the Molecap Greensand, Gingin Chalk and Poison Hill Greensand, which are present beneath the Dandaragan Plateau (see Table 6).

Downhole gamma-ray logs for the Molecap Greensand and Poison Hill Greensand typically have relatively low gamma-ray count with slightly higher count across the clay portions. However, the response is markedly lower than those observed for the Kardinya Shale Member and clay intervals in the Leederville Formation. Intervals of chalk and marl have a very low gamma-ray response.

Palynology suggests a near-shore marine depositional environment, and Turonian to Campanian age, which may extend to the Maastrichtian age, of the Late Cretaceous period (Wilde & Low 1978; Rexilius 1984; Backhouse 1986a; Moncrieff 1989; Cockbain 1990; Davidson 1995).

The distribution of these deposits is similar to the Osborne Formation with two separate areas: in the south-west beneath the Swan Coastal Plain, and in the south-east beneath the Dandaragan Plateau (Figure 46). Beneath the coastal plain, the base of the sequence extends from below –110 m AHD near Guilderton to about 0 m AHD along its northern and eastern extent. Beneath the Dandaragan Plateau, they are present at higher elevations than in the west, rising from about 20 m AHD at Gingin to about 300 m AHD in the north. They are thickest beneath the central portion of the Dandaragan Plateau, north of the Moore River, and may be up to 150 m thick east of Yallalie; however, this may include the Mirrabooka Member of the Osborne Formation that can be difficult to distinguish from the Molecap Greensand.

Molecap Greensand

The Molecap Greensand is a shallow marine deposit from the Late Cretaceous that was originally defined by Fairbridge (1953). The type section is in the greensand quarry on Molecap Hill (MGA Zone 50, 347970 m E, 6528792 m N), 2 km south of Gingin.

Typically, the Molecap Greensand comprises greenish grey-brown, very fine to medium and coarse grained, poorly to moderately sorted, subangular to well rounded, unconsolidated quartz sand. It contains abundant (5–10%) glauconite (Moncrieff 1989) with intervals of sandy clay. Thin beds of phosphatic nodules are present within the upper and lower portion of the formation in the Dandaragan area (Matheson 1948). Phosphatised wood is also common. When weathered, the glauconite is altered to limonite, and the formation is yellow, yellow-brown and brown through to a deep red-brown in outcrop.

The Molecap Greensand predominantly overlies (conformably) the Mirrabooka Member of the Osborne Formation, but beneath the western portion of the Dandaragan Plateau, it unconformably overlies the Leederville Formation. The Molecap Greensand is overlain conformably by the Gingin Chalk, or where the chalk is absent, it is unconformably overlain by the Poison Hill Greensand.

Ichthyosaur and plesiosaur bones have been collected from the formation (Teichert & Matheson 1944), and pelecypods and belemnites were observed at Gingin. Microplankton indicate that the Molecap Greensand is Turonian to Santonian in age (Davidson 1995). The Haycock Marl (argillaceous calcilutite and marl) of the Carnarvon Basin is most likely an age equivalent of the Molecap Greensand (Table 8). Hocking and Mory (2006) mentioned the presence of the Haycock Marl above the Gearle Siltstone in the Kalbarri area.

Gingin Chalk

The Gingin Chalk is a shallow marine deposit of the Late Cretaceous (Carter & Lipple 1982; Moncrieff 1989; Cockbain 1990) that was originally named by Glauert (1910). The type section is 18.9 m thick where it outcrops in McIntyres Gully, 1.6 km north of Gingin (MGA Zone 50, 395472 m E, 6534917 m N). The Gingin Chalk outcrops just north of Gingin and within Caren Caren Brook to the south of Dandaragan.

The Gingin Chalk consists of weakly to moderately consolidated chalk that is pale grey to whitish green, and is slightly glauconitic. In some areas, thin greensand beds are present that can be very difficult to distinguish from the underlying Molecap Greensand (Wilde & Low 1978). It is highly fossiliferous, containing coccoliths, foraminifera, brachiopods, molluscs, cirripedes, echinoids and crinoids, indicating a Santonian to Campanian age (Cockbain 1990).

The Gingin Chalk is present upon the southern Dandaragan Plateau, where it thins to the north and becomes sandier. Equivalent chalk units are present beneath the coastal plain in the west, where they are included into the Lancelin Formation. The formation is lenticular, and may be absent in places (Carter & Lipple 1982). The Gingin Chalk conformably overlies the Molecap Greensand or unconformably overlies the Osborne Formation (Davidson 1995) and is conformably overlain by the Poison Hill Greensand.

Toolonga Calcilutite

The Toolonga Calcilutite is a calcareous deep marine (pelagic) deposit in the Carnarvon Basin (Hocking et al. 1987) that was originally named by Johnstone et al. (1958) (Table 8). The type section near Kalbarri is 2 km north of the Yalthoo bore on Murchison House Station (Hocking et al. 1982). It is a massive, fine-grained, calcareous and fossiliferous deposit, usually containing some glauconite, with phosphate nodules locally present at the base and top of the unit (Hocking et al. 1982). It is greenish grey to white in weathered outcrop (Hocking et al. 1982; Hocking et al. 1987).

The distribution of the Toolonga Calcilutite is restricted to south of the Murchison River with very minor, thin deposits to the west of the Northampton Inlier, where it is disconformable upon the Winning Group (Hocking et al. 1982; Hocking et al. 1987). Abundant foraminifera suggest a Santonian to Campanian age (85.8 – 70.6 Ma) (Belford 1958), making it a time equivalent of the Gingin Chalk in the Perth Basin.

Poison Hill Greensand

The Poison Hill Greensand is a near-shore marine deposit that was named by Fairbridge (1953) for a sequence of greensand overlying the Gingin Chalk. The type section is in a bore at Poison Hill (MGA Zone 50, 393867 m E, 6536749 m N), about 7.5 km north–northwest of Gingin. The type section is 23 m thick but the maximum thickness probably exceeds 41 m in the subsurface (Wilde & Low 1978). Beneath the coastal plain, the upper portion of the Lancelin Formation is considered equivalent to the Poison Hill Greensand (Cockbain 1990; Davidson 1995).

The Poison Hill Greensand is similar to the Molecap Greensand in appearance, consisting of glauconitic sandstone with thin beds of dark grey-green to black glauconitic clay. The sands are unconsolidated, very fine to very coarse grained, poorly sorted, subrounded to rounded, silty and locally clayey (Playford, et al. 1976; Moncrieff 1989). Within the lower portion, the sand is very fine to medium grained and becomes coarse to very coarse grained in upper parts (Playford, et al. 1976). The sand is yellowish brown to greenish grey. In outcrop, the formation is often highly lateritised. Microplankton palynology suggests Campanian to Maastrichtian age (Playford et al. 1976; Cockbain 1990).

The Poison Hill Greensand rests conformably on the Gingin Chalk beneath the southern portion of the Dandaragan Trough and extends as far north as Watheroo. It is unconformably overlain by surficial deposits on the Dandaragan Plateau. The Poison Hill Greensand is at least 40 m thick in the Dandaragan area (Low 1965). Outcrops of Poison Hill Greensand are present from Gingin to Badgingarra (Playford et al. 1976).

Poison Hill Greensand is unconformably overlain by superficial formations on the Swan Coastal Plain in the Perth region (Davidson 1995); however, it seems it has not been identified north of AM3.

Lancelin Formation

The type section for the Lancelin Formation is between 32 and 46 m depth within Lancelin No. 2B bore (MGA Zone 50, 340068 m E, 6561938 m N), near the Lancelin township. It was previously referred to as the Lancelin Beds (Edgell 1964).

The Lancelin Formation is of marine origin comprising white, light grey to greenish brown marl with some glauconitic lenses, chalk and calcareous mudstone. It has a similar lithology to the Gingin Chalk. Wilde and Low (1978) suggested it is younger than the Gingin Chalk based on palynology, which indicates a Coniacian to late Maastrichtian age (Backhouse 1986b; Rexilius 1984).

The Lancelin Formation is present beneath the western and central portion of the coastal plain extending north to about 9 km north of the Gillingarra Line. It is an equivalent of the Poison Hill Greensand (Davidson 1995) and Gingin Chalk, and also possibly part of the Molecap Greensand (Cockbain 1990). Davidson (1995) described the formation as conformably overlying the Gingin Chalk. However, it is more likely to be conformably overlying the Molecap Greensand, or disconformably overlying the Osborne Formation. It is unconformably overlain by the superficial formations.

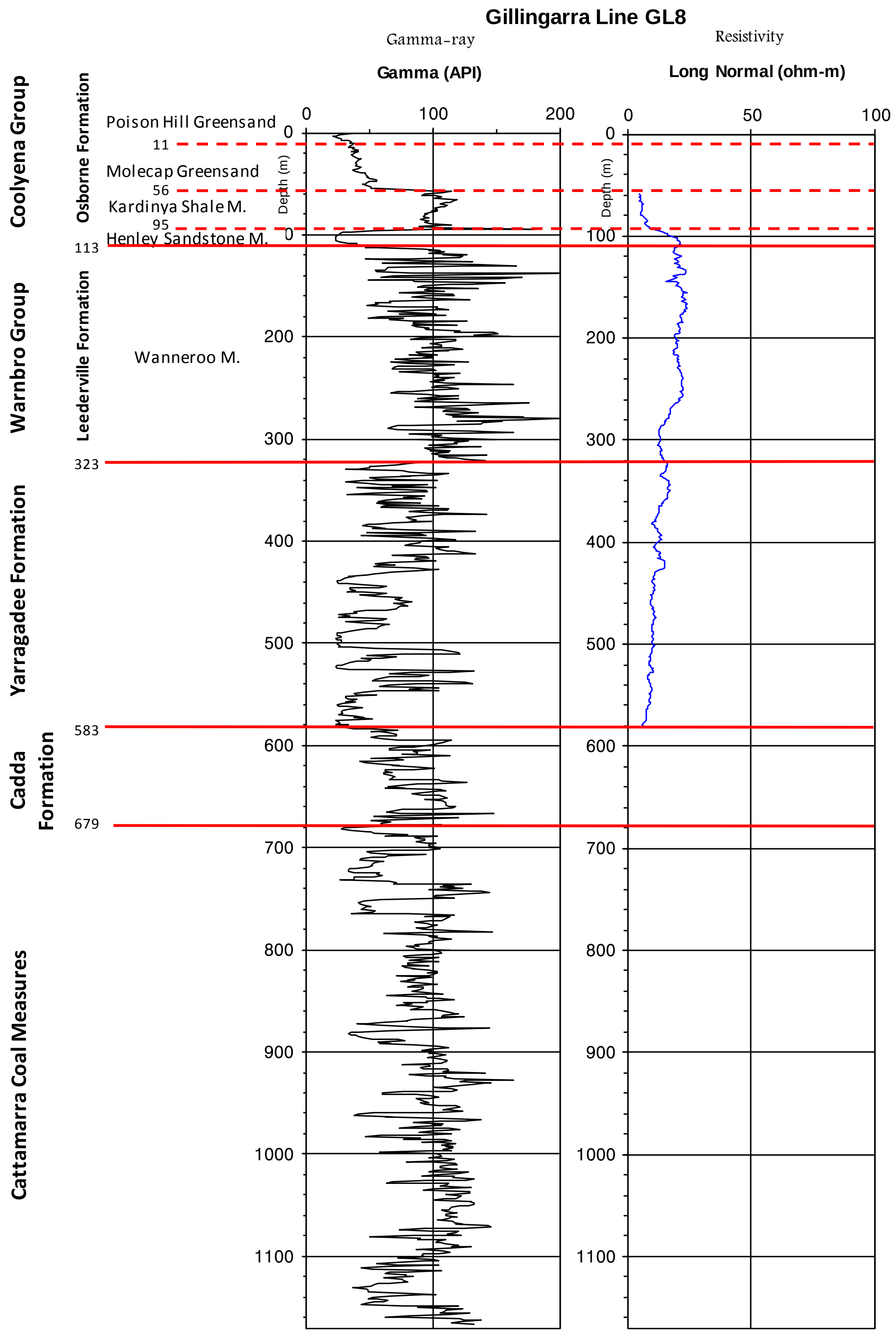


Figure 41 *Downhole geophysical log from Gillingarra Line GL8 (0–1170 m bgl) showing the Coolyena Group*

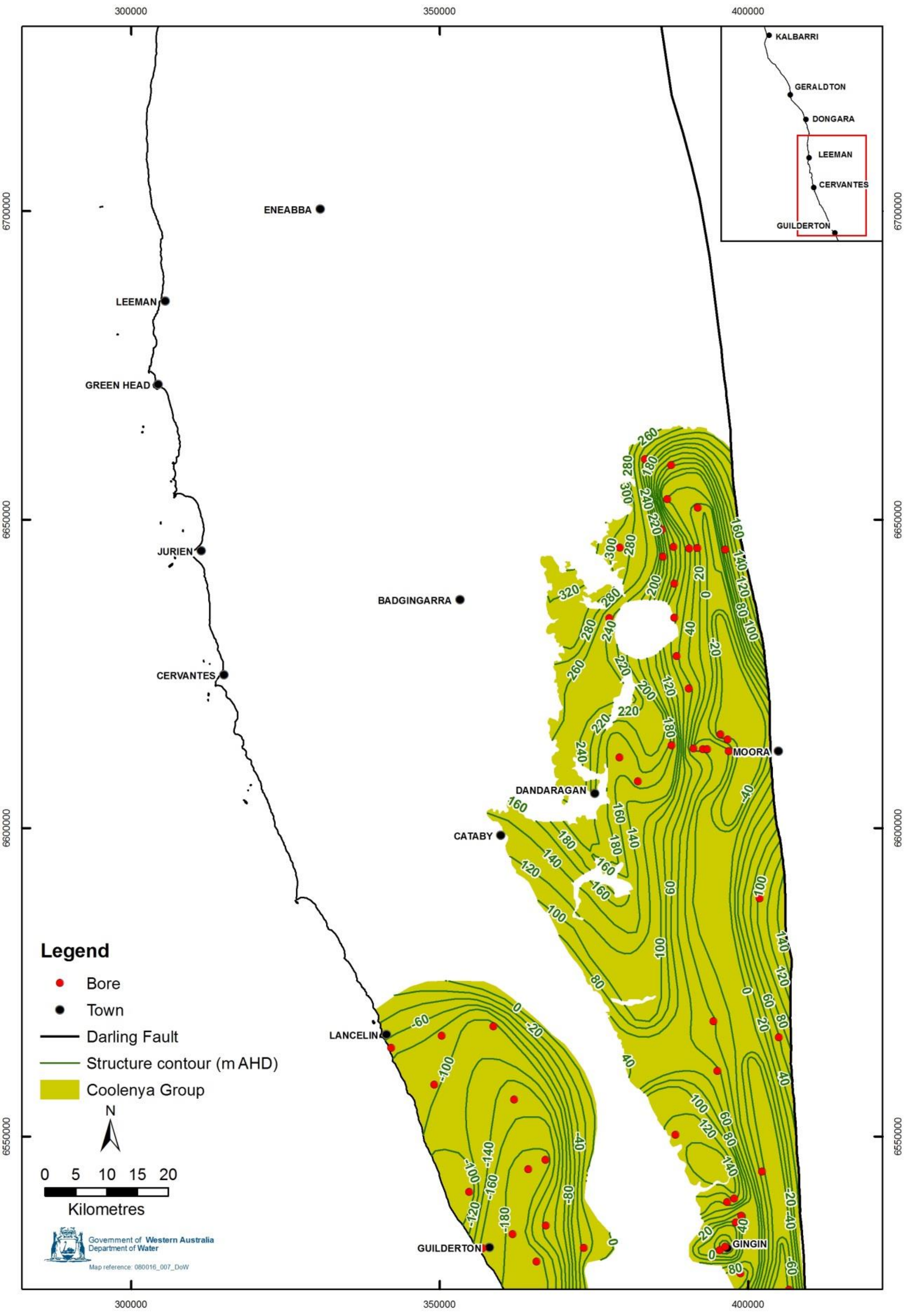


Figure 42 Coolyena Group: contours on base of unit

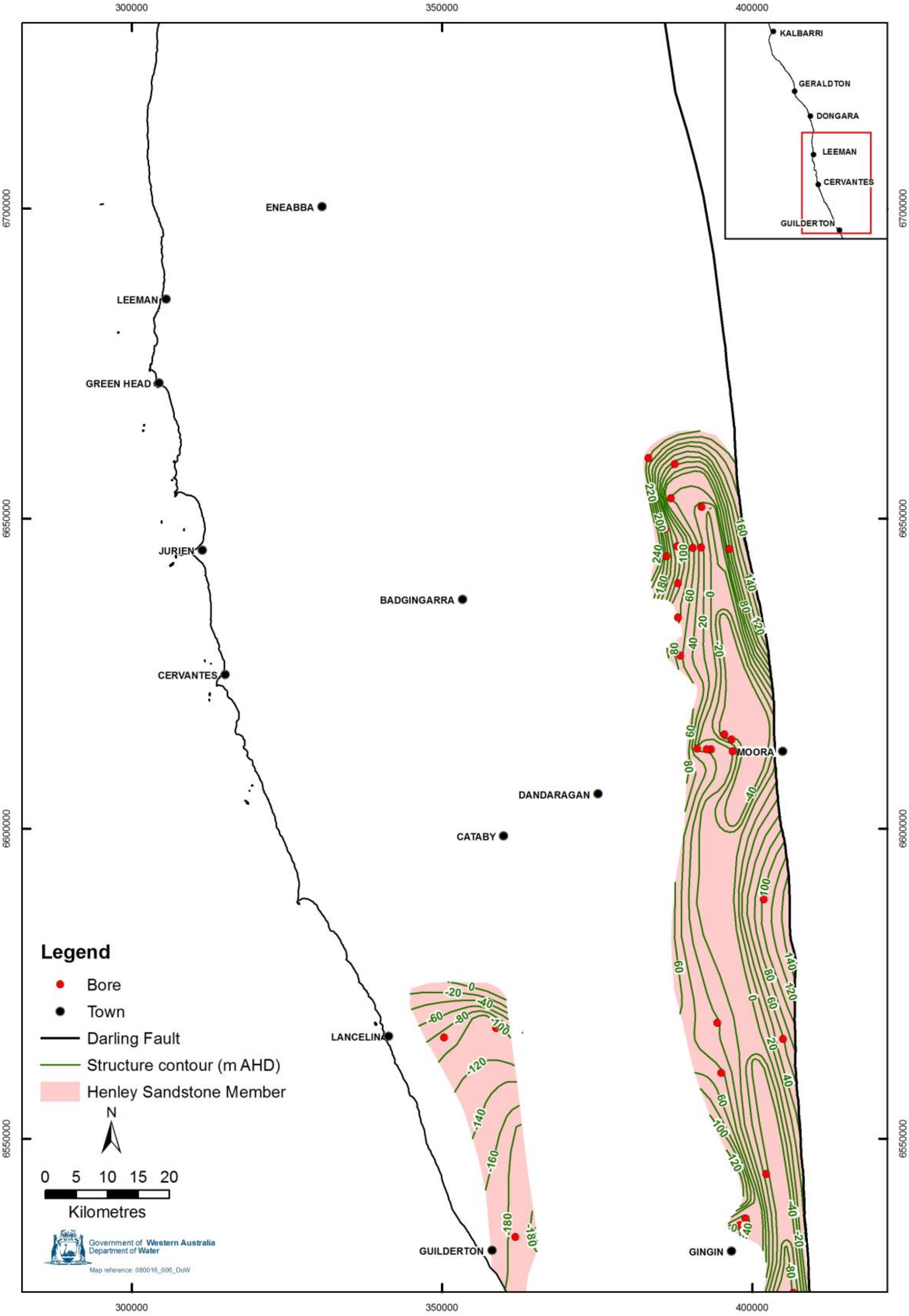


Figure 43 Henley Sandstone Member: contours on base of unit

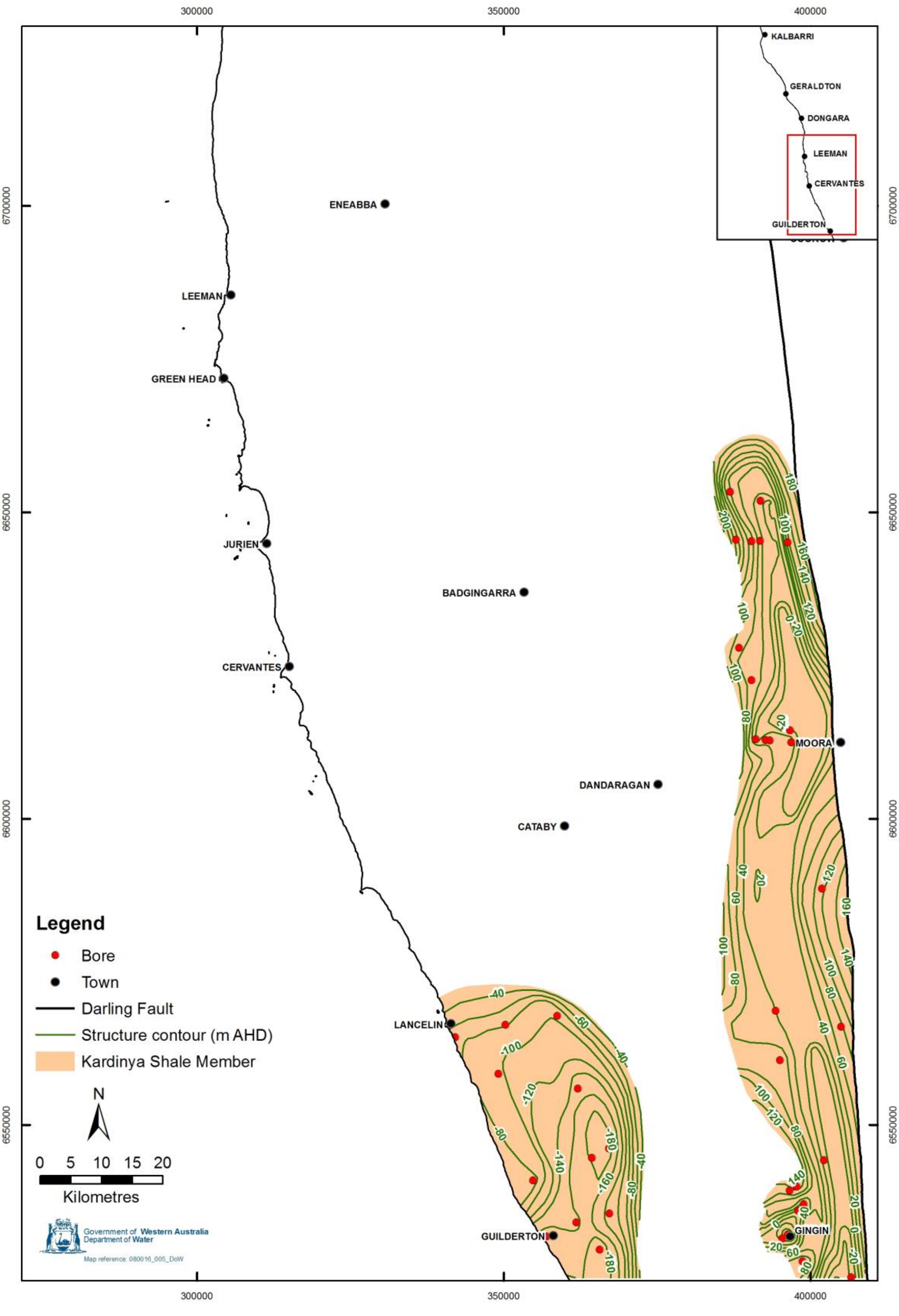


Figure 44 Kardinya Shale Member: contours on base of unit

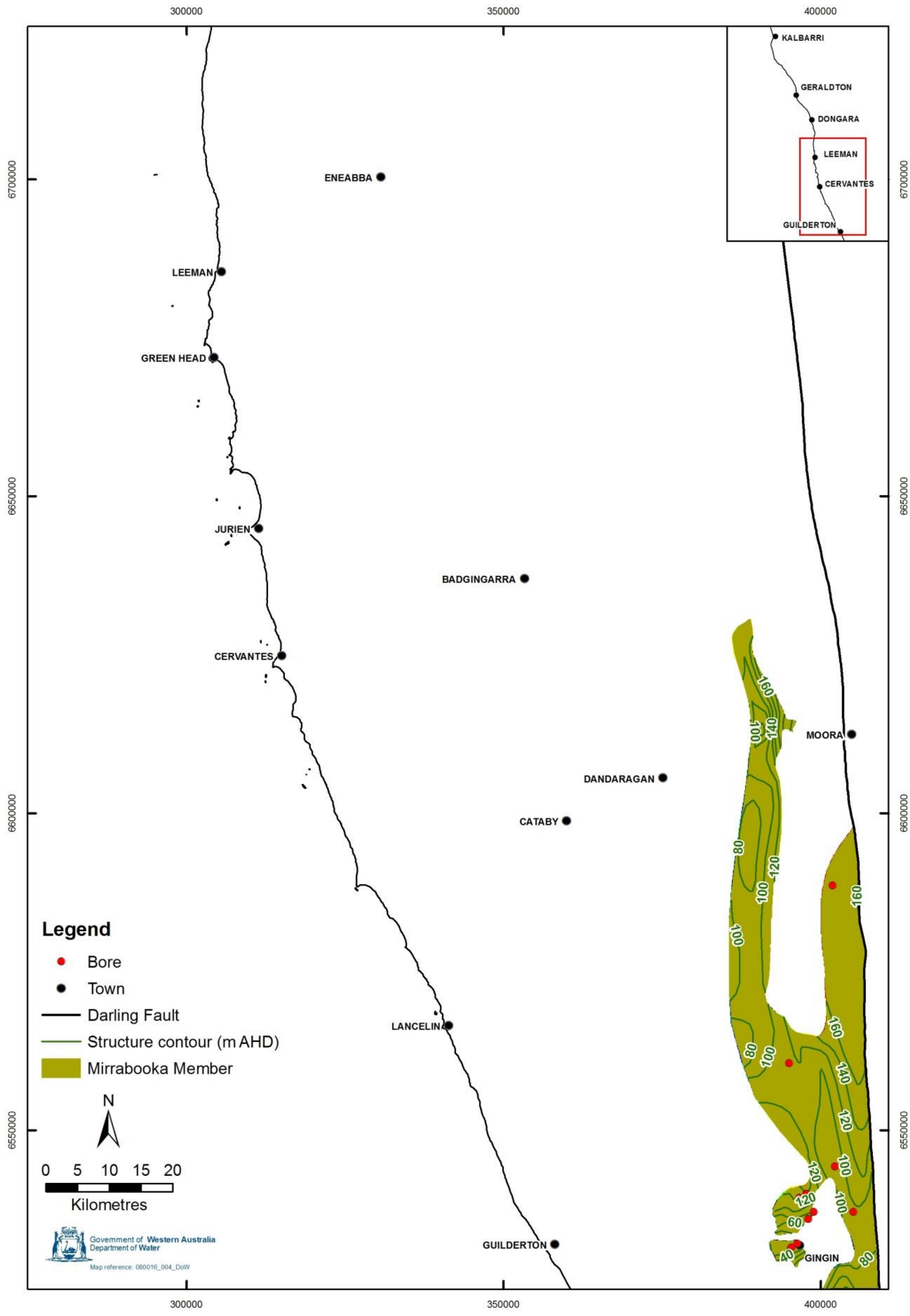


Figure 45 Mirrabooka Member: contours on base of unit

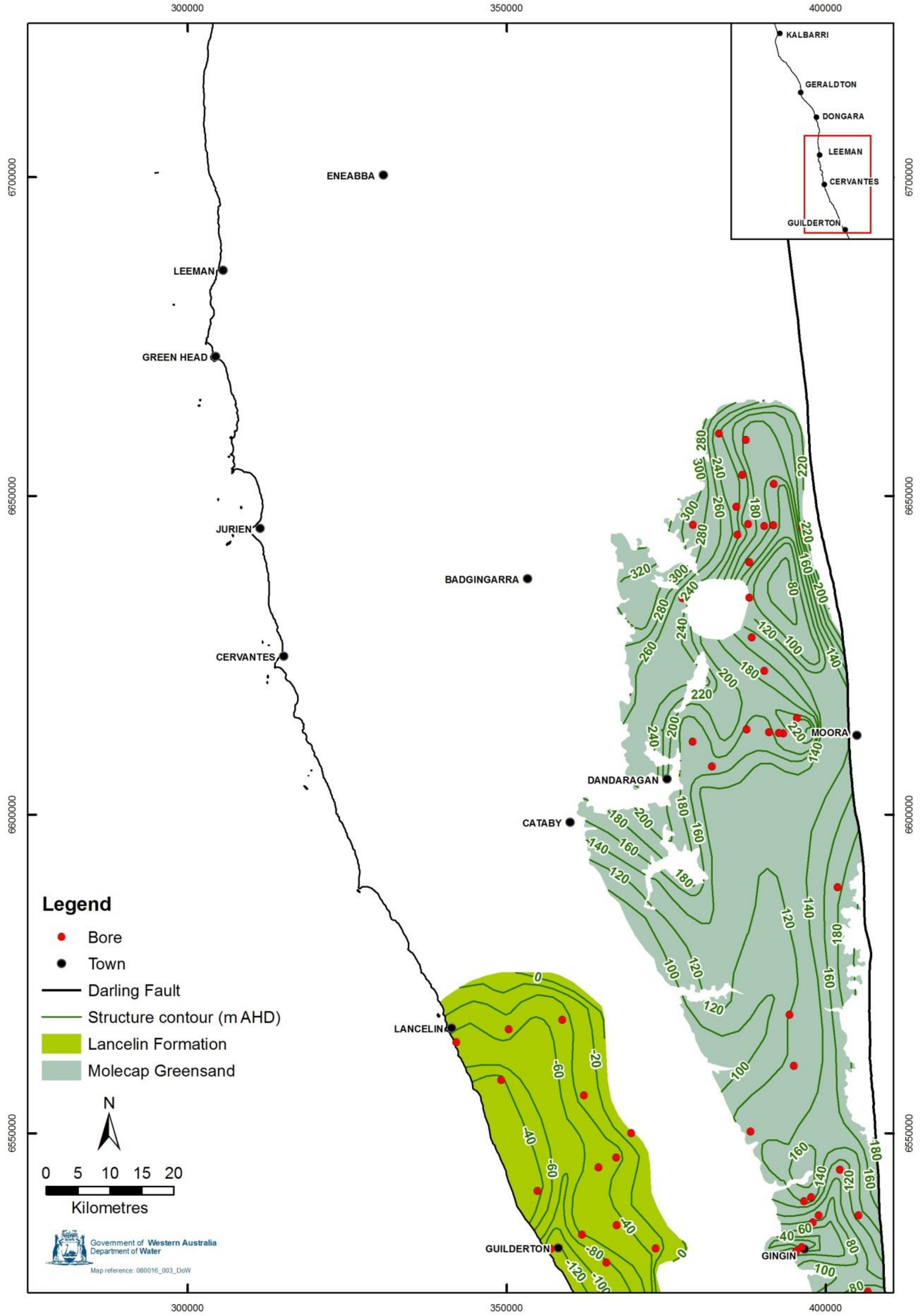


Figure 46 *Molecap Greensand (including Gingin Chalk and Poison Hill Greensand) and Lancelin Formation: contours on base of unit*

4.21 Surficial deposits

Pre-Cenozoic deposits are variably overlain by surficial deposits associated with numerous palaeochannels and a likely impact crater basin at Yallalie (Figure 47). Sediments of the surficial deposits include valley-fill, colluvial, alluvial, lacustrine, swamp and eolian deposits, and weathered lateritic profiles. Surficial deposits are considered separately to the superficial formations associated with the Swan Coastal Plain.

Table 10 Surficial stratigraphy

<table>
<tr><th>Period</th><th>Epoch</th><th>Stratigraphy</th><th>Max. onshore thickness (m)</th><th>Lithology</th><th>Depositional environment</th></tr>
<tr><td rowspan="2">Quaternary (2.6 Ma-present)</td><td>Holocene</td><td>Alluvium, colluvium, lacustrine, swamp and channel deposits</td><td>10</td><td>Sand, silt, clay, calcrete, salt</td><td>Slopes, waterways</td></tr>
<tr><td>Pleistocene</td><td rowspan="2">Channel deposits</td><td rowspan="2">153</td><td rowspan="2">Sand, clay and silt</td><td rowspan="2">Fluvial to marine</td></tr>
<tr><td rowspan="3">Neogene (23–2.6 Ma)</td><td rowspan="3">Pliocene</td></tr>
<tr><td>Yallalie Basin</td><td>111</td><td>Claystone, siltstone and sand</td><td>Lacustrine</td></tr>
<tr><td>Monger Palaeochannel</td><td>35</td><td>Sand, gravel and clay</td><td>Fluvial to lacustrine</td></tr>
</table>

Monger Palaeochannel (Yarra Yarra Lakes)

The Monger Palaeochannel is the most extensive palaeochannel deposit in the northern Perth Basin region. The palaeochannel enters the Perth Basin near Three Springs and extends below the Yarra Yarra Lakes, south along the Darling Fault to beyond Moora (Figure 47). The sediments of the palaeochannel underlie parts the Yarra Yarra Lakes and the Coonderoo River (Yesertener 1999a). It possibly follows the northern branch of the Moore River and may underlie the Wannamal Lakes system as far south as Barn Road, 15 km north-east of Gingin before joining the Brockman River east of the Darling Fault (Kay & Diamond 2001).

The Monger Palaeochannel is infilled with a basal fluvial sand and gravel variably overlain by plastic clay. The sands are fine to very coarse grained, poorly to moderately sorted, subangular to subrounded, and are coloured yellowish brown, reddish brown to greenish brown and grey. Grain size and gravel content increases with depth at some sites (Yesertener 1999b). It also contains occasional layers of clayey and silty fine-grained sand.

At the southern end of Yarra Yarra Lakes, the palaeochannel sand is overlain by pale yellowish brown clay with minor sand clay (Yesertener 1999a). This clay possibly extends northward within the channel, but is absent to the south of Yarra Yarra Lakes. Palynology from clay samples indicates a late Miocene – early Pliocene age (Milne 1999).

Calcrete up to 10 m thick is also present south of Yarra Yarra Lakes. Palaeochannel deposits 35 m thick were intersected in the Yarra Yarra Lakes investigation between Carnamah and Watheroo (Yesertener 1999a, b).

Deposits of the Monger Palaeochannel unconformably overlie the Proterozoic Moora Group; whereas south of Yarra Yarra Lakes, they overlie progressively younger Mesozoic formations including Triassic Kockatea Shale and Lesueur Sandstone, Jurassic Cattamarra Coal Measures, and the Cretaceous Parmelia and Coolyena groups. Beneath Wannamal Lakes, the palaeochannel overlies the Leederville Formation or Coolyena Group (Kay & Diamond 2001). Cenozoic sand and clay colluvium unconformably overlies the palaeochannel deposits, which can be difficult to distinguish from the palaeochannel sediments. (Yesertener 1999a).

Other channel and palaeochannel deposits

Surface water drainage lines on the Dandaragan Plateau are commonly flat-bottomed valleys with ephemeral wetlands that become infilled with sands. Some examples of this are the truncated headwaters of Eneabba Creek, and the headwaters of Minyulo and Caren Caren brooks to the south-east of Dandaragan (Commander 1981; Kay 1999). Other examples are provided below.

A significant thickness of channel infilling in modern valleys was first noted by Barnett (1970) in the Arrowsmith River valley where the Arrowsmith bores (3, 6 and 15) intersected interpreted channel deposits up to 65 m thick (Barnett 1970b). The deposits are silty, fine- to medium-grained sand with coarse-grained layers in upper parts; whereas the lower part contains mainly clay with some minor yellowish brown silt and sand, but is dark grey where unweathered. The palynology suggests a significant range in geological age. Pollen assemblages from the Arrowsmith bores are dominated by eucalyptus species indicating that the unit is non-marine and younger than Miocene, possibly Quaternary (Barnett 1970b). A dark clay outcrop between Arrowsmith bores 4 and 8 is a channel deposit remnant that has been dated as Pliocene to Pleistocene (Barnett 1970b). Subsequently, a thickness of 153 m was found in Eneabba Line bore EL6 in the valley of Eneabba Creek (Commander 1978), with a similar thickness in a nearby production bore. The channel deposits intersected in Eneabba Line bore EL6 comprise medium- to coarse-grained, well sorted sand with minor clay and accessory heavy minerals with nodular ferruginous sandstone developed at the watertable. The substantial thickness of sediments indicates that the valley was cut by a larger drainage system, with infilling occurring after capture of the headwaters of Eneabba Creek by the Hill River.

In the Capitela Palaeochannel, the sand deposits may be as much as 40 m thick (HydroConcept 2012). The channel deposits unconformably overlie older formations, mostly the Yarragadee Formation and the Parmelia Group, but also Permian formations in the east, and are typically overlain by Quaternary alluvium and colluvium. It is unknown if the channel deposits are contemporaneous with the Yallalie Basin deposits (described below), but some overlap in the time of deposition is likely.

In 2013 and 2014 DAFWA carried out exploratory drilling in the Gillingarra Palaeochannel between Gillingarra and New Norcia on the Yilgarn Craton, outside the northern Perth Basin (Figure 47). The investigation encountered up to 193 m of sediments (Speed & Kellin 2015). It is not clear how these sediments relate to palaeochannel sediments in the Perth Basin.

Yallalie Basin deposits (impact crater)

An interpreted impact crater at Yallalie, 30 km north-west of Moora, has created a sediment-filled basin about 12 km in diameter (Figure 47 and Figure 48). The impact structure coincides with a circular topographical depression and radial features evident from digital elevation mapping. Muthawandery Creek, a tributary of Minyulo Brook, drains the basin through the southern rim.

The sediments within the Yallalie Basin accumulated between 2.5 and 3.6 Ma (Dodson & Ramrath 2001) and contain a rich and diverse assemblage of Pliocene pollen types dominated by A*llocasuarina/Casuarina* and *Myrtaceae* (mostly eucalyptus), similar to modern south-western Australia flora communities (Itzstein-Davey 2003).

The deepest part of the Yallalie Basin is located near petroleum well Yallalie 1, where it is 177 m deep with a basal elevation of 38 m AHD. It gradually shallows to the east where it is 166 m deep (basal elevation of 57 m AHD) within the Agrifresh bore TB1, and 98 m (130 m AHD) at Agaton 3.

Balleau and Passmore (1972) first recognised the presence of post-Miocene sediments infilling a basin or valley based on the thick deposits and topography surrounding the ‘Yallalie depression’. Playford et al. (1976) described the area as an anticlinal feature, and named it the Muthawandery Structure; however, there was a poor appreciation of its origin. Seismic profiles captured by Ampol in 1990 indicated chaotic reflections of intensely disturbed sediments to a depth of about 2 km, characteristic of an impact feature (Economo 1991). Subsequent drilling of petroleum exploration well Yallalie 1 confirmed a localised basin with Pliocene-aged sand, clay and silt to a depth of 177 m (Economo 1991). Despite no conclusive petrographical or geochemical evidence, the morphology, presence of an allochthonous breccia deposit, and seismic reflection data is consistent with a meteorite impact feature (Dentith et al. 1999).

Geological data for the Yallalie Basin is available from a number of holes drilled within the basin, including Agaton bores 2 and 3, irrigation bore Agrifresh TB1, a stratigraphic hole drilled in 1998 and exploratory petroleum wells Cypress Hill 1 and Yallalie 1 and 2 (Dodson & Ramrath 2001).

The sedimentary sequence within the Yallalie Basin comprises a basal claystone and siltstone overlain by a sandstone unit that is concealed beneath Quaternary sand. The lower sequence of laminated silt and claystone with algal and carbonate-rich layers are black and olive grey, with traces of pyrite (Dodson & Ramrath 2001). Petroleum well Yallalie 1 intersected 111 m of this silt/claystone unit (66–177 m). The presence of dinoflagellate and algal tissue in clay and silt suggests deposition in a swamp to lacustrine setting (Dentith et al. 1999).

The overlying sandstone sequence is interbedded with carbonaceous clay and silt. It is about 54 m thick in petroleum well Yallalie 1 and is a similar thickness in other bores penetrating the unit (Economo 1991). It has a base elevation of about 150–160 m AHD. In petroleum well Yallalie 1, the overlying sandstone sequence is mottled light grey to pale yellow-brown, predominantly medium to coarse grained, moderate to well sorted, subangular to subround sand with traces of pyrite, thin carbonaceous beds and limonite (Economo 1991).

The Yallalie Basin deposits unconformably overlie the Cretaceous sediments of the Leederville Formation, which are light grey or cream at the unconformity contact (Dentith et al. 1999). There is extensive disruption of older sedimentary formations underlying the basin to a depth of about 2 km, and a central area 3–4 km across where the formations have been uplifted by about 700 m (Dentith et.al. 1999). Quaternary surface sands up to 15 m thick cover the older basin deposits.

Laterite

The surface of the Mesozoic formations has been extensively lateritised across the northern Perth Basin east of the Gingin Scarp and on basement rocks. Typically, the weathering profile consists of 2–3 m of leached quartz sand overlying massive ferruginous laterite up to 5 m thick of vesicular or concretionary rocks composed of iron and aluminium oxides (Mory 1994a). Beneath the laterite is a profile of weathered parent material up to 40 m thick that often includes a mottled zone over a pallid zone composed of significant kaolin clay. Sand at the top of the profile has been removed from substantial areas and redeposited as colluvium and alluvium within valleys, or as eolian sand, leaving laterite exposed on hilltops.

Lateritic sandstone and conglomeratic silicified deposits with minor siltstone, described as the Pindilya Formation, occur east of the Northampton Inlier, and extend into the Carnarvon Basin (Flint et al. 2000).

The laterite formed during periods of high rainfall, possibly 900 mm/yr, as a soil horizon within a zone of watertable fluctuation (Playford et al. 1976), although it is unlikely that the high gradients in the slope of the laterite surface could be maintained as a watertable in very permeable strata. It developed upon a plateau surface similar to the present day with slopes of up to 10° along surface water drainage lines (Playford et al. 1976). Originally thought to have developed during the Pliocene to Pleistocene (Prider 1966; Playford et al. 1976), palaeomagnetic data (Schmidt & Embleton 1976) suggest that the laterite formed earlier, during the Late Oligocene to Early Miocene (Johnstone et al. 1973).

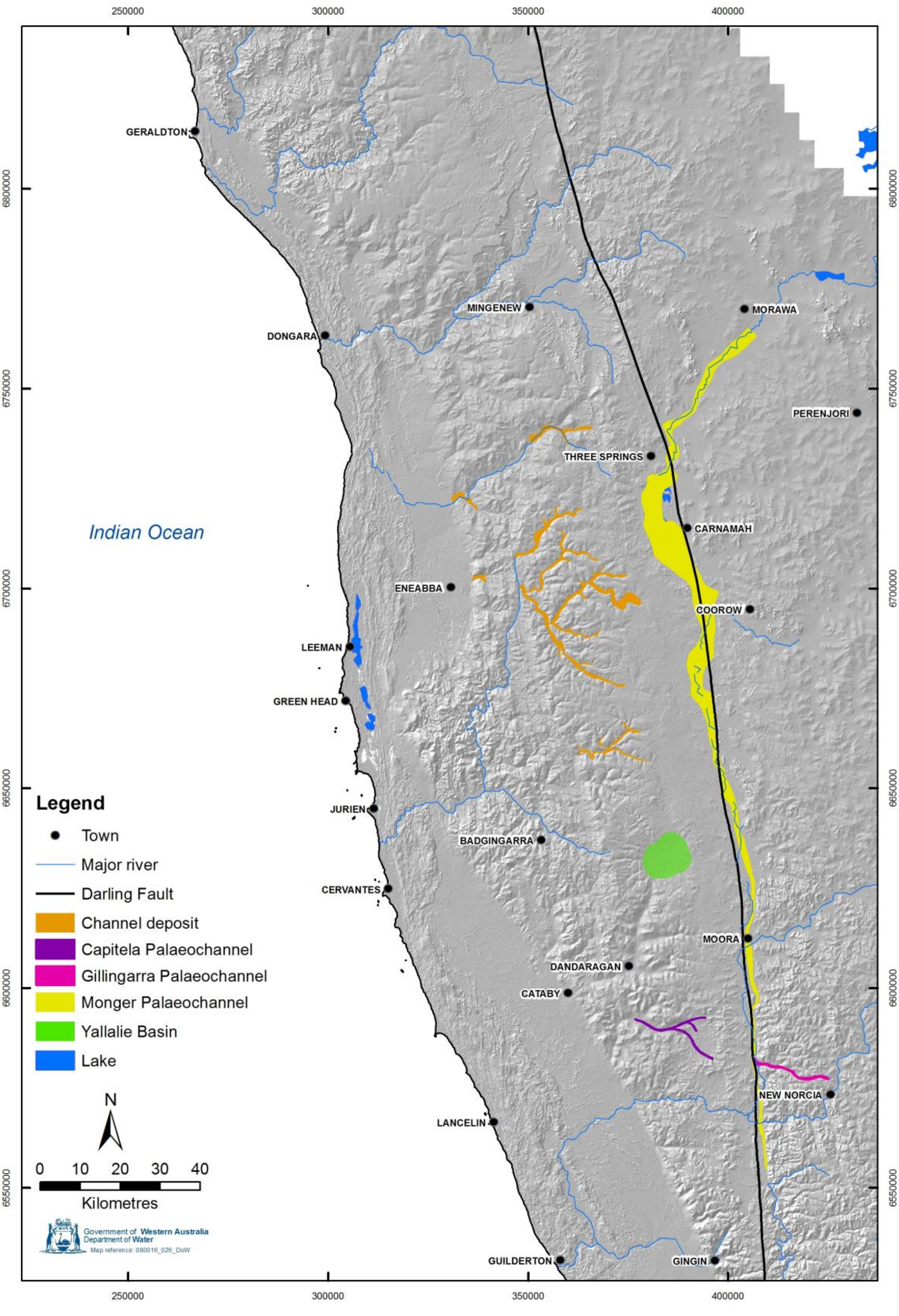


Figure 47 Surficial deposits: extent

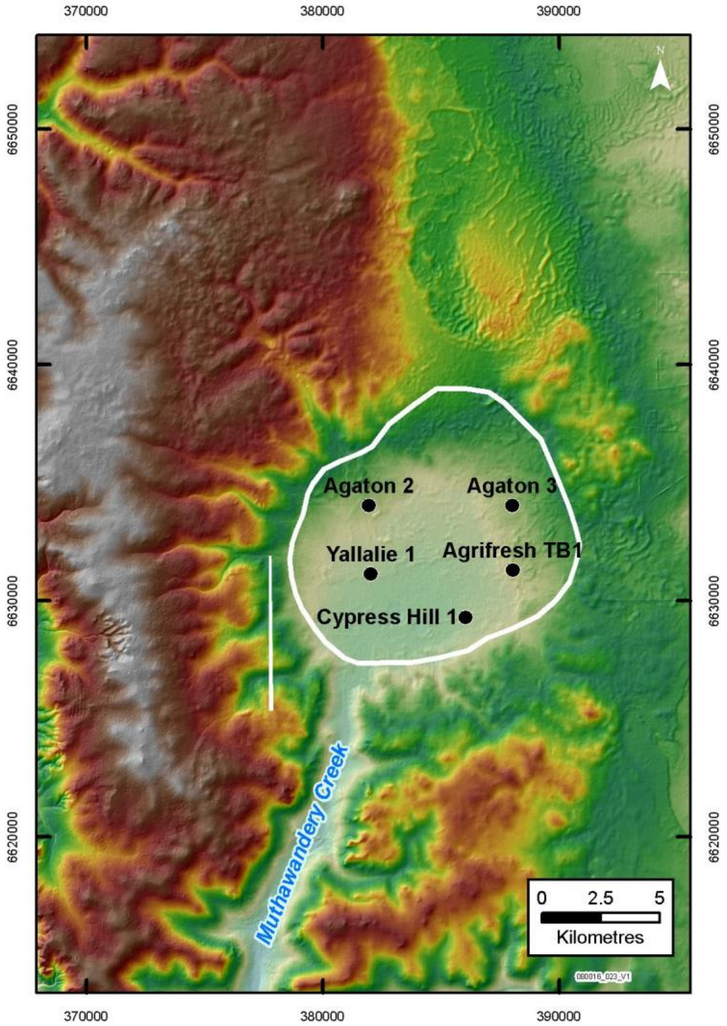


Figure 48 *Digital elevation mapping showing Yallalie Basin*

4.22 Superficial formations

The term ‘superficial formations’ was introduced by Allen (1976) to refer to the Quaternary sediments on the Swan Coastal Plain. The term has since been expanded to incorporate Pliocene sediments, including the Ascot and Yoganup formations (Moncrieff 1989; Moncrieff & Tuckson 1989) and is widely used as an informal group name (Briese 1979; Davidson 1995; Kern & Koomberi 2013, Tuffs 2011). In depositional order, they comprise the Ascot and Yoganup formations, Guildford Formation, Muchea Limestone, Bassendean Sand, Tamala Limestone, Becher Sand and Safety Bay Sand (Table 6 and Figure 49).

The superficial formations consist mainly of interbedded sand and clay, with limestone near the coast (Tamala Limestone) and at the base in some areas (Ascot Formation). They unconformably overlie a gentle, westward sloping erosional surface on Mesozoic sediments and have a maximum thickness of about 150 m and a typical thickness between 30 and 50 m (Figure 50). The geological cross-sections in Figure 51 show the stratigraphic relationships of superficial formations with underlying pre-Cenozoic lithologies.

Ascot Formation

The Ascot Formation is a calcareous marine deposit from the Pliocene age (Playford et al. 1976). The sediments were originally named the Ascot Beds (Playford et al. 1976), but were later renamed the Ascot Formation by Cockbain and Hocking (1989). The Ascot Formation is extensive between Guilderton and Cervantes, forming a north-trending belt beneath the central part of the coastal plain parallel to the Gingin Scarp (Moncrieff & Tuckson 1989; Kern 1988).

The Ascot Formation consists of hard to friable, light grey to fawn calcarenite with thinly bedded, coarse- to medium-grained sands. The calcarenite can be cavernous in the south. The sands are poorly sorted and angular to rounded and include shell fragments consisting of a rich molluscan fauna with abundant spicules and foraminifera (Kern 1988; Moncrieff & Tuckson 1989). Phosphate nodules and phosphatised fossils are at the base of the formation at some locations (Kern 1988).

The Ascot Formation was deposited in a shallow-water open-marine environment with minimal terrigenous contribution (Kern 1988), possibly a carbonate facies along a marine barrier sandbank, including a landward sand facies (Yoganup Formation) (Baxter & Hamilton 1981).

The Ascot Formation is typically 10–20 m thick, with a maximum thickness of 31.5 m in Salvado S13A near Seabird (Figure 52). The formation thins northward and is absent south of the Nambung River.

The Ascot Formation disconformably overlies the Yarragadee Formation in the north, Leederville Formation in the south, and Lancelin Formation near Lancelin. It is unconformably overlain by the Guildford Formation or Bassendean Sand and may interfinger with the Yoganup Formation to the west (Baxter & Hamilton 1981; Kern 1993a).

Yoganup Formation

The Yoganup Formation is a sand-dominated deposit representing a relic shoreline from the Pliocene age (Mory 1994a). The type section is in an open-cut mine near Yoganup (MGA Zone 50, 370433 m E, 6276070 m N), 200 km south of Perth (Low 1971).

The Yoganup Formation is a paralic deposit consisting of a prograding coastal sequence of dune, beach and deltaic deposits (Baxter 1982). The formation is dominated by fine- to coarse-grained, subangular to subrounded quartz sand, with minor clay and discontinuous concentrations of heavy minerals (Kern 1988). South of Lancelin, the sands are light grey to green-brown (Moncrieff & Tuckson 1989) and north of Cervantes, the sands are orange-brown to yellow (Nidagal 1995; Kern 1997). The sands are often leached and ferruginised, and are frequently associated with lenticular beds of kaolinised feldspar. A coarse-grained basal unit with gravels and pebbles is also common (Nidagal 1995). Heavy minerals (e.g. ilmenite, zircon and rutile) deposited along previous shorelines can be abundant and are mined at Eneabba and Cooljarloo, north of Cataby.

The Yoganup Formation is generally less than 10 m thick, but can be up to 21 m thick north of Gingin. The Yoganup Formation is a thin, discontinuous layer of fine-to-coarse sand along the eastern limit of the Swan Coastal Plain at the base of the Gingin Scarp (Baxter 1977, 1982). It has also been identified as a discontinuous deposit south of Eneabba in a belt up to 9 km wide and between Cervantes and Dongara (Kern 1993a, 1997; Nidagal 1995).

The Yoganup Formation unconformably overlies the Leederville Formation, Yarragadee Formation and Lesueur Sandstone. It may interfinger with the Ascot Formation to the west (Baxter & Hamilton 1981; Kern 1993a), although Moncrieff and Tuckson (1989) found that it overlies the Ascot Formation in the Salvado project area (Gingin Brook to Moore River). The Yoganup Formation is unconformably overlain by the Guildford Formation or Bassendean Sand, and near the Gingin Scarp is overlain by recent alluvium or colluvium. In the south near Lancelin, the western portions of the Yoganup Formation are overlain by the Tamala Limestone.

Guildford Formation

The Guildford Formation is a predominantly fluvial, clay-rich deposit adjacent to the Gingin Scarp. The sediments of the Guildford Formation were originally named as the 'Guildford Clays' by Aurousseau and Budge (1921). The terminology was later revised to 'Guildford Formation', which included a clayey and sandy facies (Low 1971). The name of Guildford Clay was later reinstated to refer to the clayey sediments, while the sand portion was attributed to the Gnangara Sand (Davidson 1995). In 2007 Gozzard reevaluated the Guildford Formation and described its relationship with the Gnangara Sand (Gozzard 2007).

The Guildford Formation comprises clay and sandy clay with lenticular beds of very fine to coarse sand. It is multicoloured, ranging from black and grey, to brown, yellow and mauve. The unit is mostly of fluvial origin, with estuarine and shallow marine intercalations, and was deposited at the coalescence of alluvial fans deposited by rivers draining the Gingin Scarp. The Guildford Formation is Pleistocene in age, based on fauna from the marine horizons in the Perth area (Darragh & Kendrick 1971).

The unit is present throughout the eastern part of the coastal plain at the base of the Gingin Scarp and is typically 30–40 m thick. The Guildford Formation interfingers with the Bassendean Sand to the west (Moncrieff & Tuckson 1989; Kern 1988; Nidagal 1995) and lies unconformably over Mesozoic lithologies or over the Yoganup Formation or Ascot Formation, where present (Moncrieff & Tuckson 1989; Kern 1997). The Guildford Formation is predominantly exposed at the surface, except where overlain by Tamala Limestone to the west or by colluvium near the Gingin Scarp (Nidagal 1995; Kern 1997).

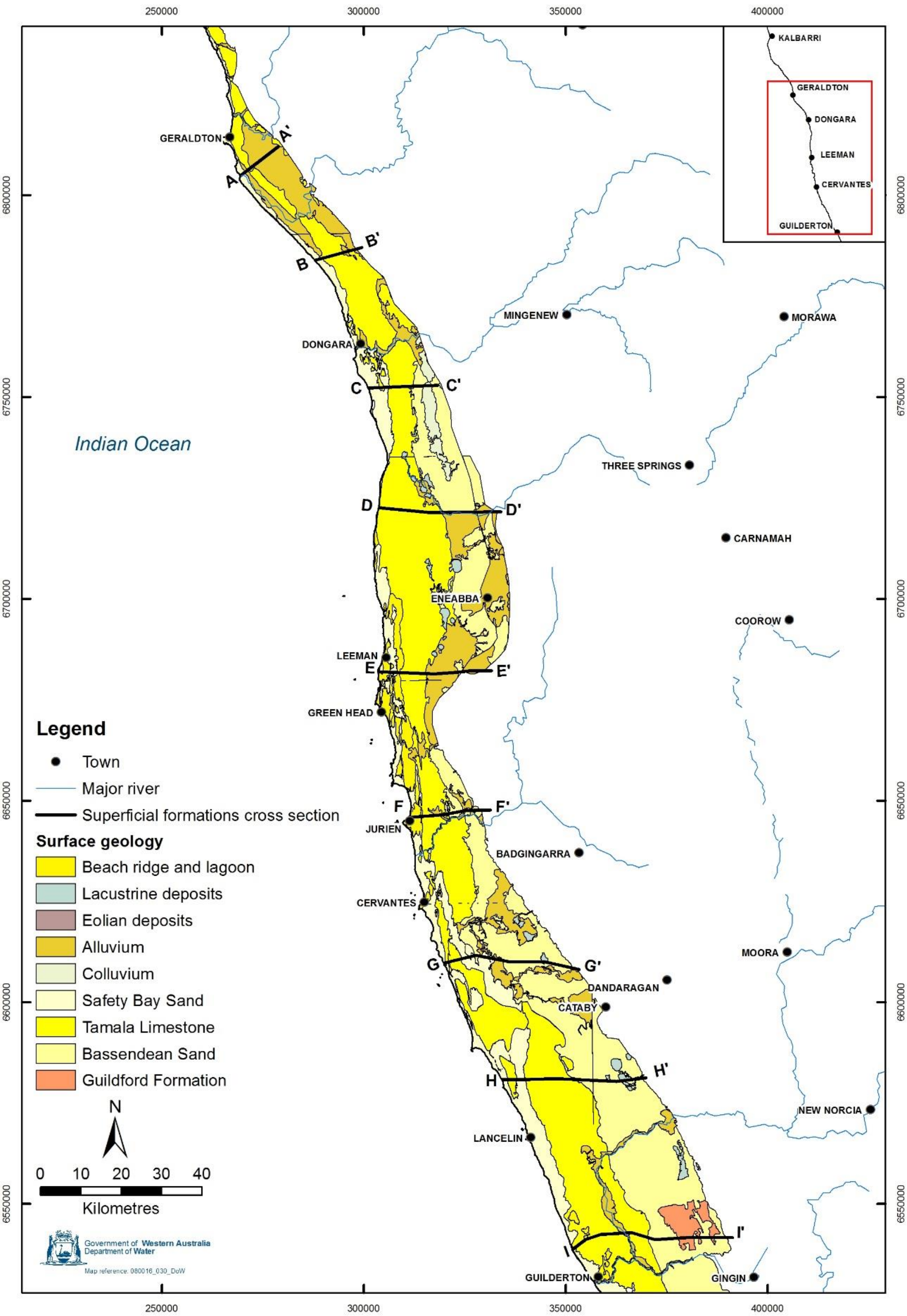


Figure 49 Superficial formations: surface geology with geological cross-sections

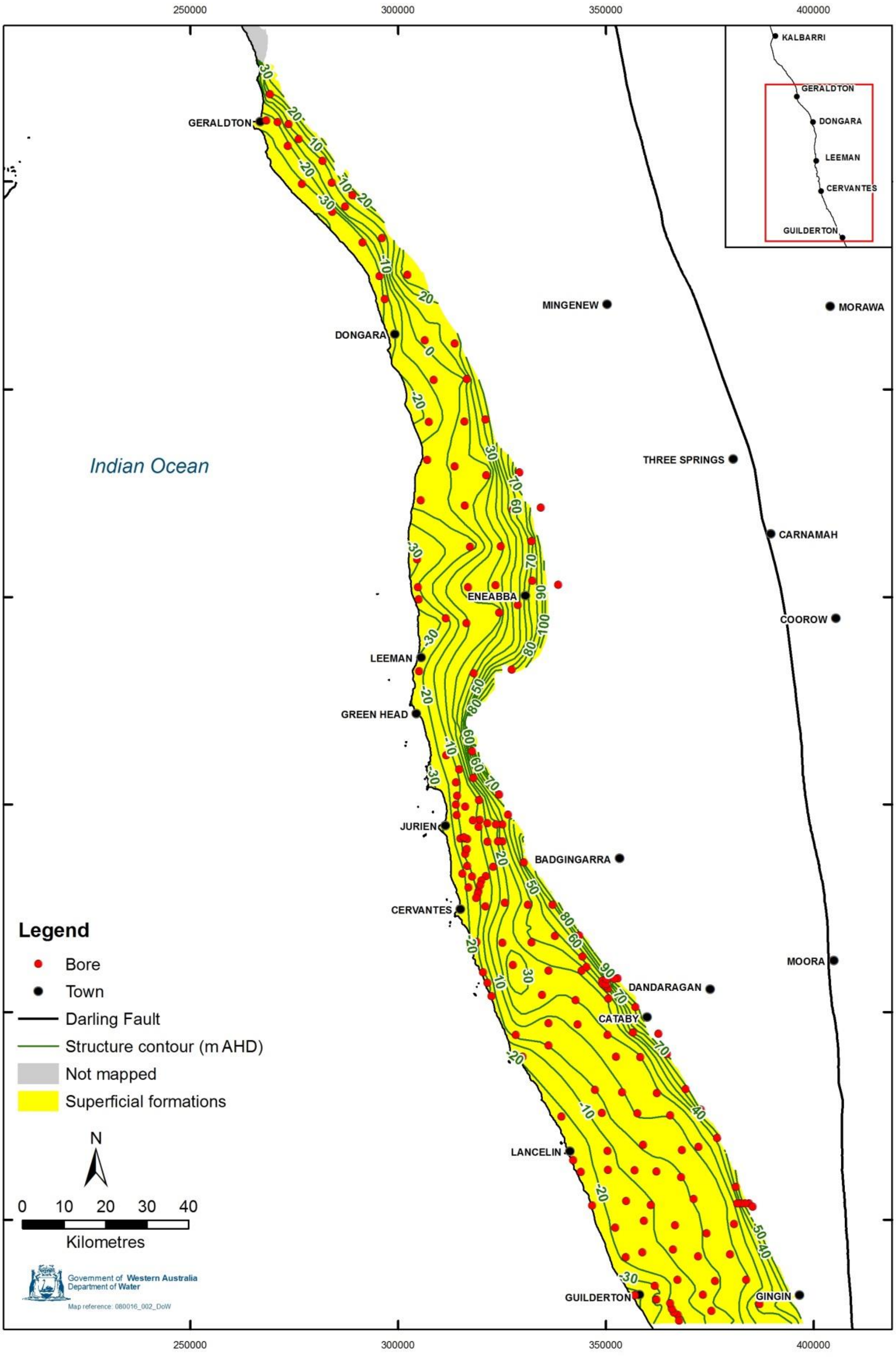


Figure 50 Superficial formations: contours on base of unit

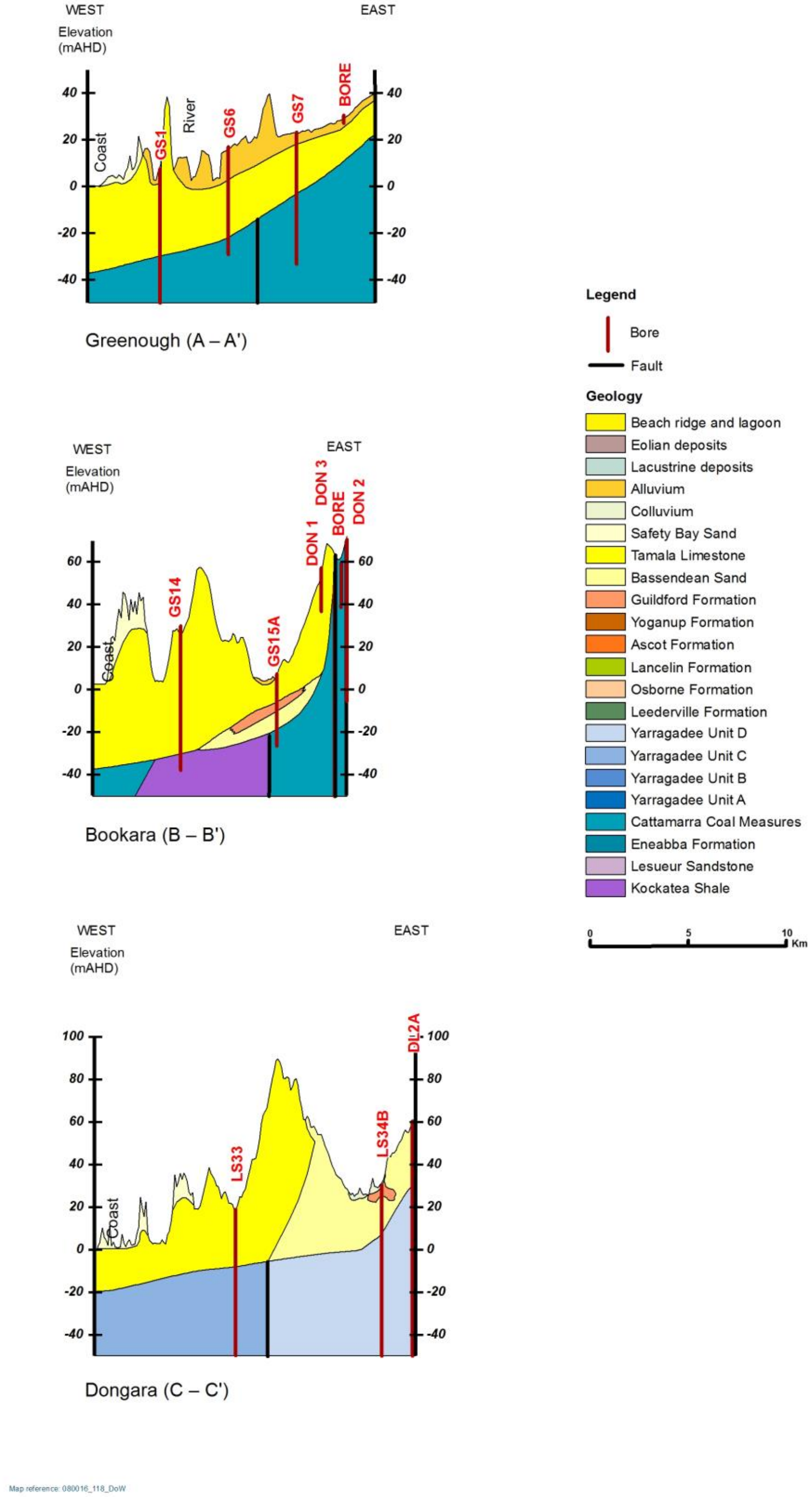


Figure 51 Geological cross-sections showing stratigraphical relationships of superficial formations

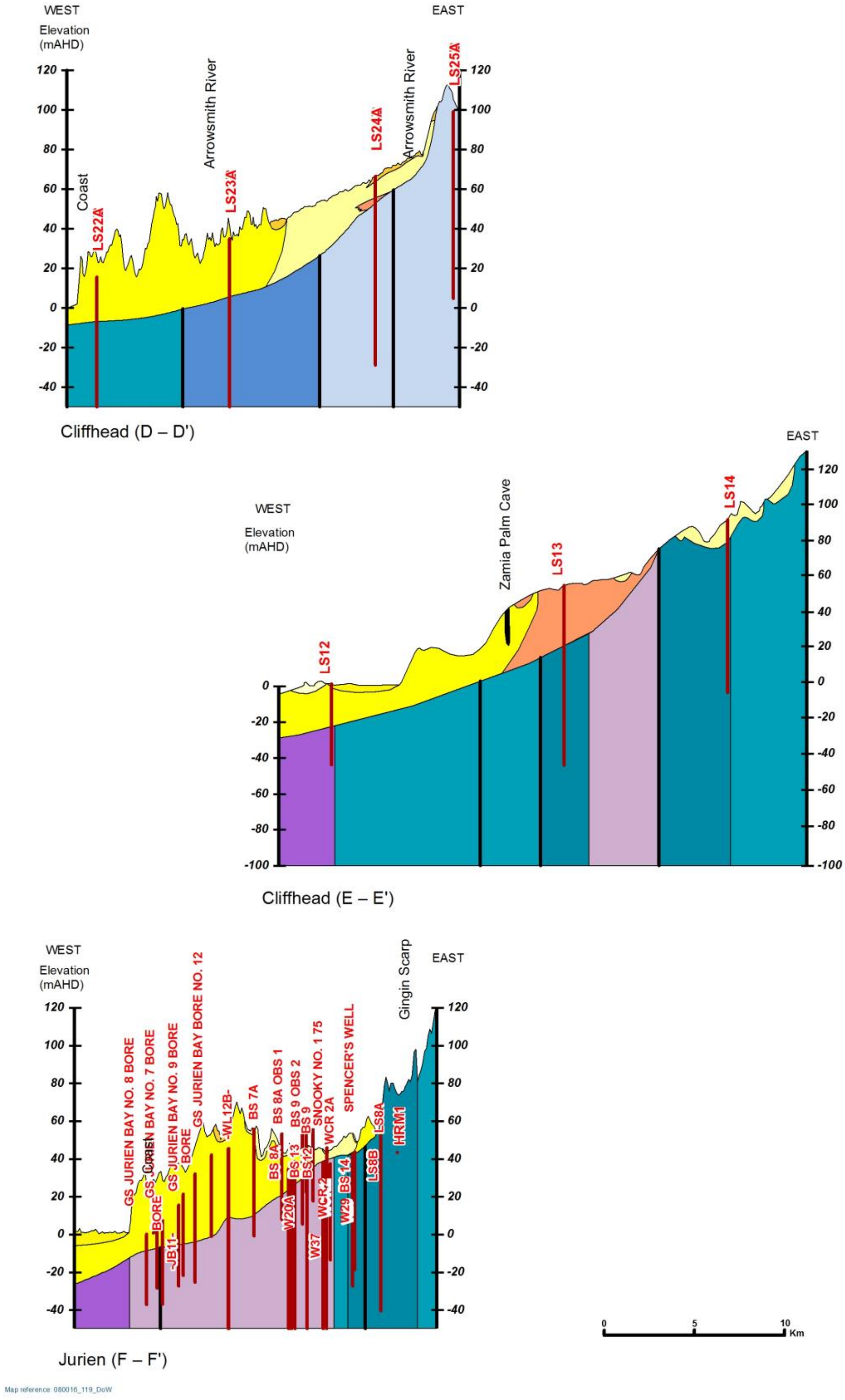
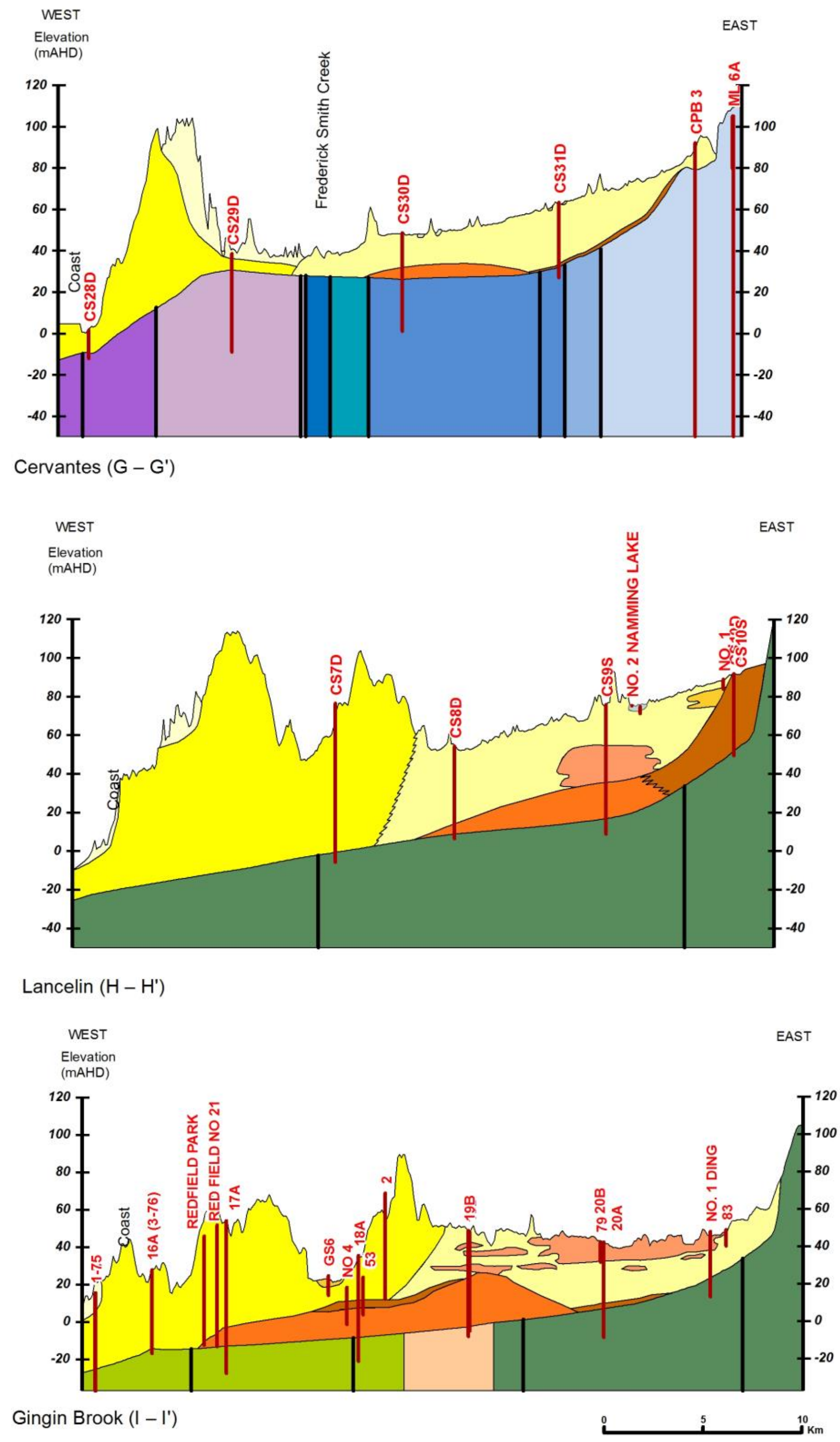
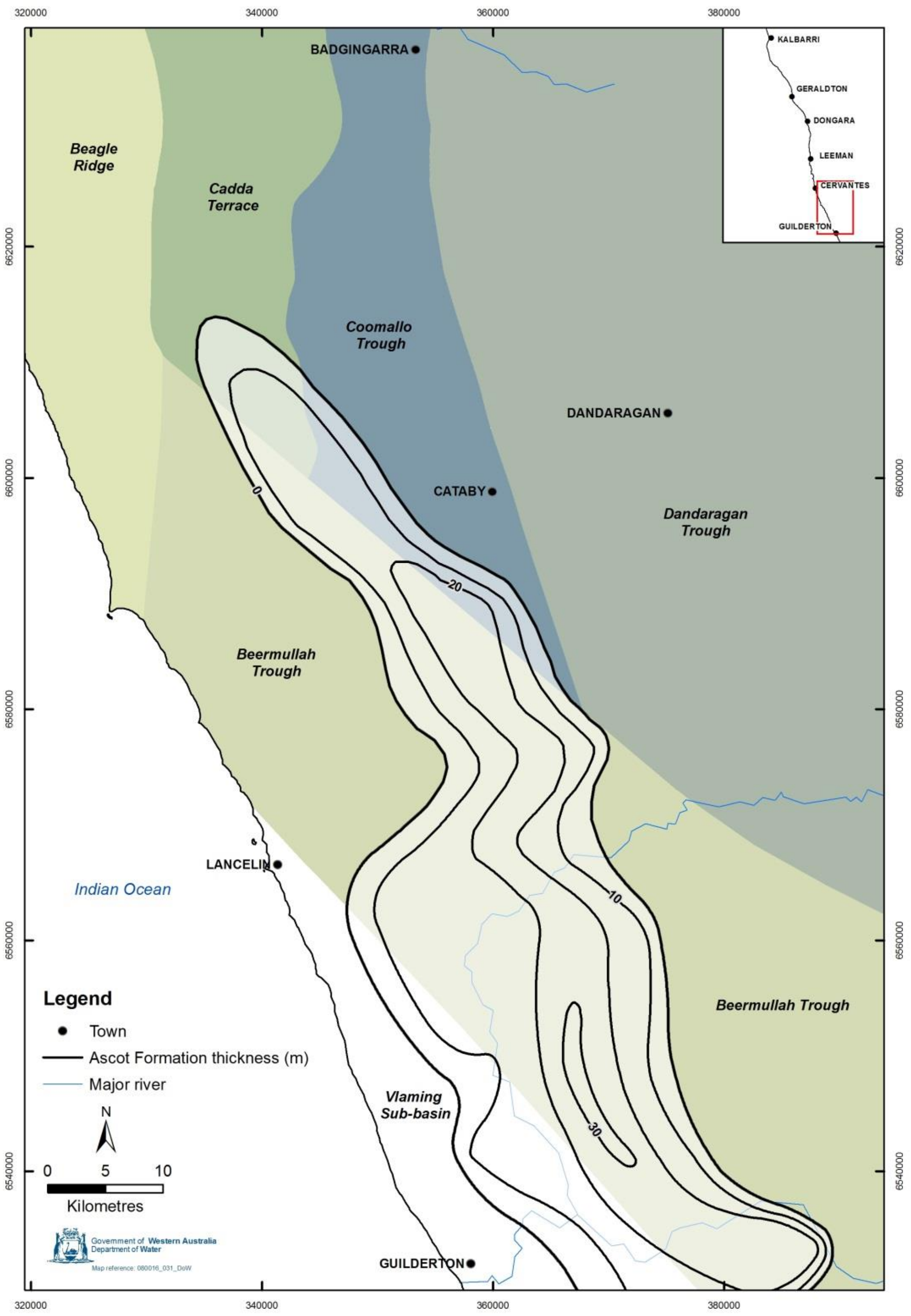


Figure 51 Geological cross-sections showing stratigraphical relationships of superficial formations (continued)



Map reference: 080016_120_DoW

Figure 51 Geological cross-sections showing stratigraphical relationships of superficial formations (continued)



(after Moncrieff & Tuckson 1989, Kern 1993a)

Figure 52 Ascot Formation: isopachs

Muchea Limestone

The Muchea Limestone is a thin shallow limestone deposit on the central and eastern Swan Coastal Plain. The unit was first recognised by Glauert (1911) and formalised by Fairbridge (1953), who named it after the town of Muchea about 40 km north-east of Perth.

The Muchea Limestone is a sandy and marly limestone (Playford et al. 1976), cream to yellow-brown, fine to medium grained, thinly bedded, and generally soft and friable, but can be hard. Some of the limestone is iron-stained to give a distinctive red colour (Hocking et al. 1976; Archer et al. 1977). The limestone contains algal laminations in places (Archer et al. 1977) and is locally fossiliferous (Moncrieff & Tuckson 1989).

The presence of freshwater gastropods suggests a lacustrine depositional environment (Kendrick 1978) during the Late Pleistocene or early Holocene (Moncrieff & Tuckson 1989). Some of the deposit may have formed by precipitation of carbonates in poorly drained pools (Archer et al. 1977).

The limestone is present in low-lying areas along Gingin Brook, near Big Bootine Swamp, and on the west bank of the Moore River (Hocking et al. 1976; Archer et al. 1977). It has not been observed to the north of Moore River. Generally, the limestone is discontinuous and less than 2 m thick, although shells in drill cuttings suggest it may reach over 11 m thick (Moncrieff & Tuckson 1989). The Muchea Limestone is either exposed at the surface or unconformably overlain by a thin cover of reworked Bassendean Sand.

Bassendean Sand

The Bassendean Sand is a widespread sand deposit from the Pleistocene epoch that covers the central Swan Coastal Plain (Playford et al. 1976). The Bassendean Sand was originally defined as a fluvial, dune, shoreline and shallow marine deposit (Playford & Low 1972). The definition of the Bassendean Sand was later restricted to the eolian sand dune deposits and the underlying fluvial and shallow marine sediments were defined as a sand facies of the Guildford Formation (Deeney 1989; Moncrieff & Tuckson 1989; Kern 1993, 1997; Nidagal 1995; Gozzard 2007). Davidson (1995) later redefined the Bassendean Sand and Guildford Formation in the Perth metropolitan area.

The Bassendean Sand consists of a light grey, grey-brown to brown, fine to medium- and coarse-grained, moderate to well sorted subangular to subrounded quartz sand. Upward-fining sequences or bimodal grain-size distribution with fine grained and coarse to very coarse grained quartz are common (Davidson 1995; Kern 1997). Traces of feldspar and carbonates are present, as well as high concentrations of heavy minerals along relic shorelines. North of Cervantes, the sands are poorly sorted (Kern 1997). North of Leeman, basal conglomerates are common, which may be calcareous in places (Nidagal 1995; Kern & Koomberi 2013). Near the watertable, the sands are frequently ferruginous and weakly cemented by limonite precipitate, which is colloquially referred to as ‘coffee rock’.

Deposition of the Bassendean Sand alternated from shallow marine to fluvial environments during one or more periods of relatively stable sea level higher than current levels (Davidson 1995). It includes shoreline, dune and fluvial settings. Estuarine and shallow marine intercalations are present at the base, while dune deposits dominate the upper portion (Kern 1993).

At the surface, the Bassendean Sand forms discontinuous low sand hills throughout the central Swan Coastal Plain, known as the Bassendean Dune System (McArthur & Bettenay 1960). The thickness of the sand is variable and largely dependent on the surface topography. The Bassendean Sand is thickest in the south, with a maximum of up to 53 m near Cataby (Kern 1988), and thins to the north where it is typically 10–30 m thick. The Bassendean Sand is not identified north of Dongara (Kern & Koomberi 2013).

The Bassendean Sand unconformably overlies Mesozoic lithologies, or where present, the Yoganup or Ascot formations (Moncrieff & Tuckson 1989; Kern 1997). It interfingers with the Guildford Formation in the east and is overlain by colluvium along its eastern extent near the Gingin Scarp (Nidagal 1995; Kern 1997). To the west, it is overlain by Tamala Limestone (Kern 1988; Davidson 1995).

Tamala Limestone

The Tamala Limestone is a calcarenite sand deposit along the coastline of both the Perth and Carnarvon basins. The Tamala Limestone was named by Playford et al. (1975) to describe calcareous sediments previously referred to as 'Coastal Limestone' or 'Tamala Eolianite' (Logan 1968) that extend along the coastal fringe of the Perth and Carnarvon basins. The type section is an outcrop at Womerangee Hill on the Zuytdorp Cliffs about 100 km north of Kalbarri in the Carnarvon Basin (Playford et al. 1975).

The Tamala Limestone consists mostly of calcarenite sand, with variable amounts of quartz sand and minor clayey sediments. It is cream, yellow-brown and light grey in colour, fine to coarse grain size and moderately to very well sorted. An orange limonite coating on the sand is common. It is composed of quartz sand and skeletal fragments, mostly of foraminifera and molluscs, together with traces of feldspar and glauconite, as well as phosphate-rich nodules near the base where it overlies Cretaceous lithologies in the south (Moncrieff & Tuckson 1989). The limestone is characterised by large-scale eolian cross-bedding and contains common relic soil horizons and calcified root structures (Playford et al. 1976; Kern 1997). Clayey lacustrine sediments are present between limestone ridges in some localities such as east of Wedge Island (Kern 1988) and near Geraldton. A basal clayey sand and clay is frequently present (Baddock & Lach 2003).

The calcarenite is variably cemented to form a lithified to friable limestone. The degree of cementation is greatest near the coast (Moncrieff & Tuckson 1989), and a hard 'capstone' is frequently developed at the top of limestone (Kern 1997). Leaching of carbonate by rainfall has left a residual yellow to white quartz sand as a surface cover, predominantly in eastern parts where it can be up to 100 m thick (Kern 1988).

In places, the loose sand has been eroded by wind action but pinnacles of calcified limestone are preserved. This effect can be observed at the Pinnacle Desert near Cervantes. Karstic features associated with dissolution of the carbonate in the limestone have developed over much of the Tamala Limestone outcrop. These karstic features include extensive development of vertical solution channels and cavities and solution pipes that may have developed from calcified root structures (Playford et al. 1976; McNamara 1983). These solution pipes and cavities are most common near the watertable and are often filled with sand. Cave systems are present at several locations including Nambung National Park, Drovers Cave National Park and nature reserves east of Leeman and Coolimba.

The Tamala Limestone developed as coastal dunes associated with successive sea-level stands (Playford et al. 1976), mostly from eolian deposits, but lower portions contain marine, littoral or lagoonal facies (Moncrieff & Tuckson 1989). Deposition commenced during the Middle Pleistocene and extended to the Late Pleistocene (Kendrick et al. 1991). The age of shell and coral material are between 117 100 and 132 000 years before present (BP) (Mory 1995b). The most easterly dunes form the Spearwood Dune System that consists of slightly calcareous eolian sand that remains after leaching of the underlying limestone (McArthur & Bettenay 1960).

The Tamala Limestone is present along the west coast as a band of successive ridges about 10–20 km in width parallel to the coast (Figure 49). North of Geraldton, on the margins of the Northampton Inlier, the formation narrows to less than 5 km. The thickness of the Tamala Limestone varies significantly, dependent on surface topography with an average thickness of about 40–50 m. The limestone probably reaches 120 m at Vern Hill (12 km north-east of Cervantes) (Kern 1997), and may be up to 150 m thick south of Nambung National Park (Kern 1988) and in the Hutt River area (Playford et al. 1976). There are frequent outcrops over the Spearwood Dunes and upon wave-cut platforms (<2 m AHD) exposed in the Coolimba–Cervantes and Denison areas. Coastal cliff outcrops are also common and are up to 75 m high (south of Hutt River). The base of the formation slopes westward, extending to about 25 m below sea level along the present coastline (Commander 1981).

The Tamala Limestone unconformably overlies various subcropping pre-Cenozoic formations. Near its eastern margin on the Swan Coastal Plain, the formation overlies and possibly interfingers the Guildford Formation and Bassendean Sand (Kern 1993; Kern & Koomberi 2013). North of the coastal plain, the Tamala Limestone unconformably overlies an eroded surface upon Proterozoic basement, and Triassic and Jurassic sediments. The Tamala Limestone is disconformably overlain by the Becher Sand (where present) and Safety Bay Sand adjacent to the coast. Sandy alluvium overlies the formation along the Moore River and Gingin Brook (Moncrieff & Tuckson 1989), and west of the Gingin Scarp sand from outwash fans north of Dongara (Kern & Koomberi 2013).

Becher Sand

The Becher Sand consists of near-shore marine deposits from the Holocene that continue to be deposited along the coast on the Swan Coastal Plain (Semeniuk & Searle 1985). Previously, these marine sands were included with the Safety Bay Sands, but were separated owing to different depositional environments and apparent age (Semeniuk & Searle 1985; Mory 1994a). The type section for the Becher Sand is an outcrop adjacent to the coast at Woodman Point, about 20 km south of Perth.

The Becher Sand is light grey to light grey-brown, fine to medium grained, well sorted, subrounded to rounded quartz and skeletal sand (Semeniuk & Searle 1985). It includes a fawn coloured, calcareous mudstone intersected over 2 m at Seabird in bore Seabird 1/75 (Moncrieff & Tuckson 1989).

The Becher Sand is present along most of the coastline of the Swan Coastal Plain and as low ridges parallel to the shore south of Leeman, at Jurien Bay and near Cervantes (Mory 1994a). The sediments of the Becher Sand are associated with littoral sandbanks, beach–dune ridges and a sea-grass bank sequence (Moncrieff & Tuckson 1989; Mory 1994a, 1995a).

The Becher Sand has been intersected by drilling at several sites between Guilderton and Lancelin, where it is generally only a few metres thick (Moncrieff & Tuckson 1989). In the Perth region, it is 10–15 m thick with a maximum of 20 m in the Rockingham area. The Becher Sand unconformably overlies the Tamala Limestone, and is often conformably overlain by the Safety Bay Sand (Moncrieff & Tuckson 1989).

Safety Bay Sand

The Safety Bay Sand encompasses the eolian sand dunes of the Holocene that continue to be deposited along the coast of the Swan Coastal Plain. The Safety Bay Sand was originally defined to include both eolian sand and shallow marine sand deposits (Passmore 1967; Playford & Low 1972) but the marine and shoreline components (Becher Sand) were later removed from the formation (Semeniuk & Searle 1985). The designated type section is from surface to 24 m depth in Rockingham bore R3 (MGA Zone 50, 378216 m E, 6427776 m N) in the Perth metropolitan area (Passmore 1967).

The Safety Bay Sand consists of cream to buff, loose to moderately cemented, fine- to medium-grain size calcareous sand. It is moderately to well sorted, and angular to rounded (Playford et al. 1976). The calcium carbonate content is generally greater than 50 per cent. The sand also includes fragments of molluscs, bryozoan and foraminifera as well as traces of heavy minerals (Kern 1997). This Holocene unit continues to be deposited (Playford et al. 1976).

The Safety Bay Sand occurs discontinuously along the entire length of the Swan Coastal Plain and extends up to 14 km inland (Kern 1988; Mory 1995a) forming dunes of the Quindalup Dune System (McArthur & Bettenay 1960). Most of the dunes are stabilised by vegetation cover, but there are significant areas of bare mobile dunes with parabolic dunes and blowouts developed north of Lancelin (Moncrieff & Tuckson 1989).

The thickness of the Safety Bay Sand is highly variable, and may exceed 100 m over parts of the coastal plain. The base of the sand is about 5 m below sea level at the coast (Kern 1988). The Safety Bay Sand unconformably overlies the Tamala Limestone, and near Cervantes overlies shoreline beach ridges of the Becher Sand (Mory 1995a).

Miscellaneous deposits

Minor Holocene deposits, usually less than 10 m in thickness, are found locally throughout the region (Lowry 1974).

Eolian deposits form isolated low sand ridges that are most extensive across the Victoria Plateau and Yarra Yarra region. The orange-coloured quartz sands have been derived mainly from sand at the top of the lateritic weathering profile. A wide dune containing gypsum sand has developed about the south-eastern margin of the Yarra Yarra Lakes (Baxter

& Lipple 1985). A similar dune sand deposit about 65 km north of Mingenew was found dated at between 15 000 and 120 000 years old (Mory 1995b).

Along the Gingin Scarp, clay to gravel and laterite clasts deposited in fans are derived from erosion of laterite-capped sediments in the Arrowsmith region and Dandaragan Plateau (Nidagal 1995; Kern 1997; Kern 1988, Kern & Koomberi 2013). Deposits of colluvium consisting mainly of sand washed down from the laterite above may also develop on slopes beneath laterite breakaways. Recent alluvium is common within the valleys of streams and rivers, including the Arrowsmith River (Nidagal 1995), the Moore River (Moncrieff & Tuckson 1989), Caren Caren, Minyulo and Mullering brooks (Kern 1988) and the Chapman, Greenough and Irwin rivers (Kern & Koomberi 2013). The alluvial deposits include silt and clay, often intercalated with fine- to coarse-grained subangular to subrounded quartz sand (Nidagal 1995; Kern 1988). The thickness of these alluvial deposits is generally less than 5 m, but can be up to 20–30 m in places (Kern 1997; Kern & Koomberi 2013).

Lacustrine and swamp deposits are found within interdunal wetlands and lakes throughout the coastal plain, particularly in the Bassendean Dunes (Kern 1988, Ryan 2012a). These sediments consist mainly of clay, peat and marl, but can also contain diatomite where there has been minimal clastic sediment input and thicknesses can vary (Mory 1994a; Kern 1988, 1997). At Lake Thetis, lakebed sediments are up to 8 m thick and underlie the Safety Bay Sand, reflecting the contraction of the lake basin (Ryan 2012a). Stromatolites are present at Lake Thetis, near Cervantes (Grey et al. 1990), and calcrete and halite salt deposits are present at the Yarra Yarra Lakes. A series of lagoonal and estuarine deposits underlying modern saltlakes are also found between Green Head, north of Jurien Bay and Coolimba, parallel to the coast. These lagoonal and estuarine deposits consist of marl, shell beds, clay, silt, gypsum and halite (Kern 1997), and at Hutt and Leeman lagoons are up to 5 m thick (Kern 1997).

5 Aquifers of the northern Perth Basin

Aquifers are geological formations that are capable of storing and transmitting water, and it is these formations that are used for groundwater abstraction. Aquifers at the top of the groundwater system are categorised as unconfined aquifers and contain the watertable at the interface of the saturated and unsaturated zones. These aquifers directly receive recharge by rainfall and may support GDEs. Deeper aquifers that are hydraulically isolated from the watertable by lithologies with low hydraulic conductivity are characterised as confined aquifers. Confined aquifers do not directly receive rainfall recharge. However, recharge is by downward leakage of groundwater from the overlying aquifers where aquitards are absent and where downward hydraulic head prevails. Hydraulic head in confined aquifers can exceed the pressure at the land surface, resulting in artesian conditions.

This chapter summarises the current knowledge of the aquifers of the northern Perth Basin. Section 5.1 presents an overview of the groundwater system, including the relationships between geological formations and hydrogeological units (aquifers and aquitards), depth to watertable across the region, the distribution of major aquifers and hydrogeological cross-sections.

Subsequent sections then describe each aquifer of the northern Perth Basin in age of formation order, from youngest to oldest (and top to bottom). This includes groundwater flow mechanisms (e.g. recharge, flow, discharge), hydraulic parameters, water levels, salinity, hydrochemistry, groundwater age and broad estimates of groundwater throughflow. In addition, this chapter includes information on the distribution of aquitards. Vertical leakage rates through confining units can be found within the groundwater recharge and discharge sections of the relevant aquifer descriptions.

This bulletin focuses only on the active meteoric groundwater flow system, where groundwater flow is maintained by recharge from rainfall, and in which groundwater has relatively low salinity (i.e. less than 1000 mg/L TDS). Groundwater below depths of more than 1000 m is progressively saline or hypersaline. The generally poor water quality and high drilling and construction costs for production bores means deep aquifers are not currently a viable groundwater resource and are therefore not addressed here.

This chapter concludes with a description of the potential geothermal resources of the northern Perth Basin.

5.1 Groundwater system overview

The primary major aquifers of the northern Perth Basin are the Superficial, Leedervile, Leederville–Parmelia and Yarragadee aquifers. The relationships between these aquifers, and distributions of hydraulic head and salinity, are shown in the hydrogeological cross-sections presented in Figure 55 and Figure 56. Each of these cross-sections corresponds to one of the deep borehole lines described in Section 2.1, and their locations are shown in Figure 53.

As part of the deep borehole line investigations and during the development of groundwater resources, a large number of aquifer tests have been undertaken. The locations of bores with aquifer test data are shown in Figure 54. The results of these aquifer tests are summarised in the aquifer descriptions and presented in detail in the appendices.

The Superficial aquifer is the major unconfined, multilayered aquifer in the northern Perth Basin present as far north as Geraldton. The aquifer is found across most of the Swan Coastal Plain between the Gingin Scarp in the east and the Indian Ocean to the west. The aquifer directly overlies aquifers or aquitards consisting of sedimentary rocks of Cretacous age or older.

The Leederville and Leederville–Parmelia are both major aquifers associated with the extensive Leederville Formation and are up to several hundred metres thick. In the south-west of the northern Perth Basin, where the Parmelia Group is absent, the Leederville Formation forms the Leederville aquifer. In the south-east, where the Leederville Formation is underlain by the Parmelia Group, these lithologies form a hydraulically continuous unit that is effectively indistinguishable and is collectively defined as the Leederville–Parmelia aquifer.

The Leederville aquifer is confined in the northern Perth Basin. The Leederville–Parmelia aquifer and Yarragadee aquifer are variably confined in the northern Perth Basin, with unconfined conditions in large areas of the Arrowsmith region and Dandaragan Plateau.

Below the Leederville and Leederville–Parmelia aquifers is the Yarragadee aquifer, which is the largest regional aquifer in the northern Perth Basin and contains low-salinity (<1000 mg/L TDS) groundwater to depths of about 1500 m near Cataby. The Yarragadee aquifer is unconfined to confined where the superficial, Leederville and Leederville–Parmelia aquifers are absent.

There are also three secondary confined aquifers: the Mirrabooka, Cattamarra and Eneabba–Lesueur aquifers. The Mirrabooka aquifer is a relatively thin, shallow aquifer with mostly fresh to brackish groundwater beneath the southern Dandaragan Plateau. The Eneabba–Lesueur aquifer is situated upon the Beagle Ridge and contains fresh to brackish groundwater to depths exceeding 800 m. The Cattamarra aquifer on the Cadda Terrace is situated between the Yarragadee and Eneabba–Lesueur aquifers containing mainly brackish groundwater.

North of Geraldton and east of Mingenew, where uplift prevented deposition of thick sedimentary sequences after the Permian period, only sparse data are available on the groundwater system. This area is hereafter referred to as the northern region (see Figure 58 and Figure 59). The formations that subcrop and outcrop in this region, which are Permian age or older, also exist under the sediments of the Perth Basin (below the Yarragadee Formation), but because of their extreme depth they are not considered viable groundwater resources within the Perth Basin south of Geraldton.

In this northern region, the major aquifer is the Tumblagooda aquifer, which is separated into two distinct areas by the intervening low permeability Northampton Inlier (Figure 53 and Figure 57). The Tumblagooda aquifer is a granular to fractured rock aquifer of the Carnarvon Basin that also extends southward into the northern margins of the Perth Basin. The Tumblagooda aquifer contains fresh groundwater locally, but is probably mostly brackish.

Three minor unconfined to confined aquifers have been defined within the Permian sediments: the Wagina, Irwin – High Cliff and Nangetty aquifers. Smaller, local aquifers exist within Proterozoic metasediments and basement. The Yandanooka Group consists of a thick sequence of sediments that is referred to as the Yandanooka aquifer. The Noondine Chert forms the locally significant Moora aquifer along the east of the Darling Fault, but groundwater is mostly saline. The Northampton and Mullingarra inliers are gneissic basement with fractures that form restricted local fractured-rock aquifers.

Close to the land surface, localised surficial aquifers are also present within sand deposits in areas of shallow watertable east of the Gingin Scarp in the Arrowsmith region, on the Dandaragan Plateau and in the Yarra Yarra region.

Hydraulic connection between aquifers is often impeded across faults (see Section 3.6) and low permeability clay/shale beds within the aquifer units. Four main aquitards are present through the Mesozoic formations, referred to as the Kardinya, South Perth, Otorowiri and Kockatea aquitards, along with two low permeability Permian formations (Carynginia Formation and Holmwood Shale).

Aquitards formed by the Kardinya Shale Member and South Perth Shale isolate parts of the unconfined Superficial and Mirrabooka aquifers from the underlying confined Leederville and Leederville–Parmelia aquifers. Groundwater in the Leederville–Parmelia aquifer is isolated from the deeper Yarragadee aquifer by the intervening Otorowiri aquitard. The Carnac Formation of the Parmelia Group in the lower part of the Leederville–Parmelia aquifer contains substantial clay, further restricting downward flow of groundwater.

The Leederville aquifer is separated from the underlying Yarragadee aquifer by the South Perth Shale over most of its extent. The Kockatea Shale is a widespread aquitard separating the Eneabba–Lesueur aquifer from deeper Permian aquifers, but is generally present at great depth (exceptions are over the Beagle Ridge, the southern Yarra Yarra Terrace in the east, and along the northern margins of the Perth Basin).

Across most of the northern Perth Basin, the base of the meteoric flow systems is the base of the Yarragadee aquifer (Commander 1981), or where the Yarragadee Formation is absent, the base of the outcropping formation. The saline groundwater at depth may be remnant seawater that was entrapped within and below the Kockatea Shale and Cadda Formation during periods of marine incursions. Seawater that would have intruded into the Warnbro and Parmelia groups and the Yarragadee Formation, as well as formations below the coastal plain when the coastline was at the Gingin Scarp, appears to have been subsequently flushed out.

The depth to watertable provides an estimate of the minimum depth of drilling required to reach the uppermost part of the unconfined aquifer. Depth to watertable can also provide an indication of the likelihood of GDEs, with shallower depth to watertable making it more likely that vegetation or wetlands are groundwater dependent. Figure 60 shows a representative depth to the regional watertable over the northern Perth Basin based on interpolation of monitoring bore data from 2007 and topography. Extensive areas of shallow watertable (<10 m) are present at the base of the Gingin Scarp mostly beneath the central–eastern portion of the coastal plain where there are numerous wetlands. The watertable is also shallow along the eastern margin of the Perth Basin, particularly where there are shallow

Permian units on the southern Irwin Terrace. The watertable depth exceeds 100 m over much of the Arrowsmith region and Victoria Plateau where the Yarragadee Formation outcrops, but is shallower within valleys such as along sections of the Hill and Irwin rivers. The watertable is also deep (up to about 100 m bgl) beneath parts of the Dandaragan Plateau in the Leederville–Parmelia aquifer, and much of the Victoria Plateau that is underlain by the Nangetty and Tumblagooda aquifers (Figure 60). The watertable can also be deep (up to 100 m bgl near Lancelin) in the Tamala Limestone of the Superficial aquifer.

Temporal changes in the depth to watertable have been observed regionally in response to extensive clearing of native vegetation and locally by the abstraction of groundwater resources. Water level changes since the 1980s are shown in Figure 61. There has been a rising trend of up to 0.3 m/yr over the Arrowsmith region, Dandaragan Plateau and southern parts of the Victoria Plateau. In southern areas, groundwater levels have declined, mainly since about 2000, as a result of groundwater abstraction for irrigation and mining, and a decrease in average rainfall.

Table 11 Geological and hydrogeological units

Period	Stratigraphy			Hydrogeological unit and lithology	Aquifer characteristics
Quaternary	Superficial formations			Superficial aquifer	
		Alluvium, lacustrine and swamp deposits		Clay, sand and peat	Minor to major aquifer beneath Swan Coastal Plain Fresh to saline
		Safety Bay Sand		Sand	
		Becher Sand		Sand	
		Tamala Limestone		Calcareous arenite, limestone, sand and clay	
		Bassendean Sand		Sand, minor silt and clay	
		Muchea Limestone		Limestone	
		Guildford Formation		Local confining bed Clay and sandy clay	
Neogene		Yoganup Formation		Sand	
		Ascot Formation		Sand, clay and limestone	
Cretaceous (Late)	Coolyena Group			Mirrabooka aquifer	
		Lancelin Formation	Poison Hill Greensand	Sandstone and clay, glauconitic; mudstone, calcareous and glauconitic	Minor to moderate aquifer beneath southern Dandaragan Plateau Fresh to brackish
			Gingin Chalk	Chalk, sandy and glauconitic	
			Molecap Greensand	Sandstone, glauconitic	
		Osborne Formation	Mirrabooka Member	Sandstone, glauconitic, with siltstone and shale	
Cretaceous (Early)				Kardinya aquitard	
			Kardinya Shale Member	Siltstone and shale, minor sandstone	
				Leederville aquifer	
			Henley Sandstone Member	Sandstone, minor siltstone and claystone	Major aquifer below the coastal plain south of Cataby (combined with Parmelia Group beneath Dandaragan Plateau to form the Leederville–Parmelia aquifer) Fresh
	Leederville Formation		Pinjar Member	Sandstone, siltstone and shale	
			Wanneroo Member	Sandstone, with lesser siltstone and shale	
			Mariginiup Member	Sandstone, siltstone and shale	

Period	Group/Formation	Stratigraphy	Hydrogeological unit and lithology	Aquifer characteristics
			South Perth aquitard	
		South Perth Shale	Siltstone and shale, minor sandstone	
			Yarragadee aquifer	
		Gage Sandstone	Sandstone, siltstone and shale	Hydraulically connected with Yarragadee aquifer
	Parmelia Group		Leederville–Parmelia aquifer	Major aquifer beneath Dandaragan Plateau (combined with overlying Leederville Formation) Mostly fresh
	Parmelia Group	Undifferentiated Parmelia Group	Sandstone, siltstone and shale, becoming more shaly to the north	
	Parmelia Group		Otorowiri aquitard	Extensive aquitard below Dandaragan Plateau (includes shaley part of the Carnac Formation)
	Parmelia Group	Otorowiri Formation	Shale and siltstone, minor sandstone	
Jurassic	Yarragadee Formation		Yarragadee aquifer	
Jurassic	Yarragadee Formation	Unit D	Local aquitard Shale, siltstone and clayey sandstone	Major regional aquifer Mostly fresh
Jurassic	Yarragadee Formation	Unit C	Sandstone and clayey sandstone	
Jurassic	Yarragadee Formation	Unit B	Siltstone, shale and sandstone	
Jurassic	Yarragadee Formation	Unit A	Sandstone, siltstone and shale	
Jurassic			Cattamarra aquifer	
Jurassic		Cadda Formation	Sandstone, siltstone, claystone/shale and limestone	Interbedded aquifer–aquitard on Cadda Terrace Mostly brackish
Jurassic		Cattamarra Coal Measures	Sandstone, siltstone, shale and coal	

Period	Stratigraphy	Hydrogeological unit and lithology	Aquifer characteristics
Jurassic	Eneabba–Lesueur aquifer		
Jurassic	Eneabba Formation	Sandstone, siltstone and claystone	Major aquifer on Beagle Ridge–Cadda Terrace Fresh to brackish
Triassic	Lesueur Sandstone	Sandstone	
Triassic	Woodada Formation	Sandstone and siltstone	
Triassic		Kockatea aquitard	
Triassic	Kockatea Shale	Shale, minor siltstone and sandstone	
Triassic	Bookara Sandstone Member	Local aquifer	
Permian (Late)		Wagina aquifer	
Permian (Late)	Wagina Sandstone / Dongara Sandstone / Beekeeper Formation	Sandstone, clayey sandstone, mudstone/shale and limestone	Local aquifer in north Saline
Permian (Early)		Carynginia aquitard	
Permian (Early)	Carynginia Formation / Mingenew Formation	Siltstone, claystone and sandstone	
Permian (Early)		Irwin–High Cliff aquifer	
Permian (Early)	Irwin River Coal Measures	Sandstone, siltstone, shale and coal	Poor to moderate aquifer Saline
Permian (Early)	High Cliff Sandstone	Sandstone, minor siltstone	
Permian (Early)		Holmwood aquitard	
Permian (Early)	Holmwood Shale Fossil Cliff Member	Shale, siltstone and calcarentie	
Permian (Early)		Nangetty aquifer	
Permian (Early)	Nangetty Formation Wicherina Member	Sandy siltstone and mudstone; sandstone	Poor to moderate aquifer Saline

Period	Stratigraphy	Hydrogeological unit and lithology	Aquifer characteristics
Silurian		Tumblagooda aquifer	
Silurian, Ordovician	Tumblagooda Sandstone	Red-bed sandstone	Regional aquifer in Carnarvon Basin and northern margin of Perth Basin. Mostly fractured rock Aquifer includes sediments of the Winning Group Brackish to saline – locally fresh
Proterozoic		Moora aquifer	
Proterozoic	Moora Group	Chert, siltstone, sandstone and arkose	Potential poor aquifer Local aquifer in Noondine Chert Mostly saline, locally fresh
Proterozoic		Yandanooka aquifer	
Proterozoic	Yandanooka Group	Sandstone, siltstone, conglomerate and arkose	Potential poor aquifer Mostly saline
Proterozoic		Mullingarra fractured-rock aquifer	
Proterozoic	Mullingarra Inlier	Gneissic rocks	Local fractured-rock aquifer Salinity unknown
Proterozoic		Northampton fractured-rock aquifer	
Proterozoic	Northampton Inlier	Gneissic rocks	Local fractured-rock aquifer Fresh to brackish

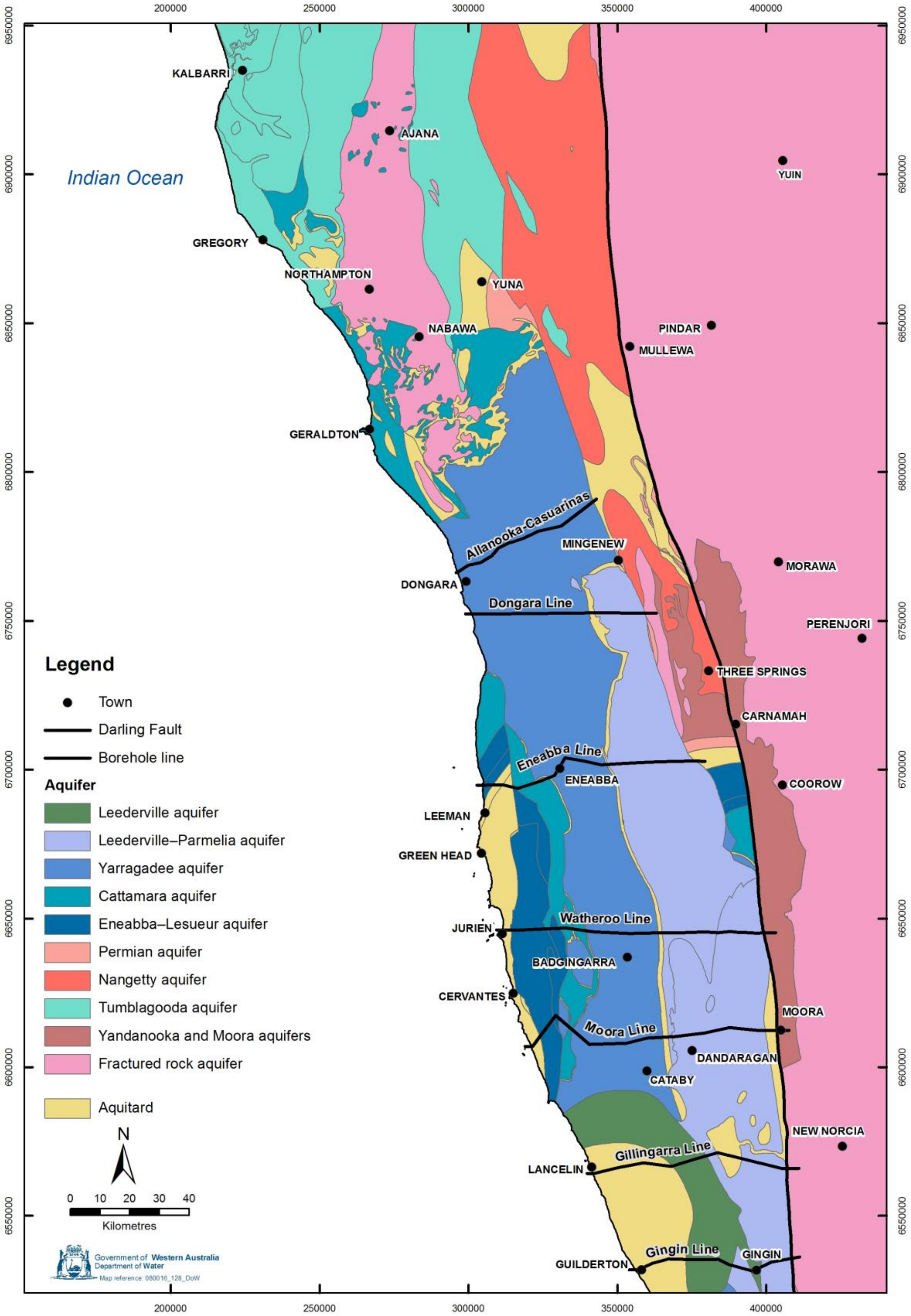


Figure 53 Aquifers and aquitards below the superficial formations or surficial deposits

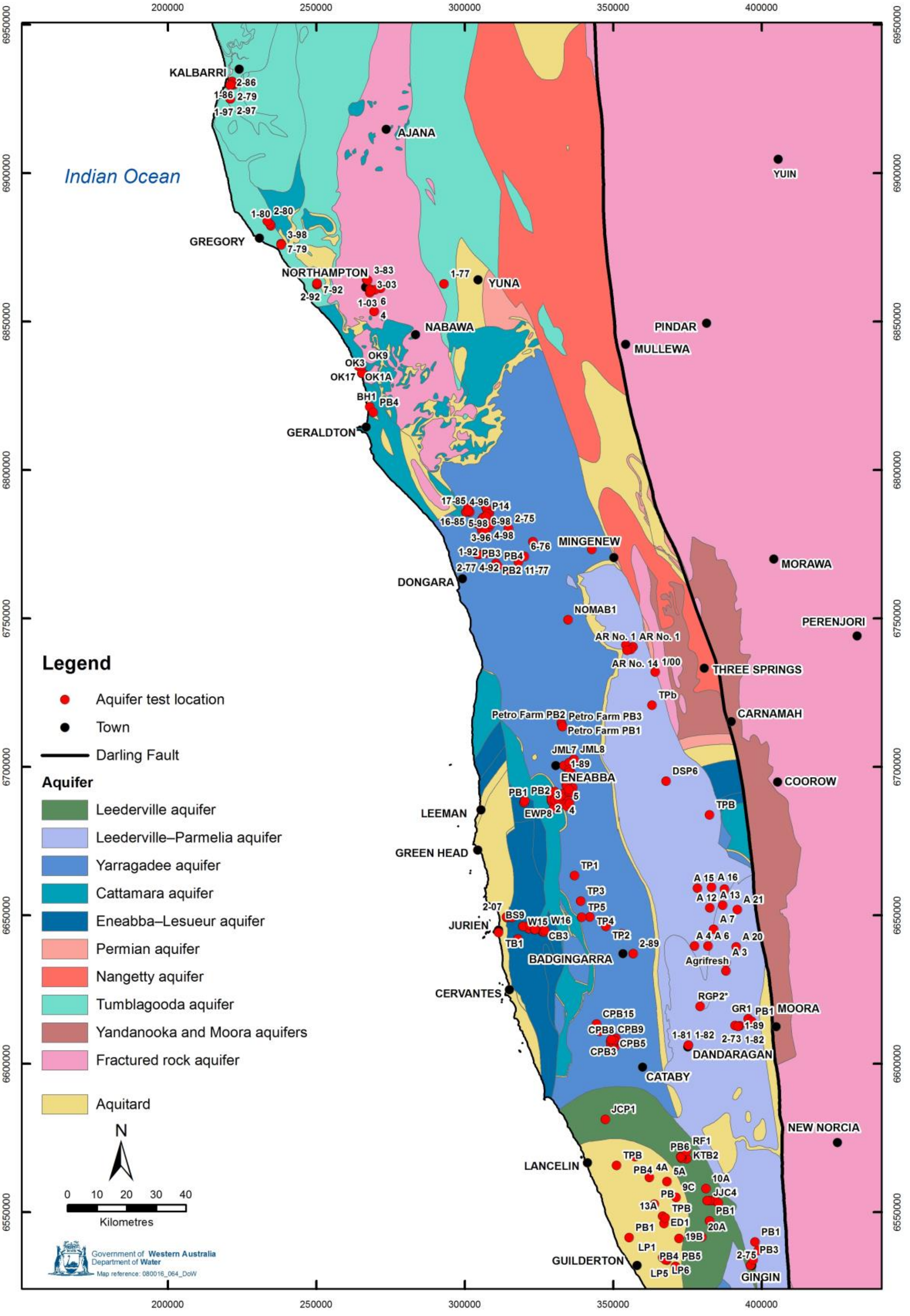


Figure 54 Bore sites with aquifer test data (bores in the Guilderton–Lancelin area are within the Superficial aquifer)

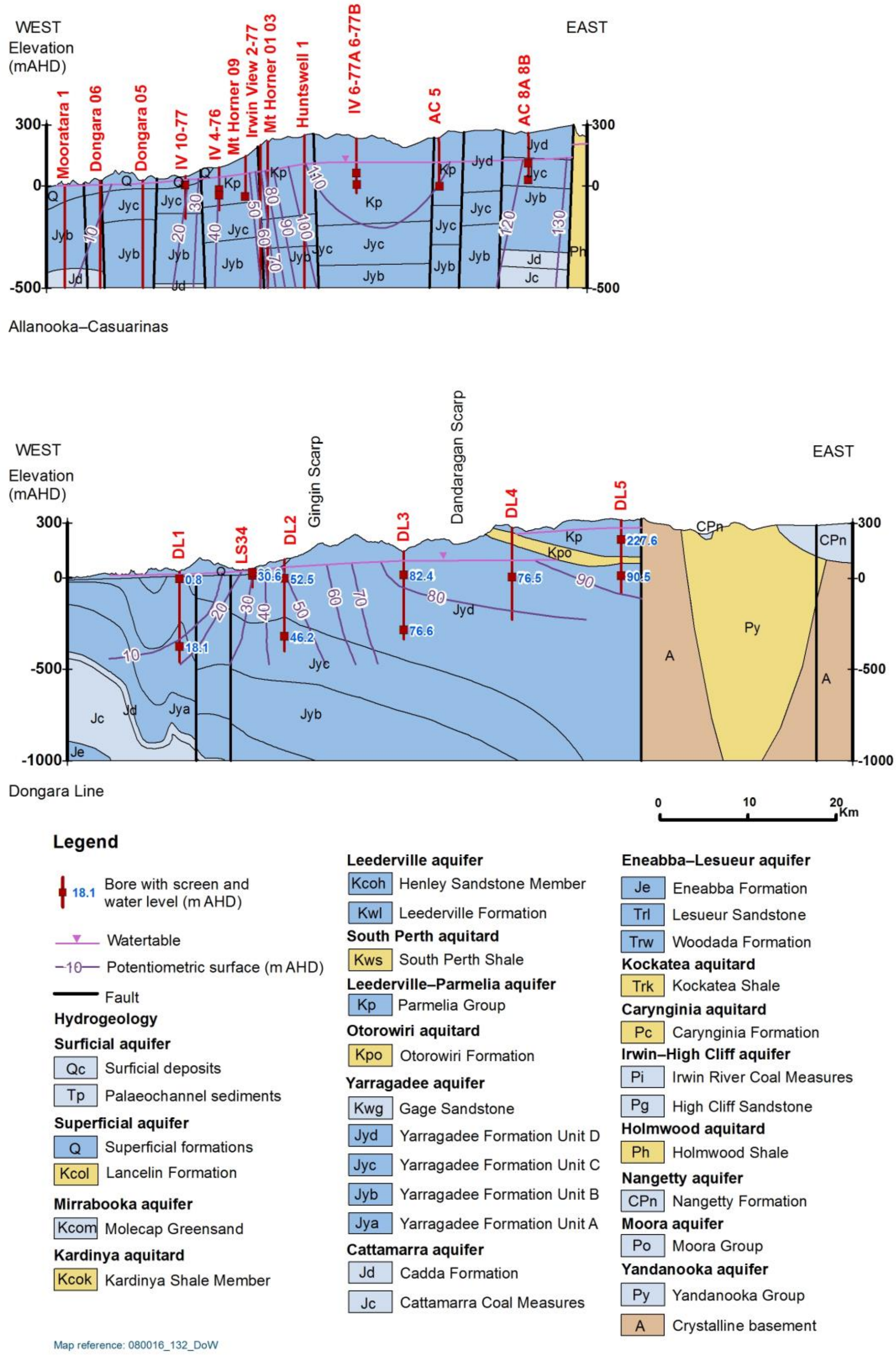


Figure 55 Hydrogeological cross-sections (hydraulic head)

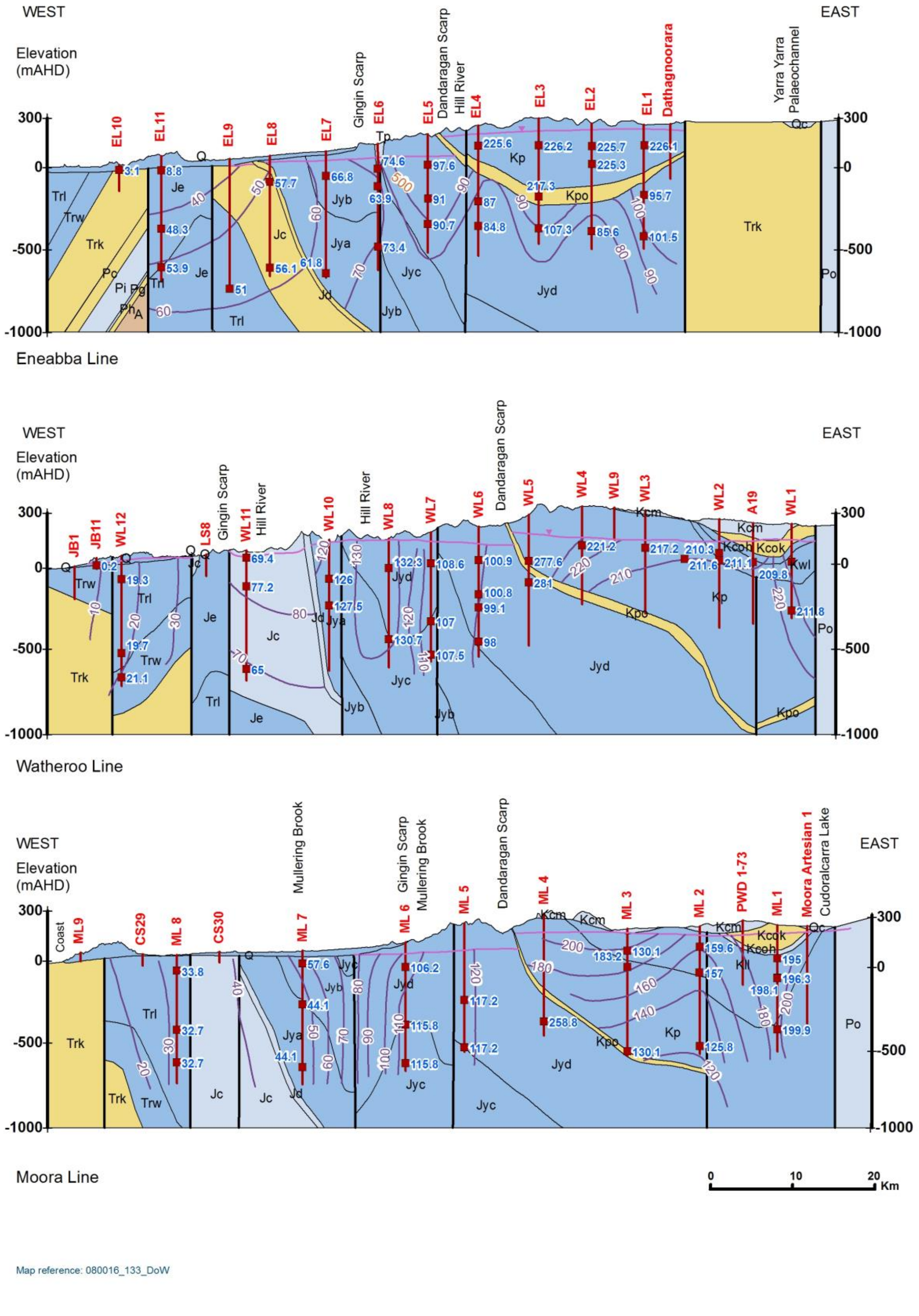


Figure 55 Hydrogeological cross-sections (hydraulic head) (continued)

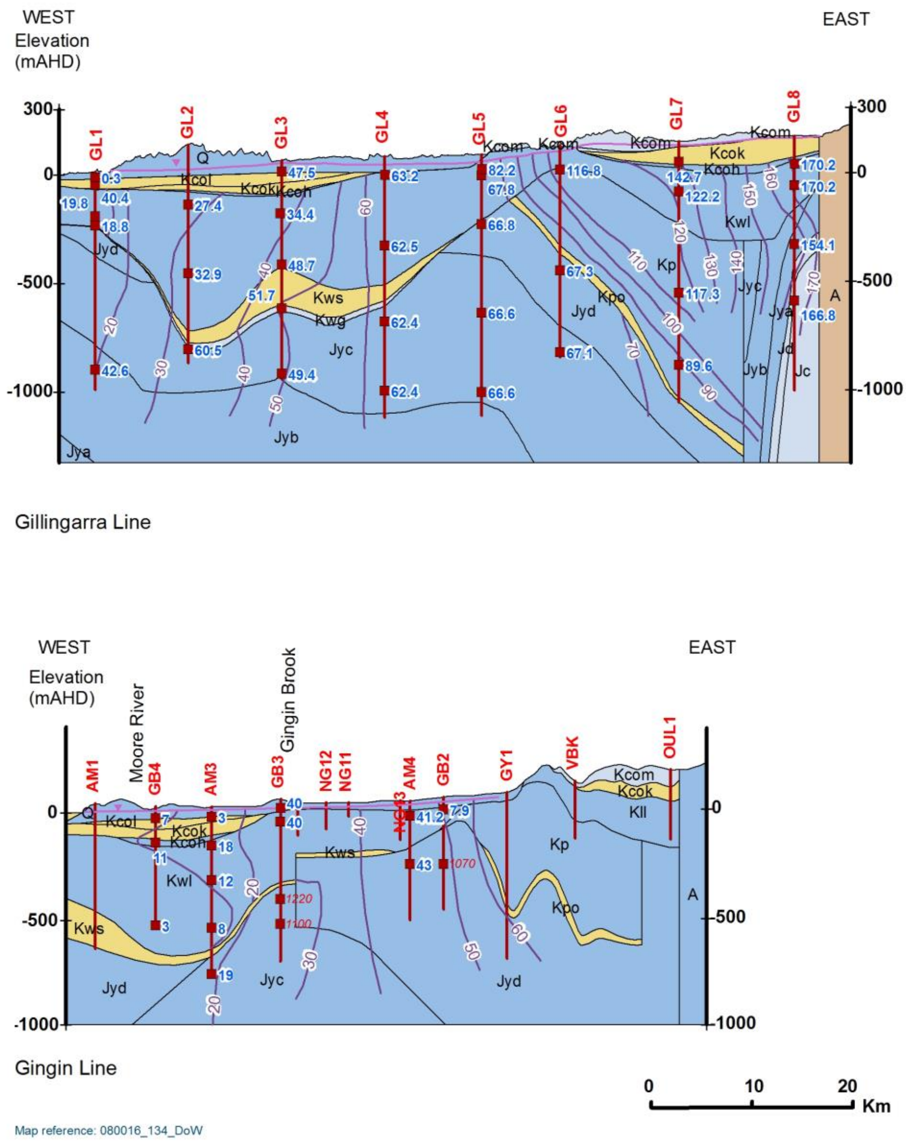


Figure 55 Hydrogeological cross-sections (hydraulic head) (continued)

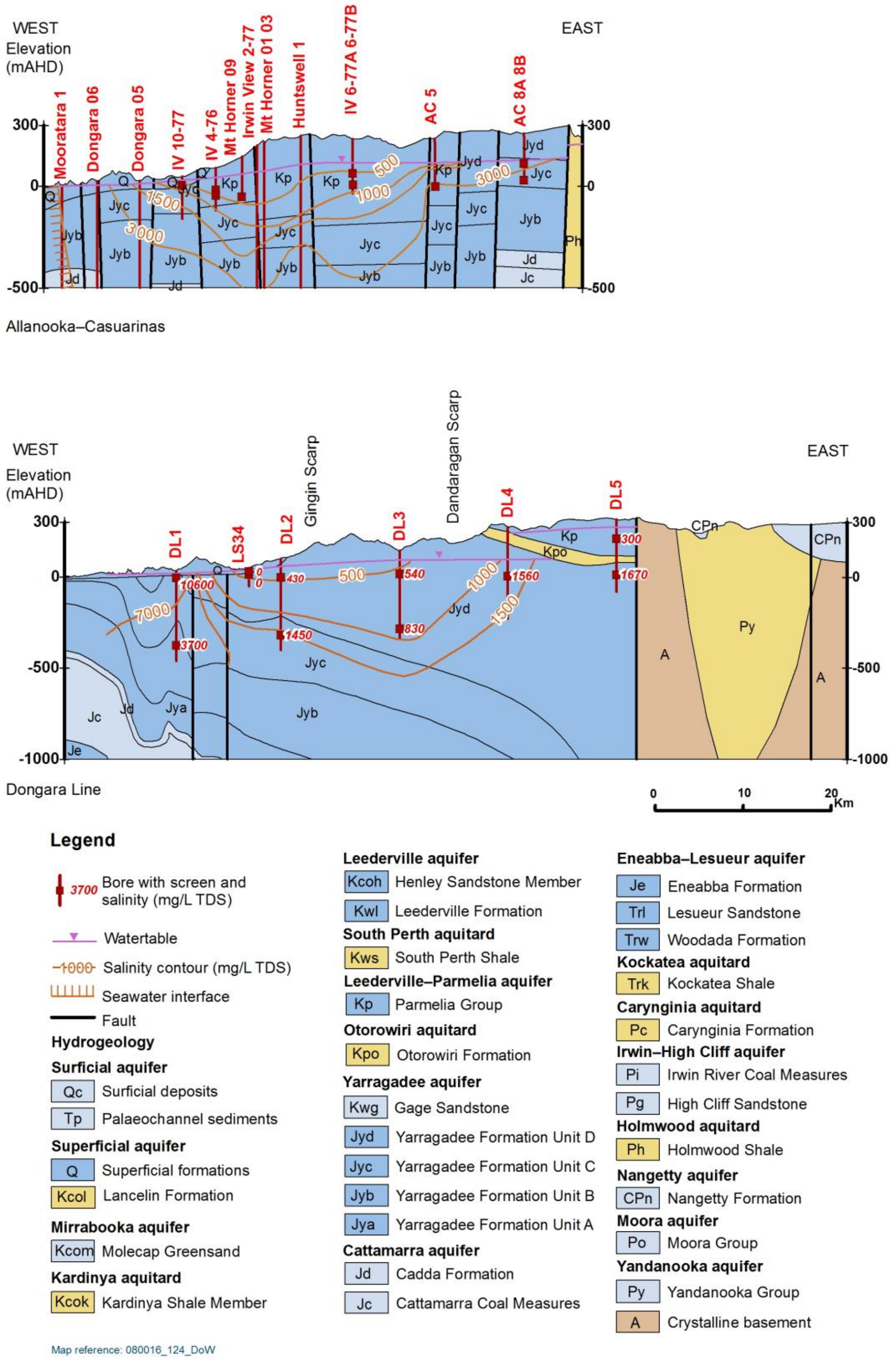
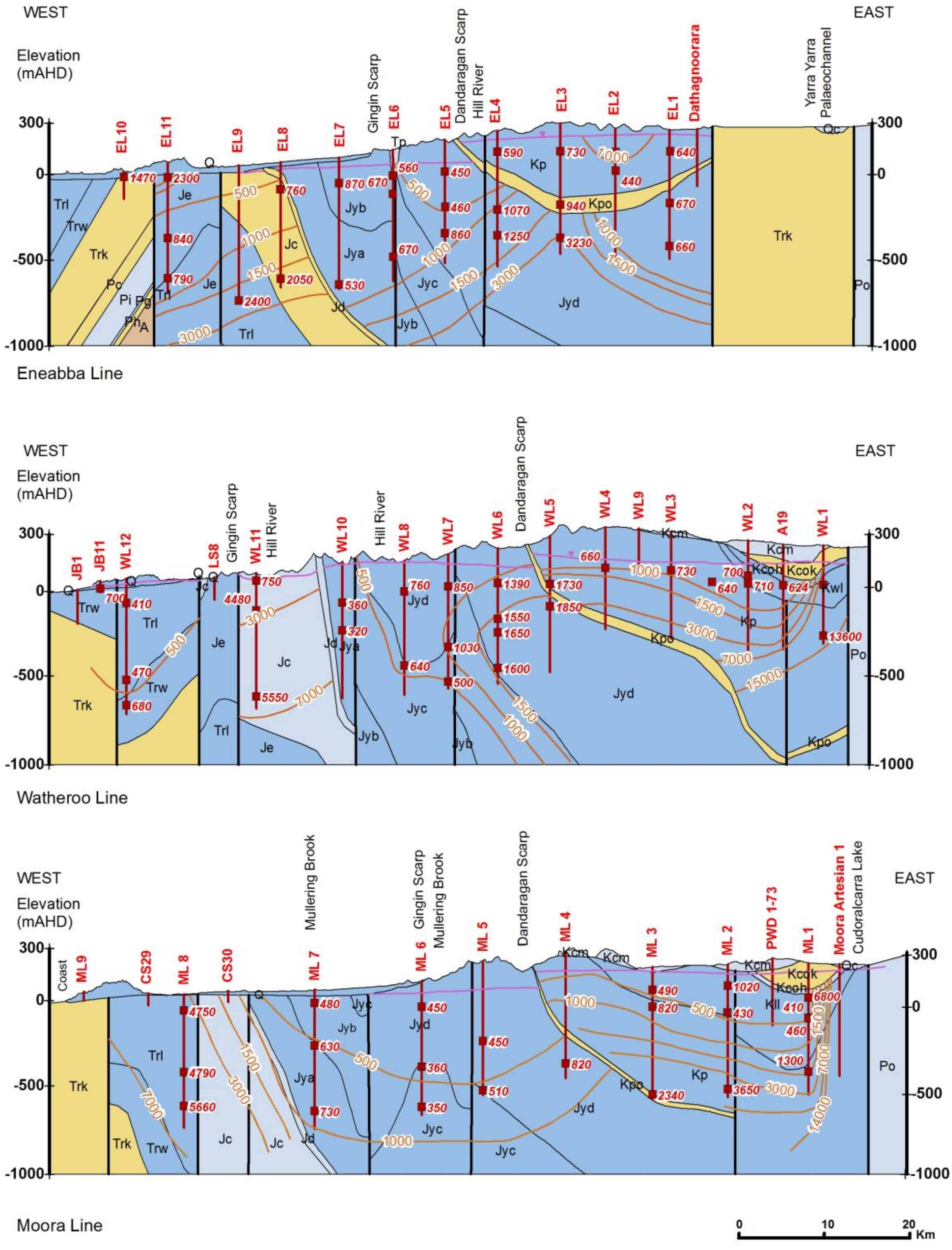


Figure 56 Hydrogeological cross-sections (salinity)



Map reference: 080016_125_DoW

Figure 56 Hydrogeological cross-sections (salinity) (continued)

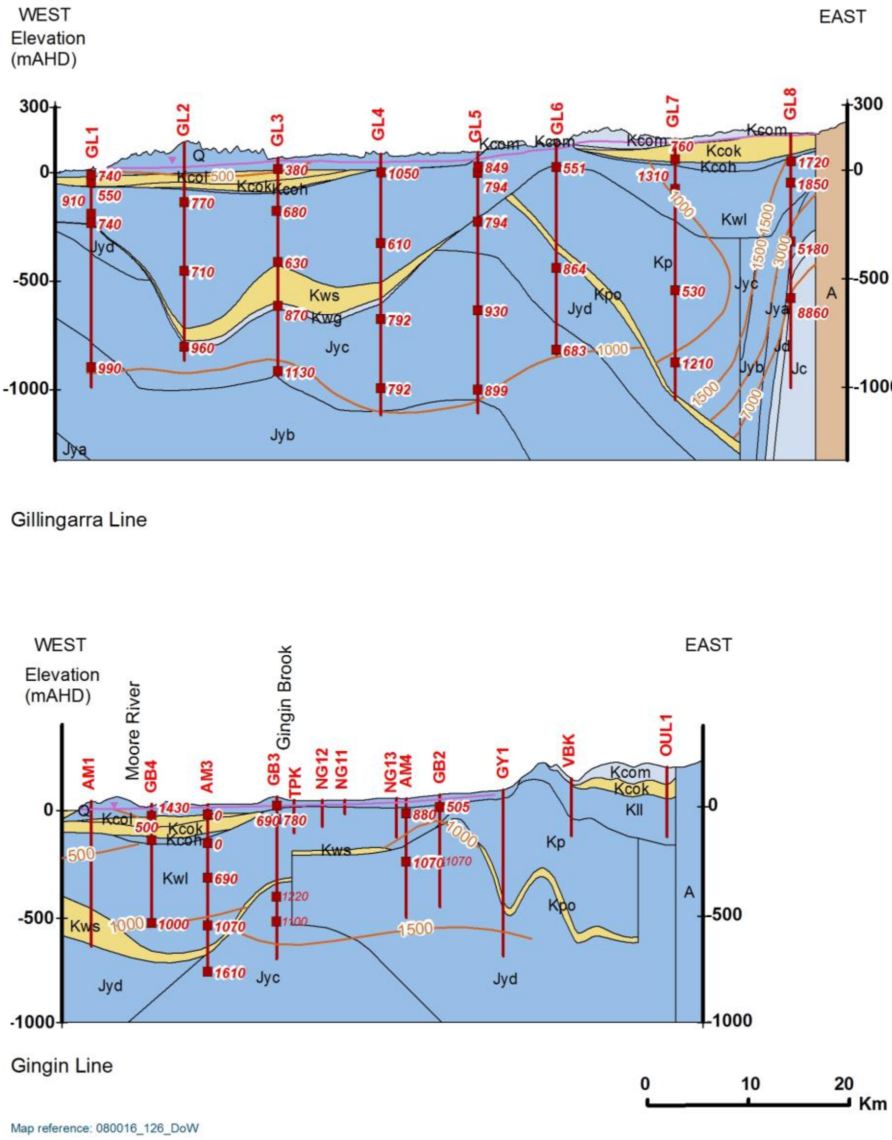


Figure 56 Hydrogeological cross-sections (salinity) (continued)

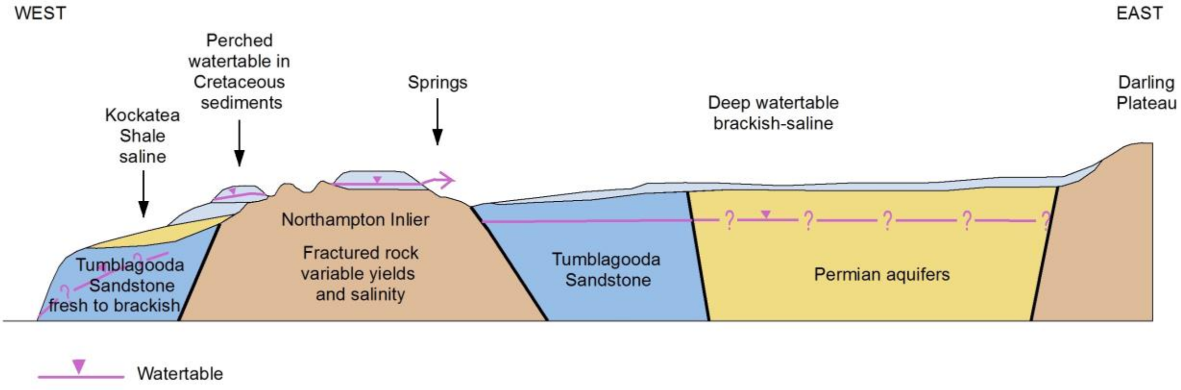


Figure 57 Hydrogeological setting across the Northampton Inlier

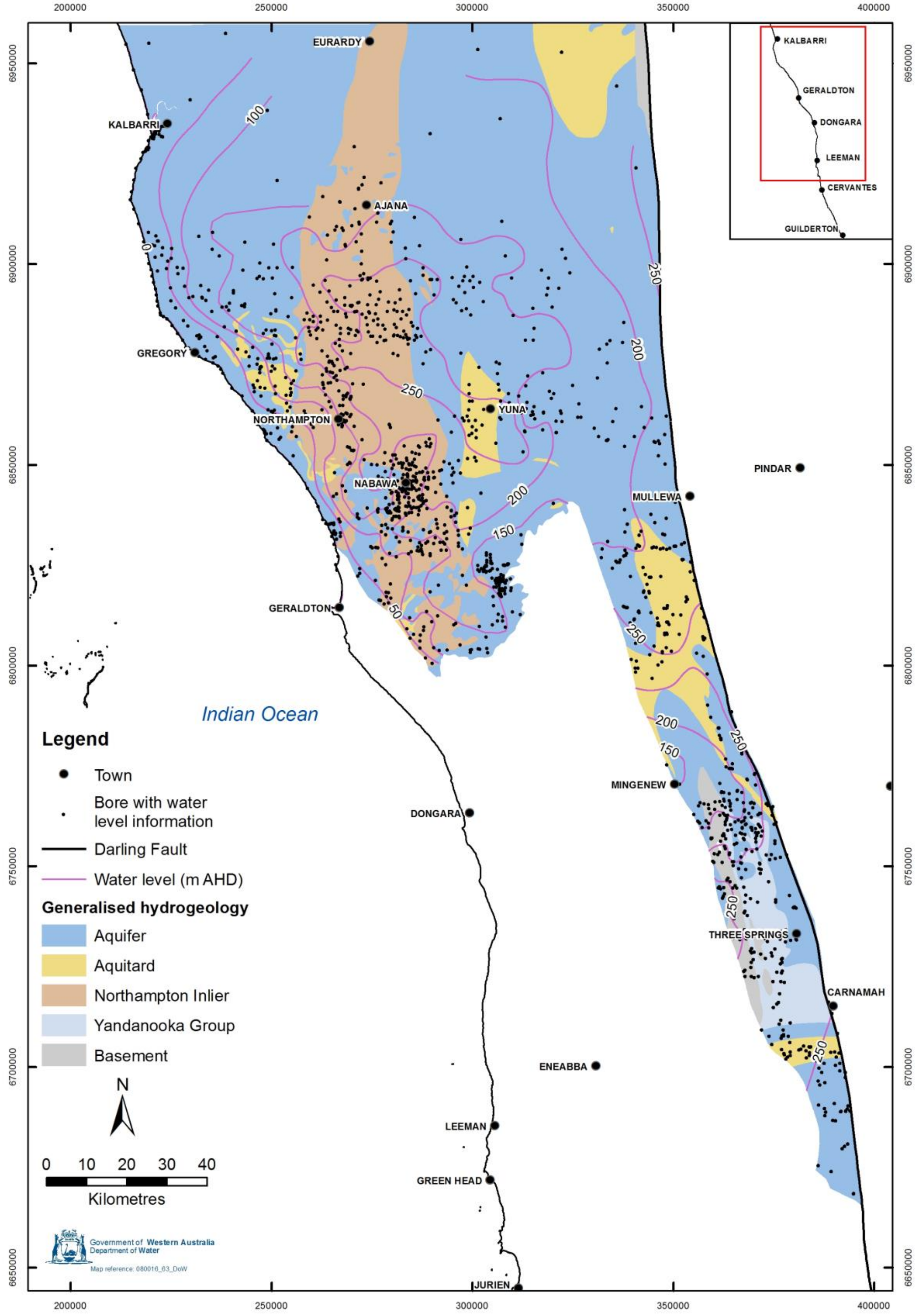


Figure 58 Northern region: hydrogeology and potentiometric surface

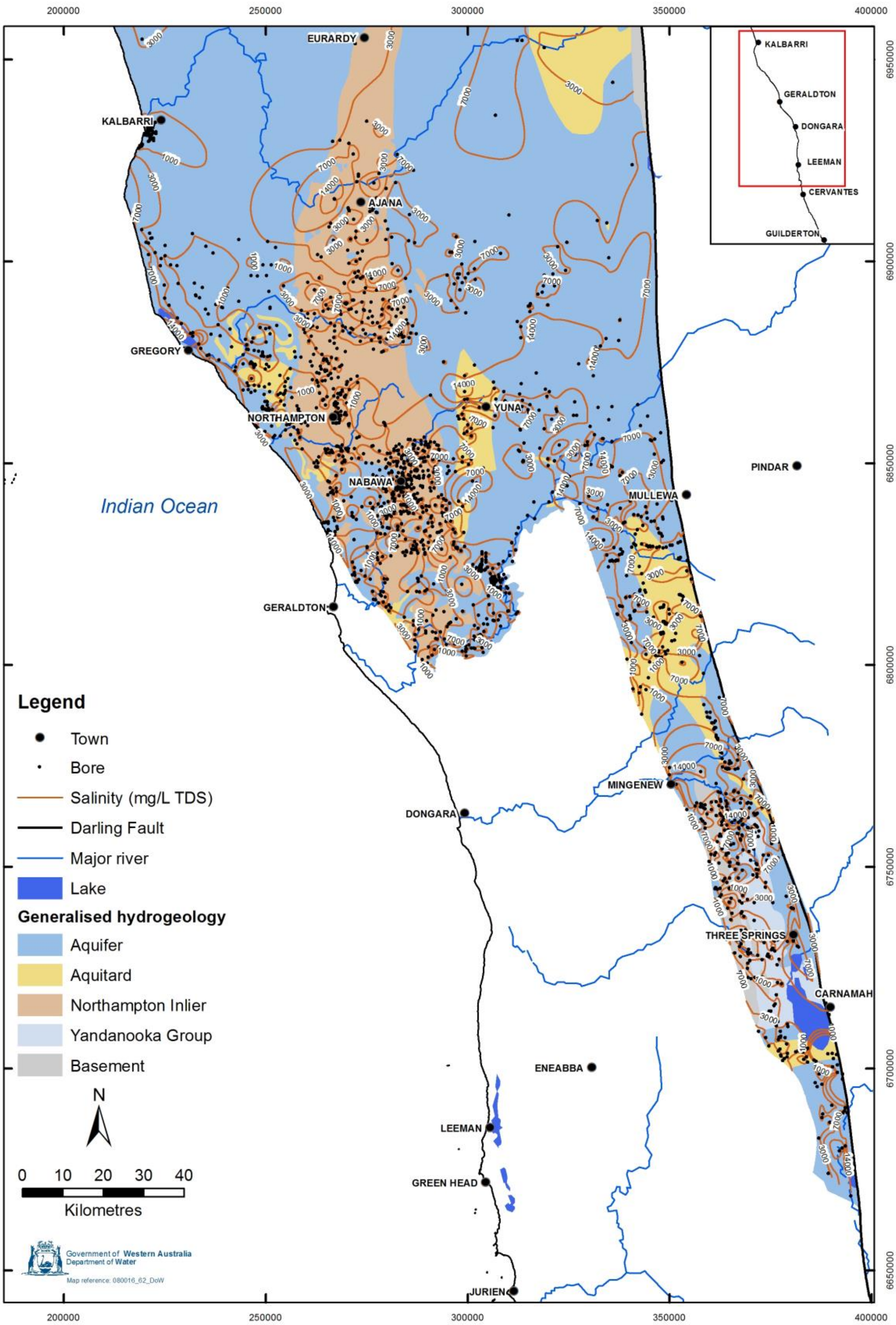


Figure 59 Northern region: groundwater salinity

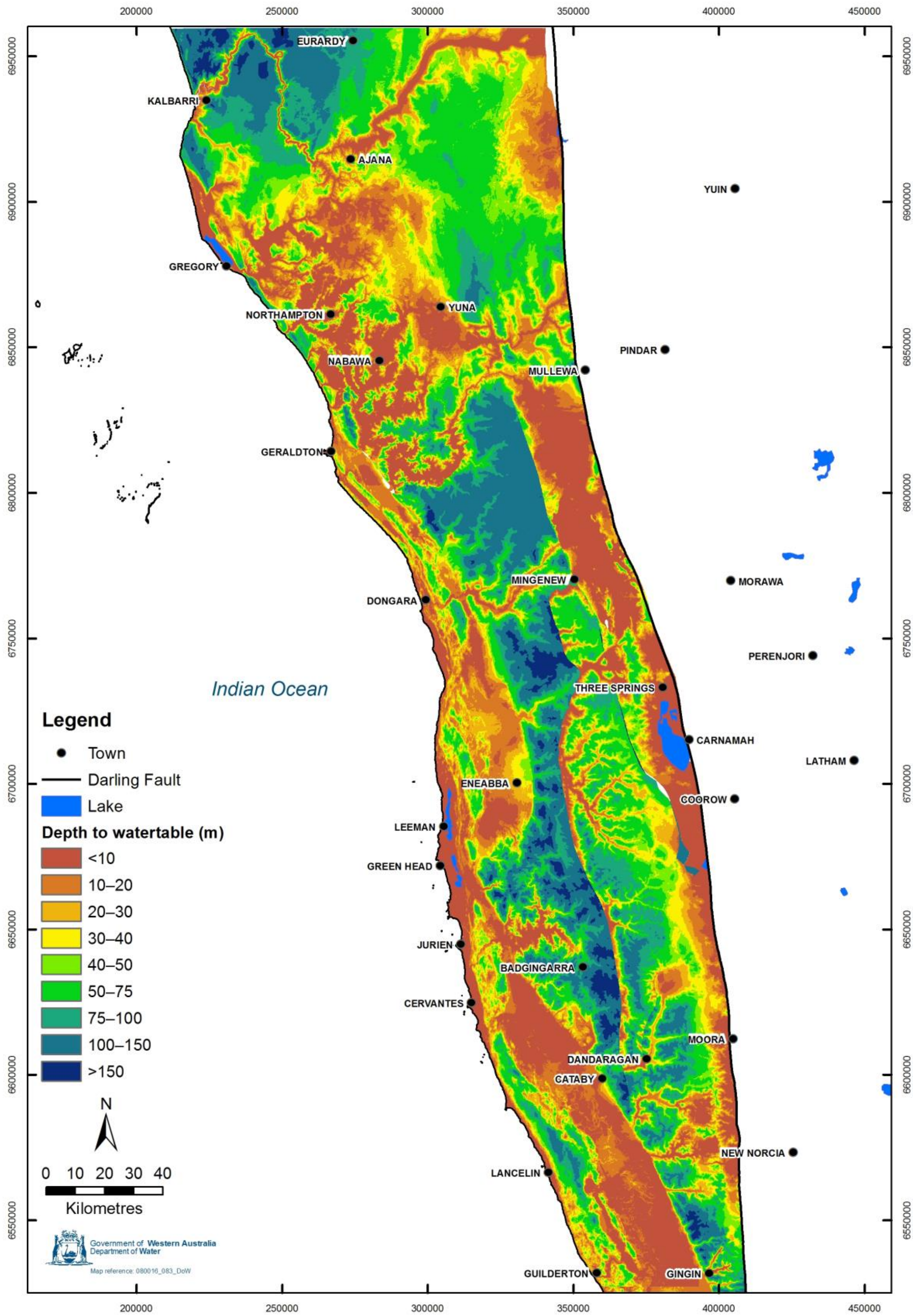


Figure 60 Representative depth to watertable (2015)

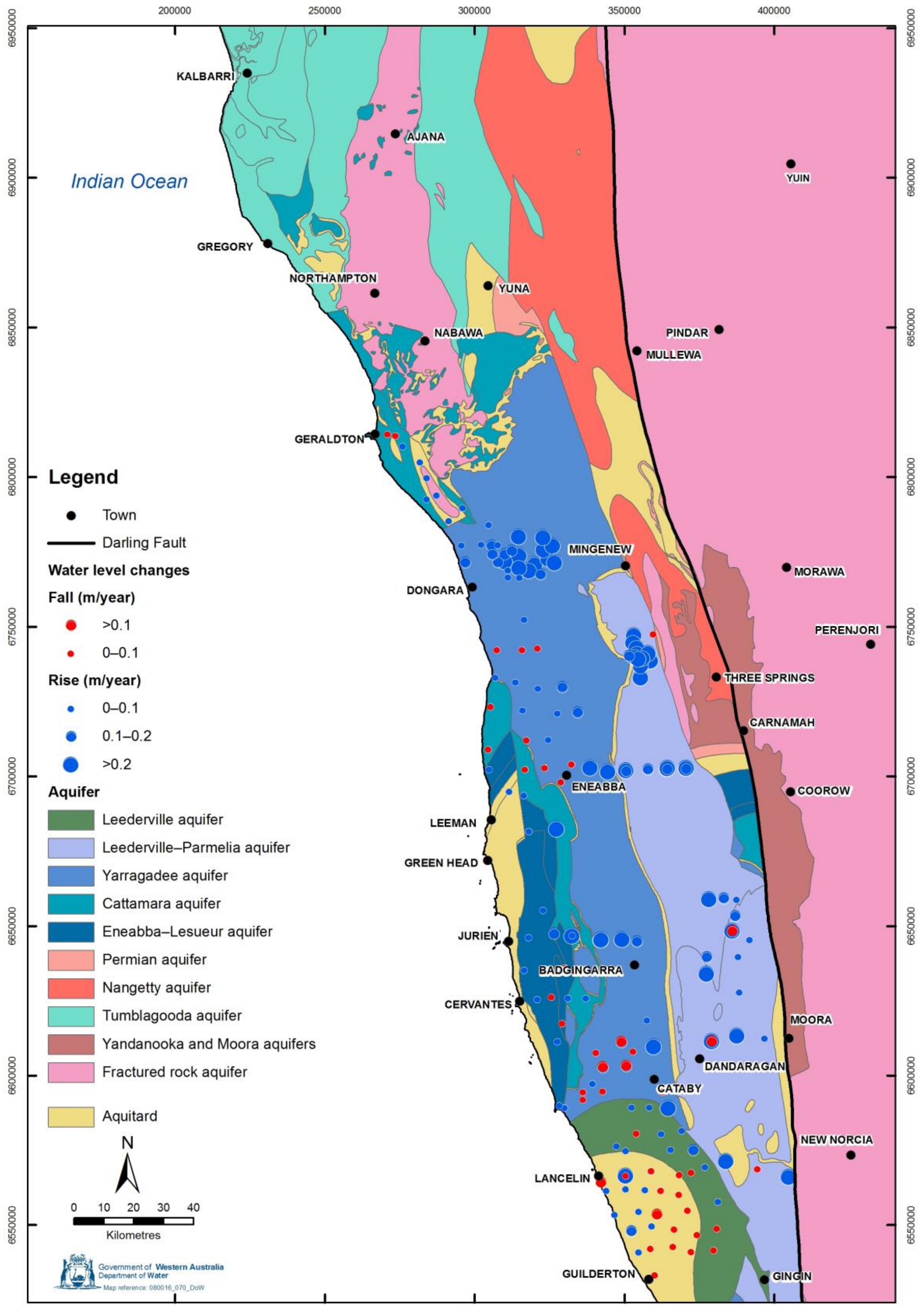


Figure 61 Water level change between mid-1980s and mid-2000s

5.2 Superficial aquifer

The Superficial aquifer is a laterally extensive but relatively thin unconfined aquifer extending throughout the Swan Coastal Plain found in the western portion of the northern Perth Basin between Geraldton in the north, Gingin in the south and bound by the Gingin Scarp to the east (Figure 62 and Figure 63). Geologically, the Superficial aquifer exists predominantly within sand and limestone of the superficial formations, but also includes the Lancelin Formation of the Coolyena Group where present. The major water-bearing formations are the Tamala Limestone, Bassendean Sand and Yoganup and Ascot formations. Adjacent to the coast, the Safety Bay Sand and Becher Sand form local aquifers. The Guildford Formation and interbedded clay layers within the other formations form local aquitards, creating a multilayered groundwater flow system in some areas in the eastern portion of the Swan Coastal Plain.

The Superficial aquifer is typically 20–30 m thick, with a maximum saturated thickness of about 60 m west of Regans Ford (Moncrieff & Tuckson 1989; Kern 1993a). The superficial formations are commonly unsaturated along their inland margin, and are also unsaturated south-east of Cervantes in the Nambung National Park area, where the watertable is within the underlying Lesueur Sandstone (Figure 63).

Groundwater recharge

Groundwater recharge to the Superficial aquifer is mainly by direct infiltration from rainfall over permeable sand and limestone, predominantly during winter and early spring. In the Jurien Bay area, rainfall recharge over the Tamala Limestone, particularly on the coastal ridge, is dominated by infiltration through sand-filled, vertical solution pipes (Baddock & Lach 2003). The Superficial aquifer also receives groundwater recharge by infiltration of surface water from lakes and streams, and from vertical groundwater flow from underlying Mesozoic aquifers where there is an upward hydraulic gradient.

Rates of groundwater recharge from rainfall infiltration vary considerably over the coastal plain depending on land use, lithology and depth to watertable. Recharge rates from rainfall are probably low over the eastern portion of the coastal plain, near the Hill River area, where a thin cover of Bassendean Sand overlies the Guildford Formation, and much of area can be seasonally waterlogged.

Historical recharge rates estimated in the 1980s, based on the chloride mass balance method, were around 7 per cent of average annual rainfall over the eastern part of the coastal plain between the Moore River and Gingin Brook (Moncrieff & Tuckson 1989), and 8 per cent for the area between Cervantes and Lancelin (Kern 1993a). However, annual average rainfall up to the 1980s was considerably higher than now (annual average of 680 mm compared to an annual average of 585 mm at Lancelin for the 1975–2003 period). More recent analysis of the relationship between rainfall and recharge on the Gnangara Mound near Perth (Yesertener 2009), and near Albany (Ryan et al. in prep.) shows that for every unit decline in rainfall, the reduction in recharge can double. Further, it has been shown that groundwater will only be recharged once a rainfall threshold is reached. If rainfall does not exceed the threshold, there may be no recharge at all (Yesertener 2009).

Areas cleared of native vegetation will likely have higher rates of rainfall recharge than those quoted above, unless native vegetation is replaced with deep-rooted vegetation such as timber plantations.

The Superficial aquifer is also recharged by upward groundwater flow from underlying Mesozoic aquifers (Leederville, Yarragadee, Cattamarra and Eneabba–Lesueur aquifers) where the aquifers are hydraulically connected and there is an upward hydraulic gradient (Figure 64). There is potential for upward groundwater flow from the Yarragadee aquifer beneath the eastern part of the coastal plain north of Cataby, from the Leederville aquifer adjacent to the coast south of Wedge Island and from the Eneabba–Lesueur aquifer to the north (Kern 1988, 1993a; Ryan 2012a). North of Eneabba, there is an upward hydraulic gradient between the underlying Mesozoic aquifer (either Eneabba–Lesueur, Yarragadee or Cattamarra aquifers) beneath the western to central part of the coastal plain (Nidagal 1995; Irwin 2007).

There is episodic recharge of groundwater by infiltration from rivers and streams crossing the coastal plain along lengths of the watercourse where the bed lies above the watertable. This is common for parts of the Irwin and Arrowsmith rivers (Commander 1978), and the Hill and Nambung rivers (Baddock & Lach 2003, Lindsay 2004). In the south, there is seasonal recharge from the Moore River between Karakin and Bidaminna lakes, and from Red Gully Creek and other small streams that dissipate across the coastal plain (Moncrieff & Tuckson 1989). These streams typically contain brackish water, which can recharge the aquifer and may elevate groundwater salinity (Commander 1978). Some of the smaller rivers, such as the Nambung River, dissipate over the coastal plain or flow directly into caves and lakes. Surface water from Lake Logue and Arromall Lake discharge via karstic conduits, while Stockyard Gully flows directly into caves (Commander 1978a, 1978b).

Groundwater discharge

Groundwater within the Superficial aquifer predominantly discharges into the ocean at the coast over a seawater interface. The seawater interface was encountered at shallow depth up to 1.5 km inland in several shallow monitoring bores of the Salvado (S6D, S6E), Cataby (CS11 and CS28) and Leeman investigations (LS12 and LS15) (Moncrieff & Tuckson 1989; Kern 1988, 1993a, 1997). Between Jurien Bay and Coolimba, groundwater is discharged to large coastal salt lakes adjacent to the coast (Kern 1997; Ryan 2012a). Groundwater within limestone caves flows towards the coast, where it possibly discharges as springs (Nidagal 1994).

There is significant evaporative loss of groundwater in the Bassendean Dunes and Eneabba Plain, where the watertable is shallow and numerous wetlands are present. Many of the rivers and streams crossing the coastal plain receive baseflow where the watercourse is positioned below the watertable. This baseflow is seasonal, with groundwater discharging when groundwater levels are elevated by winter rains. Groundwater discharges to Gingin Brook in the headwaters upstream of Gingin townsite and in the lower reaches west of the confluence with Mungala Brook (Tuffs 2011). The Moore River discharges between Regans Ford and Karakin Lakes and between Bidaminna Lake and the coast (Moncrieff & Tuckson 1989). Seasonally, groundwater discharges along Nambung River north of bore CS35

(Kern 1988, 1993a), Hill River upstream of Canover Pool (Kern 1997; Baddock & Lach 2003), and to the Chapman, Greenough and Irwin rivers (Kern & Koomberi 2013).

Some groundwater discharges via downward leakage of groundwater from the Superficial aquifer into underlying Mesozoic aquifers where there is hydraulic connection and a downward hydraulic gradient. Beneath the eastern margin of the coastal plain, there is potential for downward leakage into the Leederville aquifer near Regans Ford (Moncrieff & Tuckson 1989) and into the Yarragadee aquifer 15–30 km west of Cataby (Figure 64). North of Eneabba, downward hydraulic gradients beneath the eastern part of the coastal plain suggest there may be significant leakage into the Yarragadee aquifer (Nidagal 1995; Irwin 2007).

Groundwater levels and flow

Groundwater flow in the Superfical aquifer is predominantly east to west, from the elevated areas along the Gingin Scarp towards the coast (Figure 62). The watertable is highest adjacent to the Gingin Scarp, where it is up to about 90 m AHD near Eneabba and Cataby, and declines westward to the coast. In the Jurien Bay area, water levels are less than 0.5 m AHD up to 5 km inland (Baddock & Lach 2003). Over the eastern part of the coastal plain, where the Guildford Formation is present, the watertable is generally close to the ground surface with numerous swamps and lakes (Kern 1993a). Under the Beermullah Plain, groundwater in the Superficial aquifer is locally confined by the Guildford Formation with the potentiometric surface above ground level (Moncrieff & Tuckson 1989). Waterlogging can develop after periods of heavy rainfall in this area, resulting in surface flooding (Moncrieff & Tuckson 1989). Near the coast, beneath the Spearwood Dunes, the high permeability of the Tamala Limestone allows the watertable surface to deviate from the surface topography. Depth to the watertable can be up to 70 m near Lancelin (e.g. 69 m bgl in CS2D).

The hydraulic gradient in the Superficial aquifer is relatively steep in the eastern portion of the coastal plain, becoming less abrupt west of the transition from Bassendean Sand to the more permeable Tamala Limestone (Kern 1993a 1997; Nidagal 1994; Baddock & Lach 2003). At the transition between Bassendean Sand and Tamala Limestone, groundwater rapidly drains to the west, resulting in a locally steep horizontal hydraulic gradient on the eastern margin of the Tamala Limestone. Inland of Green Head, where the coastal plain narrows to less than 10 km, the hydraulic gradient becomes locally steeper. Moncrieff and Tuckson (1989) described a steep gradient zone (about 12 km wide) within the Tamala Limestone beneath the north–south reach of the Moore River, which may reflect low hydraulic conductivity due to cementation of deposits or finer grained sediments.

Water levels in the Superficial aquifer fluctuate seasonally in response to rainfall, with levels typically lowest during March to May after summer, and highest in August to October following the winter rains (Figure 65). Seasonal fluctuations typically range from 0.3 to 1.7 m in sandy facies of the Guildford Formation, where there is a rapid response to rainfall (Kern 1988, 1993a). There is a smaller seasonal fluctuation in water levels in sand beds that are locally confined by clay or where the Superficial aquifer is hydraulically connected with the underlying Leederville aquifer (Kern 1988, 1993a). Due to the high transmissivity of the Tamala Limestone, seasonal fluctuations of groundwater levels are low and normally less than 0.2 m. Water level fluctuations related to ocean tides are observed in the Tamala

Limestone adjacent to the coast in Salvado bores S1A and S6A (Moncrieff & Tuckson 1989), Mid West GDE bores at Lake Thetis (Brodie & Reid 2013) and at sites over 3 km inland of the coast at Jurien Bay (Baddock & Lach 2003). Kern (1994) described the presence of fresh marine algae in cavities in the Tamala Limestone at Leeman Shallow bore LS12.

Longer term fluctuations in groundwater levels are observed in response to changes in annual rainfall. Following a very dry year and a decline of water levels in 1979, the subsequent years of higher rainfall caused water levels to rise in the Lancelin–Gingin area, which was possibly accentuated by higher recharge rates in response to land clearing (Moncrieff & Tuckson 1989). A similar recovery was noted following low rainfall in 1985 in the Lancelin–Cataby area (Kern 1988, 1993a). Since 2000, an overall declining watertable trend has been observed in many monitoring bores, in response to an extended period of below average annual rainfall. The decline is most pronounced in the lower permeability Guildford Formation, but is not as apparent in the Tamala Limestone due to its high transmissivity and proximity to the coast.

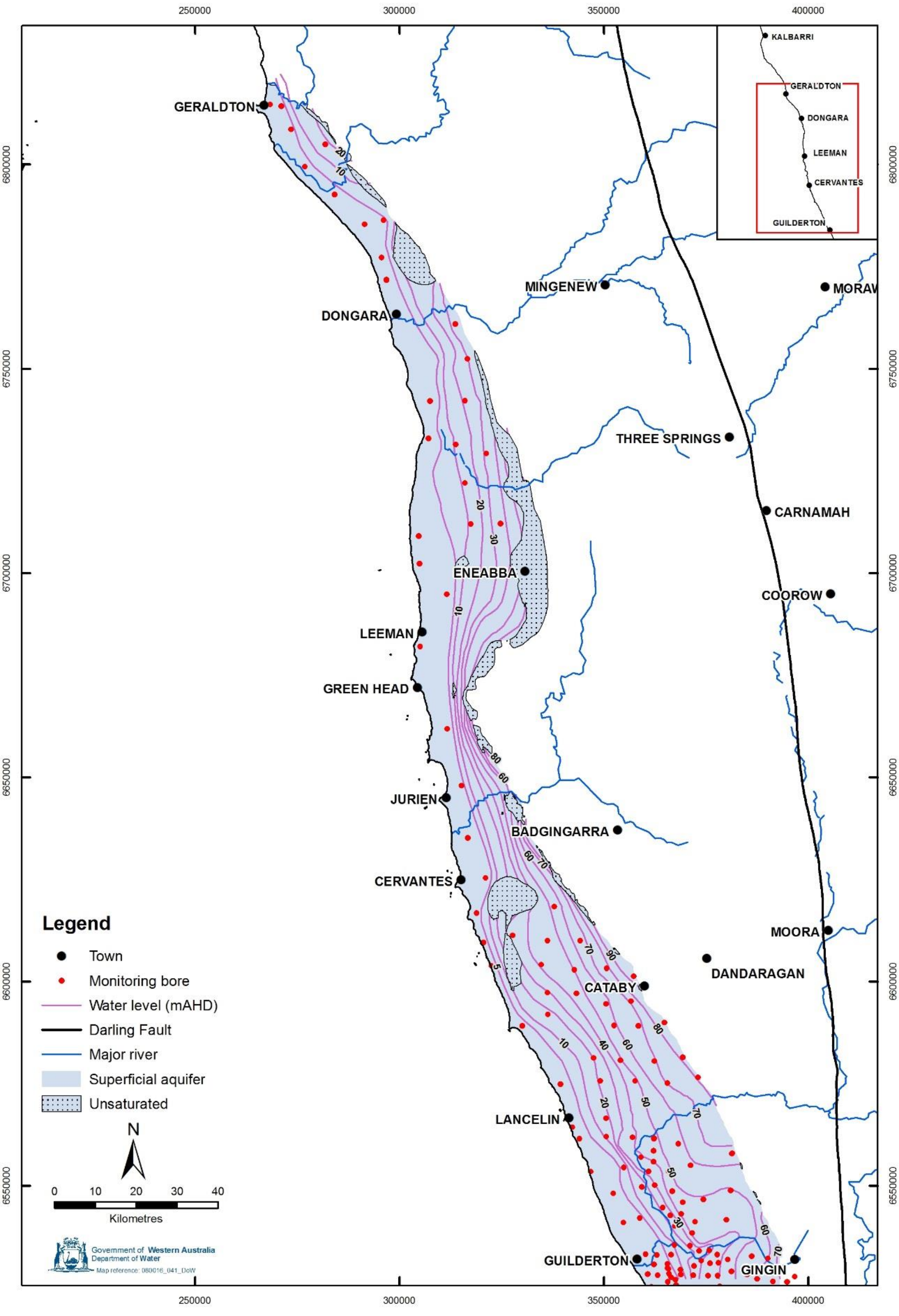


Figure 62 Superficial aquifer: watertable elevation (2015)

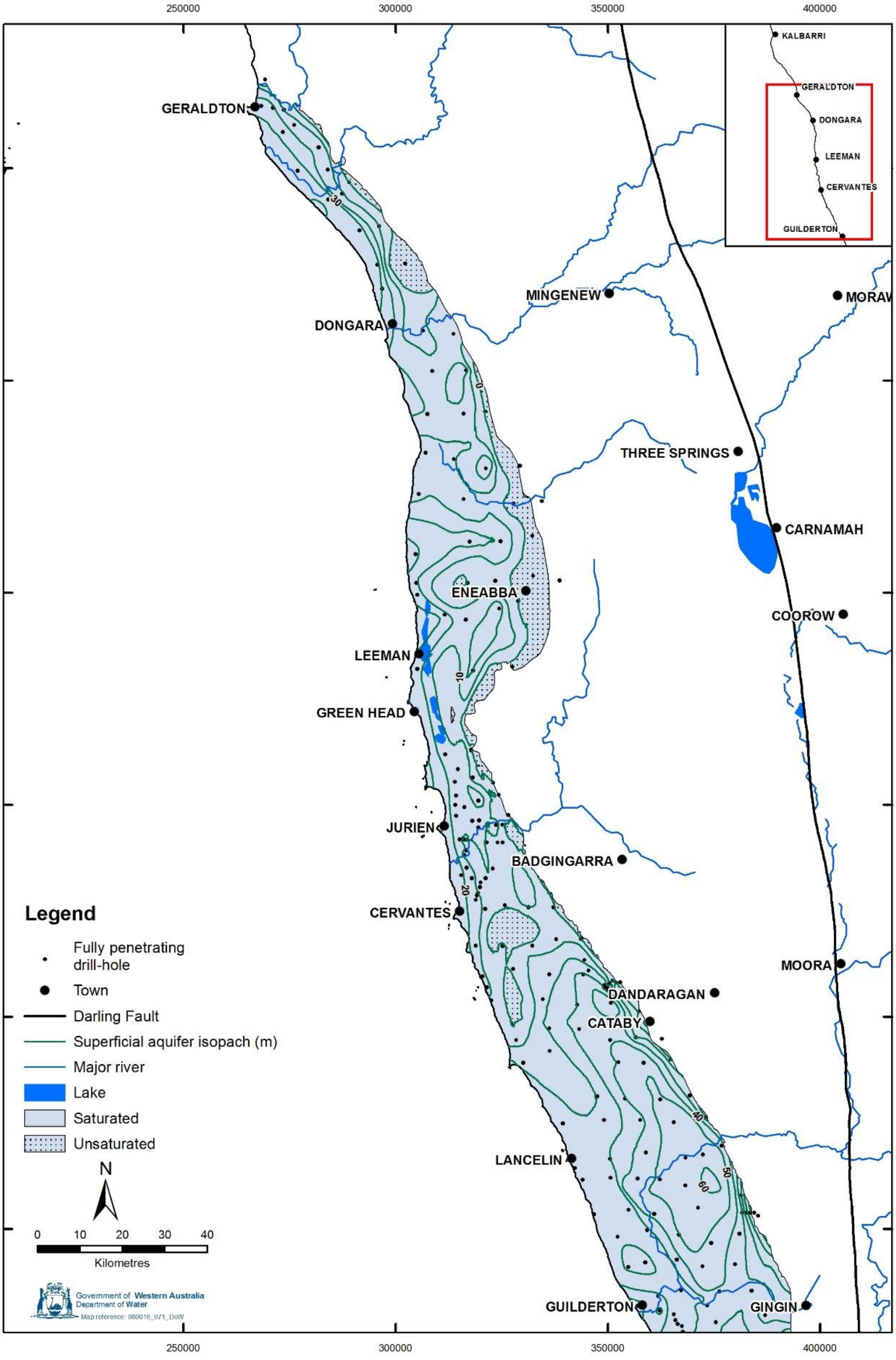


Figure 63 Superficial aquifer: saturated thickness

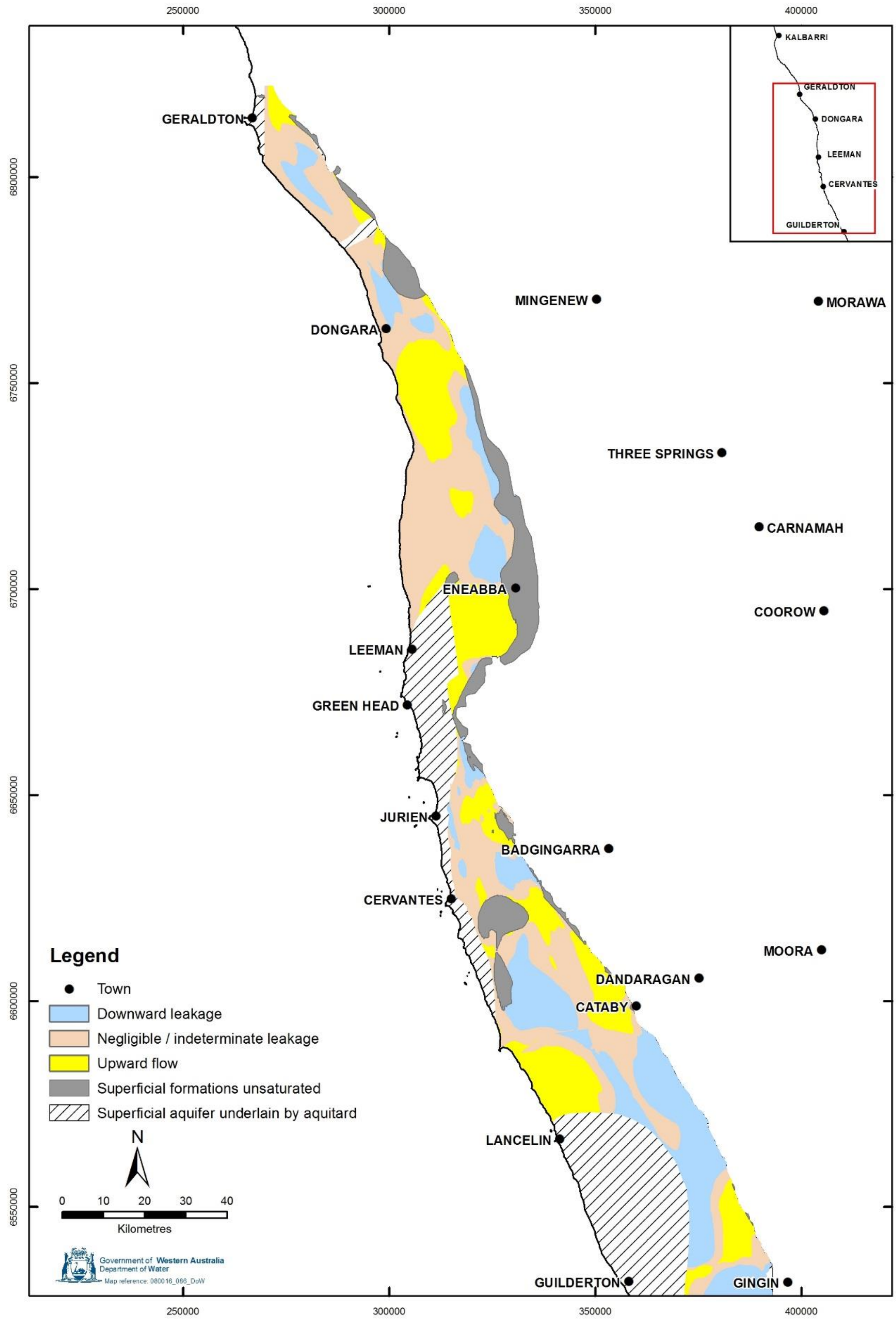
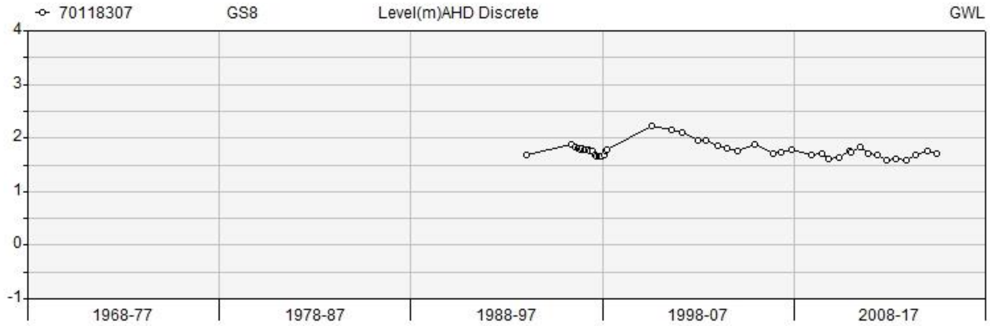
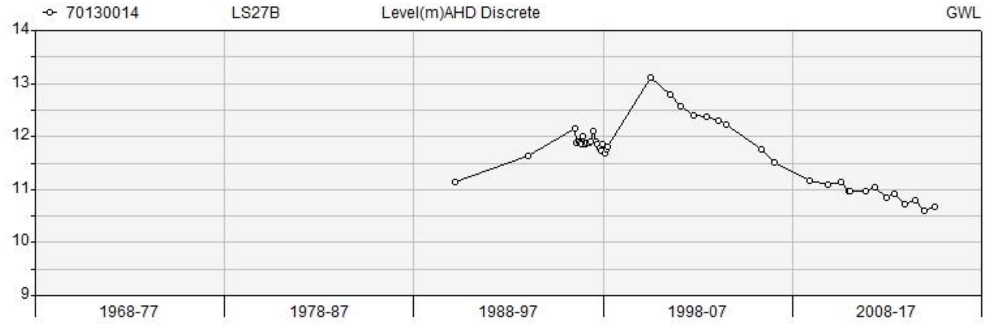


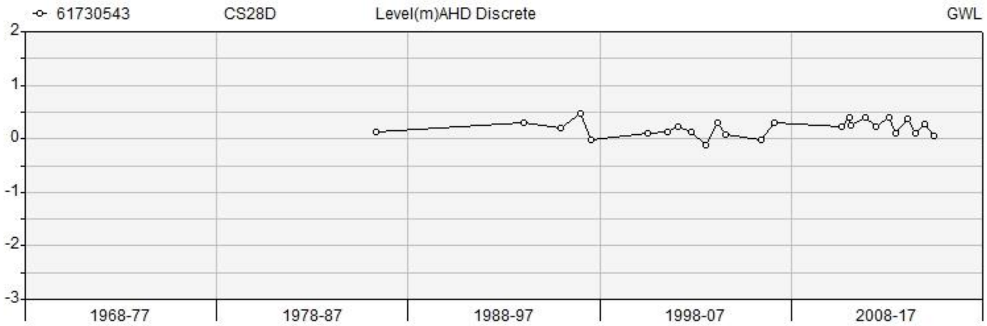
Figure 64 *Direction of vertical leakage between Superficial aquifer and underlying aquifers (Leederville, Yarragadee, Cattamarra and Eneabba–Lesueur)*



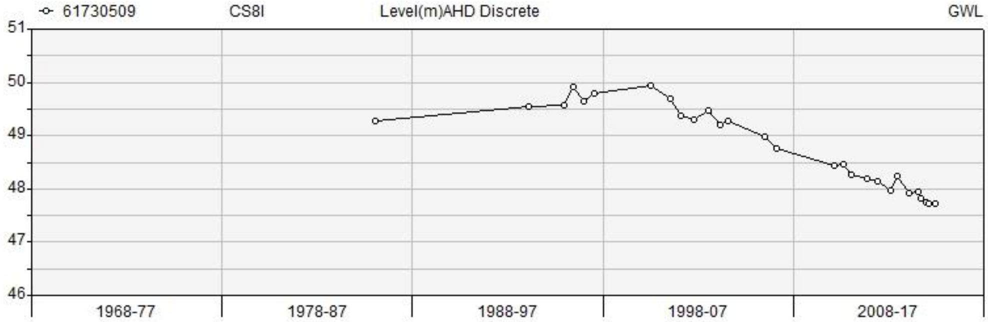
Greenough Shallow 8



Leeman Shallow 27B



Cataby Shallow 28D



Cataby Shallow 8I

Figure 65 Superficial aquifer: selected bore hydrographs

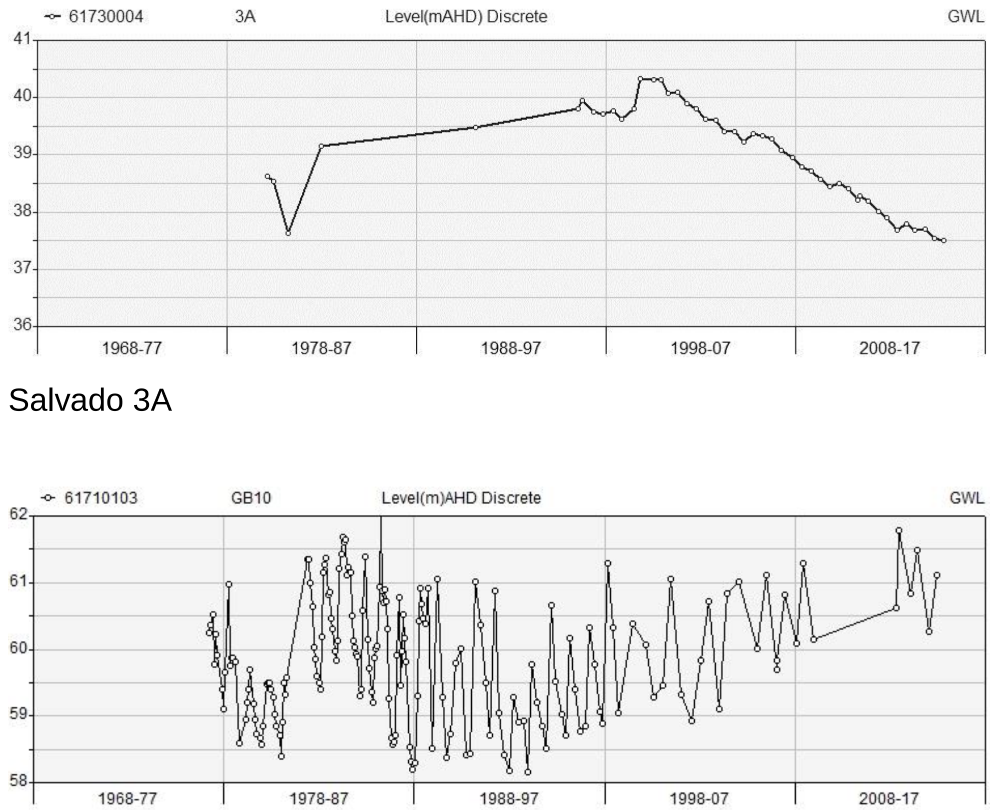


Figure 65 Superficial aquifer: selected bore hydrographs (continued)

Hydraulic parameters

The transmissivity of the Superficial aquifer typically increases from east to west, coincident with progressively more permeable lithologies toward the coast.

In the eastern part of the aquifer, the highest transmissivity unit in the Superficial aquifer is probably in the Yoganup Formation, which is a discontinuous sand unit at the base of the aquifer south of Eneabba. Aquifer testing of bores screened across sandy facies in the lower Guildford Formation and in the Yoganup Formation at a site 2 km south of Regans Ford gave a hydraulic conductivity value of 26 m/day (Woodward Clyde 2000b), which is similar to earlier estimates of 30 m/day (Moncrieff & Tuckson 1989) across these formations.

Beneath the central part of the coastal plain, the Superficial aquifer consists mainly of the Bassendean Sand and Ascot Formation (south of Cervantes). Based on aquifer tests, the hydraulic conductivity of the Bassendean Sand varies significantly but typical values range from 5 to 20 m/day (Rockwater 1980a; McPhar Geophysics 1974, 1975; ERM 2001b; Dames & Moore 1998). Aquifer test estimates of the hydraulic conductivity in the Ascot Formation, ranged from 5 to 14 m/day, averaging about 8 m/day, with a storage coefficient of around 3×10^{-4} (Moncrieff & Tuckson 1989).

The western portion of the Superficial aquifer is dominated by Tamala Limestone, which is karstic over a significant extent being the most transmissive part of the aquifer. High transmissivity is demonstrated by water-level fluctuations that respond to ocean tides at distances of over 3 km inland in the Jurien Bay area (Baddock & Lach 2003). Hydraulic conductivity of the limestone is highly variable, depending mostly on the development of karstic features below the watertable, but it commonly ranges from 50 to 1000 m/day (Hydro Plan 1993; Rockwater 1996, 1999; Water Supply Services 2001; Baddock & Lach 2003). In the eastern portion of the Tamala Limestone where karstic features are mainly absent in the saturated zone, the hydraulic conductivity is comparable to the Bassendean Sand. In the Jurien Bay area, production bores in the Jurien Bay and Cervantes town water supply borefields commonly have groundwater drawdowns of about 0.2 m for an abstraction rate of 1000 m^3/day, which is typical for karstic aquifers (Lach & Baddock 2003). Groundwater-level fluctuations in the limestone at Jurien Bay in response to ocean tides (the tidal lag method) suggest hydraulic conductivity values of between 200 and 5600 m/day (Rockwater 2002). Selected aquifer test analyses for the Superficial aquifer are summarised in Appendix B.

Estimates of groundwater throughflow

Groundwater throughflow in the Superficial aquifer has been calculated for most sections of the coastal plain based on watertable contour data from the 1990s. These earlier calculations accounted for the flat gradient and potential complexities from cavernous flow, by using the watertable contour near the contact between Tamala Limestone and Bassendean Sand to derive a hydraulic gradient. An estimate of recharge over the Tamala Limestone area (i.e. area from the contact between Tamala Limestone and Bassendean Sand to the coast) was added to calculate discharge at the coast. These early estimates of throughflow at the coast range from 35 GL/year between Dongara and Leeman to 100 GL/year between Cervantes and Lancelin. A total groundwater throughflow for the Superficial aquifer may be in excess of 300 GL/year. Throughflow estimates recalculated using 2009 watertable contours show no significant difference from previous estimations provided in Table 12.

Table 12 Superficial aquifer groundwater throughflow estimations

Area		Calculations at coast				Reference
From	To	Length (km)	Recharge area (km^2)	Throughflow (GL/year)	Throughflow (GL/year/km of coastline)	
Dongara	North of Leeman	45	900	35	0.78	Nidagal 1995
North of Leeman	Cervantes	88	1685	83	0.94	Kern 1997
Cervantes	Lancelin	98	2000	100	1.02	Kern 1993a

Groundwater salinity

Groundwater salinity in the Superficial aquifer is highly variable, but is typically less than 1000 mg/L total dissolved solids (TDS) beneath the southern portion of the coastal plain and mainly brackish north of Green Head (Figure 66) (DoW 2007; Astron 2013).

Low groundwater salinity can indicate recharge by rainfall or infiltration of fresh surface water. Areas of elevated groundwater salinity can result from the concentration of salts by evapotranspiration, infiltration of brackish water from watercourses, upward movement of groundwater from underlying Mesozoic aquifers, or from the seawater interface along the coast.

The lowest groundwater salinity (<250 mg/L TDS) is found beneath the dunes of Bassendean Sand both to the north and south of the Moore River (Kern 1988, 1993a; Moncrieff & Tuckson 1989) and east of Jurien Bay (DoW 2007). Groundwater less than 500 mg/L TDS is present in the Tamala Limestone west of Wedge Island. North of Eneabba, to the Irwin River, groundwater less than 1000 mg/L TDS is increasingly restricted to the eastern edge of the coastal plain adjacent to the Gingin Scarp. Groundwater salinity exceeds 1000 mg/L TDS north of the Irwin River, and increases to over 5000 mg/L TDS north of the Greenough River (Kern & Koomberi 2013). Locally, a thin lens of low-salinity groundwater can be present above saline groundwater in the Quindalup Dunes, as found in the coastal dunes at Port Denison (Commander 1994a, 1994b).

Over the eastern portion of the coastal plain, within the clayey sediments of the Guildford Formation, groundwater salinity is elevated owing to evapotranspiration from areas of shallow watertable and numerous wetlands. Groundwater salinity is greater than 1000 mg/L TDS in these areas, with the highest salinity at bore sites CS8, CS24 and CS36 near swamps. Plumes of higher salinity groundwater are believed to extend down gradient from the lakes (Kern 1988, 1993a).

Brackish groundwater also originates from leakage of saline rivers and streams crossing the coastal plain, such as the Moore, Arrowsmith and Irwin rivers. Groundwater salinity in excess of 1000 mg/L TDS is present near the Moore River near Karakin and Bidaminna lakes (Moncrieff & Tuckson 1989). Groundwater salinity exceeds 3000 mg/L TDS near Frederick Smith Creek and the upper section of the Nambung River (Kern 1988, 1993a, 1997), and the Hill River over the central and western parts of the coastal plain (Baddock & Lach 2003). Relatively high groundwater salinity of 1700 mg/L TDS in Leeman Shallow bore LS24 near the Arrowsmith River may also be caused by recharge from brackish river water (Nidagal 1995).

Groundwater salinity in excess of 1000 mg/L TDS at the base of the aquifer beneath the eastern portion of the coastal plain north of Gingin Brook may be caused by upward flow of marginal to brackish groundwater from the Leederville aquifer (Moncrieff & Tuckson 1989). This was recently confirmed by Tuffs (2011) in the area surrounding Gingin Brook just upstream of the confluence with Mungala Brook. Gingin Brook bore GGB7A screened at the base of the Superficial aquifer recorded a salinity of 1190 mg/L TDS compared with 730 mg/L TDS at GGB7B screened at the watertable. Similarly, groundwater discharge from the underlying Eneabba–Lesueur and Cattamarra aquifers to the Superficial aquifer may cause high salinity in the Nambung River flats area that locally exceeds 8000 mg/L TDS (Kern 1997).

A saltwater wedge extends inland from the coast under the fresh water within the Superficial aquifer. The saltwater and freshwater meet in a transition zone where mixing occurs through dispersion and diffusion. There is a significant mixing zone between the saltwater and freshwater that extends up to 4 km inland at Jurien Bay (Baddock & Lach 2003), and possibly 8 km from the coast south of Dongara (Nidagal 1995), due to the high transmissivity of the Tamala Limestone. This mixing zone is responsible for the elevated groundwater salinity (5800 mg/L TDS) at Salvado Shallow S6 (Moncrieff & Tuckson 1989). A similar saltwater interface is associated with coastal salt lakes east of Leeman–Green Head (Commander 1994a, b). A recent airborne electromagnetic (AEM) survey undertaken near Cervantes in 2011 confirms the migration and diffusion of salinity inland (Brodie & Reid 2013).

Hydrochemistry

A survey of 185 monitoring bores across the northern Perth Basin in 2011 provides the most recent snapshot of the hydrochemical characteristics of the Superficial aquifer (Astron 2013). Groundwater is mainly sodium chloride type (Figure 67) but can range to calcium bicarbonate type if aquifer lithology is very calcareous (Moncrieff & Tuckson 1989). Field pH is typically close to neutral. Lower field pH has been recorded near wetlands, which can be due to organic acids (Ryan 2012b, Astron 2013). Groundwater hardness tends to be higher in the north of the basin where it generally exceeds 300 mg CaCO3/L. Nitrate in groundwater is generally low across the basin, with concentrations less than 3.4 mg/L, which is the trigger value for the protection of 90 per cent of aquatic freshwater species (ANZECC 2000). Higher levels of nitrate are in agricultural areas where fertilisers are leached (Astron 2013).

Sulfate concentrations in groundwater across the northern Perth Basin range from less than 50 mg/L to over 500 mg/L (Astron 2013). Higher concentrations of sulfate in groundwater can result from oxidised peaty sediments that contain pyritic material. High Cl/SO4 ratios, an indicator of pyrite oxidation, are known from the Cataby area (Kern 1993a; Astron 2013). Likewise, high dissolved iron concentrations (Fe2+) have also been measured in groundwater around the Cataby area (>40 mg/L). Elsewhere, Fe2+ concentrations are typically low, less than 0.3–5 mg/L (Astron 2013).

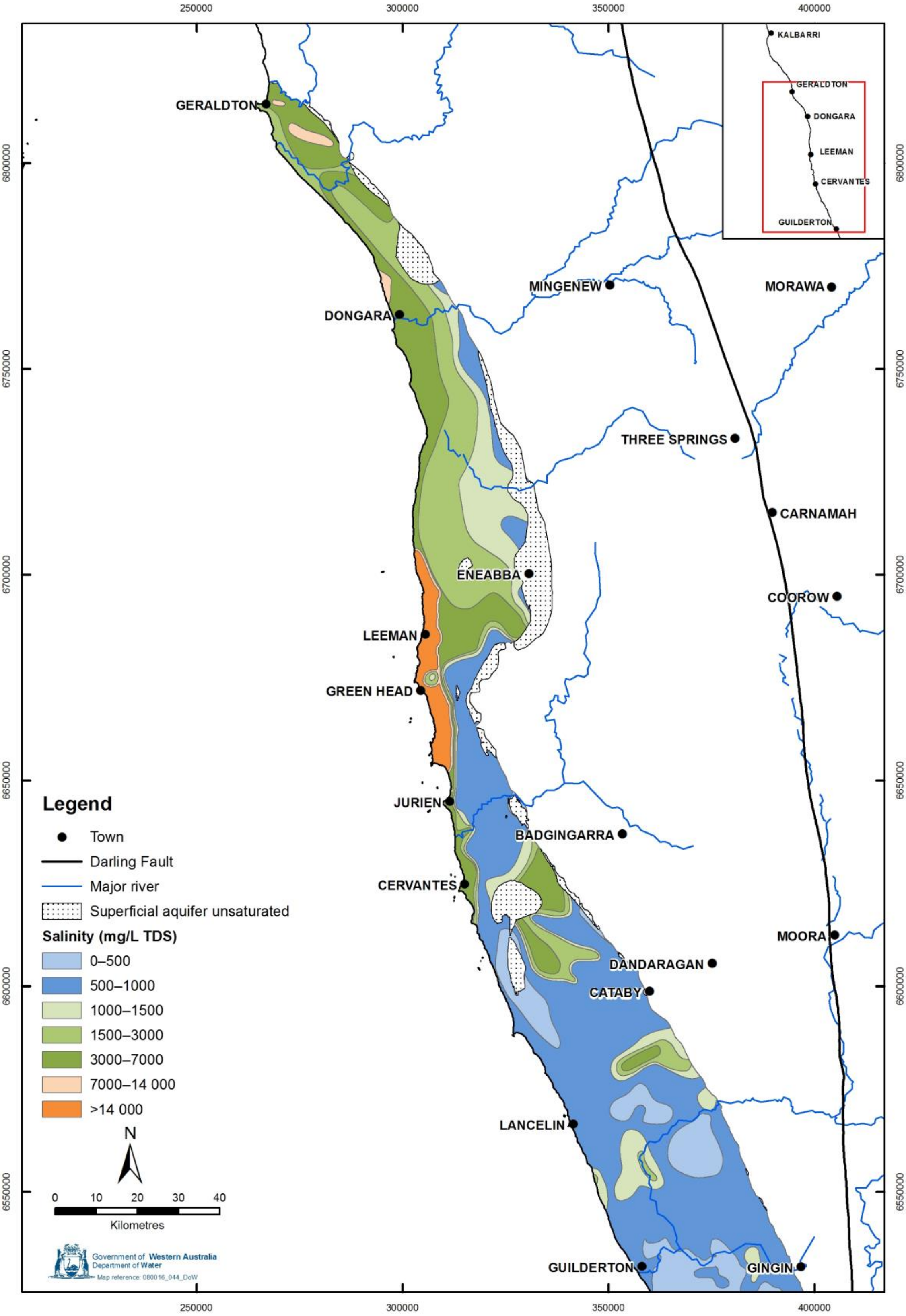


Figure 66 Superficial aquifer: groundwater salinity

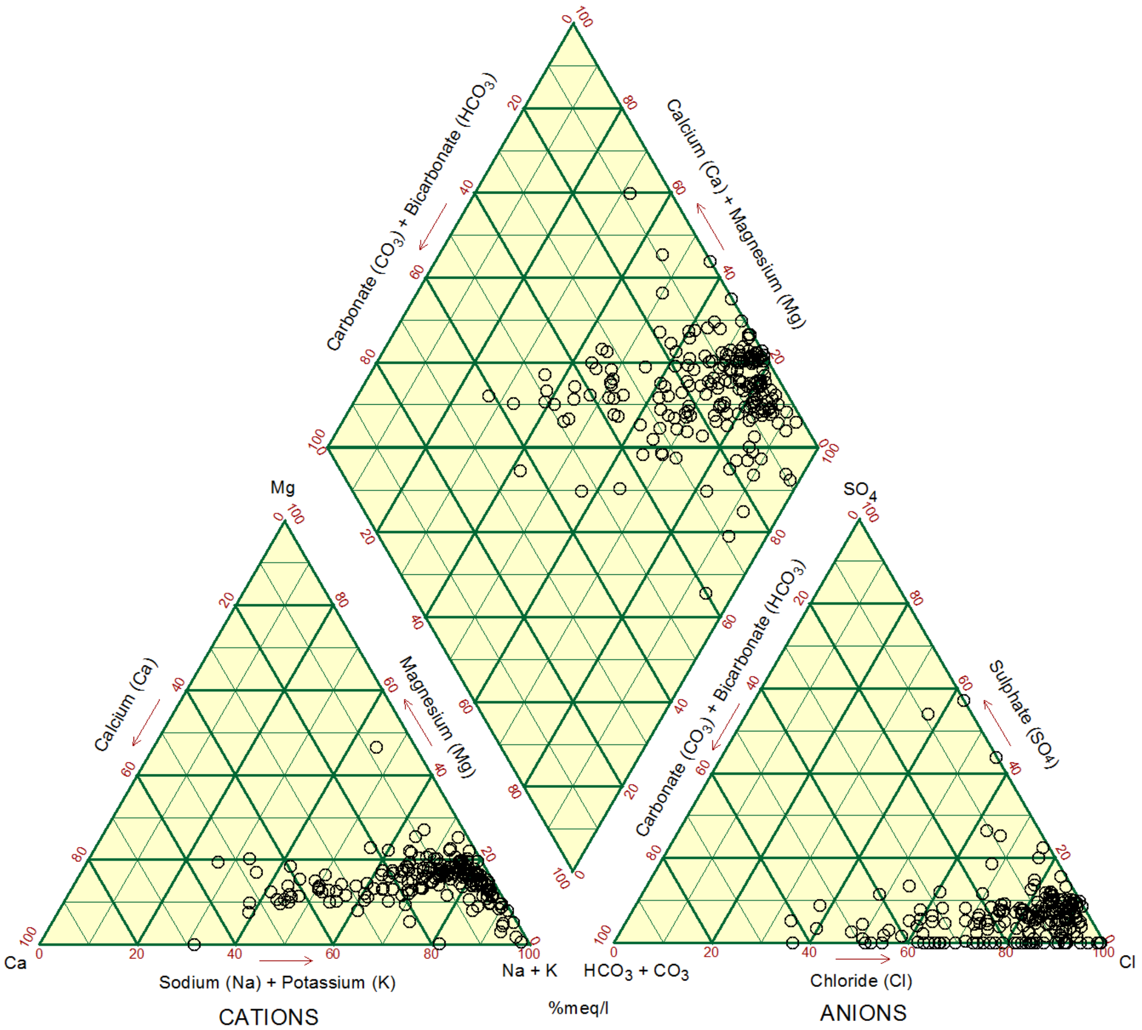


Figure 67 Superficial aquifer: hydrochemical trilinear diagram

5.3 Surficial aquifer

The unconfined surficial aquifer consists of hydraulically disconnected, locally saturated areas of the Cenozoic surficial deposits located east of the Swan Coastal Plain (i.e. east of the Gingin Scarp). As such, the surficial aquifer is considered separately to the Superficial aquifer which extends throughout the Swan Coastal Plain.

Groundwater in the surficial aquifer can be found in palaeochannels, weathered lateritic profiles and valley-fill, colluvial, alluvial, lacustrine, swamp and eolian deposits (Figure 47). Groundwater is also present in surficial deposits that have infilled the impact crater basin at Yallalie. The Monger Palaeochannel, channel sands, and Yallalie Basin deposits are regionally important surficial aquifers and are discussed separately below.

Monger Palaeochannel (Yarra Yarra Lakes)

The Monger Palaeochannel comprises Miocene to Pliocene deposits, extending along the eastern margin of the Perth Basin from Three Springs to the Wannamal Lakes south of Mogumber. The channel is largely parallel to the Moore River and is up to 35 m thick near the Yarra Yarra Lakes (Yesertener 1999).

Near the Yarra Yarra Lakes, groundwater levels are generally close to the surface (Commander 1981) and groundwater salinity ranges from fresh to saline. Recharge to the aquifer is from rainfall and local runoff as well as lateral and upward flow from the Mesozoic aquifers where it cuts them south of the Yarra Yarra Lakes (Yesertener 1999). Groundwater flows in a southerly direction and discharges into salt lakes near Moora and the Wannamal Lakes at the southern end of the channel.

At the southern extent of the Monger Palaeochannel, near the Bindoon–Moora Road and Midlands railway line, groundwater levels and salinity are rising, due to discharge from the Gillingarra Palaeochannel to the Monger Palaeochannel (Speed & Killen 2015) (Figure 47).

Bore yields of up to 15 m^3/day of fresh groundwater have been abstracted from the palaeochannel system (Moncrieff 1989) with airlift yields of up to 194 m^3/day (Yesertener 1999). Groundwater is hypersaline at Yarra Yarra Lakes, up to 280 000 mg/L TDS. Salinity becomes progressively lower along the flow path to the south due to groundwater recharge from the adjacent Mesozoic aquifers, decreasing to 14 000 mg/L TDS near Coorow (Yesertener 1999) and less than 500 mg/L TDS south of Moora (Kay & Diamond 2001).

Channel deposits

The channel deposits comprise an extensive palaeodrainage system on the Dandaragan Plateau (Commander 1978b) consisting of mid to late-Quaternary sediments up to 65 m thick (Barnett 1970b).

Recharge is from rainfall and local runoff. Groundwater levels are generally close to the surface (Kay & Diamond 2001). Groundwater flow is likely to be towards the west, discharging as small springs where the surficial deposits pinch out as the Coolyena Group outcrops (Briese 1979; Kay 1999; HydroConcept 2012). Recent groundwater investigations in the Capitela Palaeochannel reported the presence of fresh groundwater (<500 mg/L TDS) and potential bore yields of up to 2500 m^3/day (HydroConcept 2012). Otherwise little information is available on groundwater salinity in channel deposits, and water quality is likely to be highly variable.

Yallalie Basin deposits

The Yallalie Basin is a sediment-filled impact crater about 30 km north-west of Moora. The basin is infilled with Quaternary sediments, mainly sandstone, up to 177 m deep. These sediments were intersected in Agaton bores A2 and A3 but no aquifer tests have been undertaken. Bore A2 had freshwater in sands between 26 and 30 m bgl overlying saline water in silt and clay units (Balleau & Passmore 1972). Brackish to saline water has also been identified in the wetlands in the middle of the Yallalie impact crater and underlain by low permeable silts and clays (Water Direct 2004). Groundwater in the upper sands of the Yallalie Basin may be a recharge source for the underlying Leederville–Parmelia aquifer.

5.4 Mirrabooka aquifer

The Mirrabooka aquifer is a relatively thin, sandy, semi-confined aquifer within the Mirrabooka Member of the Osborne Formation, including the Molecap and Poison Hill greensands, where these are in hydraulic connection (Kay & Diamond 2001). The

Mirrabooka aquifer is present in the eastern half of the northern Perth Basin between Coorow and Gingin and extends southward into the Perth region but its distribution is discontinuous (Davidson 1995; Tuffs 2011).

The Lancelin Formation that is age-equivalent to the Molecap and Poison Hill greensands and the Gingin Chalk forms a confining bed in the western half of the northern Perth Basin south of Lancelin, separating the Superficial aquifer from the Leederville aquifer.

The thickness of the Mirrabooka aquifer is generally less than 50 m, but was found to be up to 90 m near the Muchea Fault (Kay & Diamond 2001). Generally, the thickness of the aquifer decreases towards the Gingin Scarp. Perched groundwater may exist within the aquifer and saturated sand beds are often discontinuous.

The Mirrabooka aquifer is generally hydraulically isolated from the underlying Leederville–Parmelia aquifer by the Kardinya Shale Member of the Osborne Formation. However, east of the Muchea Fault (and particularly near the Moore River where the Kardinya Shale Member thins or is absent), the potentiometric levels in the Mirrabooka and Leederville–Parmelia aquifers are similar, suggesting hydraulic connection (Kay & Diamond 2001). To the west of the Muchea Fault, where the Kardinya Shale Member is present, a downward hydraulic head difference of up to 50 m has been observed between the Mirrabooka and Leederville–Parmelia aquifers (Kay & Diamond 2001).

Recharge to the Mirrabooka aquifer is mainly via rainfall recharge, particularly where the aquifer outcrops (see Figure 45 and Figure 46). The aquifer may be locally confined where interbedded shale units or impermeable ferricrete layers are present, restricting direct rainfall recharge (Kay & Diamond 2001).

Groundwater from the Mirrabooka aquifer discharges at the surface via springs along the valleys of Red Gully, parts of the Moore River and locally in Gingin, Moondah and Lennard brooks, providing baseflow to these river systems (Kay & Diamond 2001, Tuffs 2011). In the headwaters of Lennard Brook and in the lowest reaches of Moondah and Wowra brooks where they flow into Gingin Brook, the Kardinya Shale Member is absent and there is potential for hydraulic connection between the Mirrabooka and Leederville–Parmelia aquifers and also the brooks. Around the headwaters of Gingin Brook, the Kardinya Shale Member is present, isolating the Leederville–Parmelia aquifer from the Mirrabooka aquifer which is the main contributor of baseflow to the brook (Tuffs 2011). The Mirrabooka aquifer may also discharge into the Wanammal Lake system.

Groundwater flow in the Mirrabooka aquifer is broadly to the west, with groundwater levels decreasing from 170 m AHD near the Muchea Fault to 140 m AHD near the Dandaragan Scarp. However, flow patterns are locally variable because of undulating topography and the patchy distribution of the aquifer (Kay & Diamond 2001). Broad-scale groundwater-level monitoring in the Mirrabooka aquifer from Gillingarra Line GL7W indicates a gradual decline in water levels of about 1.5 m between 2000 and 2016.

5.5 Leederville aquifer

The Leederville aquifer is a major multilayered aquifer of sandstone, siltstone and shale below the coastal plain. The Leederville aquifer consists of the Leederville Formation and the

Henley Sandstone Member of the Osborne Formation (where present). About half of the aquifer consists of sandstone, although parts of the sandstone are clayey (Moncrieff 1989). The greatest portion of sand is found within the Wanneroo Member of the Leederville Formation. Individual waterbearing sand beds are lenticular and of limited extent but these individual beds are interconnected to form a single multilayered aquifer.

The aquifer extends from south of Cataby in a southerly direction towards the Perth region (Davidson 1995). The Leederville and Leederville–Parmelia aquifers are hydraulically connected beneath the Gingin Scarp. However, in this transition zone, the Leederville Formation is thin and comprises the less permeable Mariginiup Member, which limits groundwater flow between these two aquifers.

The Leederville aquifer is thickest beneath the western part of the coastal plain, between the Moore River and the coast (Figure 68). It thins eastward to less than 100 m at the Gingin Scarp north of Beermullah, which corresponds with the Gingin Anticline as described by Playford et al. (1976) and Moncrieff (1989). The maximum intersected thickness is about 650 m in Gillingarra Line bore GL2B (Moncrieff 1989) with a maximum thickness of only 490 m recorded further south by Tuffs (2016) at North Gingin bore NGG2A on the eastern side of Moore River, 13 km north-east of the coastal settlement of Seabird.

Groundwater within the Leederville aquifer is confined by the overlying Kardinya Shale Member, which forms an aquitard beneath the western and central parts of the coastal plain south of Lancelin. Where the Kardinya Shale Member is absent, the Leederville aquifer is hydraulically connected with the overlying Superficial aquifer (Moncrieff 1989), for example between Gillingarra Line bores GL4 and GL5 (Figure 53 and Figure 55). Beneath the Leederville aquifer, the South Perth Shale forms an aquitard between the Leederville and underlying Yarragadee aquifer. Along the northern margins of the Leederville aquifer and beneath the eastern margin of the coastal plain, the South Perth aquitard is absent and the Leederville is hydraulically connected to the underlying Yarragadee aquifer (Schafer 2016).

Groundwater recharge

Groundwater within the Leederville aquifer is replenished mainly by downward leakage from the overlying Superficial aquifer, and from westward flow from the Leederville–Parmelia aquifer beneath the Gingin Scarp (Moncrieff 1989). Recharge from the overlying Superficial aquifer takes place mostly over the eastern part of the coastal plain where the Kardinya Shale Member is absent and a downward hydraulic head gradient exists (Figure 69). Low-salinity groundwater at the top of the aquifer north-east of Lancelin (Gillingarra Line bore GL1B) suggests there is also some recharge from the Superficial aquifer in this area (Moncrieff 1989). Direct infiltration of rainfall and runoff from the Dandaragan Plateau occurs locally along the Gingin Scarp where the Leederville Formation outcrops. In the north-western portion of the aquifer, north of Lancelin, the South Perth Shale is absent and the hydraulic head within the Yarragadee aquifer is higher than that in the Leederville aquifer, resulting in upward groundwater flow into the Leederville aquifer.

Groundwater discharge

Groundwater within the Leederville aquifer is discharged either upward into the Superficial aquifer or downward to the Yarragadee aquifer. Upward flow to the Superficial aquifer occurs where the hydraulic head in the Leederville aquifer is greater than the watertable in areas where the Kardinya Shale Member is absent (Figure 69 and Figure 70). Groundwater discharges into the underlying Yarragadee aquifer along the northern extent of the Leederville aquifer where the South Perth Shale is absent and the hydraulic head of the Leederville aquifer is greater than in the underlying Yarragadee aquifer (see Figure 53). At the coast, groundwater from the Leederville aquifer flows offshore and discharges into the ocean via the superficial formations. The major zone of offshore discharge probably takes place between Lancelin and Wedge Island where the Kardinya Shale Member is interpreted to be absent.

Groundwater levels and flow

Groundwater flows in the Leederville aquifer from the north-east to the south-west and from the Gingin Scarp towards the coast. The hydraulic head within the Leederville aquifer decreases from up to 80 m AHD adjacent to the Gingin Scarp to 10–20 m AHD at the coast (Figure 70). There is a steep hydraulic gradient through the transitional area from the Leederville–Parmelia and Leederville aquifers, probably due to thinning of the Leederville Formation. There is also a steep hydraulic gradient between Gillingarra Line bores GL3 and GL4, which may be a result of reduced sand content and aquifer transmissivity, or lower permeability across a fault (Moncrieff 1989). Artesian flow is possible in low-lying areas near the coast where the hydraulic head is above ground surface.

Groundwater flows westward from the Leederville–Parmelia aquifer into the Leederville aquifer between Gingin and Regans Ford, predominantly within sandstone beds. There is potential for groundwater to move into deeper parts of the aquifer along the Gillingarra Line east of bore GL3, where the hydraulic head decreases with increasing depth (Moncrieff 1989). Within the western portion of the aquifer, there is a predominantly upward hydraulic head gradient suggesting upward potential for groundwater flow. Along the coast, the hydraulic head is well above sea level (10 m AHD) suggesting that low-salinity groundwater may flow a significant distance offshore (Moncrieff 1989).

Groundwater flow between the Leederville aquifer and overlying Superficial aquifer is possible where they are hydraulically connected in the eastern and northern portions of the Leederville aquifer. There is also potential for groundwater flow into the underlying Yarragadee aquifer about the eastern and northern limits of the Leederville aquifer where the intervening South Perth Shale is absent.

The hydraulic head fluctuates seasonally, although monitoring has not been sufficiently frequent to observe the magnitude of seasonal change in the Gillingarra Line bores. A seasonal variation in hydraulic head of about 1.5 m has been observed in bore AM3 along the Gingin Line. A declining trend in hydraulic head is mainly attributed to groundwater abstraction and, to a lesser extent, to declining rainfall. The hydraulic head has been declining in the south since 1985 within Artesian Monitoring bores AM1 and AM3 (0.15 m/year). Hydraulic head in the north appears to have commenced declining later. Figure 71 shows representative bore hydrographs within the Leederville aquifer.

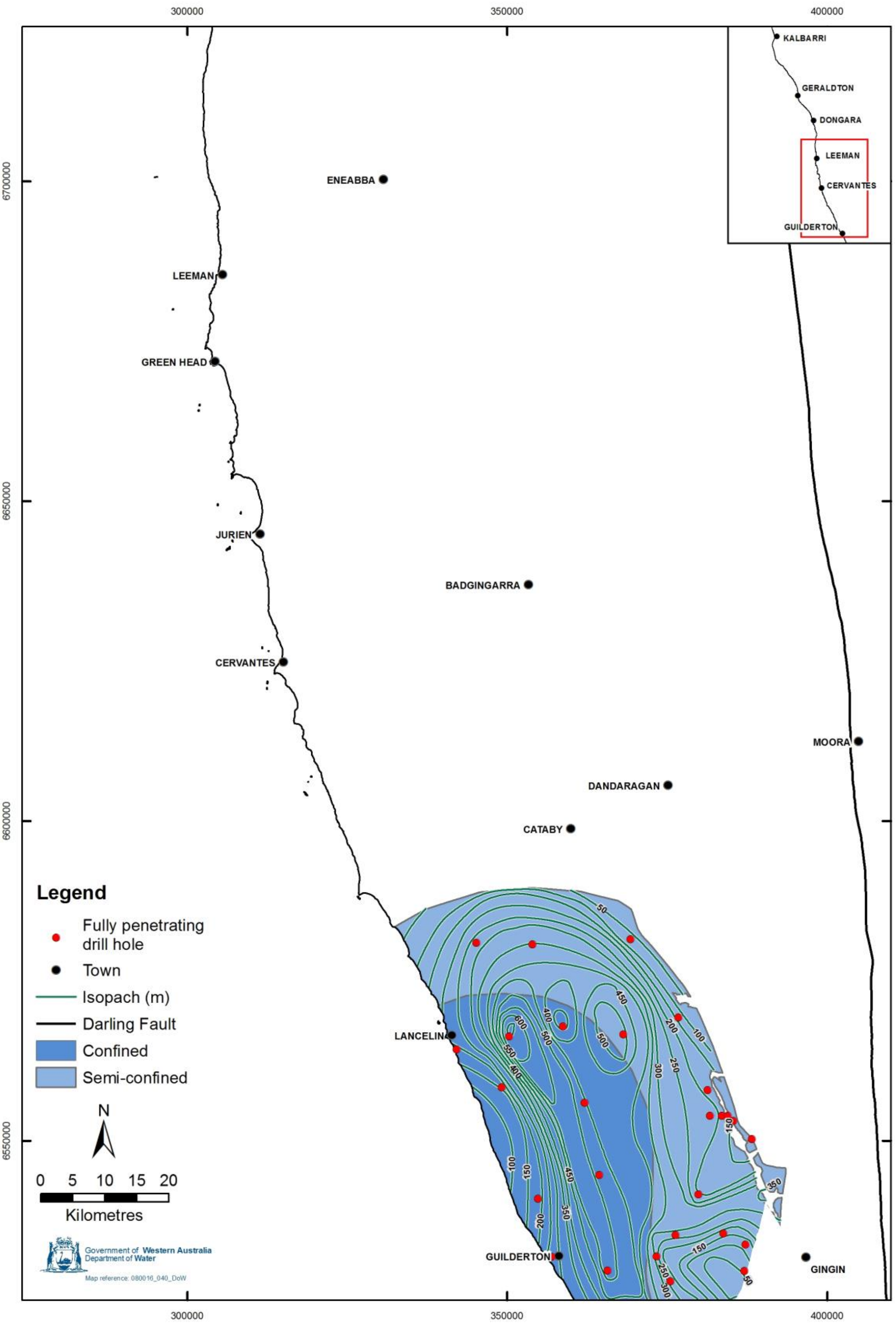


Figure 68 Leederville aquifer: aquifer thickness

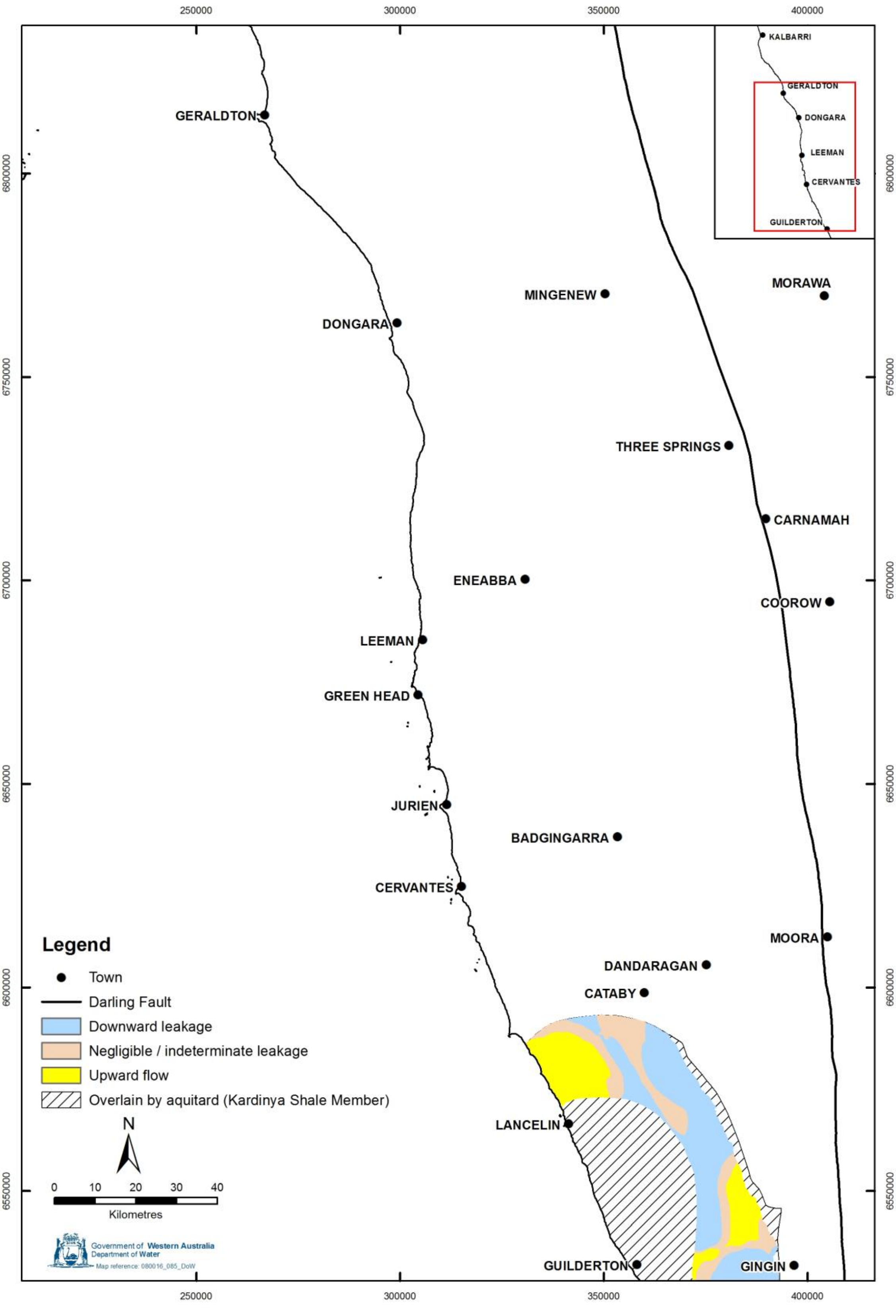


Figure 69 Groundwater connection between Leederville aquifer and overlying Superficial aquifer

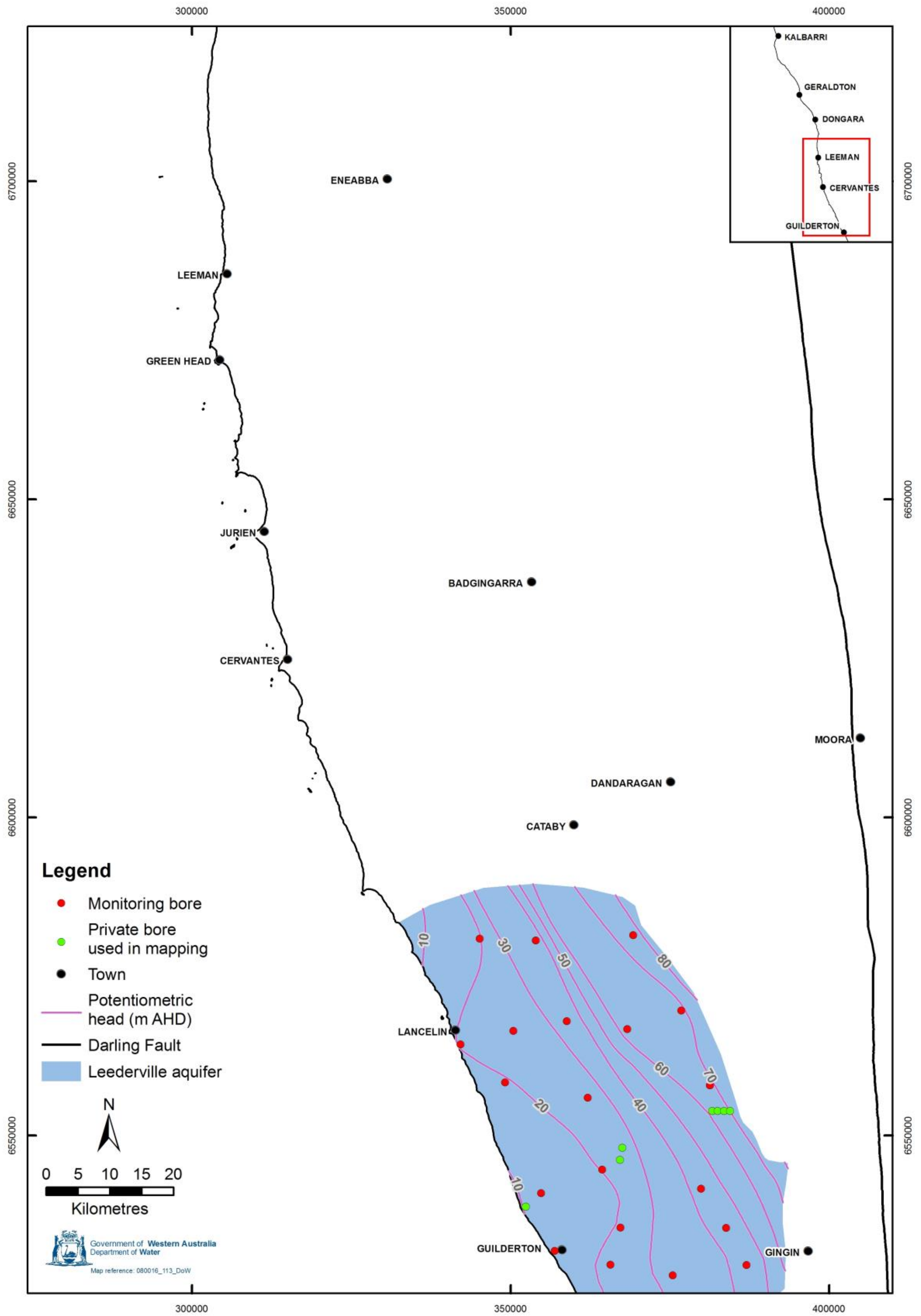
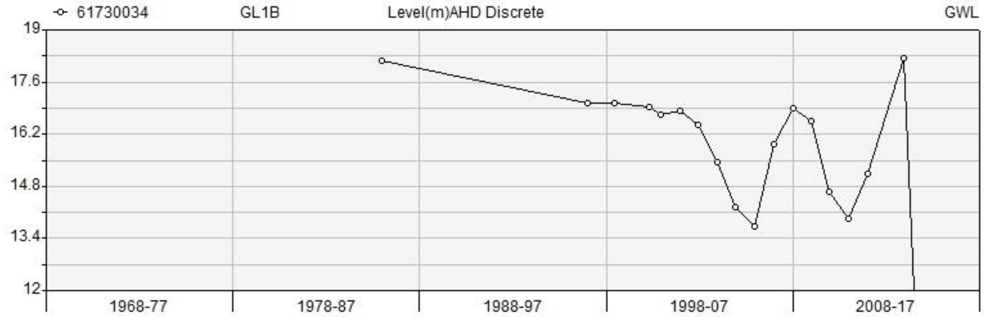
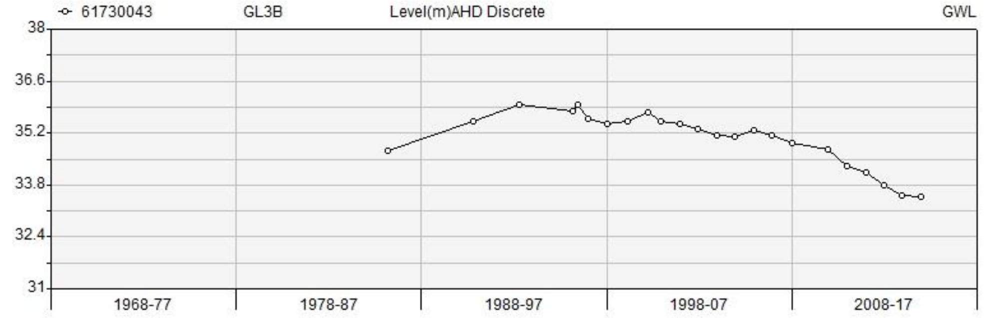


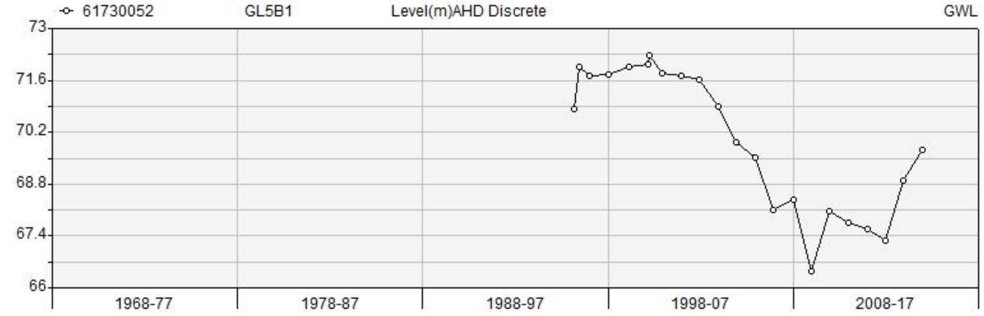
Figure 70 Leederville aquifer: potentiometric surface (2015)



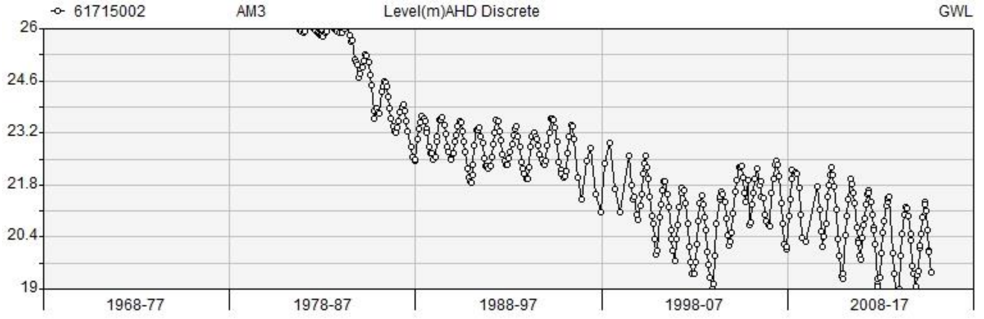
Gillingarra Line 1B



Gillingarra Line 3B



Gillingarra Line 5B1



Artesian Monitoring 3

Figure 71 Leederville aquifer: selected bore hydrographs

Hydraulic parameters

The Leederville aquifer is heterogeneous and stratified with considerable variability in hydraulic properties. Lateral variation in transmissivity is driven by the variable thickness of the permeable sand intervals, the extent and thickness of individual beds, and the interconnection between beds. Where sand beds are offset due to faulting, this may result in lower aquifer permeability.

The highest hydraulic conductivities in the Leederville aquifer are generally associated with the Wanneroo Member, which has thick sand horizons. The hydraulic conductivity of the Pinjar and Mariginiup members is likely to be lower due to finer grained and overall reduced sand content in aquifer horizons in these members relative to the Wanneroo Member. Sand beds in the Pinjar and Mariginiup members are also likely to be less laterally continuous than the sand beds in the Wanneroo Member. The hydraulic properties of the Henley Sandstone Member are likely to be comparable with the Wanneroo Member because their lithologies are similar.

Transmissivity and hydraulic conductivity has been estimated from aquifer tests of numerous Leederville aquifer bores in the northern Perth Basin (Appendix C and Appendix D). Transmissivity ranges from 26 to 2090 m^2/day and hydraulic conductivity ranges from 2 to 61 m/day, with an average of 20 m/day. Some of the higher transmissivity values are possibly due to aquifer leakage effects during pumping. Some aquifer test results will be skewed towards higher values because the bores are preferentially screened over sand intervals. The average permeability incorporating sand, siltstone and shale intervals, considered as bulk permeability, will be lower than values determined from these aquifer tests.

Leederville aquifer parameters in the Perth region have been estimated by numerous methods. Early aquifer tests estimated the horizontal hydraulic conductivity of sandstone beds at about 10 m/day (Smith 1979). Average horizontal hydraulic conductivity for the aquifer has been estimated to be about 5 m/day based on a lithological composition of about 50 per cent sandstone and 50 per cent siltstone plus shale, and a hydraulic conductivity of 1×10^{-6} m/day for siltstone (Davidson 1995). This calculation also assumes that sand beds are laterally continuous. However, if the sand lenses are laterally discontinuous over short distances, the hydraulic conductivity will approach that of the shale and siltstone beds.

Using flownet analysis, Davidson (1995) estimated the average hydraulic conductivity for the Leederville aquifer north of the Swan River was between 1 and 9 m/day, with an average of 1.5 m/day. The lithology of the Leederville aquifer at the northern limit of the basin is similar to the Leederville aquifer south of the Swan River (e.g. 50% sandstone, 50% siltstone and shale) (Moncrieff 1989). Therefore, an upper value for the average aquifer horizontal hydraulic conductivity of 8–10 m/day may be expected in this area, dependent on continuity of sand beds. The hydraulic conductivities of the Pinjar and Mariginiup members are likely to be lower due to fewer, thinner and more discontinuous sand beds compared to the Wanneroo Member.

There has been no analysis of vertical hydraulic conductivity for the Leederville aquifer north of the Gingin Brook. However, vertical hydraulic conductivity of the Pinjar, Wanneroo and Mariginiup members of the Leederville Formation was recently directly measured from undisturbed core samples taken from north of Perth at Beenyup by the centrifuge method (Anderson & Rahman 2015). The highest vertical hydraulic conductivities were measured in sandstone samples from the Wanneroo (8×10^{-2} m/day) and Pinjar (6×10^{-2} m/day) members. The lowest vertical conductivities were measured from well-consolidated siltstone and shale samples from the Pinjar Member (3×10^{-7} m/day to 4×10^{-7} m/day respectively) (Anderson & Rahman 2015).

These results are within the ranges previously reported in Davidson (1995) who estimated values within the Wanneroo Member to be in the order of 10^{-2} to 10^{-3} m/day. They are consistent with aquifer parameters estimated during model calibration and sensitivity analysis for the Perth Regional Aquifer Modelling System (PRAMS) (De Silva et al. 2013).

The Kardinya Shale Member, which forms an aquitard overlying much of the Leederville aquifer, is assumed to have a vertical hydraulic conductivity of about 1×10^{-6} m/day. Leakage through this aquitard is considered to be negligible (Davidson 1995).

Storativity and specific yield of the Leederville aquifer have not been evaluated in the northern Perth Basin. In the Perth region, Davidson (1995) assumed a specific yield of 0.2 for the sandstone beds, and a storage coefficient of 1×10^{-4}.

Groundwater salinity

Groundwater salinity within the Leederville aquifer is generally between 500 and 1000 mg/L TDS (Figure 72). North of Gingin Brook and Moore River, the lowest recorded groundwater salinity is 480 mg/L TDS in North Gingin bore 4B (NGG4B), 3 km east of Ledge Point. The highest salinity recorded was 1360 mg/L TDS in NGG7B, 15 km north-east of Lancelin. Moncrieff (1989) attributed elevated salinity in the Leederville aquifer to seepage of brackish water from the Superficial aquifer, which is derived from the Moore River.

An interface of freshwater overlying saline seawater is present in the west, and probably occurs from a number of interfingering seawater interfaces associated with separated sand beds. Based on the onshore potentiometric gradient of the Leederville aquifer, it is likely that the seawater interface will be some distance offshore. However, the seawater interface may be close to the coastline in the aquifer north of Lancelin where the overlying Kardinya Shale Member is absent and the hydraulic head in the aquifer is lower.

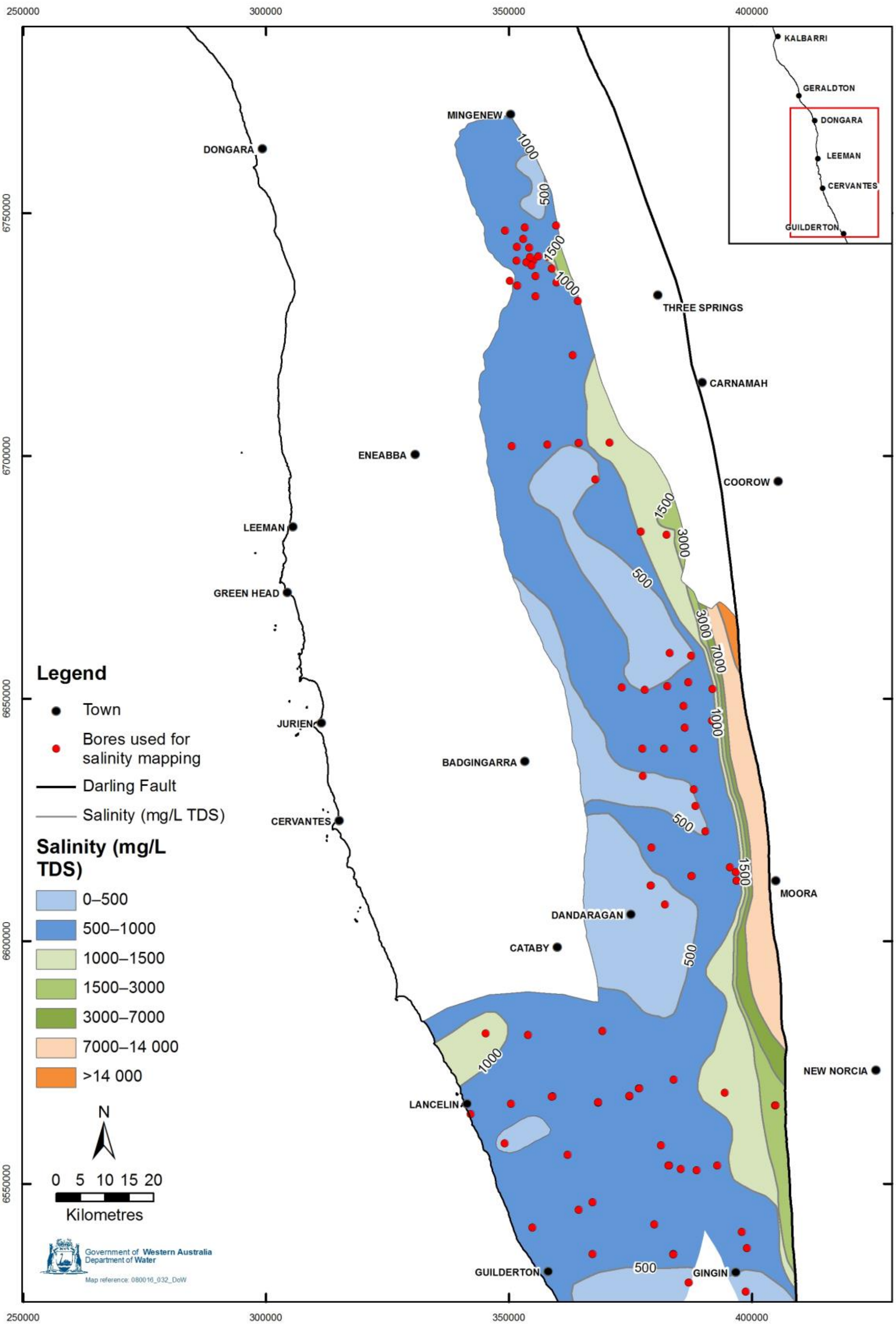


Figure 72 Leederville and Leederville–Parmelia aquifers: groundwater salinity

Hydrochemistry

The major ion chemistry of groundwater samples for the Leederville aquifer is summarised in the hydrochemical trilinear plot shown in Figure 73. Groundwater in the Leederville aquifer is of sodium chloride type. In the Perth region, groundwater from the Mariginiup Member commonly has significant calcium and bicarbonate, probably due to the presence of calcareous beds (Davidson 1995). The chemical composition of groundwater in the Leederville aquifer is generally similar to that in the Leederville Formation component of the Leederville–Parmelia aquifer.

Field pH averages 6.9 based on sampling of selected North Gingin and Gillingarra Line bores and Seabird town water supply bore 1/75. Dissolved iron concentrations in the Leederville aquifer frequently exceed 1 mg/L and can be highly variable, with reported values ranging from less than 0.05 mg/L (GL3B) up to 18 mg/L (GL2B2) (Moncrieff 1989; Egis 1999; Tuffs 2016). Dissolved iron concentrations are highest in the deeper portions of the aquifer, beneath the central and western parts of the coastal plain. South of Gingin Brook, where the Wanneroo Member directly underlies the Superficial aquifer, iron concentrations are typically low (Davidson 1995), and this may also be the case about the eastern and northern margins of the Leederville aquifer in the northern Perth Basin.

Groundwater from the upper portion of the Leederville aquifer contains a higher ratio of calcium to sodium and potassium relative to deeper portions of the aquifer along the Gillingarra Line (Moncrieff 1989). The higher proportion of calcium in the shallower parts of the aquifer may represent dissolution of calcareous sediments in the overlying superficial formations, as noted by Tuffs (2016) in North Gingin bore NGG7B 15 km north-east of Lancelin with calcium of 100 mg/L. Calcium concentrations are likely to decrease along groundwater flow paths after the groundwater enters the Leederville aquifer. Groundwater bicarbonate values are typically greater in deeper portions of the aquifer (Moncrieff 1989). A slightly higher than usual bicarbonate value of 224 mg/L was obtained from GL4W at a shallow interval being associated with slightly brackish groundwater derived from the Moore River (Moncrieff 1989).

Groundwater isotopic composition and age

Groundwater ages determined from carbon-14 analysis of collected samples from the Leederville aquifer range from 4960 years BP from Gillingarra Line GL3B to greater than the dating limit of carbon-14 (>37 500 years BP) in GL1A1 (Thorpe 1995; Egis Consulting 1999). Relatively old groundwater (9000 years BP) from GL5W in a recharge area of the aquifer suggests hydraulic connection and input from the Leederville–Parmelia aquifer to the east. The younger groundwater age in GL3B relates to groundwater recharge to the north-east of the Leederville aquifer. Older groundwater is present within deeper portions of the aquifer and the less permeable Mariginiup Member (see Table 13).

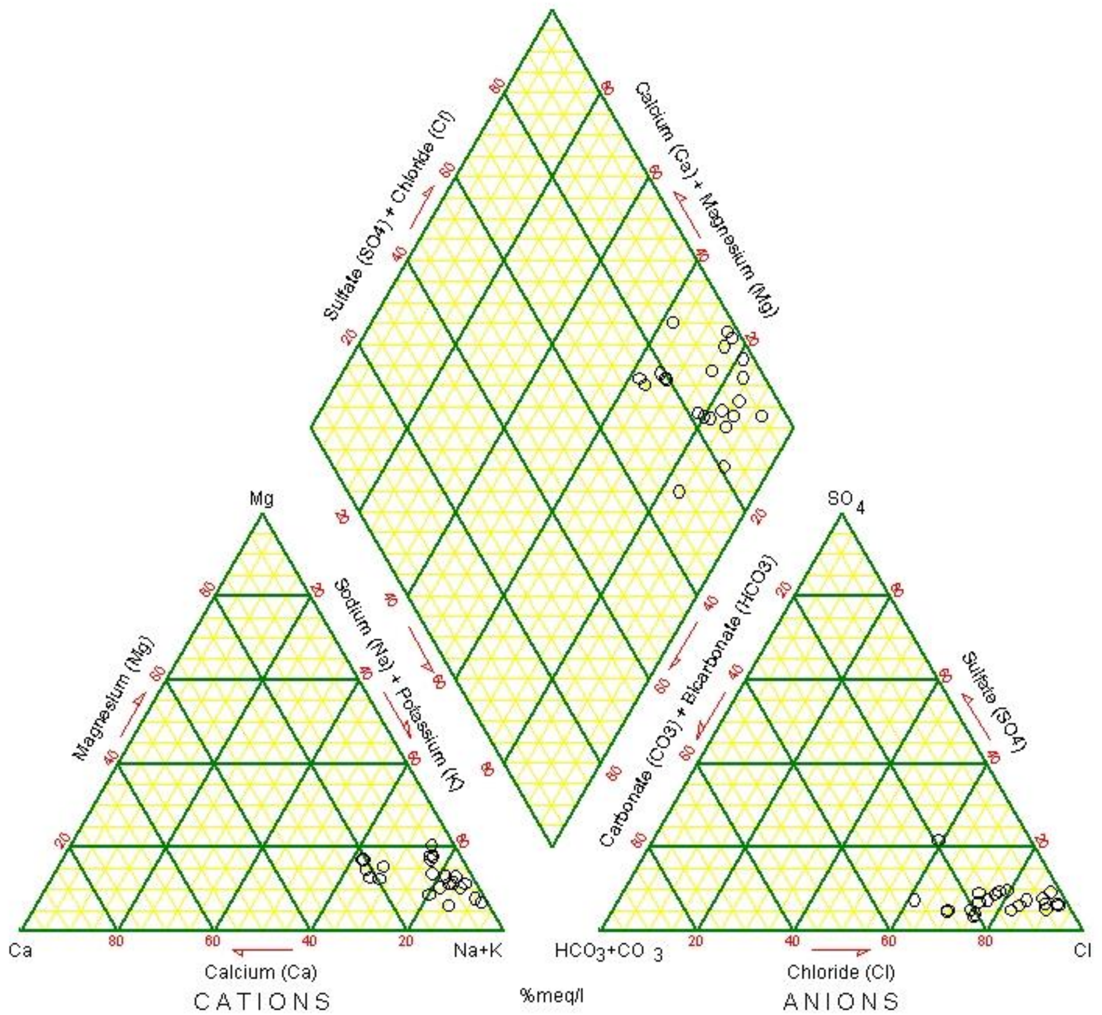


Figure 73 Leederville aquifer: hydrochemical trilinear diagram

Table 13 Groundwater isotope data for the Leederville aquifer

Project / Town	Bore	Screen interval (m gl)	14C (pmC)	14C error (pmC)	14C age, corrected (yr BP)	14C age error (yr BP)	δ13C (‰ PDB)	δ18O (‰ SMOW)	δ 2H (‰ SMOW)
Seabird TWS	1/75	97–103	4.4	0.5	25 860	960	–15.1	–4.7	–18.3
Gillingarra Line	GL1A1	201–207	1.1	0.6	>37 500	–	–16.4	–5.1	–22.2
Gillingarra Line	GL1B	102–108	9.9	0.5	17 700	420	–14.7	–4.3	–18.5
Gillingarra Line	GL3B	239–251	41.3	0.5	4960	100	–16.1	–	–
Gillingarra Line	GL4C	408–414	9.7	0.2	18 410	170	–16.0	–	–
Gillingarra Line	GL5W	52–58	33.8	1.1	9000	260	–	–	–

Data from Egis Consulting (1999)

Notes: 14C – carbon-14; 13C – carbon-13; 18O – oxygen-18; 2H – deuterium; pmC – per cent modern carbon; PDB – 13C standard; δ – ratio of sample to standard; SMOW – standard mean ocean water; ‰ – per mil (parts per thousand). Different correction models have been used to generate 14C age, corrected (yr BP); refer to the original project reports for more information.

5.6 Leederville–Parmelia aquifer

The Leederville–Parmelia aquifer extends from Mingenew to Gingin over an area of about 6650 km^2 beneath the Dandaragan Plateau, within a predominantly eastward-deepening portion of the Perth Basin (Figure 74). The Leederville–Parmelia aquifer has been referred to as the 'Agaton Groundwater System' (Harley 1974), the 'Upper aquifer' in the Arrowsmith River area (Barnett 1969), and the 'Upper Yarragadee aquifer' along the Eneabba Borehole Line (Commander 1978).

In the west, the Leederville–Parmelia aquifer is bound by the outcropping Otorowiri Formation (Commander 1981) and the Leederville aquifer beneath the Gingin Scarp. In the east, the Leederville–Parmelia aquifer abuts the crystalline rocks of the Mullingarra Inlier and Yilgarn Craton at the Darling Fault, and Proterozoic metasedimentary rocks of the Yandanooka and Moora groups at the Urella Fault. In the north-east, north of the Arrowsmith River, the aquifer is bound by Permian formations at the Urella Fault.

The Leederville–Parmelia aquifer consists of the Parmelia Group, and in the south, the Leederville Formation and the Henley Sandstone Member of the Osborne Formation.

On the Yarra Yarra Terrace, layered sandstones within Mesozoic formations (Yarragadee Formation, Cadda Formation, Cattamarra Coal Measures, Eneabba Formation and Lesueur Sandstone) may be hydraulically connected with the Leederville–Parmelia aquifer across the

Urella Fault (Yesertener 1999). However, the degree of hydraulic connection between the Mesozoic formations and the Leederville–Parmelia aquifer is variable, and would depend on the distribution of sand and clay layers in the Mesozoic sequence and the juxtaposition of sand and shale beds by faulting (mostly unmapped), which would impede groundwater flow. Near the northern limit of the Leederville–Parmelia aquifer, clay sediments of the Kockatea Shale would hydraulically separate sand beds in the Permian formations from Mesozoic formations to the south on the Yarra Yarra Terrace. There is limited hydrogeological data for the Mesozoic formations in this area, although groundwater salinity is mostly brackish to saline due to the overlying saline palaeochannel system and slow rates of groundwater throughflow.

The proportion of sand varies significantly throughout the Leederville–Parmelia aquifer, and consequently the permeability is highly variable. Sand comprises about 50 per cent of the Leederville Formation component, but the fraction of sand can be less for some intervals, particularly in the Mariginiup Member. The average sand content of the Parmelia Group (excluding the basal Otorowiri Formation) is about 30 per cent. The sand content in the Carnac Formation of the Parmelia Group is highly variable with about 20–50 per cent sand in the south, increasing to over 50 per cent sand in the north, and possibly greater than 70 per cent sand north of Agaton.

The Leederville–Parmelia aquifer thickens eastward from the margin of Otorowiri Formation outcrop, reaching a maximum thickness of about 1300 m west and south of Moora, but elsewhere it is generally between 300 and 500 m thick (Figure 74). The Leederville Formation component is mostly over 300 m thick below the eastern part of the Dandaragan Plateau, reaching a maximum intersected thickness of up to 443 m within Moora Line 1 (ML1). On the Barberton Terrace, between the Darling and Muchea faults, the Parmelia Group is absent and the Leederville–Parmelia aquifer is mostly between 200 and 400 m thick and consists solely of the Leederville Formation and overlying Henley Sandstone Member.

The Leederville–Parmelia aquifer is unconfined where the Parmelia Group outcrops, between the Watheroo Line and Mingenew (see Figure 18). The Leederville–Parmelia aquifer is hydraulically connected with the overlying surficial aquifer of the Yallalie Basin and Monger Palaeochannel (Yesertener 1999). The Leederville–Parmelia aquifer is also hydraulically connected to the overlying Mirrabooka aquifer beneath the south-western Dandaragan Plateau, where the Kardinya Shale Member is absent. In the south, the Leederville–Parmelia aquifer is confined beneath interbedded siltstone and shale of the Coolyena Group, particularly the Kardinya Shale Member. Locally, these confining beds have been eroded along valley systems, such as the Caren Caren and Minyulo brooks, and along the Dandaragan and Gingin scarps (Kay & Diamond 2001). Towards the Darling Fault, the Kardinya Shale Member is increasingly sandy. Lithological descriptions from petroleum well Barberton 1 indicate predominantly sandstone for the Osborne Formation, including an interval identified as equivalent to the Kardinya Shale Member (50–100 m). Similar hydraulic heads within both aquifers suggest that the Leederville–Parmelia and Mirrabooka aquifers are hydraulically connected towards the Darling Fault (Kay & Diamond 2001).

The thick shale of the Otorowiri Formation forms a significant regional aquitard (Commander 1981) that hydraulically separates most of the Leederville–Parmelia aquifer from the underlying Yarragadee aquifer. Faulted displacement of the Otorowiri Formation may allow hydraulic connection between these aquifers at some locations. For example, water levels and groundwater salinity in the north-east at the Dathagnoorara bore (Carnamah–Coorow water supply), adjacent to the Urella Fault, imply hydraulic connection between the Leederville–Parmelia and Yarragadee aquifers (Commander 1978). There is also potential for hydraulic connection with the underlying Yarragadee aquifer on the Yarra Yarra Terrace along the Urella Fault, on the Barberton Terrace and possibly through the Noondine Chert along the Darling Fault. There may also be some hydraulic connection between the Yarragadee and Leederville–Parmelia aquifers across the Muchea Fault.

Groundwater recharge

Groundwater within the Leederville–Parmelia aquifer is recharged in outcropping areas by direct rainfall recharge. Groundwater recharge rates are probably highest just east of the Dandaragan Scarp where valleys infilled with sand are widest and easterly formational dips allow rapid infiltration of rainfall and seepage from valley slopes and ephemeral swamps along bedding planes (Commander 1981).

High groundwater salinity within the eastern portion of the aquifer suggests some downward leakage of saline water from the Coonderoo River via surficial deposits, including the Monger Palaeochannel. High salinity adjacent to the Darling Fault west of Watheroo, where the Leederville Formation subcrops, also suggests downward leakage of saline water from the Coonderoo River. There may be minor groundwater flow into the Leederville–Parmelia aquifer across the Darling Fault, particularly from the Noondine Chert, which is permeable to at least 60 m depth. South of Agaton, downward leakage from the eastern margin of the Mirrabooka aquifer is possible because the Kardinya Shale Member is sandier and more permeable (Kay & Diamond 2001). For example, brackish groundwater present in the upper portion of the Leederville–Parmelia aquifer at Moora Line 1 may reflect recharge from the Surficial and Mirrabooka aquifers that has penetrated through the Kardinya Shale Member. Kay and Diamond (2001) suggested that there was also recharge to the Leederville–Parmelia aquifer from losing river reaches: along a 5 km section of the Moore River east of Gillingarra Line 6 (GL6), and along parts of the Gingin, Boonanerring and Lennard brooks.

Rising groundwater levels in the Arrowsmith River area and on the Dandaragan Plateau indicate that groundwater recharge rates have increased significantly compared to rates under native vegetation cover. Groundwater recharge rates for the Leederville–Parmelia aquifer have been estimated using the chloride mass balance approach and the watertable fluctuation method. Several studies using the chloride balance estimated recharge to the Leederville–Parmelia aquifer and found the recharge rates are typically 2–5 per cent of average annual rainfall, and as such they probably represent pre-clearing conditions (Hingston & Gailitis 1976; Bekele et al. 2003, 2006a, 2006b).

Commander (1981) calculated recharge between 1.6 per cent and 2.2 per cent of average annual rainfall over different portions of the Parmelia aquifer. Balleau and Passmore (1972) adopted a recharge rate of 4.7 per cent locally in the Agaton area based on the minimum groundwater chloride concentrations, but this rate may not be representative of the larger region (Commander 1981).

Bekele et al. (2003, 2006a, 2006b) report the largest range of recharge rates, ranging from 1.1 per cent to 7.5 per cent of average annual rainfall over the northern Parmelia Group. This large range will reflect local variations in recharge rates. Recharge estimates greater than 5 per cent of rainfall may reflect post-clearing recharge rates. Most recently, Pennington Scott (2007) estimated a pre-clearing recharge rate over the Parmelia aquifer of 1.7 per cent of annual rainfall, equivalent to 8 mm/year, based on a spatially averaged groundwater chloride concentration of 345 mg/L determined from 67 reliable measurements.

Bore hydrographs have been used to estimate groundwater recharge rates resulting from vegetation clearing by using the rate of rising water levels for particular values of specific yield. Bekele et al. (2003) applied the hydrograph method in the Arrowsmith River area to calculate an average recharge of 33–50 mm per year, equivalent to about 8–12.5 per cent of average annual rainfall, obtained using 330 mm/year as the rate of rise for cleared areas and a specific yield value of 0.1. Pennington Scott (2007) calculated an average recharge rate of 7 per cent of rainfall from hydrographs over the larger outcrop area for the Leederville–Parmelia aquifer, and considered that the rate of rise for different locations was highest where native vegetation was cleared.

Groundwater levels before native vegetation clearing were probably stable, and groundwater recharge rates determined using rising water levels are likely to represent additional recharge rates. Consequently, total recharge over farmland cleared of native vegetation possibly averaged about 9 per cent of average annual rainfall, comprising about 2 per cent of rainfall from pre-clearing recharge plus 7 per cent post-clearing.

Groundwater recharge rates for the Leederville–Parmelia aquifer over the Leederville Formation have not been estimated, but it is likely that the greater portion of clay beds in the Leederville Formation will result in a lower rate of recharge compared to recharge to the Parmelia Group in the north. Estimates in the range of 2.5 per cent are considered reasonable where the Leederville Formation subcrops the superficial formations based on the work of Davidson (1995) south of Gingin Brook.

Groundwater discharge

Groundwater is discharged from the Leederville–Parmelia aquifer to rivers, streams, seeps and springs by evapotranspiration where there is shallow groundwater, and by groundwater flow into adjacent aquifers. In the north, groundwater is discharged as spring flow into the Arrowsmith River (Barnett 1970b). Channel deposit sands within the river may facilitate the shallow westward flow of groundwater discharging over the Otorowiri Formation into the Yarragadee aquifer (Commander 1981).

Groundwater within the southern portion of the Leederville–Parmelia aquifer discharges along sections of the Moore River, and Gingin and Moondah brooks to support baseflow and perennial pools (Kay & Diamond 2001). Groundwater seeps along the Dandaragan Scarp, mostly north of the Eneabba Line, represent groundwater discharging from the western and northern margins of the Leederville–Parmelia aquifer. Evapotranspiration directly from the aquifer is a significant groundwater discharge process in areas of shallow groundwater, particularly along the Arrowsmith River and Dandaragan Scarp.

Groundwater in the Leederville–Parmelia aquifer is largely isolated from the underlying Yarragadee aquifer by the Otorowiri Formation, but at some locations groundwater may be able to leak downward into the Yarragadee aquifer. This vertical leakage is most likely near the Urella Fault, at the eastern end of the Eneabba Line. The potentiometric head observed in the Dathagnoorara water supply bore is considerably lower at 183 m AHD within the lower portion of the aquifer compared to levels in the west. This may represent an isolated portion of the aquifer with downward leakage into the Yarragadee aquifer associated with faulted offsets in the Otorowiri Formation (Commander 1978, 1981). Groundwater in the southern portion of the Leederville–Parmelia aquifer flows laterally in a south-westerly direction into the Leederville aquifer across the transition zone beneath the Gingin Scarp.

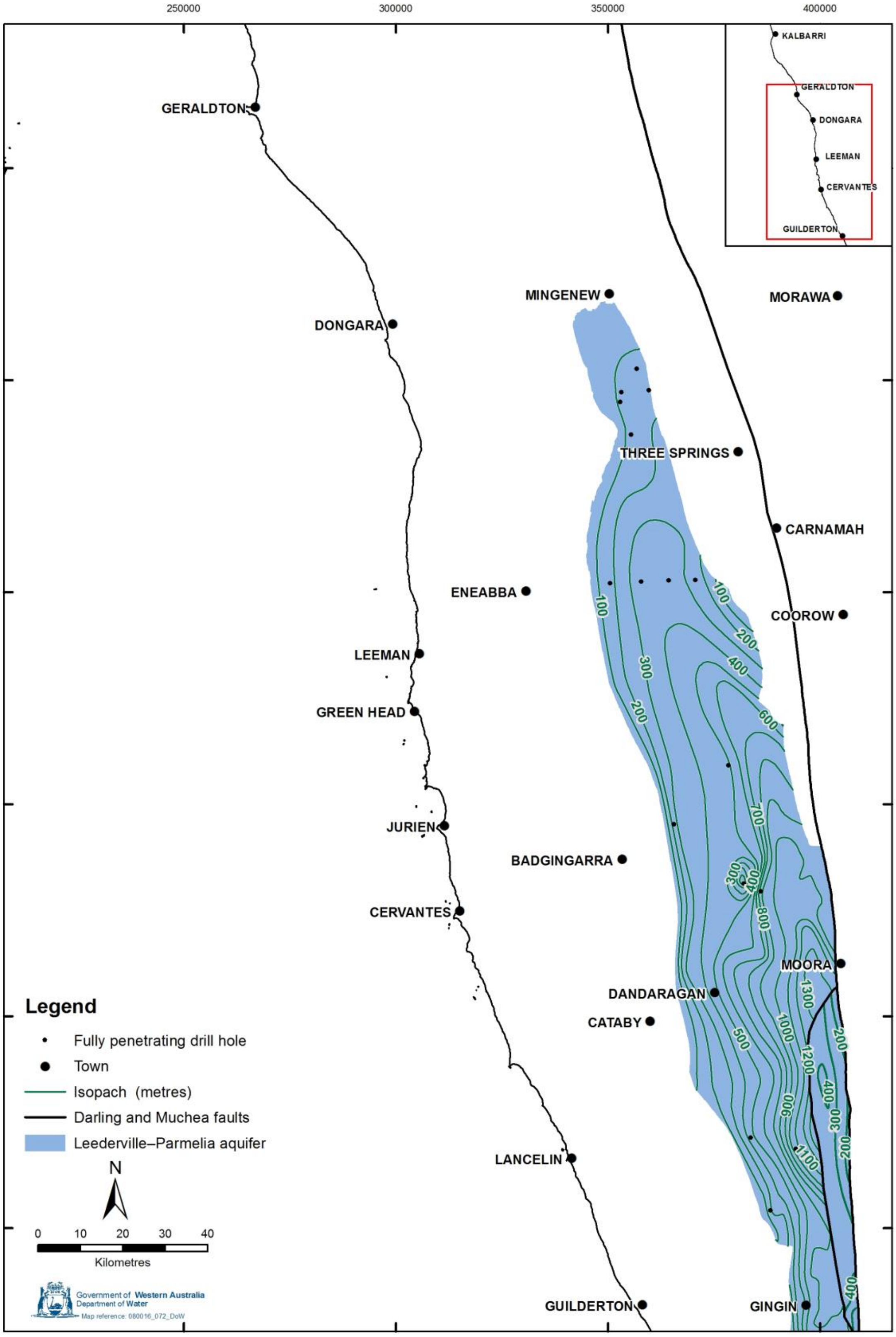


Figure 74 Leederville–Parmelia aquifer: aquifer thickness

Groundwater levels and flow

Groundwater levels during Autumn 2007 are shown for both the Parmelia Group and the Leederville Formation portion of the Leederville–Parmelia aquifer in Figure 75 and Figure 76. There is a maximum water-level elevation of about 230 m AHD south of the Eneabba Borehole Line, and water levels may reach 235 m AHD north of the Arrowsmith River. There is a very small hydraulic head gradient through the central and northern portions of the aquifer between the Yallalie Basin and Arrowsmith River and towards the Dandaragan Scarp. Steeper hydraulic gradients are present south of the Yallalie Basin where the aquifer is predominantly confined. Potentiometric heads decline to about 70 m AHD towards the south-western limit of the aquifer, where it transitions into the Leederville aquifer.

An east–west groundwater divide is present within the Leederville–Parmelia aquifer between the Agaton–Watheroo area and Eneabba Line (Commander 1981), with groundwater flow away from the divide, either to the north or south. North of the divide, groundwater flows towards the edges of the aquifer or discharges to the Arrowsmith River. South of the divide, groundwater flows to the south and south-east, and is deflected eastward near the Yallalie Basin.

The steep hydraulic gradient in the southern portion of the Leederville–Parmelia aquifer may relate to a decrease in aquifer transmissivity, particularly within the clayey Parmelia Group, and possibly also due to hydraulic discontinuity along faults impeding groundwater flow (Briese 1979).

There appears to be hydraulic discontinuity across one or more north–south-trending faults within the southern portion of the aquifer. An inferred fault about 12 km west of Moora has a hydraulic head that is 20–30 m higher in the east relative to the western side of the fault. Across the Muchea Fault, the hydraulic head is lower by 10–15 m (Kay & Diamond 2001). The hydraulic discontinuity across the faults is associated with the offsetting of sandstone beds.

South of the Moore River, groundwater flow continues south to south-west into the Leederville aquifer and the Perth region (Allen 1979; Davidson 1995). Across this transitional area, the aquifer thins and is discontinuous in places south of Gingin Brook (Pigois 2009).

The depth to groundwater beneath the Dandaragan Plateau varies, depending on topographical elevation, with the potentiometric surface in the Leederville–Parmelia aquifer being relatively flat. North of the Yallalie Basin where the aquifer is unconfined, groundwater levels are deep, typically 50–100 m below ground level, reaching a maximum depth of about 150 m in the central–western portion of the Dandaragan Plateau north of Gingin. Areas of shallow groundwater are present along the lower flanks of the Dandaragan Scarp where there are numerous seeps, below the western portions of palaeovalleys (mostly within 15 km either side of the Eneabba Borehole Line), and within valleys of the Arrowsmith River and the Coonderoo River in the east. There is also shallow groundwater within lower portions of the Yallalie Basin. Artesian flow has been encountered in the Arrowsmith River valley adjacent to the Arrowsmith River where the flows were obtained from Arrowsmith bores 1, 6 and 10 (Barnett 1970b), with a hydraulic head of about 10 m above ground surface in bore 1.

South of the Yallalie Basin in the western portion of the aquifer, there is a significant degree of hydraulic separation between the Leederville Formation and underlying Parmelia Group, with markedly greater hydraulic head in the Parmelia Group. At Moora Line 3, the hydraulic head is about 50 m higher in the Parmelia Group than in the Leederville Formation. Bore ML3B, screened in the Parmelia Group, produced a small artesian flow with a hydraulic head of 5 m above ground surface (Briese 1979). Within Minyulo Brook valley, near Muthawandery Spring (about 14 km north of Dandaragan), below a depth of 170 m, the hydraulic head in the Parmelia Group is up to 30 m above ground surface. At this location, there is about 25 m of shale and siltstone that results in a hydraulic head increase from 160 m AHD in the Leederville Formation to 230 m AHD in the Parmelia Group (ERM 2001c; Aquaterra 2004). Groundwater salinity also tends to be much higher in the Parmelia Group in this area, where marginally brackish groundwater of 1250 mg/L TDS is reported from the Muthawandery Spring area. To the south, in the Dandaragan town water supply bores, hydraulic head between the Leederville Formation and Parmelia Group components appear to have largely equalised (Briese 1979).

Groundwater levels have responded over time to changes to the water balance, mostly associated with increasing recharge rates related to land clearing in the north and groundwater abstraction in the south. Selected bore hydrographs are shown in Figure 77. Over the northern and central Dandaragan Plateau, a widespread rise in water levels has been observed since large areas of native vegetation were cleared in the 1960s and 1970s. The maximum rate of rise is about 0.3 m/year adjacent to the Arrowsmith River, with about 0.2 m/year observed in the Eneabba bore line, and 0.15 m/year in the Agaton bores. In the south, near Gingin, potentiometric water levels have been declining (Kay & Diamond 2001), most likely due to groundwater abstraction.

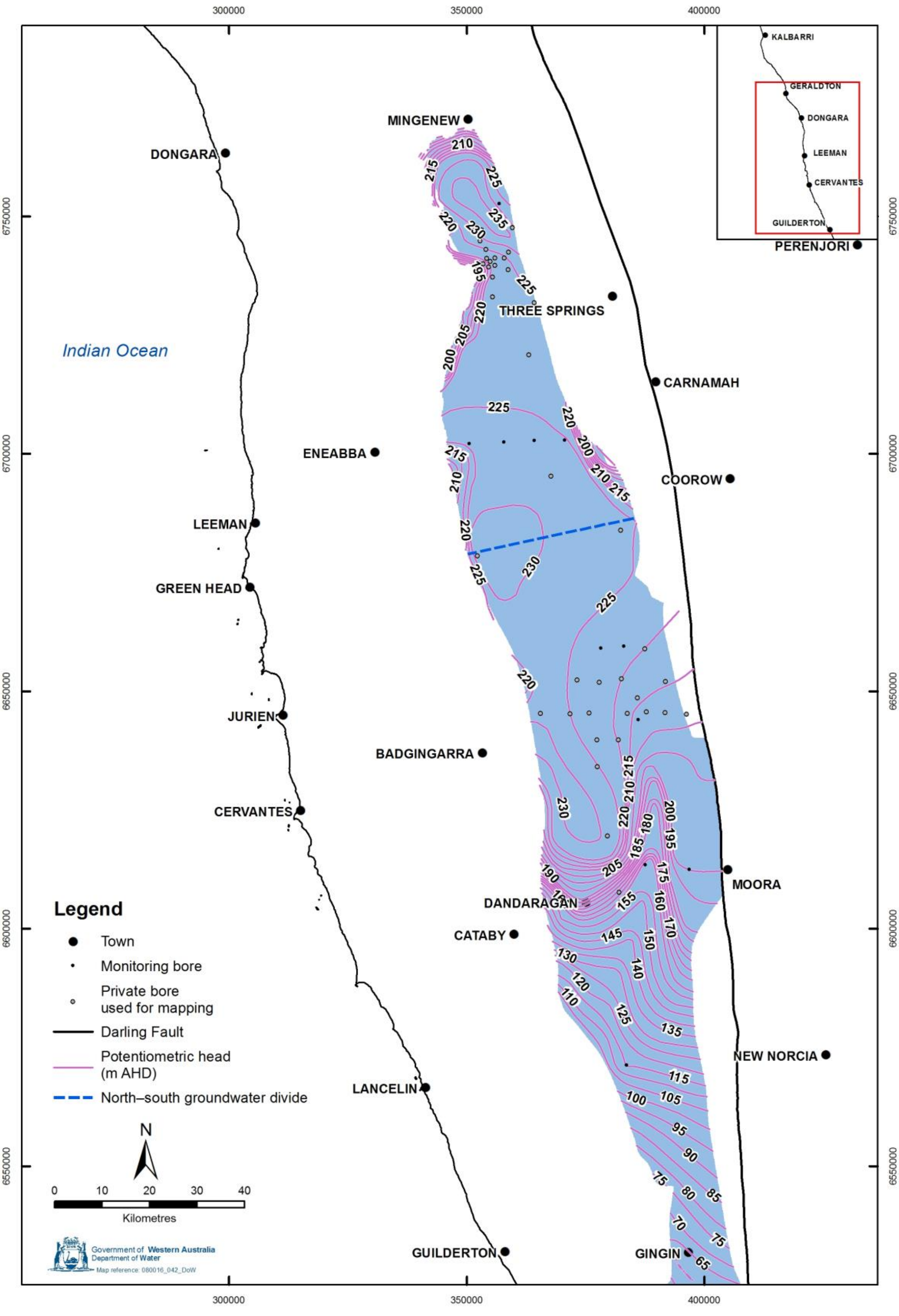


Figure 75 *Leederville–Parmelia aquifer: potentiometric surface (Parmelia Group component) (2015)*

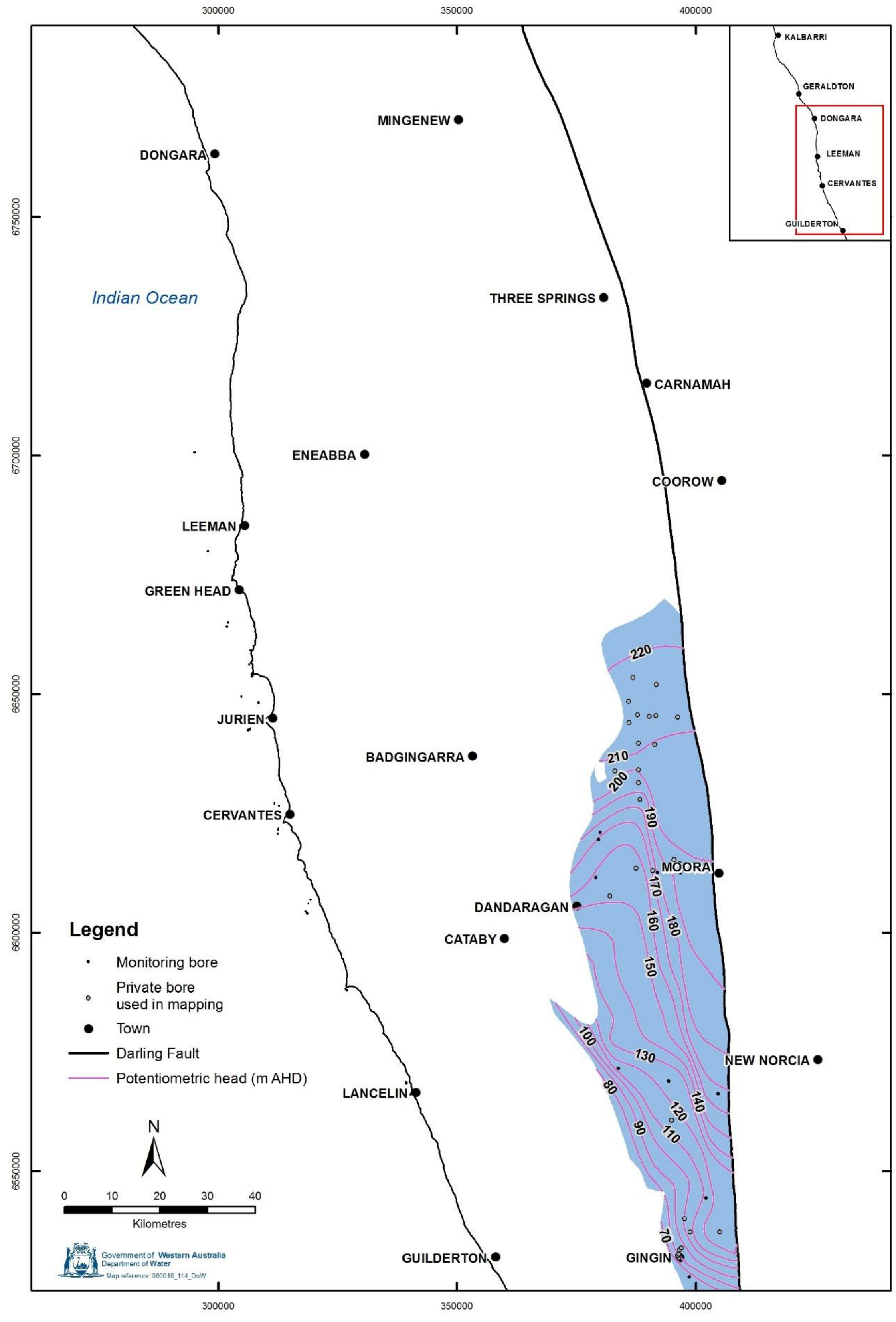
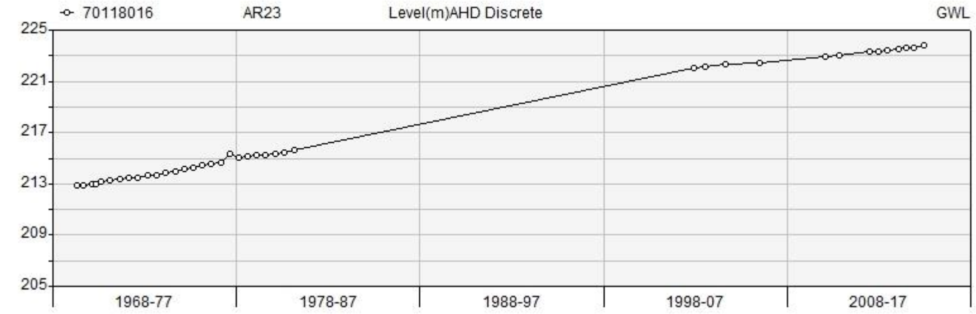
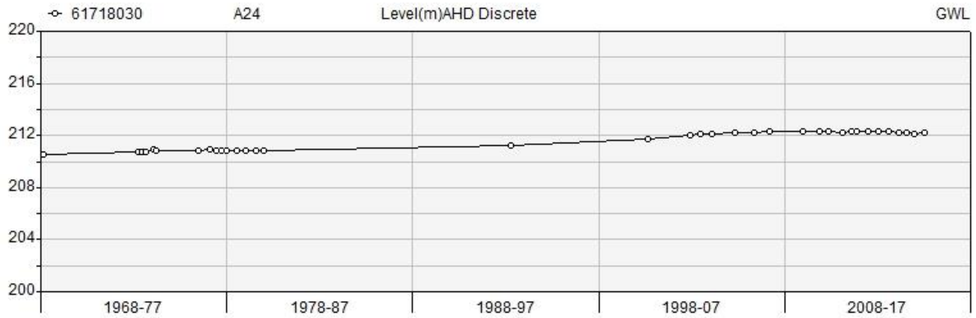


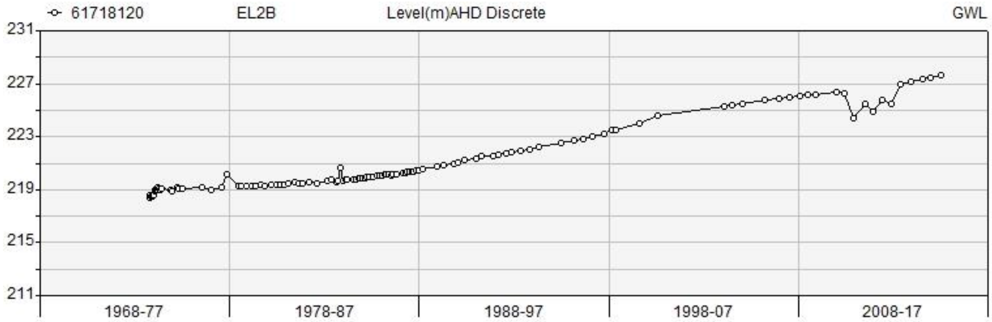
Figure 76 *Leederville–Parmelia aquifer: potentiometric surface (Leederville Formation component) (2015)*



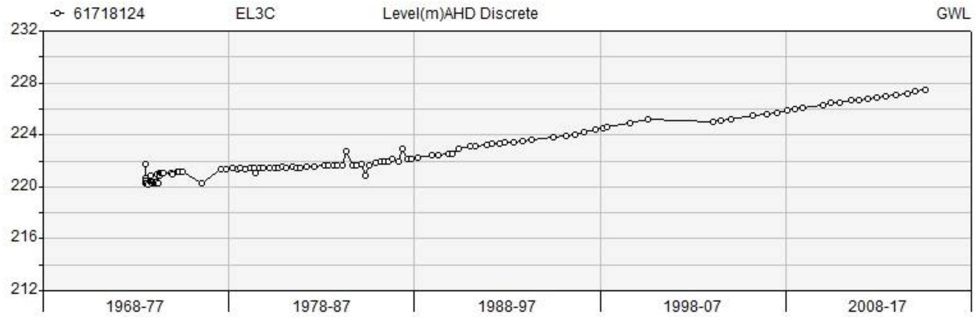
Arrowsmith River 23



Arrowsmith River 24

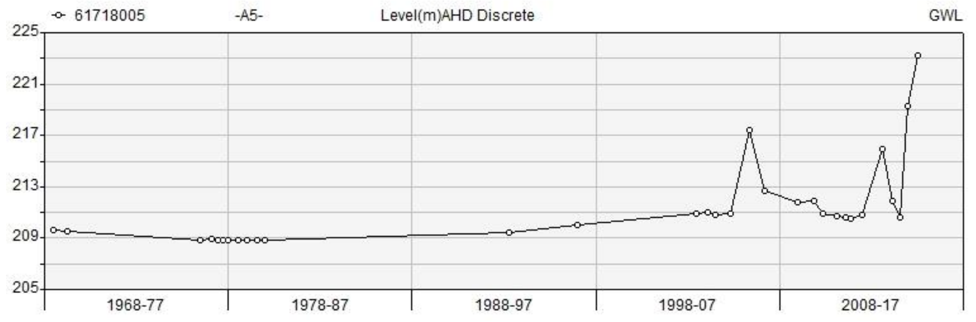


Eneabba Line 2B

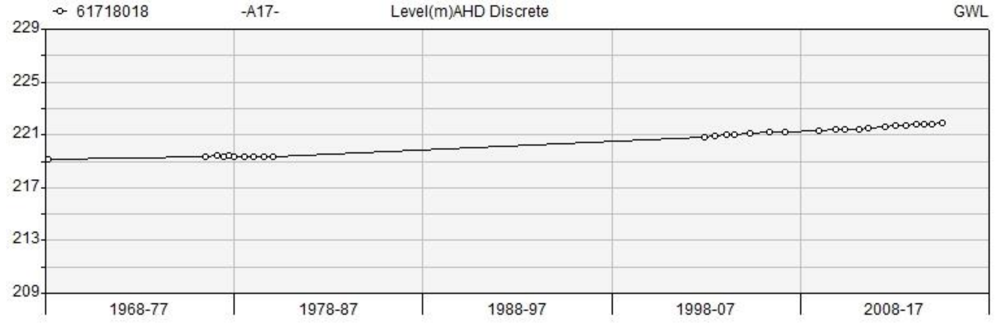


Eneabba Line 3C

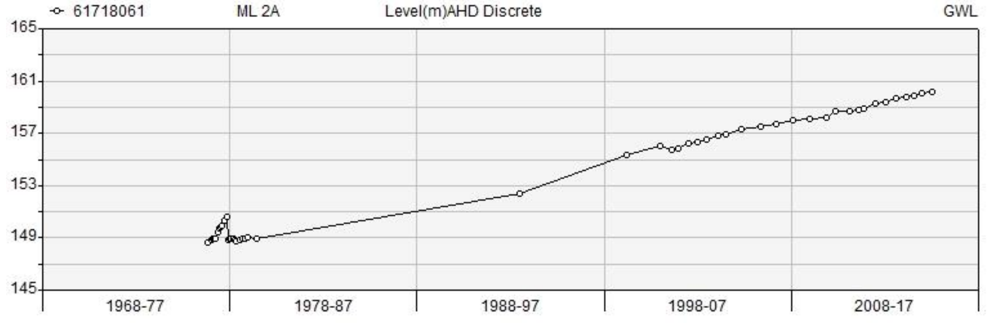
Figure 77 Leederville–Parmelia aquifer: selected bore hydrographs



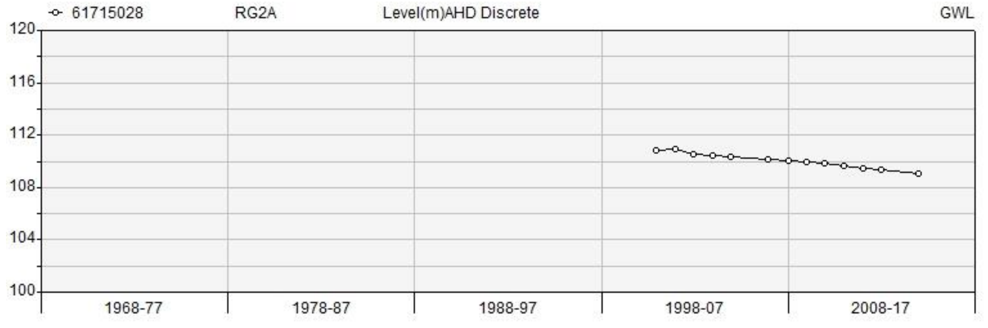
Agaton 5



Agaton 17



Moora Line 2A



Red Gully 2A

Figure 77 Leederville–Parmelia aquifer: selected bore hydrographs (continued)

Hydraulic parameters

The hydraulic properties of the Leederville–Parmelia aquifer are highly variable and depend on the portion of sand compared with silt and clay beds, lateral continuity of beds, and the clay matrix content of sand beds. The highest horizontal hydraulic conductivity is in the Wanneroo Member of the Leederville Formation, east and south of Agaton, where there are thick sequences of coarse-grained sand. The lithology of the Henley Sandstone Member of the Osborne Formation is comparable to the Wanneroo Member and probably has similar hydraulic properties. North of Agaton, the Carnac Formation comprises about 40 per cent sand, which form permeable layers. South of Agaton, on the western edge of the aquifer, the clayey Carnac Formation dominates and hydraulic properties are more typical of an aquitard, with low hydraulic conductivity.

A summary of aquifer tests within the Leederville–Parmelia aquifer is presented in Appendix D. Transmissivity varies widely ranging from 12.7 to 1600 m^2/day. Hydraulic conductivities derived from these aquifer tests are significantly higher in the Leederville Formation, with an average of 17 m/day and a median of 12 m/day. In the Parmelia Group, hydraulic conductivity averages 9 m/day (excluding outlier values at Arrowsmith test bores 1 and 14), with a median value of 8 m/day. As the bores used for aquifer tests are selectively screened over sand intervals, the test-derived values of hydraulic conductivity are biased towards higher hydraulic conductivities. They are not representative as a bulk parameter for the aquifer as a whole. Sand beds comprise about 50 per cent of the Leederville Formation, suggesting that the bulk hydraulic conductivity for the entire formation may be 10 m/day. North of Agaton, the Parmelia Group contains about 40 per cent sand beds, for which a bulk hydraulic conductivity value would be 3.6 m/day, but it is probably less than 1 m/day south of Agaton where there is considerably less sand. Discontinuity of sand beds due to lensing and faulting will result in lower regional values of hydraulic conductivity for the aquifer, but this effect is difficult to evaluate.

Vertical hydraulic conductivity within the Leederville–Parmelia aquifer is not well understood. The highest vertical hydraulic conductivities will be associated with lithologies containing the most sand and the least interbedded shale, which are the Wanneroo Member of the Leederville Formation, and the sandy portion of the Carnac Formation. Abundant interbedded silt and shale beds through the Pinjar and Mariginiup members of the Leederville Formation, and the Carnac Formation north of Agaton will result in lower vertical hydraulic conductivities. South of Agaton, the Carnac Formation is dominated by clayey lithologies, and therefore a very low hydraulic conductivity vertically through the formation is likely. Where there is limited connectivity between sand beds, vertical hydraulic conductivity will approach that of the intervening silt and clay beds, and may be in the order of 10^{-4} to 10^{-5} m/day. Thorpe and Davidson (1991) determined an average vertical hydraulic conductivity across the Superficial and Leederville aquifers of 5×10^{-4} m/day from carbon-14 dating in the Perth region. Vertical hydraulic conductivity within the Wanneroo Member of the Leederville Formation is likely to be about 10^{-3} m/day, while the more clayey units may be less than 10^{-4} m/day.

The storativity and specific yield of the Leederville–Parmelia aquifer have not been evaluated, but values are likely to be similar to the Leederville Formation in the Perth region.

Davidson (1995) assumed a specific yield of 0.2 for the sandstone beds of the Leederville Formation, and a storage coefficient of 10^{-4}.

Bore yields of up to 8000 m^3/day have been achieved from the Leederville–Parmelia aquifer (Appendix D). More typically, yields are between 1000 and 4000 m^3/day, averaging about 2300 m^3/day. The largest yields are expected from bores within the Wanneroo Member of the Leederville Formation, and sandy sections of the Carnac Formation north of Agaton. Lower bore yields of less than 1000 m^3/day are expected from bores developed in the Pinjar and Mariginiup members of the Leederville Formation. Specific capacity of bores screened in the Leederville Formation (Wanneroo Member) is on average almost 70 per cent greater than for bores screened in the Parmelia Group (A17 and RGP2 screen across both units and are excluded from this comparison), reflecting higher transmissivity through the Wanneroo Member. On the Yarra Yarra Terrace, airlift yields from selected bores ranged from 26 to 277 m^3/day (Yesertener 1999), but this is probably an under-representation of potential yields that could be obtained from these formations. It is expected that bore yields comparable to those obtained from the Yarragadee, Cattamarra and Eneabba–Lesueur aquifers elsewhere in the basin could be obtained from the same formations on the Yarra Yarra Terrace.

Estimates of groundwater throughflow

Rates of groundwater throughflow for the Leederville–Parmelia aquifer have been determined using Darcy's Law:

$$Q = kbiL$$

where Q is the volume of groundwater (m^3/d), k is the horizontal hydraulic conductivity, b is the saturated aquifer thickness and L is the section width of the flownet cell.

In the Agaton area, Commander (1981) estimated groundwater throughflow of 5 GL/year moving south across the Watheroo bore line. This flow is mostly between Agaton 7 and the Darling Fault where sand comprises about 50 per cent of the aquifer with an effective area of 2.4×10^6 m^2, a hydraulic conductivity of 10 m/day and hydraulic gradient of 0.0006. This throughflow estimate is substantially lower than earlier estimates of 12.6 GL/year calculated using two sections (Balleau & Passmore 1972). This study also estimated that 5.1 GL/year flows into the confined eastern portion of the Agaton borefield from the north across the 220 m hydraulic head contour between Agaton 16 and Agaton 17. Over the western portion of the aquifer, Balleau & Passmore (1972) determined that 7.56 GL/year of groundwater flows from the Agaton borefield across the 205 m hydraulic head contour. This assumed a cross-sectional area of 2.82×10^6 m^2, hydraulic conductivity of 4.7 m/day and hydraulic gradient of 0.0016. However, the western throughflow calculation is considered inaccurate as it includes the Yallalie Basin, which would influence groundwater flow.

Northward groundwater throughflow across the Eneabba Line has been estimated to be 2.5 GL/year by Commander (1981), based on a hydraulic conductivity of 10 m/day, cross-sectional area of 2.7×10^6 m^2, and hydraulic gradient of 0.00025. Commander (1981) suggested that the discrepancy between the calculated throughflow and recharge of 6.5 GL/year over the contributing area is either due to substantial groundwater discharge to the west across the Otorowiri Formation or east at the Urella Fault or an erroneously low estimate of the hydraulic gradient.

Groundwater salinity

Groundwater salinity for the Leederville–Parmelia aquifer is shown in Figure 72. This figure maps the salinity in the top of the Leederville–Parmelia aquifer (i.e. in the top of the Leederville Formation where it is present, and in the top of the Parmelia Group where the Leederville Formation is absent).

Groundwater salinity in the Leederville–Parmelia aquifer ranges from 200 mg/L to 4500 mg/L except along the eastern margin of the aquifer, but is mostly between 500 and 1000 mg/L TDS (Commander 1981; Bekele et al. 2006). In the western part of the aquifer, groundwater with less than 500 mg/L TDS is associated with palaeodrainage valleys (Commander 1981). Groundwater with a salinity of about 200 mg/L TDS is also present east of Eneabba Spring (Commander 1981). Many of the Agaton bores (Balleau & Passmore 1972) and the eastern Eneabba Line bores (Commander 1981) have decreasing salinity with depth, suggesting that permeable sediments within the lower aquifer are connected to areas of higher recharge towards the west. South of Agaton, low-salinity groundwater of less than 500 mg/L TDS is present within the Leederville Formation component near the Moora borehole line (Briese 1979), while the Parmelia Group component has groundwater of more than 1000 mg/L TDS. Further south, in the Gillingarra Line bores, groundwater salinity is more than 1000 mg/L TDS, except about the western margin in the Leederville Formation where brackish groundwater is progressively diluted by fresher water to the west and parts of the Parmelia Group to the east where groundwater is less than 1000 mg/L TDS. This is possibly due to higher hydraulic conductivity than in other parts (Moncrieff 1989). Within Minyulo Brook valley, where there are artesian heads in the Parmelia Group component of the aquifer, groundwater salinity tends to be marginally brackish with 1250 mg/L TDS reported from the Muthawandery Spring area.

Brackish to saline groundwater is present along the eastern margin of the aquifer, south of the Yarra Yarra Terrace. Groundwater salinity in the Leederville Formation in Watheroo Line WL1 was 9160 mg/L TDS, and in the deeper Parmelia Group was 13 600 mg/L TDS (Harley 1974). The source of this saline groundwater is downward leakage from the Coonderoo River and Monger Palaeochannel, and possibly also groundwater flow from formations on the Yarra Yarra Terrace. This saline groundwater within the eastern portion of the aquifer is contained by either low-permeability faults (Harley 1974) or hydraulic pressure of fresh groundwater in the west (Commander 1981).

Other areas of high salinity groundwater may develop through evapotranspiration (Commander 1981), including in locations overlying the Otorowiri Formation, along the Dandaragan Scarp, and within the Arrowsmith River valley. Groundwater below the palaeodrainage valley south-east of Eneabba Spring is brackish at its western margin (Commander 1981), and water contains over 4000 mg/L TDS at Whitehorse Soak, 3.7 km south-west of Eneabba Line site 4 (Rutherford et al. 2005).

Hydrochemistry

The major ion chemistry of water samples for the Leederville–Parmelia aquifer are presented in the hydrochemical trilinear plot shown in Figure 78. Groundwater is of sodium magnesium chloride type, which is consistent with groundwater derived from rainfall recharge (Bekele et al. 2006).

Field-measured pH values collected during a carbon-14 sampling program (Egis 1999) ranged from 9.4 (recorded from Moora Line bore ML1A, screened over a deep interval at 622.5 – 629.5 m) to 5.3 (measured from Three Springs production bore 1/79). Average field pH was 6.4.

The Leederville–Parmelia aquifer often has elevated iron concentrations that require treatment before irrigation or public water supply. Dissolved iron concentrations range from 0.1 to 20 mg/L in the Arrowsmith area (Barnett 1970b), and are much higher north of the river (Commander 1981). Dissolved iron concentrations range from 1.5 to 5.6 mg/L in the Agaton area (Balleau & Passmore 1972), and up to 5.7 mg/L in the Eneabba Line bores (Commander 1978a, b). Similar concentrations are reported for private groundwater bores (Aquaterra 2005; Pennington Scott 2007).

Calcium and magnesium cation concentrations are usually low. The bicarbonate concentration is typically greater in the deeper, confined portion of the aquifer, where a maximum value of 204 mg/L was obtained from Gillingarra Line bore GL7A2 (693–699 m screen depth) (Moncrieff 1989). Bicarbonate concentrations determined by field titration ranged from 24.4 to 198.2 mg/L with an average of 78 mg/L (Egis 1999).

Nitrate concentrations are generally less than 2 mg/L. Higher concentrations have been measured in perched aquifers along the Dandaragan Scarp (Harley 1974, 1975), in the Agaton borefield (4 mg/L in Agaton 20 and 11 mg/L in Agaton 27) (Balleau & Passmore 1972) and in Watheroo Line WL2 (6–7 mg/L) (Harley 1975).

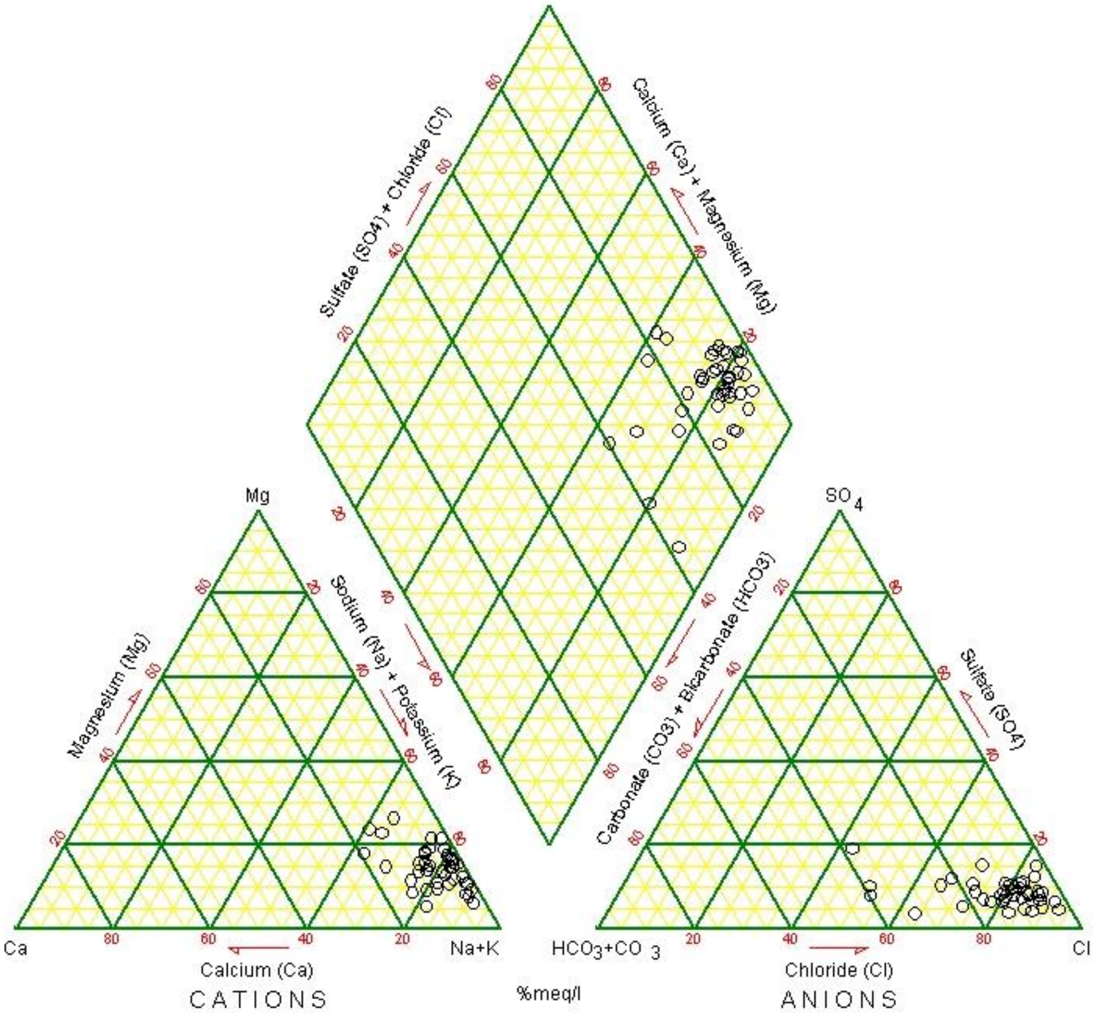


Figure 78 Leederville–Parmelia aquifer: hydrochemical trilinear diagram

Groundwater isotopic composition and age

In the Leederville–Parmelia aquifer, groundwater age estimates in test bores range from 2580 to 29 560 BP (Table 14) (Thorpe 1993; Egis Consulting 1999). The youngest groundwater (<5000 years BP) is within the Parmelia Group component in the central and northern portions of the aquifer. These younger ages reflect higher recharge rates, unconfined conditions and shallow bore depths. Groundwater in the Leederville Formation component of the aquifer, south of Agaton, is generally older than in the Parmelia Group to the north. This is possibly due to confined conditions and distance from recharge areas. Samples from various depths in the Leederville Formation component at Moora Line bore ML1, where the aquifer is confined beneath the Kardinya Shale Member, range from 18 710 to 29 560 years BP, reflecting the travel times of groundwater from the recharge area near Agaton.

Variation in groundwater age, even in relatively close sites at comparable depths, suggests complex groundwater flow patterns. For example, 14C age in Agaton bore A6 was significantly older (21 090 years BP) than groundwater in bore A5 (4200 years BP), about 6 km to the east and screened at a similar depth.

Table 14 Groundwater isotope data for the Leederville–Parmelia aquifer

Project / Town	Bore	Screen interval (m bgl)	14C (pmC)	14C error (pmC)	14C age, corrected (yr BP)	14C age error (yr BP)	δ13C (‰ PDB)	δ18O (‰ SMOW)	δ 2H (‰ SMOW)
Parmelia Group									
Arrowsmith	1/87	41–59	42.3	1.1	7120	220	–20.1	–4.6	–18.2
Arrowsmith	11	43–49	68.7	0.6	3100	70	–20.1		
Arrowsmith	12	72–85	38	0.5	8000	110	–18.0		
Arrowsmith	13	140–156	10.5	0.3	18 630	230	–19.1		
Arrowsmith	14	105–118	40.2	0.5	7530	100	–20.3		
Arrowsmith	17	106–118	55.5	0.6	4870	90	–19.1		
Arrowsmith	21	84–85	28.8	0.4	10 290	110	–17.8		
Arrowsmith	22	76–79	73.2	0.7	2580	80	–19.6		
Dathagnoorara	2/86	150–200	44.3	2.3	6730	410	–20.3	–4.8	–21.1
Agaton	A1	140–232	52.7	0.5	5300	80	–20.9		
Agaton	A5	131–227	44.8	0.4	4200	70	–16.1		
Agaton	A6	174–181	7.8	0.3	21 090	310	–19.4		
Agaton	A10	180–198	10.6	0.3	18 550	230	–18.6		
Agaton	A19	216–320	9.5	0.3	19 460	260	–20.0		
Agaton	A24	91–146	68.7	0.6	3100	70	–19.3		
Moora Line	ML3A	730–740	28.1	0.4	10 490	120	–17.3		
Moora Line	ML3B	228–235	22.8	0.4	12 220	140	–19.2		
		Leederville Formation							
Moora	1/89	298–343	13.9	0.9	16 290	510	–19.6	–5.14	–23.9
Moora Line	ML1A	623–630	2.8	0.1	29 560	290	–19.1		
Moora Line	ML1D	316–322	10.4	0.3	18 710	230	–20.6		
Moora Line	ML1E	189–195	2.8	0.3	29 560	840	–18.3		
Moora Line	ML2A	273–281	5.9	0.3	23 400	410	–17.5		
Moora Line	ML3C	88–95	60.4	0.5	4170	70	–19.0		
Gillingarra Line	GL6 W	100–106	9.2	0.2	19 730	180	–18.1		
Gillingarra Line	GL8 W	97–103	18.2	0.3	14 090	140	–20.5		

Data from Egis Consulting (1999)

Notes: 14C – carbon-14; 13C – carbon-13; 18O – oxygen-18; 2H – deuterium; pmC – per cent modern carbon; PDB – 13C standard; δ – ratio of sample to standard; SMOW – standard mean ocean water; ‰ – per mil (parts per thousand). Different correction models have been used to generate 14C age, corrected (yr BP); refer to the original project reports for more information.

5.7 Yarragadee aquifer

The Yarragadee aquifer is the largest regional aquifer in the northern Perth Basin, containing a great thickness of low-salinity groundwater (Figure 79). The Yarragadee aquifer extends south from the Greenough River into the Perth region, covering a total area about 17 600 km^2. The Yarragadee aquifer includes the Yarragadee Formation and the hydraulically connected Gage Sandstone, which overlies the Yarragadee Formation in the south. Previous reports have referred to the Yarragadee aquifer as the 'Lower aquifer' (Barnett 1970b) in the Arrowsmith River area, 'Badgingarra aquifer system' (Harley 1974), 'Lower Yarragadee Formation aquifer' (Commander 1978), and the 'Yarragadee Formation aquifer' (Commander 1981).

The Yarragadee aquifer consists of a multilayered sequence of sandstone beds with very fine to very coarse grained and granule-sized quartz sand that are often feldspathic with variable amounts of matrix clay, and interbedded siltstone, shale and claystone. There are four sub-units within the Yarragadee Formation that have distinctive lithologies: units A and C are predominantly unconsolidated sandstone, while units B and D are predominantly siltstone, shale and claystone.

The Yarragadee aquifer is unconfined where the Yarragadee Formation outcrops in the Arrowsmith region (between the Dandaragan and Gingin scarps), and in the Victoria Plateau to the north. The aquifer becomes semi-confined to confined at depth due to the interbedded siltstone, claystone and shale. Extensive shale beds within the upper portion of Unit D effectively confine the aquifer adjacent to the Otorowiri Formation in the eastern portion of the northern Perth Basin and south of Mingenew. The aquifer is compartmentalised by faulting and by stratigraphy. Extensive argillaceous beds (up to 120 m thick) within Unit B hydraulically separate Unit A from the overlying units C and D within the aquifer (Commander 1980).

The Yarragadee aquifer is confined by either the Otorowiri Formation beneath the Dandaragan Plateau, or by the South Perth Shale beneath the Swan Coastal Plain (between Guilderton and Lancelin). North-east of Lancelin, the South Perth Shale is absent below the Leederville Formation, and the Leederville aquifer directly overlies the Yarragadee aquifer. However, hydraulic connection between the two aquifers is restricted by the low permeability of the clayey Mariginiup Member at the base of the Leederville Formation. North of Wedge Island and Cataby, the Leederville aquifer is absent, and the Yarragadee aquifer is overlain by the superficial formations, with some hydraulic connection with the Superficial aquifer.

The Yarragadee aquifer is bound in the east by the Darling or Urella faults. At its western margin, upon the Cadda Terrace, it abuts the Cattamarra aquifer along faulted contacts such as the Warradarge Fault. It also is in contact with the Lesueur Sandstone over a short distance along the Wedge Fault north of Lancelin. The Yarragadee aquifer extends offshore in the Beermullah Trough, south of Wedge Island, and upon the Dongara Terrace and Greenough Shelf, roughly between Cliff Head (29 km south of Dongara) and Bookara (23 km north of Dongara).

On the Barberton Terrace, a long and narrow section of the Yarragadee Formation is present at shallow depth. Here, it is bound by the Darling Fault in the east and the Muchea Fault to the west, across which the formation abuts the Parmelia Group. This portion of the Yarragadee Formation contains brackish groundwater and is isolated from the Yarragadee aquifer in the west. Gillingarra Line GL8A was initially thought to be the only bore drilled into the Yarragadee Formation on the Barberton Terrace. Drill logs from petroleum well Barberton 1, drilled in the northern part of the terrace intersected almost 500 m of the formation below 443 m depth.

An outlier of the Yarragadee Formation is present upon the Cadda Terrace (on the western margin of the Arrowsmith region), south-east of Jurien Bay, extending south of Cowalla Peak to Bibby Creek. Data from exploration bore JE5 indicates that groundwater is fresh to its full depth of 250 m (AGC 1988). Another smaller outlier of Yarragadee Formation is present east of Nambung National Park on the coastal plain. Cataby Shallow bore CS35D is the only bore in this area and yields brackish groundwater in the uppermost portion of the aquifer. This outlier is possibly hydraulically connected with the Eneabba–Lesueur aquifer.

North and west of the Greenough River, outliers of the Yarragadee Formation on or adjacent to the Northampton Inlier are mostly unsaturated, or yield small supplies of typically saline water (Swarbrick 1964a; Allen 1965). The formation is also unsaturated for at least 2 km south of the Greenough River (Allen 1965).

In the northern Perth Basin, the Yarragadee aquifer is mostly less than 1000 m thick but has a maximum thickness of 4000 m in the Dandaragan Trough (Figure 79). The maximum reported intersected thickness is 3693 m in petroleum well Warro 2. Isopach maps for each of the units (A through to D) within the Yarragadee Formation are shown in Figure 80 to Figure 83. The northern extent of the aquifer has been recently confirmed by Schafer (2016) (Figure 79 to Figure 83).

Unit A is the lowermost unit and is typically about 800 m thick (but possibly thicker within the Dandaragan Trough) (Figure 83). Unit B is up to 900 m thick in the Dandaragan Trough but thins where the upper portion has been eroded (Figure 82). Unit C is typically 700 m thick within the Dandaragan and Coomallo troughs, but has a limited extent elsewhere (Figure 81). Unit D is largely restricted to the Dandaragan and Coomallo troughs and is up to 700 m thick within the eastern Coomallo Trough, thickening towards the east in the Dandaragan Trough, where it probably exceeds 1500 m in thickness (Figure 80).

The Gage Sandstone is present at the top of the aquifer only beneath the coastal plain south of Namming Lake. It is mostly between 20 and 40 m thick, with the thickest intersection interpreted to be 62 m in Gingin Brook Line bore GBL3.

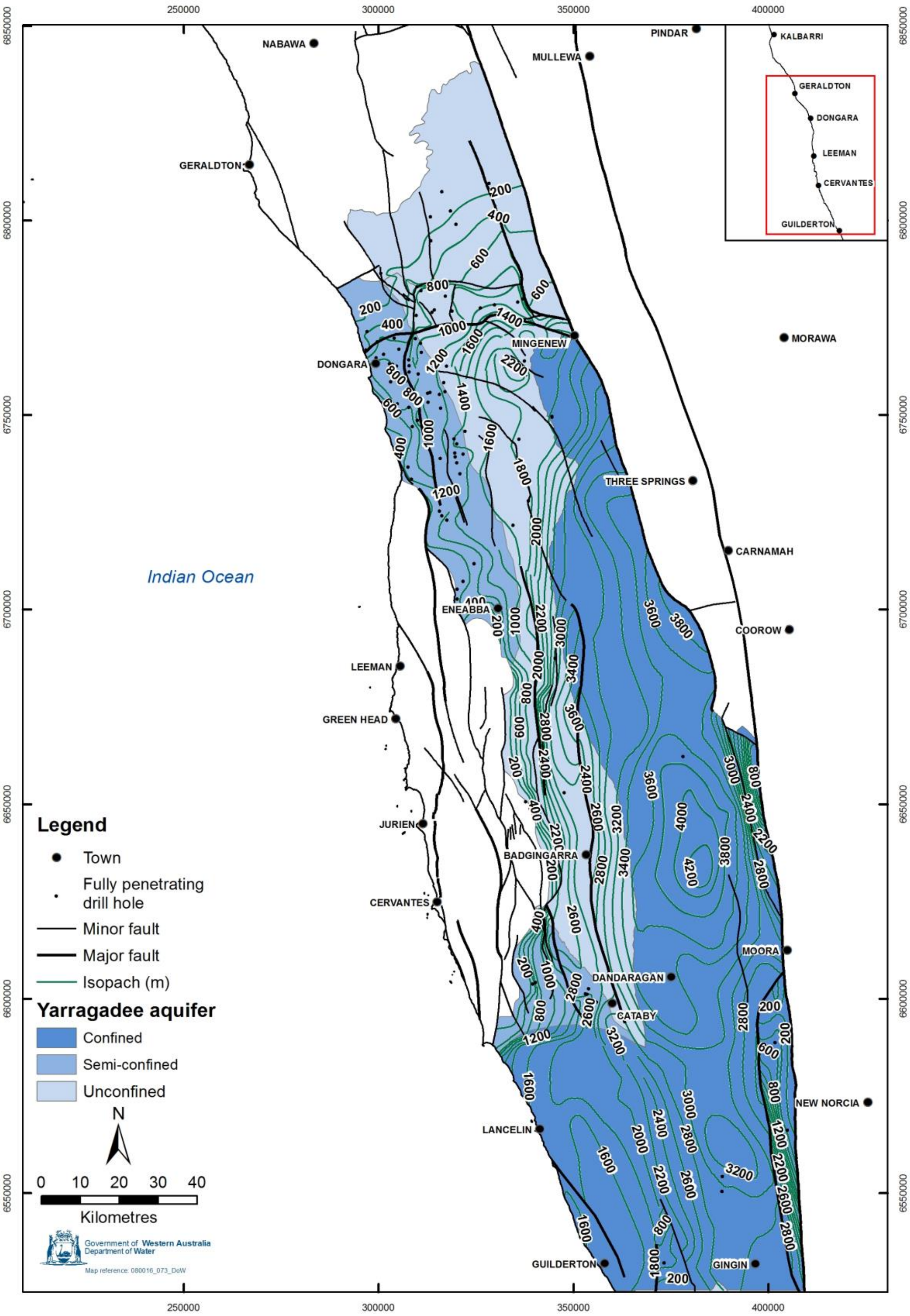


Figure 79 Yarragadee aquifer: saturated aquifer thickness

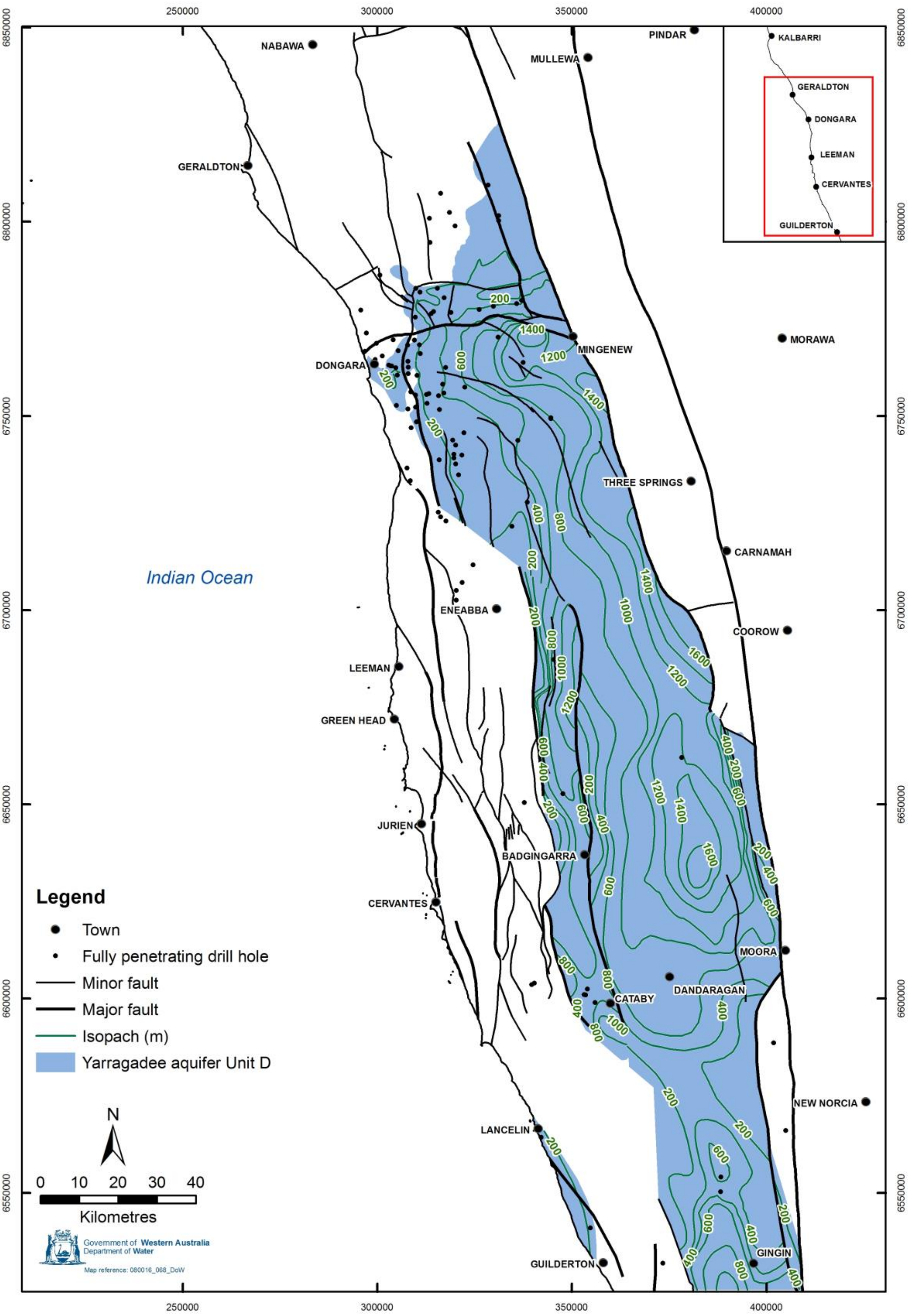


Figure 80 Yarragadee aquifer Unit D: aquifer thickness

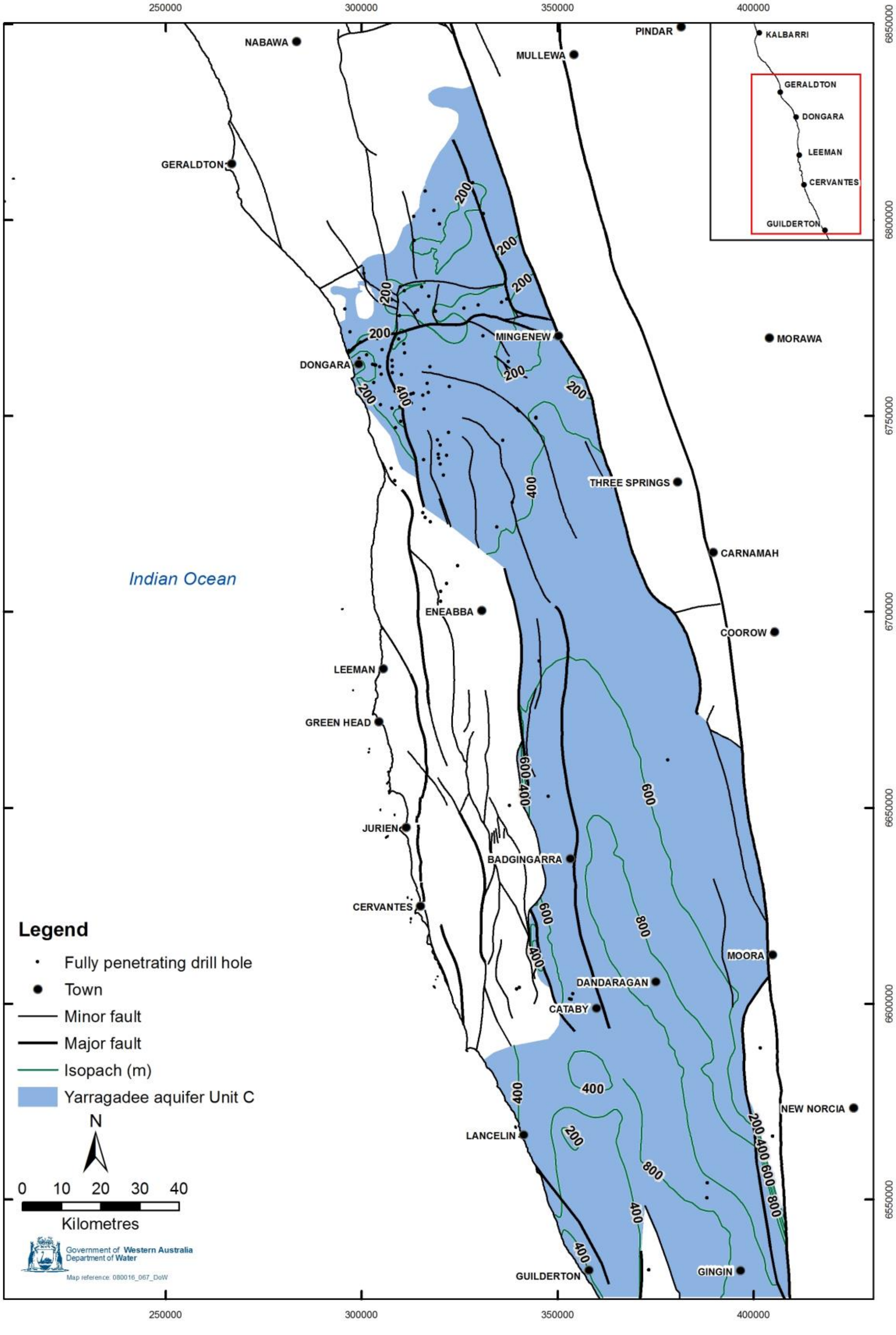


Figure 81 Yarragadee aquifer Unit C: aquifer thickness

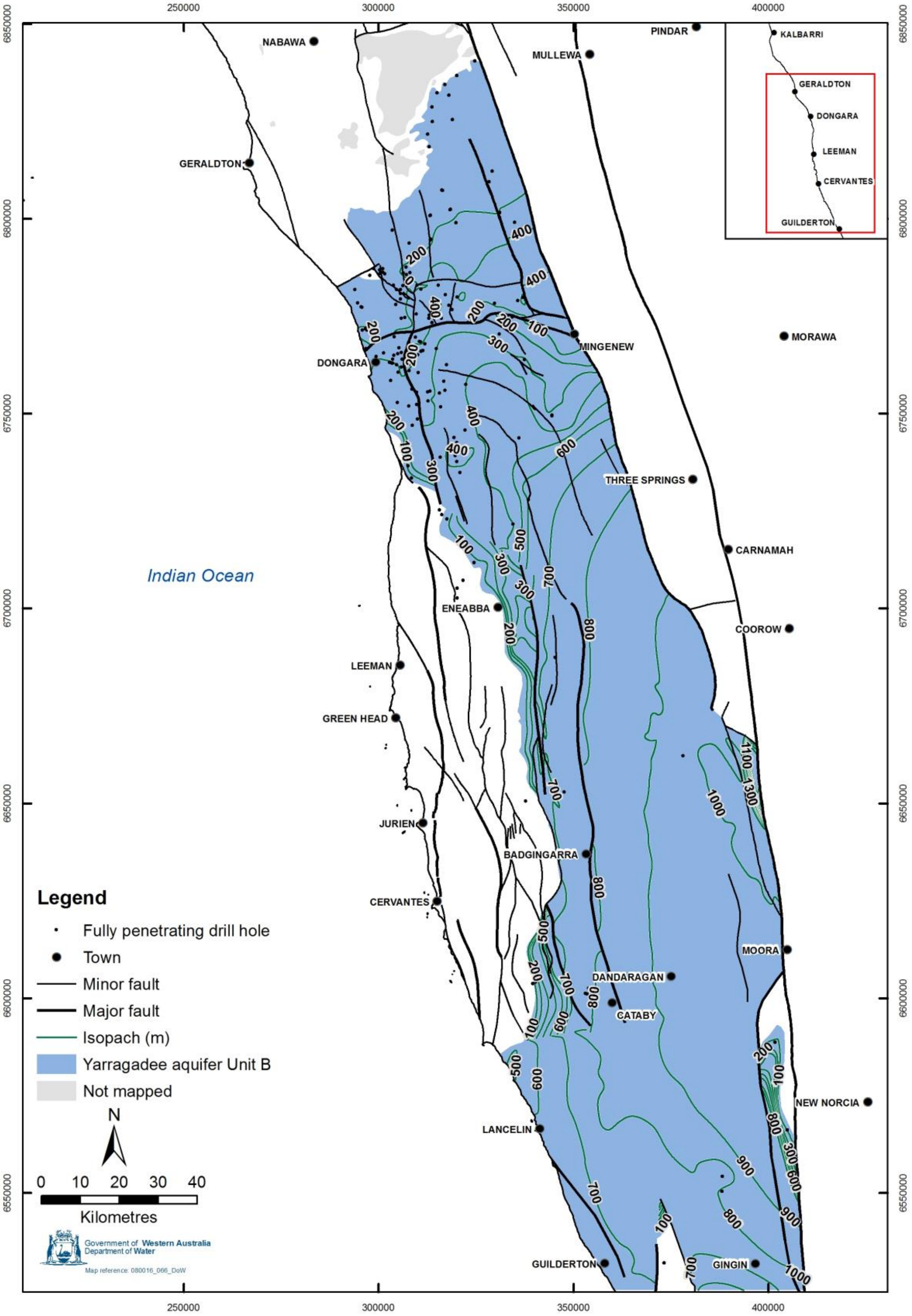


Figure 82 Yarragadee aquifer Unit B: aquifer thickness

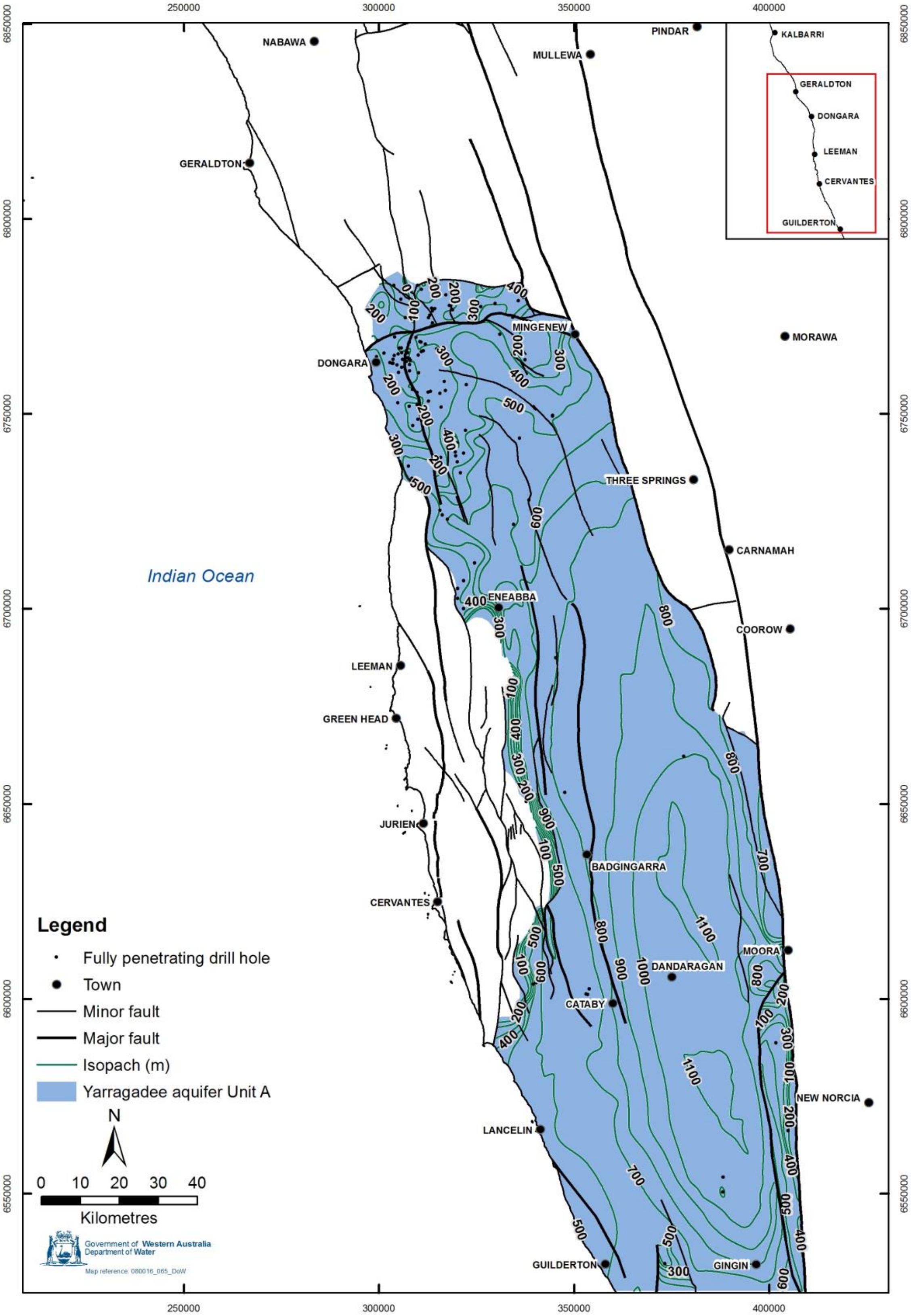


Figure 83 Yarragadee aquifer Unit A: aquifer thickness

Groundwater recharge

Groundwater recharge into the Yarragadee aquifer is mostly by direct rainfall infiltration over outcrop areas as well as downward leakage from overlying aquifers. Concentrated recharge from rivers and streams is also important in some areas.

In the Arrowsmith region, low groundwater salinity and groundwater mounding near and west of Badgingarra suggests substantial groundwater recharge. Significant recharge is also likely where sand beds of the Yarragadee Formation are exposed at the surface (Commander 1981), which is most prevalent over the western portion of the aquifer. In the Arrowsmith region, recharge is likely to be concentrated within the river valleys (Commander 1981) that receive runoff from hill slopes. A large downward hydraulic gradient at Eneabba Line EL5 suggests groundwater recharge rates may be higher in that area because the Yarragadee aquifer is unconfined west of the outcrop of the Otorowiri Formation (Commander 1981). Thick sand sheet deposits that cover the Victoria Plain may also facilitate enhanced rainfall recharge (Allen 1980).

Where clayey lithologies dominate outcropping areas, infiltration will be impeded, and groundwater recharge rates will be lower than in sand-dominated outcrops. This is common over much of the eastern Arrowsmith region, where the clayey Unit D outcrops resulting in elevated groundwater salinity within the upper portion of the aquifer. Recharge can be locally impeded by siltstone and shale beds above the regional watertable that may support a perched watertable.

Rivers and streams that cross outcropping areas provide some recharge to the Yarragadee aquifer. The most significant losing river sections are along the Hill, Arrowsmith and Irwin rivers. The Yarragadee aquifer is recharged by leakage from the Hill River east of Watheroo Line bore WL8 (Lindsay 2004) and from the Irwin River upstream of the junction with the Lockier River (Commander 1981). As streamflow in the Arrowsmith and Irwin rivers is mostly brackish to saline, groundwater salinity below and adjacent to these rivers is relatively high.

There is potential for groundwater recharge to the Yarragadee aquifer from overlying aquifers where they are hydraulically connected and there is a downward hydraulic gradient. The Superficial and Leederville aquifers directly overlie the Yarragadee aquifer in many locations in the northern Perth Basin. The Superficial aquifer beneath the coastal plain is hydraulically connected with the Yarragadee aquifer where the Leederville aquifer is absent. A downward hydraulic gradient permits groundwater leakage from the Superficial aquifer over the central portion of the coastal plain east of Wedge Island (Kern 1988), and the eastern edge of the coastal plain north of Eneabba (Nidagal 1995). There is improved hydraulic connection between the Superficial and Yarragadee aquifers where sand dominates the lower portion of the superficial formations, such as the Bassendean Sand or Yoganup Formation. The potential for downward leakage from the Leederville aquifer into the Yarragadee aquifer is increased where the confining South Perth Shale is absent.

Groundwater from the Leederville–Parmelia aquifer flows into the Yarragadee aquifer in the Arrowsmith River area via channel deposits (Barnett 1970; Commander 1981). There is direct groundwater leakage between these aquifers at the eastern end of the Eneabba Line associated with a downward hydraulic gradient near the Urella Fault (Commander 1981). This hydraulic connection may be via faults that have displaced the Otorowiri Formation so that the Parmelia aquifer abuts the Yarragadee aquifer. Additional downward leakage is possible along the Dandaragan Scarp where the Otorowiri Formation is cut by faults (Commander 1981).

Numerous estimates of rainfall recharge to the Yarragadee aquifer have been made using the chloride mass balance method. Briese (1979) estimated annual recharge over the outcrop area between the Moora and Watheroo lines to be 37 GL/year based on a recharge rate of 6 per cent average annual rainfall (about 39 mm/year). In the Allanooka area, Schafer (2015) found recharge estimated using the chloride mass balance, assumed to be indicative of pre-clearing recharge rates, to be highest at the edge of the Victoria Plateau at around 30 mm/year. Estimates of recharge in the Allanooka area decrease significantly to the east and north. Recharge studies over the Parmelia Group (Leederville–Parmelia aquifer), which has comparable hydrogeological conditions to the Yarragadee aquifer, yielded an average rate of 16 mm/year (about 4% of average annual rainfall) using chloride mass balance (Bekele et al. 2003), which probably represents the rate of recharge under natural vegetation cover.

Widespread clearing of native vegetation for agricultural purposes has resulted in increased groundwater recharge rates and a persistent rising trend in groundwater levels within the Yarragadee aquifer. An average rise of about 0.3 m/year has been observed since 1980 in the Hill River area (Lindsay 2004). Given a specific yield of 0.1, this rate of groundwater-level rise implies a recharge rate of about 30 mm per year (about 6% of rainfall). Groundwater recharge rates determined based on rising water levels may reflect recharge in addition to pre-clearing recharge rates under native vegetation (i.e. no long-term rise or fall before clearing). Total recharge under cleared areas may therefore be about 10 per cent of average annual rainfall, calculated as the sum of recharge under native vegetation (4% of average rainfall) plus recharge induced by clearing (6% of average rainfall).

Groundwater discharge

Groundwater discharges from the Yarragadee aquifer via upward groundwater flow to the surface or into overlying aquifers. This upward groundwater flow is driven by upward vertical hydraulic gradients present along the western edge of the Arrowsmith region and over much of the coastal plain (Figure 85). Some groundwater also discharges offshore into the Indian Ocean.

Across the Arrowsmith region, groundwater discharges to western sections of Hill River, the lower Irwin River and its tributary. Groundwater that discharges to the western section of Hill River maintains vegetation. Streamflow is not perennial but numerous pools and springs are present where the Hill River valley is incised below the hydraulic head in the Yarragadee aquifer (downstream of Watheroo Line WL8) (Commander 1981). These Yarragadee aquifer-supported surface water features on the northern branch of Hill River include Hill River Spring about 5 km upstream of the confluence (Commander 1981), and Bitter and Coomallo pools (Rutherford et al. 2005). Groundwater discharges to Springy Creek downstream of the 80 m AHD potentiometric contour (Commander 1981). This groundwater discharge supports Mendara Spring in the Irwin River (Rutherford et al. 2004), and Irwin Spring on Springy Creek (Allen 1980).

There are several springs at the margins of the Yarragadee aquifer outlier on the Cadda Terrace south-east of Jurien Bay. Here groundwater is discharged to the surface over faulted contacts with the Cadda Formation or Cattamarra Coal Measures, which form low-permeability barriers (Rutherford 1999). Springs at the northern limit of the outlier include Cowalla, Cadda and Yerramullah springs (Commander 1981), while Bibby Spring is at the south-western margin of the outlier about 23 km east of Cervantes.

Beneath the coastal plain, groundwater flows upward into the Superficial aquifer at several localities (Figure 84). In the south, groundwater discharges to the Superficial aquifer in the Cooljarloo area north-west of Cataby, and adjacent to the coast east of Wedge Island (Kern 1988). In the north, groundwater flows upward beneath the central and western parts of the plain north-west of Eneabba (Nidagal 1995). There is also local upward flow into the channel deposits at Eneabba Line bore EL6 near Eneabba. In the Dongara–Yardarino area, there may also be upward flow into the overlying Tamala Limestone of the Superficial aquifer (Maitland 1913; Commander 1981; Irwin 2007). For example, there is a significant hydraulic head difference of about 5 m between the Yarragadee aquifer and the Superficial aquifer at Leeman Shallow LS31 about 26 km south-east of Dongara (Nidagal 1995). West of Allanooka, fresh groundwater at the top of the Yarragadee aquifer discharges into the Superficial aquifer in the eastern portion of the Swan Coastal Plain, while groundwater from deeper, more saline parts of the Yarragadee aquifer is probably discharged near the coast (Allen 1980).

Upward groundwater flow from the Yarragadee aquifer to the Leederville aquifer is likely about the north-western extent of the Leederville aquifer near Mimegarra (15 km south-west of Cataby).

Offshore groundwater discharge is more common in areas where the Yarragadee aquifer is overlain by permeable parts of the Superficial aquifer. Superficial formations overlie the Yarragadee aquifer offshore between Cliff Head and Bookara in the north, and a smaller area south-west of Wedge Island in the south. There may also be some discharge of groundwater along and upward within faulted zones.

Groundwater levels and flow

Regional groundwater levels within the Yarragadee aquifer for 2015 are presented in Figure 85. Groundwater within the Yarragadee aquifer moves down gradient from a groundwater high south of Moora, south of Badgingarra and on the eastern margin of the Victoria Plateau. Beneath the Arrowsmith region, groundwater flow is constrained by the Cadda Formation and Cattamarra Coal Measures upon the Cadda Terrace in the west and the Urella and Darling faults in the east. There is a groundwater divide near Badgingarra, separating groundwater flowing either to the south or north. The southern system flows to the south-west beneath the coastal plain towards Wedge Island – Lancelin, with some flow towards the Hill River. In the south, where the Yarragadee aquifer is confined beneath the Otorowiri Formation or Warnbro Group, groundwater flow is to the south and south-west under a relatively low hydraulic gradient. In the northern flow system, groundwater flows to the north-west towards Eneabba. North of the Arrowsmith River, including the Victoria Plateau, groundwater flow is to the west and south-west.

Groundwater levels within the Yarragadee aquifer decrease with depth at most sites over the Arrowsmith region (Commander 1981) and Victoria Plateau (Allen 1980). These downward hydraulic gradients will drive groundwater flow into the deeper part of the aquifer (Allen 1980). In Moora Line bores ML7 and ML5, downward hydraulic head differences of 13 and 0.9 m, respectively, were observed (Briese 1979). The hydraulic head decreases upward, indicating potential upward movement of groundwater within the aquifer, near the Hill River at Watheroo Line WL10, and potential discharge to the river (Harley 1974). Upward groundwater flow into the channel sand has also been observed in Eneabba Line EL6 (Commander 1981). Beneath the western portion of the coastal plain, hydraulic head mostly decreases upward within the Yarragadee aquifer.

Over most of the Arrowsmith region, the depth to groundwater exceeds 100 m but is shallower within valleys adjacent to wetlands where the Superficial aquifer is hydraulically connected with the underlying Yarragadee aquifer (see Figure 60). Depth to groundwater is shallow (≤5 m bgl) adjacent to the lower reaches of the Hill River where groundwater discharges. Artesian groundwater flow was obtained in this area from bore ROB 1, about 8 km north-west of Badgingarra, near Watheroo Line WL7 (AGC 1989a). Further south, artesian flow has been obtained from Moora Line ML6A (screened 493–503 m) near the base of the Gingin Scarp. Artesian flows have also been obtained in North Gingin bore NGG2A (screened 1008–1020 m) 15 km north-east of the coastal settlement of Seabird, next to the eastern bank of the Moore River, which has a flowing artesian head of over 12 m above ground level at the bore (Tuffs 2016).

Faulting influences groundwater movement by creating zones of low transmissivity (Commander 1981) related to silicification along fault planes or the juxtaposition of sandstone and siltstone/shale beds (Commander 1974). In the Allanooka area, groundwater is compartmentalised by faults (Allen 1965), with faulting possibly responsible for the water-level contour configuration near Lake Allanooka (Allen 1965). Ventriss and Parsons (1978) also considered that faulting formed boundary conditions that limited the area affected by drawdown from the Allanooka production bores. Groundwater contours across the Eneabba Fault suggest that flow is impeded, but it is uncertain whether this is due to the fault or different hydraulic properties on either side of the fault. Hydraulic connection between the Cattamarra aquifer over the Warradarge Fault (east of Leeman and Green Head) and the Yarragadee aquifer is indicated by declining groundwater levels in the Cattamarra aquifer associated with groundwater abstraction from the Yarragadee aquifer (Commander 1981). There may also be some westward flow of groundwater to the Cattamarra aquifer across the Beagle Fault in the Arrowsmith area (Commander 1981). On the Barberton Terrace, where the Muchea Fault separates the Yarragadee aquifer from the Leederville–Parmelia aquifer (Moncrieff 1989), the low permeability of the Carnac Formation probably prevents hydraulic connection between these two aquifers.

Representative bore hydrographs within the Yarragadee aquifer are shown in Figure 86. Seasonal fluctuations in groundwater levels are generally not apparent in the Yarragadee aquifer (Earth Tech Engineering 2002) because of large depth of the aquifer below the watertable, as well as confined conditions below the Otorowiri Formation and Warnbro Group and in the deeper parts of the aquifer.

Groundwater levels in the Arrowsmith region have risen since the early- to mid-1970s because of higher recharge rates associated with widespread clearing of native vegetation (Figure 61). An increase of about 0.3 m/year has been observed since 1980 in the Hill River area (Lindsay 2004), with maximum rates of up to 0.44 m/year in Watheroo Line WL8 (Earth Tech 2002). Rising groundwater levels have also been observed in the Allanooka and Irwin View monitoring bores near the north-western margin of the aquifer. However, there has been localised decline of water levels at the Allanooka borefield due to groundwater abstraction since 1967, with increased abstraction since 2000 (Water Corporation 2008). Near Eneabba, groundwater levels that were previously rising stabilised between 1995 and 2001 (Eneabba Line bores EL5A, EL6B and EL7B), reflecting increased abstraction at Eneabba and consecutive years of lower rainfall. Where the aquifer is overlain by the Parmelia or Warnbro groups, the rate of groundwater-level rise has been less than 0.1 m per year (Kay & Diamond 2001).

Declining water levels have been observed in southern monitoring bores (including Artesian Monitoring AM2 and AM4) since about the early- to mid-1980s. Since 2000, groundwater levels have also been falling in Moora Line bores ML6 and ML7, and Gillingarra Line bores GL4, GL5 and GL6. These declining water levels are mostly due to increased local or regional groundwater abstraction.

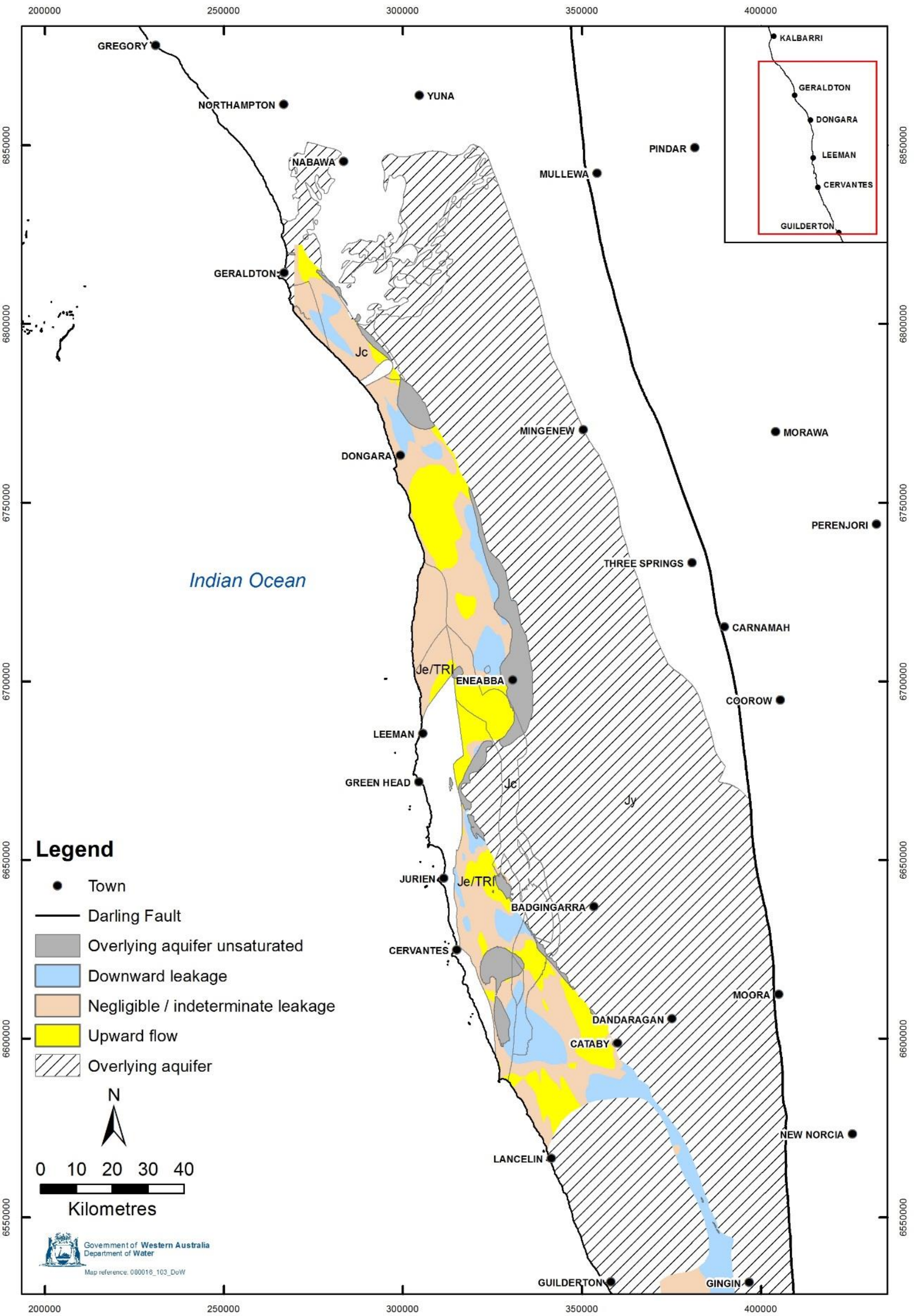


Figure 84 Vertical leakage between Yarragadee, Cattamarra and Eneabba–Lesueur aquifers and overlying Superficial and/or Leederville aquifer(s)

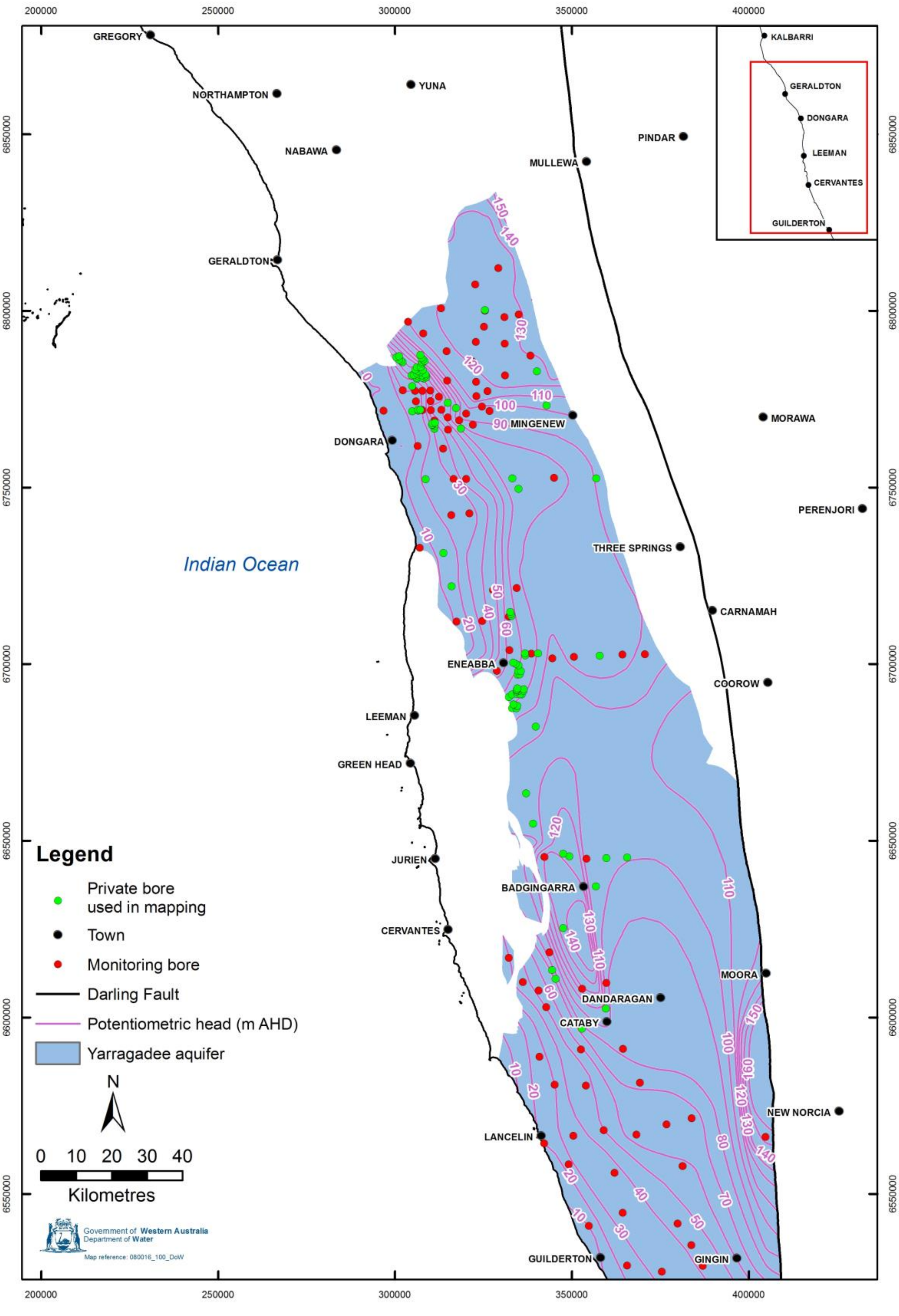
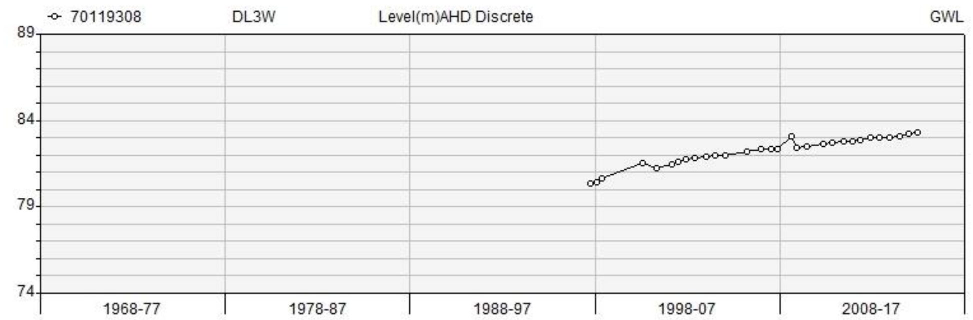
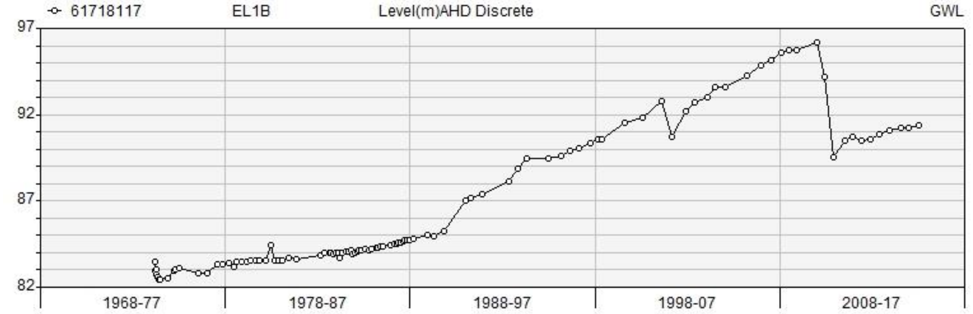


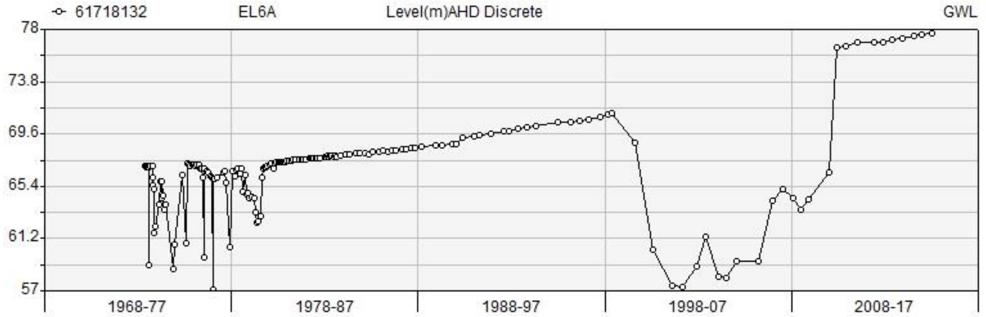
Figure 85 Yarragadee aquifer: potentiometric surface (2015)



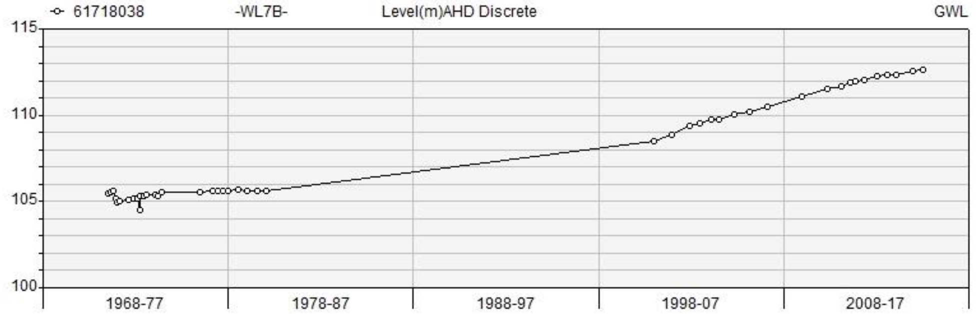
Dongara Line 3W



Eneabba Line 1B

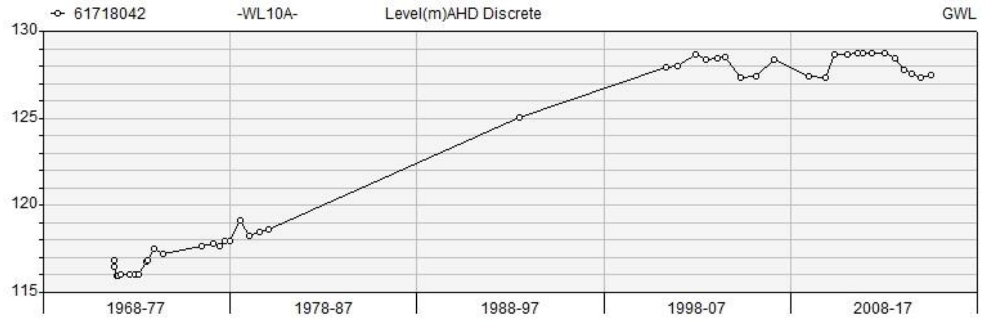


Eneabba Line 6A

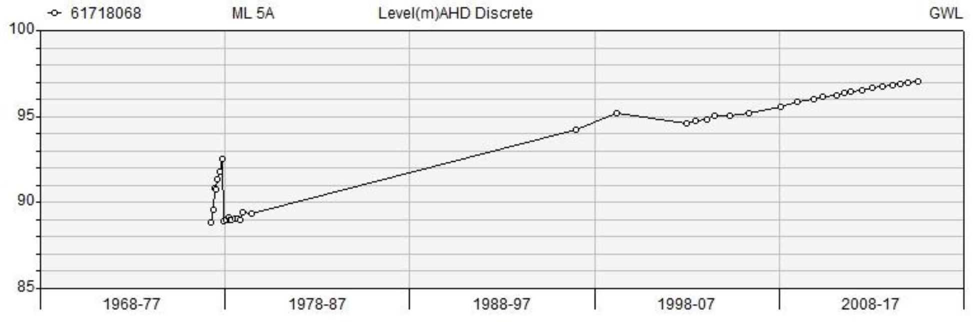


Watheroo Line 7A

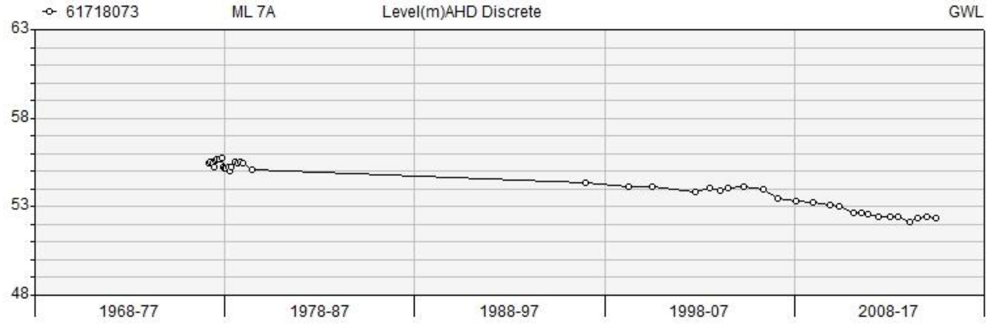
Figure 86 Yarragadee aquifer: selected bore hydrographs



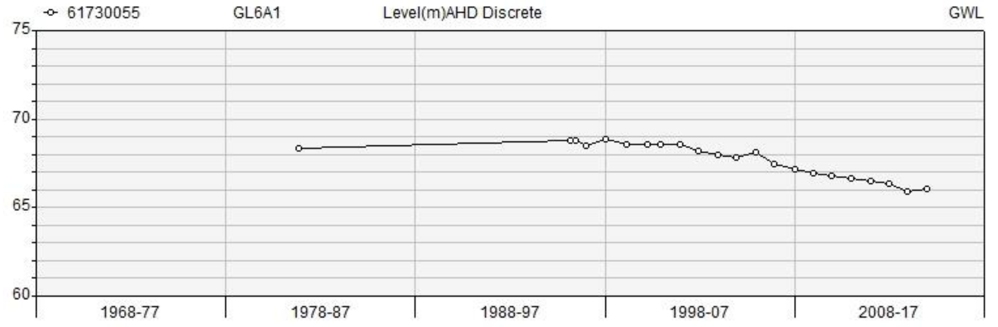
Watheroo Line 10A



Moora Line 5A



Moora Line 7A



Gillingarra Line 6A1

Figure 86 Yarragadee aquifer: selected bore hydrographs (continued)

Hydraulic parameters

There is considerable variability in hydraulic properties through the Yarragadee aquifer, depending on the proportions of sand and clay, and, in deeper parts of the aquifer, the degree of diagenesis. Permeable sandstones are prevalent within Unit C, which is the most permeable portion of the Yarragadee aquifer, consisting of coarse-grained sands in a low-clay matrix with minimal cementation. The permeability of sandstone beds tends to decrease with depth due to an increasing clay matrix and cementation of the sandstone. The deeper Unit B is less permeable than Unit C, owing to fine-grained sandstone and an increased proportion of shale (about 60–70%). Sandstone beds are dominant within Unit A but have relatively low permeability because of cementation and a kaolin clay matrix. The Gage Sandstone, which is part of the Yarragadee aquifer in the south, has not been well tested, but probably has similar hydraulic properties to Unit C of the Yarragadee Formation or the Wanneroo Member of the Leederville Formation.

Shale and siltstone layers are more extensive within units B and D, forming local aquitards. The upper portion of Unit D forms an extensive aquitard adjacent to the Otorowiri Formation, but becomes sandier in the lower portion where it forms a low permeability, interbedded part of the aquifer with some higher permeability sand beds. Regionally, the permeability of the Yarragadee Formation is lower than that of individual sandstone beds due to the discontinuity of sandstone beds and faulting.

Aquifer test results for the Yarragadee aquifer are highly variable (Appendix E). In the broader Allanooka area, the hydraulic conductivity ranges from 5 m/day (Forth 1971) to 17 m/day (Forth 1973). The hydraulic conductivity in the Allanooka borefield is greater, with an average hydraulic conductivity of 85.6 m/day and a median of 54.7 m/day. These high values are due to greater permeability of the aquifer in this area or analysis errors of the aquifer test data. Excluding the Allanooka borefield, hydraulic conductivity in the Yarragadee aquifer averages about 12 m/day with a median of 5.6 m/day (Appendix E). In the Eneabba area, most aquifer tests were undertaken within Unit B, which had an average hydraulic conductivity of 5 m/day, and a maximum hydraulic conductivity of 11.1 m/day. A bulk hydraulic conductivity for the whole Yarragadee aquifer of 5 m/day has previously been assumed in the Eneabba area (Rockwater 1980b). The lower permeability of Unit D is demonstrated at Cooljarloo near Cataby, with several bores having an average hydraulic conductivity of 0.7 m/day.

The vertical hydraulic conductivity of the Yarragadee aquifer is highly variable and difficult to assess. Vertical hydraulic conductivity is dependent on the presence of shale beds that restrict the vertical movement of groundwater within the aquifer. Shale beds are more extensive within units B and D, and so these units will have the lowest vertical permeability, particularly the upper portion of Unit D west of the area overlain by the Otorowiri Formation. The vertical permeability will be highest within Unit C, which has minimal shale layers. Based on the lithologies present in the Yarragadee aquifer, the vertical hydraulic conductivity across the whole aquifer is likely to range between 1×10^{-2} and 1×10^{-4} m^2/day.

Storativity (or storage coefficient) for confined conditions have been determined from various aquifer tests, and are summarised in Table 15. Storativity ranges from 1.0×10^{-4} to 9.4×10^{-3}, with an average of 1.7×10^{-3}. At Eneabba, storativity of between 2×10^{-4} and 9×10^{-3} were determined by Rockwater (1989, 1995), while Commander (1980) determined values of 3×10^{-4} to 2×10^{-3}. Aquifer tests of bore TP1 in the Hill River area yielded a storativity of 1.5×10^{-4} using the Jacob method and 2.1×10^{-4} using the Theis method (AGC 1989).

Bore yields are generally large (2000–4000 m^3/day). At Eneabba, production bores in the most permeable sections of the Yarragadee aquifer can yield up to 6000 m^3/day (Johnson & Commander 2006), while bores screening the low-permeability portions of Unit D are likely to yield less than 2000 m^3/day.

Table 15 Storativity results for the Yarragadee aquifer from aquifer tests

Bore	Storativity	Bore	Storativity	Bore	Storativity
CPB17	3.0×10^{-4}	TP1	1.8×10^{-4}	WTE32s	4.0×10^{-3}
CPB3	1.0×10^{-4}	TP2	9.5×10^{-4}	WTE33s	9.0×10^{-3}
PB2	1.1×10^{-3}	TP3	3.5×10^{-4}	WTE36s	2.0×10^{-4}
PB3	9.7×10^{-4}	WTE1	2.6×10^{-4}	WTE37s	1.5×10^{-3}
PB4	5.1×10^{-4}	WTE7	3.0×10^{-4}	WTE38s	5.3×10^{-4}
REM1A	9.9×10^{-4}	WTE31s	7.0×10^{-4}	WTE39s	9.4×10^{-3}

Estimates of groundwater throughflow

South-east of the Allanooka borefield, Allen (1980) calculated groundwater throughflow at 11.1 GL/year across the 90 m watertable contour over a 14 km section of the aquifer, which is equivalent to about 0.8×10^6 m^3/year/km. This was based on a hydraulic gradient of 0.005, an aquifer thickness of 100 m containing 40 per cent sand, and a hydraulic conductivity of 10 m/day. This throughflow value was then extrapolated along 47 km of the 60 m contour to give an estimated throughflow of 37.6 GL/year for the larger Allanooka area, equivalent to a recharge rate of 10.7 per cent of rainfall over a recharge area of 735 km^2. However, Allen (1980) considered this rate of recharge to be too large (see discussion on recharge above) and proposed a recharge rate of 3 per cent or less of average annual rainfall to be more appropriate, resulting in a throughflow of 10.5 GL/year in the Allanooka area. Commander (1981) suggested that impedance of groundwater flow by faulting contributed to the steep hydraulic gradients, and consequently the high throughflow estimation in the Allanooka area.

Annual throughflow in the southern Yarragadee aquifer was estimated by Briese (1979) to be 205 GL/year across the 50 m hydraulic head contour between the Warradarge Fault and Moore River (an aquifer width of about 50 km). This estimate assumed an aquifer thickness of 1000 m, 75 per cent sands (or sandstone) with a hydraulic conductivity of 7.5 m/day, and a hydraulic gradient of 0.002. South of the Irwin River, Commander (1981) estimated the annual recharge for northward throughflow from the groundwater divide to be 29×10^6 m^3 over an outcrop area of 2620 km^2, assuming 2 per cent of rainfall recharge.

Groundwater salinity

Groundwater within the Yarragadee aquifer is generally fresh to marginally brackish (Figure 87), but varies considerably both laterally and with depth. This variability is due to salt input from recharge, depth of groundwater flow and residence time.

In the Arrowsmith region, groundwater is generally fresh, less than 1000 mg/L TDS, and less than 500 mg/L TDS beneath the main recharge areas. Between Cataby and Badgingarra, groundwater has salinity of mostly less than 400 mg/L TDS, with the lowest at about 100–200 mg/L TDS at the watertable near the confluence of Coomaloo Creek and Hill River. Groundwater salinity less than 500 mg/L TDS is also present at the margins of the Arrowsmith region east of Eneabba, between the Arrowsmith and Irwin rivers, and locally north of the Irwin River.

Low-salinity groundwater of 470 mg/L TDS was recorded south-east of Cataby at North Gingin bore NGG12A, between 225 and 228 m bgl. Here the Gage Sandstone (part of the Yarragadee aquifer) outcrops and the Yarragadee aquifer bears the watertable receiving direct rainfall recharge (Tuffs 2016).

Groundwater salinity tends to increase along the direction of groundwater flow. There is a slight increase westward along the Gillingarra Line (Moncrieff 1989) and eastward of Watheroo Line bore WL6 (Commander 1981). Bores near the Arrowsmith River have higher groundwater salinity, mostly 1000–1400 mg/L TDS, from river recharge (Commander 1981). Similar areas of brackish groundwater are also present beneath the Irwin and Lockier rivers.

Beneath the coastal plain north of Eneabba and in discharge areas near the coast, groundwater salinity is over 1500 mg/L TDS (Nidagal 1994). Groundwater is generally brackish to saline beneath the coastal plain west of Allanooka (Rockwater 1991). Where the overlying Superficial aquifer contains saline groundwater, downward leakage can elevate salinity within the upper part of the Yarragadee aquifer, reaching up to 7510 mg/L TDS in Cataby Shallow bore CS30D (Kern 1997). Beneath the Otorowiri Formation, groundwater salinity in the aquifer is mostly brackish, exceeding 1500 mg/L TDS.

Localised areas of lower salinity groundwater (<1000 mg/L TDS) have been observed below the Otorowiri Formation in Eneabba Line bores EL1 and EL2 (Commander 1981), corresponding to downward leakage from the overlying Leederville–Parmelia aquifer via faults or lithological contacts. Beneath the South Perth Shale in the south, groundwater is fresh, and TDS is less than 1000 mg/L.

There is a general trend of increasing salinity with depth. In the Arrowsmith region, groundwater is often brackish in the upper parts associated with clayey lithologies, and is frequently elevated within Unit D. In the Allanooka borefield, groundwater salinity increases with depth (Maitland 1913; Allen 1965, 1980; Schafer 2016), with low-salinity groundwater forming a relatively thin layer zone extending 12–144 m below the watertable, averaging about 90 m thick (Allen 1980), and generally thickening eastward (Allen 1979; Schafer 2016). There is a local exception between the Watheroo and Moora lines with lower salinity at the contact of units D and C. Groundwater salinity in Unit C ranges between 300 and 430 mg/L TDS in Watheroo Line bores WL7 and WL10 (Harley 1974), and Moora Line bores ML5A and ML6A (Briese 1979). At the coastal settlement of Seabird, south of Lancelin, saline groundwater of 21 000 mg/L TDS was recorded in North Gingin bore NGG1A screened in the Yarragadee aquifer from 850 to 856 m bgl. The Yarragadee Formation here is thought to comprise Unit D with the saline groundwater possibly being fault-bound or a result of long residence time in the aquifer.

Downhole geophysical logs from petroleum wells suggest that fresh to marginally brackish groundwater extends to a considerable depth within the aquifer. Groundwater in petroleum well Walyering 1 near Cataby has a salinity of less than 1000 mg/L TDS to a depth of 1500 m, and less than 1500 mg/L TDS to a depth of 2500 m (Nowak 1978). Similarly, brackish groundwater extends to the base of the Yarragadee Formation at 2743 m depth in petroleum well Gingin 1 (Johnson 1965; Moncrieff 1989), 2660 m in petroleum well Ocean Hill 1 (SAGASCO 1991), and 1695 m in petroleum well Eneabba 1 (Pudovskis 1962). Groundwater underlying the Yarragadee Formation is generally hypersaline (Commander 1981).

The outlier aquifer formed by the Yarragadee Formation between Cowalla Peak, south of the Hill River, and Bibby Creek, probably contains groundwater with a salinity of less than 1000 mg/L TDS. On the Barberton Terrace between the Darling and Muchea faults, brackish to saline groundwater is present with Gillingarra Line bore GL8A2 having a groundwater salinity of 5180 mg/L TDS (Moncrieff 1989).

A seawater interface is present adjacent to the coast north of Cliff Head, and appears to extend 8 km inland of the coast (Nidagal 1994). Saline groundwater from the interface and associated mixing zone has been intersected in bores between Cliff Head and Dongara. Groundwater salinity in Dongara Line bore DL1 is 10 600 mg/L TDS (Irwin 2007) and in Leeman Shallow bores LS30A and LS33A it is up to 26 700 mg/L TDS (Nidagal 1994).

A seawater interface may occur within the aquifer where it is directly overlain by superficial formations about 20 km north of Lancelin. Closer to Lancelin, the Yarragadee aquifer is confined by the South Perth Shale which isolates the aquifer from overlying saline water, and probably allows fresh groundwater to extend offshore (Moncrieff 1989).

Hydrochemistry

The major anions are displayed as a percentage of the total milliequivalents per litre on the trilinear plot in Figure 88. The groundwater is of a sodium chloride type suggesting it has been derived from and is recharged by rainfall (Harley 1974; Briese 1979; Commander 1981; Moncrieff 1989).

Groundwater in the Yarragadee aquifer tends to be slightly acidic, with a pH of less than 7, and can be corrosive to metal (AGC 1975; Commander 1978a, 1978b; Rockwater 1980b). Field pH values of 30 pumped samples from the carbon-14 sampling program (Egis 1999) averaged 6.8.

Groundwater tends to become more enriched in calcium bicarbonate with depth (Harley 1974; Briese 1979a, b). Bicarbonate concentrations range from 39.7 to 201 mg/L for samples collected as part of the carbon-14 sampling program (Egis 1999). Groundwater from Watheroo Line WL8 is unusual as it appears to be magnesium-chloride rich (Harley 1974). These data are not shown in Figure 88.

Dissolved iron concentrations vary considerably throughout the Yarragadee aquifer. Measured variations may be an artefact of the sampling procedure with the aeration of samples resulting in oxidation and iron precipitation (Commander 1978a, 1978b). Dissolved iron concentrations are highest beneath the recharge area between the Moora and Watheroo lines, with a maximum value of 25 mg/L recorded from ML6A (Egis 1999). Elsewhere, beneath the Arrowsmith region, Victoria Plateau and Swan Coastal Plain, dissolved iron values of up to about 10 mg/L have been measured, but concentrations are commonly less than 0.3 mg/L. Groundwater from the Allanooka borefield generally has less than 0.3 mg/L dissolved iron, which is sufficiently low as to not require treatment for potable water supply (Water Corporation 2008). Concentrations of dissolved iron are below 0.1 mg/L where the Yarragadee aquifer is confined along the Gillingarra Line (Egis 1999) and along the Gingin Brook Line (Sanders 1967a, b).

Groundwater nitrate concentrations in the Yarragadee aquifer are generally less than 1 mg/L, except at some locations where the aquifer is unconfined and impacted by the application of fertilisers for agricultural activities (Harley 1974). Other chemical constituents of groundwater are typically within guideline limits for potable water.

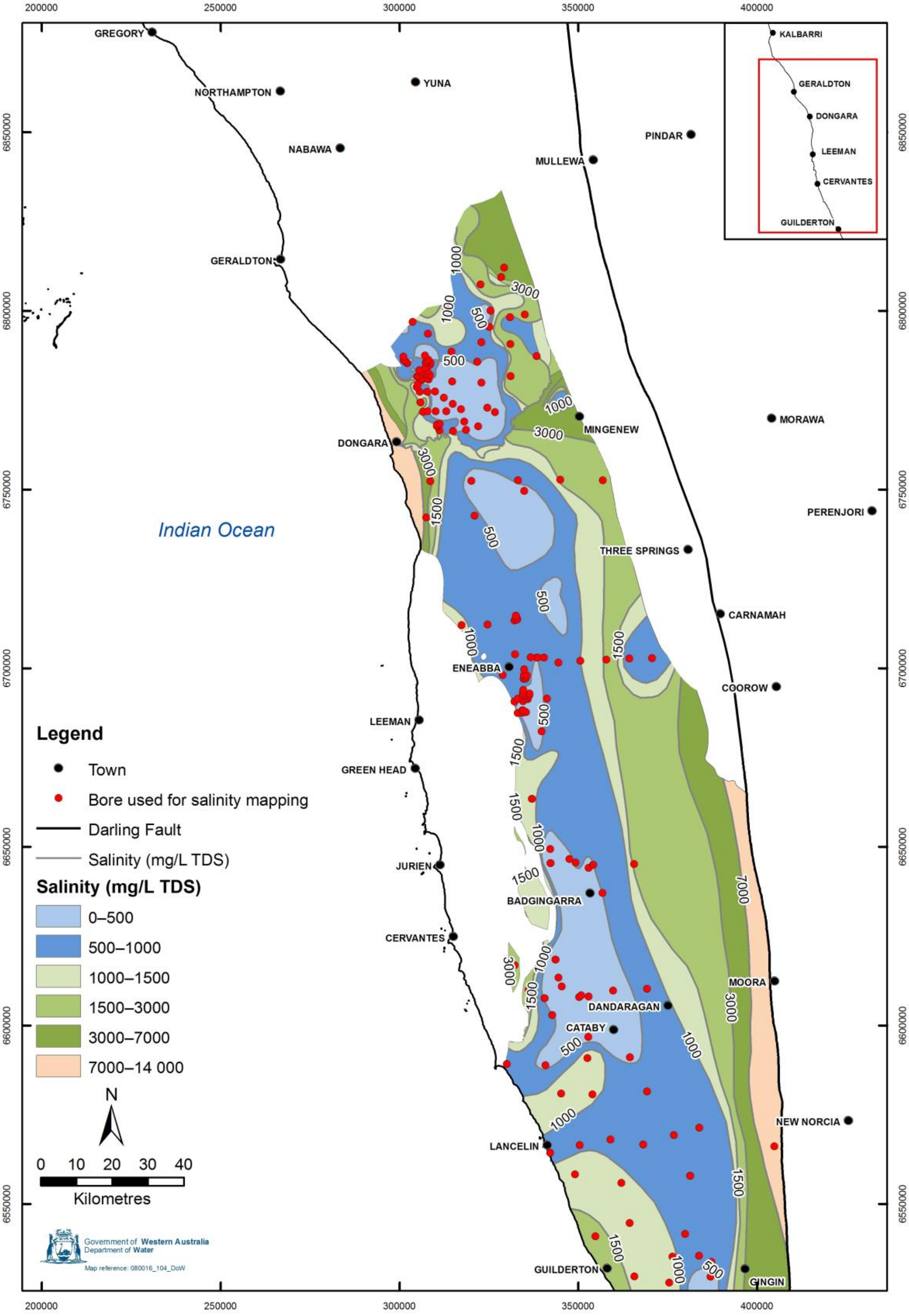


Figure 87 Yarragadee aquifer: groundwater salinity

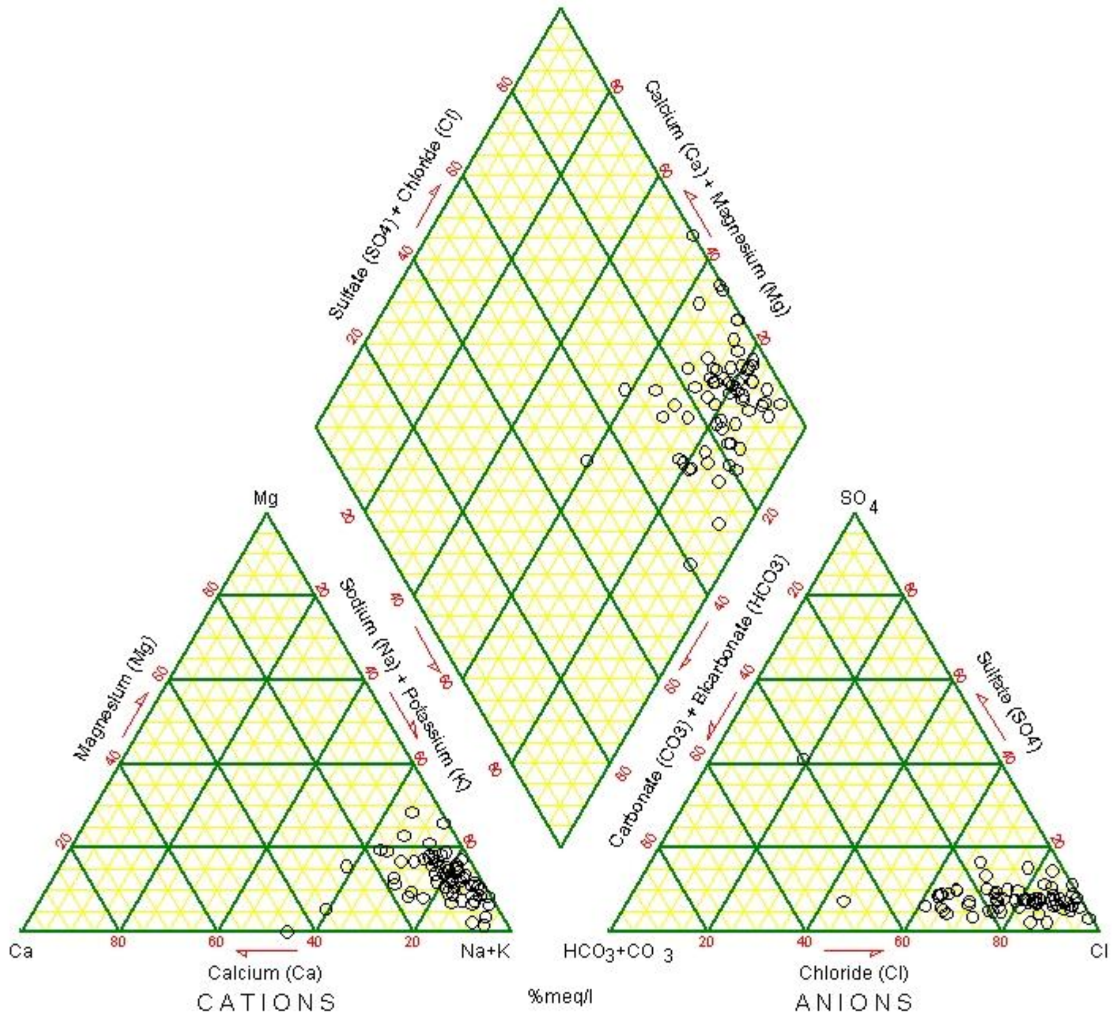


Figure 88 Yarragadee aquifer: hydrochemical trilinear diagram

Groundwater isotopic composition and age

Groundwater age estimates in tested bores range from 2140 years BP (Irwin View 11/77) to 36 560 years BP (GL5A2). The youngest groundwater age is associated with shallow bores where the aquifer is unconfined, particularly within the Irwin View bores. Relatively young groundwater ages were also obtained from Watheroo Line bores WL8 and WL10. However, at site WL8 groundwater from the deeper interval at 587–597 m depth (WL8) had an inferred age of 3010 years BP, which was younger than the shallower interval between 171–174 m (WL8A), which was estimated at 3680 years BP. This younger groundwater age at depth in WL8 may be related to enhanced groundwater throughflow at the top of Yarragadee Unit C. Within Watheroo Line WL10, groundwater ages of 2560 years BP at 225–231 m depth (WL10A) and 5520 years BP at 381–388 m (WL10) suggest significant groundwater recharge near WL10. The oldest groundwater (up to 36 500 years in GLA2) was obtained from Gillingarra Line bores where the aquifer is confined beneath the South Perth Shale or Leederville Formation of the Warnbro Group.

Table 16 Groundwater isotope data for the Yarragadee aquifer

Project / Town	Bore	Screen interval (m bgl)	14C (pmC)	14C error (pmC)	14C age, corrected (yr BP)	14C age error (yr BP)	δ13C (‰PDB)	δ18O (‰SMOW)	δ2H (‰ SMOW)
Allanooka	1/82	83–93	64.3	1.19	3650	150	–19.0	–4.3	–17.6
Allanooka	12/85	58–70	40.3	1.45	7520	290	–17.0	–4.3	–18.2
Allanooka	16/85	112–133	42.6	1.17	7060	220	–17.2	–4.3	–17.2
Eneabba Line	EL7B	144–150	57.2	0.5	4620	70	–7.5	–	–
Gillingarra Line	GL1A3	953–959	2.4	0.56	30 900	1800	–	–	–
Gillingarra Line	GL3A3	980–986	1.8	0.5	33 200	2000	–	–	–
Gillingarra Line	GL4A2	1076–1082	3.35	0.6	28 300	1300	–	–	–
Gillingarra Line	GL5A2	1092–1098	1.2	0.2	36 560	1280	–17.8	–	–
Gillingarra Line	GL5B2	318–324	2.4	0.2	30 510	660	–16.7	–	–
Irwin View	1/74	194–200	42.6	0.5	7 050	100	–17.3	–	–
Irwin View	2/75	188–196	46.6	0.5	5 640	90	–16.9	–	–
Irwin View	4/76	99–138	50.2	0.5	4 840	80	–16.8	–	–
Irwin View	5/76	117–148	35.7	0.4	7 690	90	–16.1	–	–
Irwin View	6/76	104–109	70.9	0.6	2 840	70	–19.4	–	–
Irwin View	2/77	196–205	38	0.4	6 260	90	–15.4	–	–
Irwin View	4/77	41–51	27.9	0.4	8 760	120	–16.1	–	–
Irwin View	9/77	39–48	21.8	0.4	11 000	150	–16.1	–	–
Irwin View	10/77	45–54	22.7	0.4	10 430	140	–15.4	–	–
Irwin View	11/77	81–90	77.2	0.7	2 140	70	–19.3	–	–
Irwin View	13/77	111–144	56.1	0.5	4 780	70	–19.1	–	–
Mingenew	13	31–38	53.4	1.7	5 190	260	–18.4	–4.4	–18.2
Moora Line	ML6A	723–733	22.6	0.4	12 300	150	–20.6	–	–
Moora Line	ML6A (ann)	493–503	21.84	0.9	12 600	340	–	–	–
Moora Line	ML6B	147–157	32.1	0.4	9 390	100	–21.5	–	–
Moora Line	ML7B	75–81	65.5	0.6	3 500	80	–19.2	–	–
Three Springs	1/79	205–220	75.9	2.2	2 300	240	–19.9	–4.6	–20.4
Watheroo Line	WL10	381–388	51.3	0.5	5 520	80	–21.3	–	–

Project / Town	Bore	Screen interval (m bgl)	14C (pmC)	14C error (pmC)	14C age, corrected (yr BP)	14C age error (yr BP)	δ13C (‰PDB)	δ18O (‰SMOW)	δ2H (‰ SMOW)
Watheroo Line	WL10A	225–231	73.4	0.3	2 560	30	–20.7	–	–
Watheroo Line	WL8	587–597	69.5	1.2	3 010	140	–	–	–
Watheroo Line	WL8A	171–174	64.1	0.5	3 680	60	–20.5	–	–

Data from Egis Consulting (1999)

Notes: 14C – carbon-14; 13C – carbon-13; 18O – oxygen-18; 2H – deuterium; pmC – per cent modern carbon; PDB – 13C standard; δ – ratio of sample to standard; SMOW – standard mean ocean water; ‰ – per mil (parts per thousand); ann – annulus. Different correction models have been used to generate 14C age, corrected (yr BP); refer to the original project reports for more information.

5.8 Cattamarra aquifer

The Cattamarra aquifer comprises the Cattamarra Coal Measures and Cadda Formation. The Cattamarra Coal Measures consist of interbedded sandstone, carbonaceous siltstone and claystone. The Cadda Formation contains predominantly sandstone and siltstone in upper parts and clay/shale in lower parts. The substantial clay and siltstone layers confine waterbearing horizons.

The Cattamarra aquifer outcrops or underlies the Superficial aquifer across the Cadda Terrace and Greenough Shelf, parallel to the coast from Cataby to Eneabba and from Mount Hill to the Oakajee River, north of Geraldton. It is also in limited hydraulic connection with the underlying Eneabba–Lesueur aquifer.

In the Dandaragan Trough, groundwater below the Cadda Formation is saline or hypersaline, suggesting an inactive groundwater flow system.

Groundwater recharge

Rainfall and surface runoff contribute to recharge in the outcropping areas on the Cadda Terrace and Greenough Shelf, with downward leakage from the Superficial aquifer in the eastern Swan Coastal Plain (see Figure 64) (Commander 1981; Nidagal 1994; Kern & Koomberi 2013). Recharge to the Cattamarra aquifer from the overlying Yarragadee aquifer takes place directly and along fault zones, especially the Beagle Fault, where the units juxtapose (Allen 1980) as well as across the Warradarge Fault (Commander 1981). On the Nabawa Sandplain, recharge is derived from rainfall (Koomberi 1995; Hundi 1999). Recharge to the Catamarra aquifer in the Hill River area is much lower than recharge to the Yarragadee aquifer, owing to a greater proportion of shale beds in the Cattamarra Coal Measures and Cadda Formations (Commander 1981).

Recharge estimations using the chloride mass balance method are not possible due to the lack of groundwater salinity data, but recharge is likely to be about 1 per cent of rainfall (Commander 1981).

Groundwater discharge

In the central outcrop area, springs in the Hill River and its tributaries represent discharge from the Cattamarra aquifer (Commander 1981). North of Leeman, groundwater from the Cattamarra aquifer discharges offshore.

Where the Cattamarra aquifer is in direct hydraulic connection with the Superficial aquifer, groundwater discharges from the Cattamarra aquifer into the overlying Superficial aquifer (Commander 1981; Kern & Koomberi 2013). Some of this discharge into the Superficial aquifer subsequently discharges into Bindoon and Erindoon creeks south-west of Eneabba (Kern 1997).

In the northern outcrop area, around the Northampton Inlier, discharge is offshore or indirectly through the Tumblagooda aquifer. There is also local discharge into the Chapman River (Koomberi 1995) and to springs around the Nabawa Sandplain.

Groundwater levels and flow

Groundwater levels for the Cattamarra aquifer are shown in Figure 89. Groundwater levels up to 200 m AHD have been recorded where the aquifer overlies the Northampton Inlier, decreasing rapidly towards the coast. In the main outcrop area (between Cataby and Eneabba), there is a groundwater divide north of Cockleshell Gully, between Jurien Bay and Green Head (Commander 1978; Kern 1997). Groundwater flows either to the north-west or to the south of the divide, with flow in both cases towards the Eneabba–Lesueur aquifer and upward into the Superficial aquifer near the coast.

Bore hydrographs are shown in Figure 90. A general water level rise of about 0.2 m/year is apparent in Watheroo Line 11A from the mid-1960s to 2000 and is most likely related to regional land clearing.

Hydraulic parameters

Limited aquifer tests have been completed in the Cattamarra aquifer, with most being associated with mining in the Eneabba region (Appendix F). Permeability is generally lower than the Yarragadee aquifer due to the lower proportion of sand, but moderate to high yields can still be locally obtained. Transmissivity has a large range from about 9 to 153 m^2/day (AGC 1972; Rockwater 1990), with pump test flow rates ranging from about 500 to 1350 m^3/day. The variation in hydraulic parameters between bores reflects the heterogeneous nature of the aquifer, being influenced by the permeability and thickness of sand-rich horizons, as well as proximity to faults and fractures that may provide either a conduit or barrier to groundwater flow.

Groundwater salinity

Groundwater salinity of the Cattamarra aquifer is shown in Figure 91. In the central outcrop area, fresh groundwater of less than 1000 mg/L TDS is only found in isolated areas along the eastern boundary, and the groundwater salinity increases in the direction of groundwater flow (Commander 1978) to more than 3000 mg/L TDS (Kern 1997; Kern 1988; Nidagal 1995). In the northern region, groundwater is mostly brackish to saline, ranging from about 1000 to 10 000 mg/L TDS (Allen 1980; Koomberi 1995; Kern & Koomberi 2013).

Hydrochemistry

Groundwater in the Cattamarra aquifer is sodium chloride type (Figure 92) (Commander 1978, AGC 1972). Hydrochemistry is similar to the Eneabba–Lesueur and Yarragadee aquifers, reflecting the same derivation from rainfall recharge (Commander 1978), and hydraulic connection between the aquifers. Along the Watheroo Line, elevated nitrate concentrations associated with agricultural practices were observed in the upper part of the aquifer, where the aquifer is unconfined (Harley 1975).

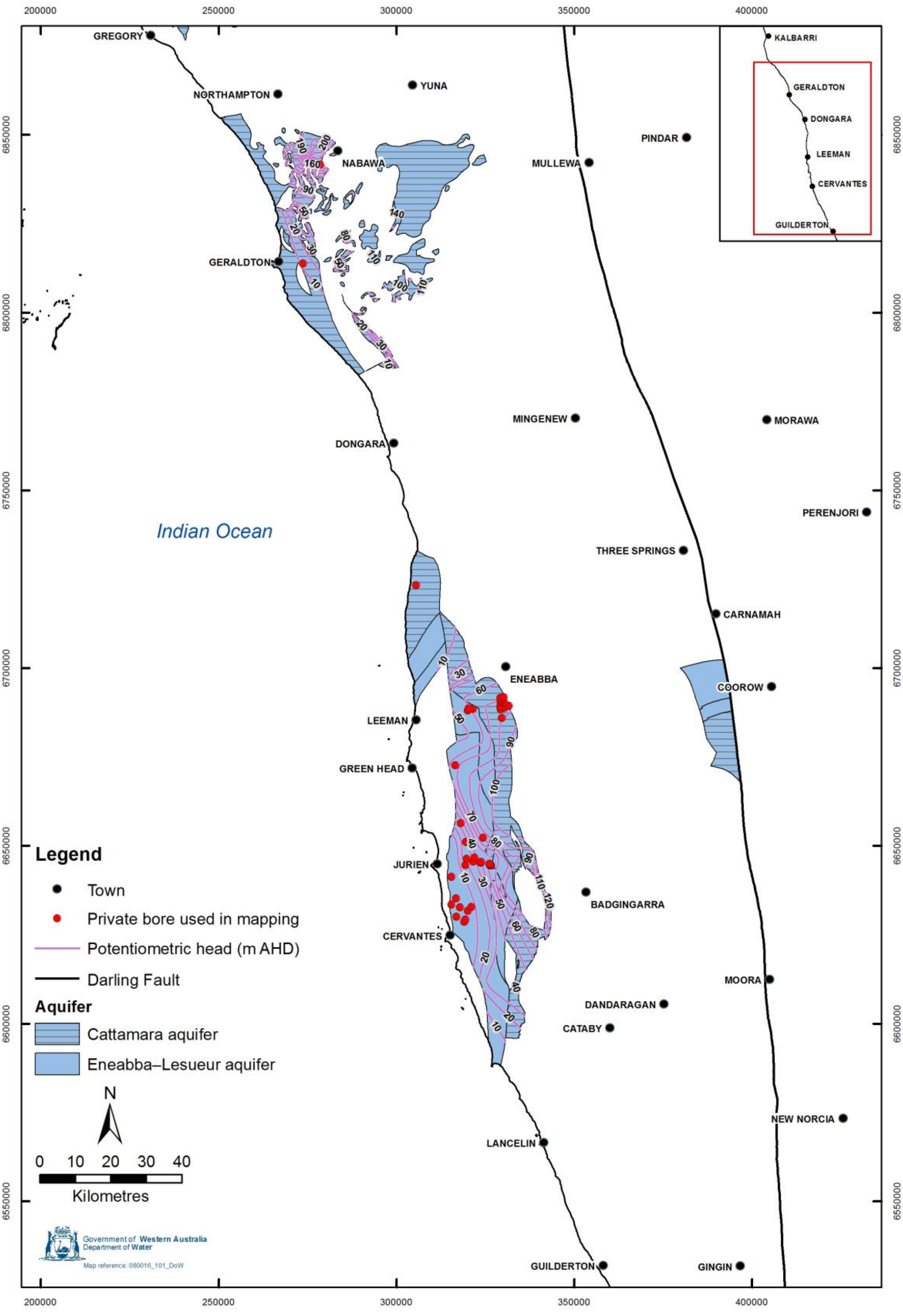


Figure 89 Cattamarra and Eneabba–Lesueur aquifers: potentiometric surface

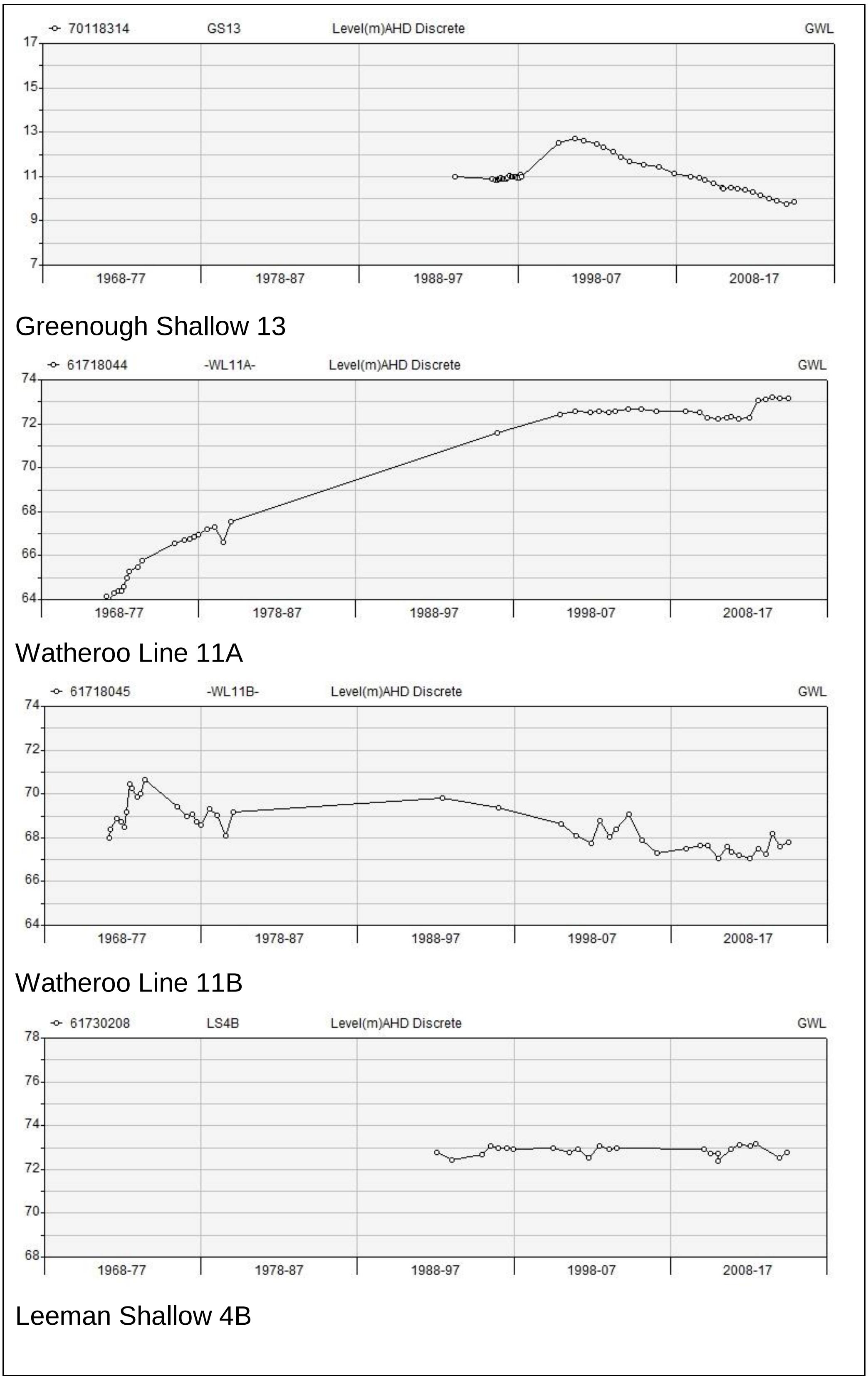


Figure 90 Cattamarra aquifer: selected bore hydrographs

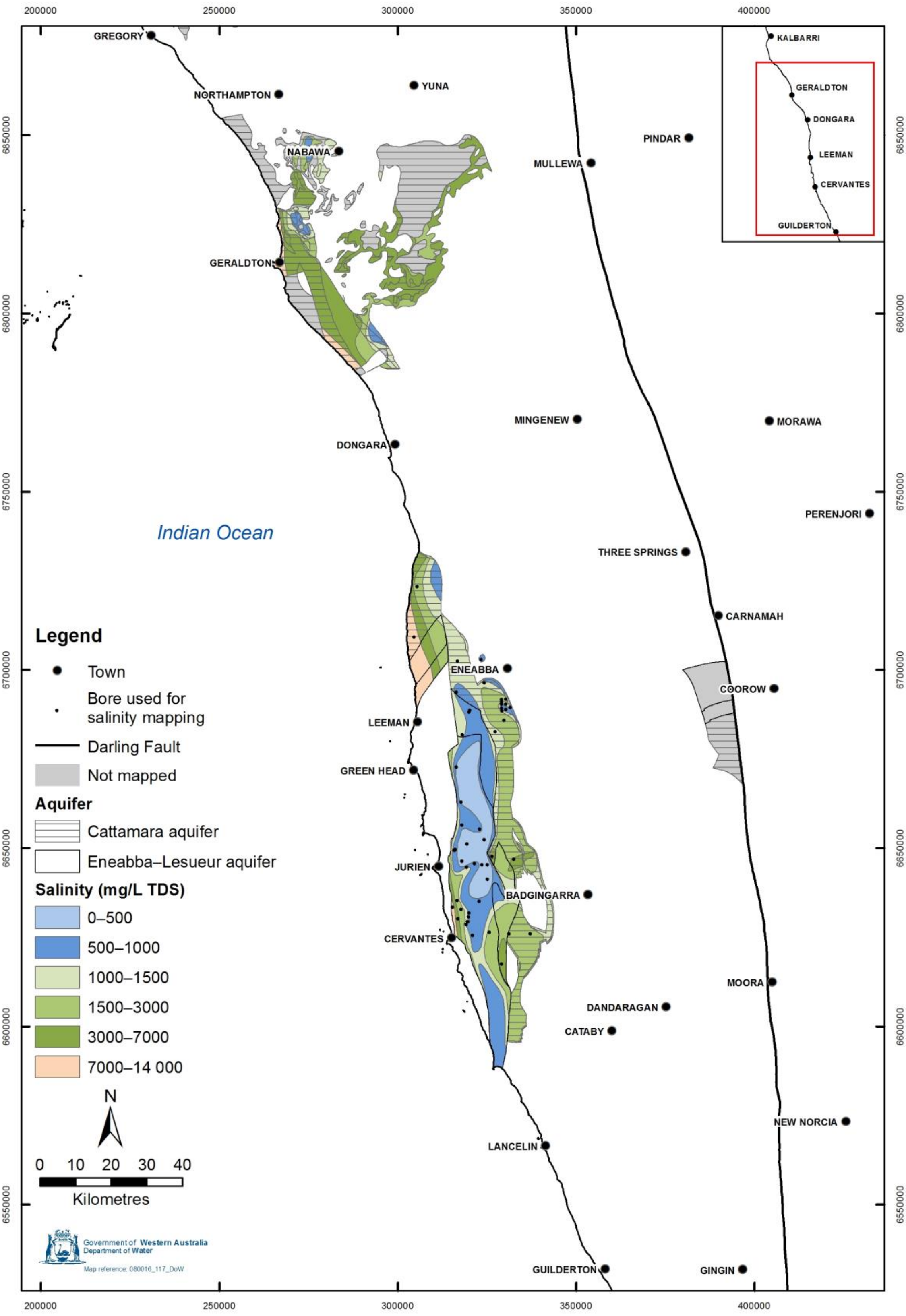


Figure 91 Cattamarra and Eneabba–Lesueur aquifers: groundwater salinity

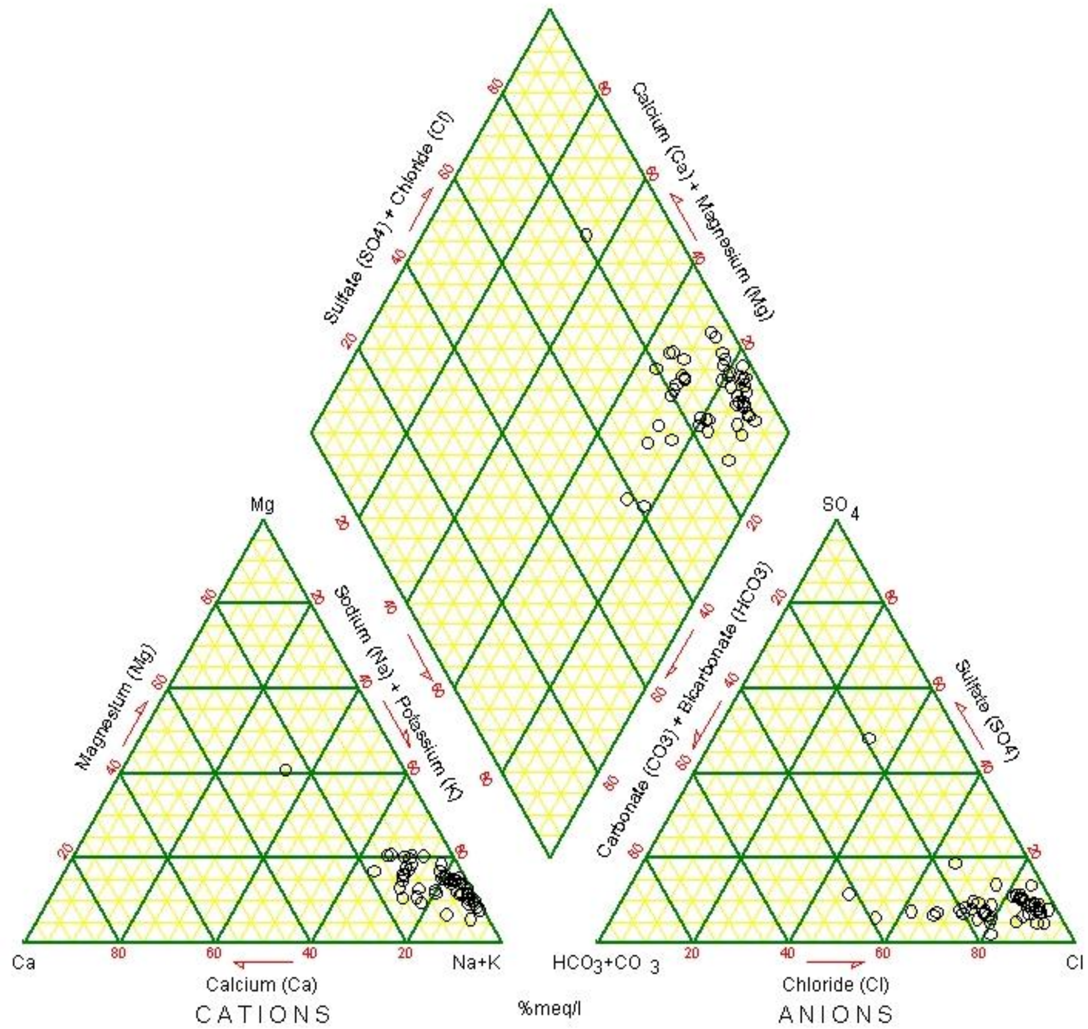


Figure 92 Cattamarra aquifer: hydrochemical trilinear diagram

5.9 Eneabba–Lesueur aquifer

The Eneabba Formation and Lesueur Sandstone, together with the underlying Woodada Formation, form a hydraulically connected aquifer (Kern 1997; Commander 1977), which is referred to as the Eneabba–Lesueur aquifer (Earth Tech Engineering 2002). On the Beagle Ridge and western portion of the Cadda Terrace, the aquifer contains fresh groundwater extending 100 km north of Wedge Island and up to 18 km wide, bound by the Cattamarra aquifer in the east and the Kockatea Shale to the west. The aquifer also extends through most of the basin at depth, confined by thick shale and siltstone beds of the Cattamarra Coal Measures. Here, the aquifer contains saline groundwater and is considered to be below the zone of active groundwater flow.

The aquifer comprises sandstone with interbedded siltstone and claystone of the Eneabba Formation, dominantly fine to very coarse grained quartz sand through the Lesueur Sandstone, and fine-grained sandstone interbedded with siltstone in the Woodada Formation.

The thickness of the Eneabba–Lesueur aquifer where it is present at shallow depth is shown in Figure 93. The thickest section is about 1800 m south-west of Eneabba, and about 1400 m east of Cervantes. The aquifer generally thins westward.

Groundwater recharge

Recharge into the Eneabba–Lesueur aquifer is from infiltration of rainfall and surface runoff over the outcrop area across the Arrowsmith region (Commander 1978), or by downward leakage from the Superficial aquifer beneath the eastern and central portion of the coastal plain where there is a downward hydraulic gradient. The aquifer also receives some throughflow contribution from the adjacent Cattamarra aquifer in the east, across the Lesueur and Wedge faults (Commander 1981). Low-salinity groundwater suggests that throughflow from the Cattamarra aquifer, which contains brackish groundwater, is minimal compared to rainfall recharge. Commander (1981) estimated groundwater recharge (using chloride mass balance) to be 5.6 per cent of rainfall over the outcrop area.

Kern (1997) estimated the recharge of the Eneabba–Lesueur aquifer between Cervantes and Leeman by summing up recharge from direct rainfall in outcrop areas of the Eneabba Formation and Lesueur Sandstone, plus the recharge from downward leakage from the overlying Superficial aquifer. Recharge in outcropping areas was assumed to be 5 per cent of rainfall and 2.5 per cent in subcrop areas.

Recharge rates may have increased because of clearing of native vegetation for pasture in outcrop areas, and may be greater than 10 per cent in these cleared areas (Baddock & Lach 2003).

Groundwater discharge

Groundwater discharge is mainly by upward groundwater flow into the Tamala Limestone portions of the Superficial aquifer in this area (see Figure 64) (Baddock & Lach 2003). Groundwater flow westward towards the coast is restricted by the impermeable Kockatea Shale along the Beagle Fault, which causes groundwater to flow upward and discharge into the Superficial aquifer. This has been observed at Cockleshell Gully and nearby Three Springs (Commander 1981; Ryan 2012a), but is probably widespread along the western margin of the aquifer. Groundwater discharge into the Tamala Limestone may have contributed to the formation of caves (Commander 1981) that are prevalent near the Beagle Fault.

Some groundwater discharge from the Eneabba–Lesueur aquifer to the Superficial aquifer probably also takes place along the eastern margin of the coastal plain, between the Hill River and Cockleshell Gully. Some of this discharge probably subsequently discharges into Canover Pool in the Hill River (Commander 1981), and Woomulla Pool along the Cockleshell Gully. Several permanent wetlands near the Jurien Road are possibly maintained by upward flow from the Lesueur Sandstone component of the Eneabba–Lesueur aquifer (Baddock & Lach 2003).

Groundwater levels and flow

Groundwater levels in the Eneabba–Lesueur aquifer are shown in Figure 89 (see Section 5.8). A groundwater divide is located north of Cockleshell Gully (Commander 1981; Baddock

& Lach 2003), with flow to the north-west and south-west of this divide. The watertable reaches about 80 m AHD about the Gingin Scarp, and possibly a maximum of about 100 m AHD adjacent to the Lesueur Fault near Mount Lesueur. Water levels decline towards the coast, with a steep hydraulic gradient near the scarp in the east, and flattening as groundwater flows reach a hydraulic barrier formed by the Beagle Fault (Baddock & Lach 2003).

The hydraulic head is above ground level in the vicinity of White Lake, east of Leeman, resulting in artesian flow from the Eneabba Formation (GRC Dames & Moore 1990). Artesian flow is also possible from the Lesueur Sandstone adjacent to the Gingin Scarp, north of the Hill River. Selected bore hydrographs in the Eneabba–Lesueur aquifer are shown in Figure 94.

There is seasonal variability related to rainfall recharge, but a slight increase in water levels over time can be observed where water levels are not influenced by groundwater abstraction. This rise is probably related to land clearing that has resulted in additional groundwater recharge. Recent declines in water levels recorded in Eneabba Line 8A and marked seasonal variations in Enabba Line 11D west of Eneabba are likely to be associated with groundwater abstraction.

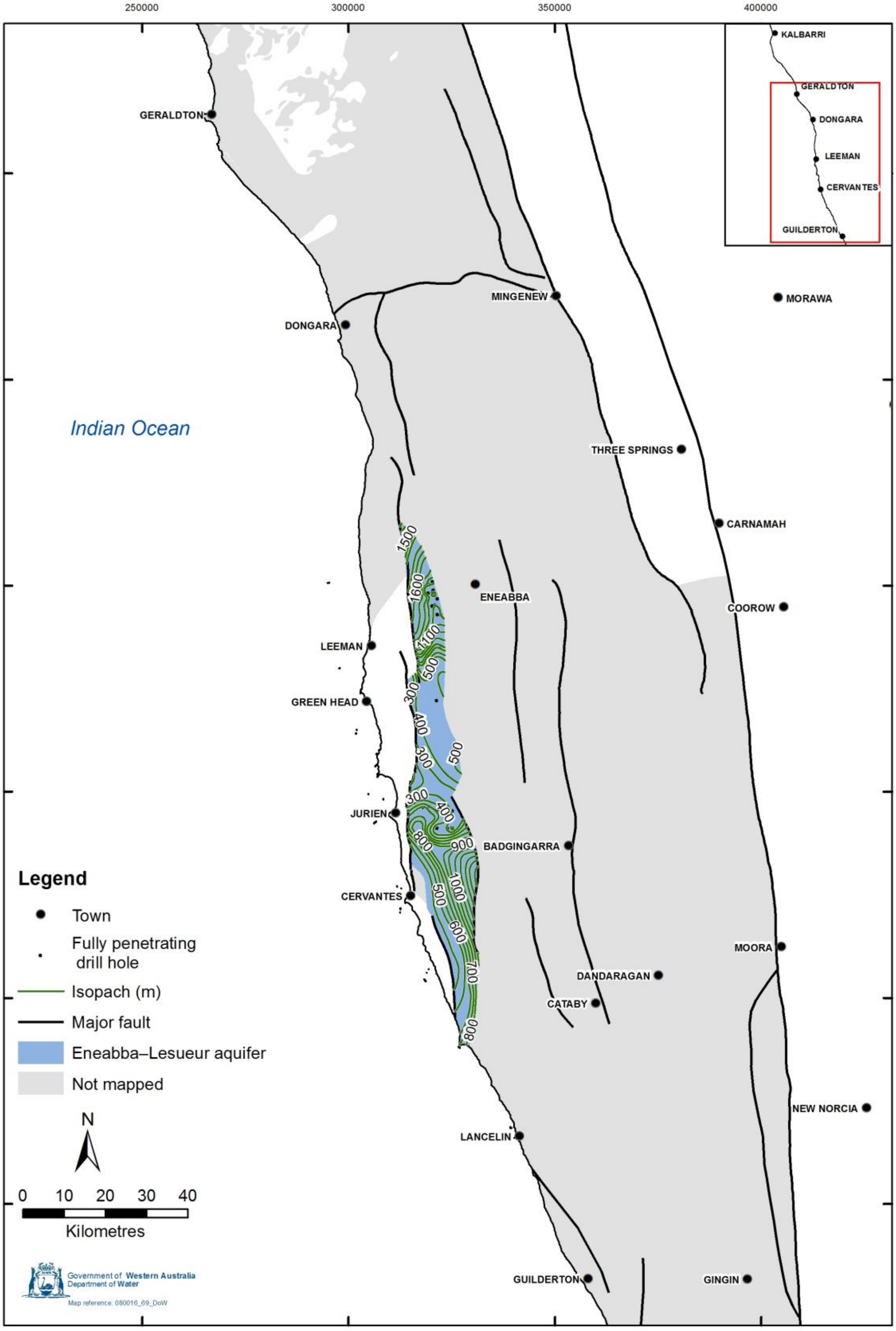
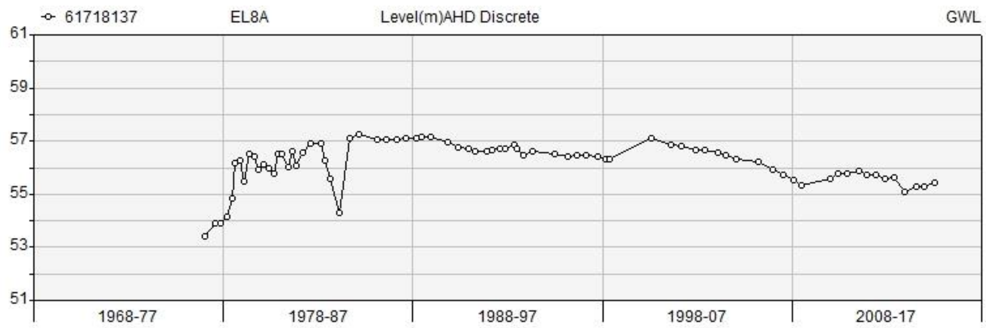
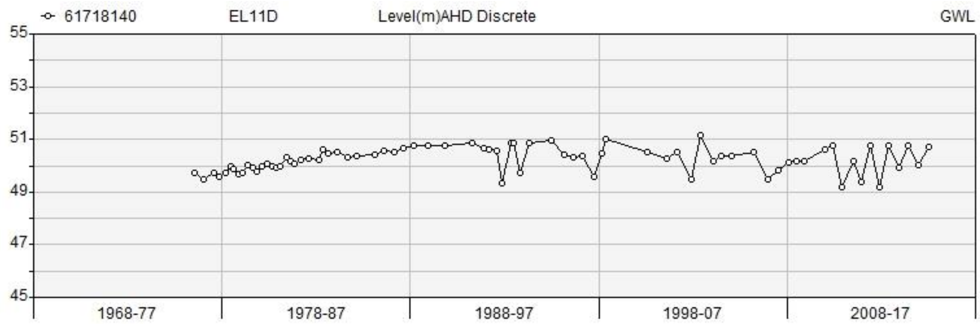


Figure 93 Eneabba–Lesueur aquifer: aquifer thickness



Eneabba Line 8A



Eneabba Line 11D

Figure 94 Eneabba–Lesueur aquifer: selected bore hydrographs

Hydraulic parameters

Aquifer test data for the Lesueur–Eneabba aquifer is summarised in Appendix G, with most of the aquifer tests associated with the Lesueur Sandstone. Baddock and Lach (2003) noted that the upper 75 m of the Lesueur Sandstone east of Jurien Bay was sand with a significantly higher permeability than the deeper, more consolidated parts of the formation. Typically, hydraulic conductivity in the lower Lesueur Sandstone component of the aquifer is between 0.2 and 0.4 m/day, but it can be an order of magnitude greater in the unconsolidated upper portion (Baddock & Lach 2003). Hydraulic conductivity determined for the Eneabba–Lesueur aquifer intersected in the Black Sands Mine bores ranged between 0.2 and 2.1 m/day.

Production bores in the Eneabba Formation component of the aquifer near White Lake, about 15 km east of Leeman, have higher hydraulic conductivity than values reported for the Lesueur Sandstone. GRC Dames and Moore (1990) found that the hydraulic conductivity in two bores was 4.7 and 8.1 m/day, and the storativity for one of the bores was 1.8×10^{-4}.

Production bores in the Eneabba–Lesueur aquifer can yield between 2000 and 3000 m^3/day from the Lesueur Sandstone (Kern 1993a; Baddock & Lach 2003), although a significant length of screen and substantial development may be required. Bore yields at the Black Sands Mine were up to 1800 m^3/day from screen lengths of up to 250 m (Kern 1997). The Water Corporation's Leeman – Green Head 1/91 bore is capable of producing 3000 m^3/day (Kern 1993a), and the deeper Jurien 29/01 bore can produce 1800 m^3/day. Production bores constructed in the Eneabba Formation at White Lake were tested at rates of up to 7000 m^3/day (GRC Dames & Moore 1990).

Estimates of groundwater throughflow

Commander (1981) calculated throughflow north of the groundwater divide at 4 GL/year, and included additional leakage from subcropping areas beneath the Superficial aquifer and contributions from the Eneabba Formation component of the aquifer. There is not sufficient data on the hydraulic gradient or aquifer geometry to make meaningful calculations of groundwater throughflow south of the divide although Kern (1997) has made very broad estimates.

Groundwater salinity

Groundwater salinity in the Eneabba–Lesueur aquifer over the Beagle Ridge and western Cadda Terrace is shown in Figure 91 (see Section 5.8). Low-salinity groundwater in the aquifer is related to areas where the aquifer outcrops about the western margins of the Arrowsmith region or subcrops the superficial formations beneath the coastal plain. Groundwater with a salinity of less than 500 mg/L TDS is present north of the Cervantes Road and possibly extends north of the Coorow – Green Head Road.

Brackish groundwater is present beneath the eastern coastal plain, inland of Cervantes and adjacent to the Beagle Fault south of Jurien Bay (Baddock & Lach 2003). The high groundwater salinity may be related to connection with saline groundwater in the overlying Superficial aquifer (Baddock & Lach 2003) or upward flow of deeper, brackish groundwater adjacent to the Beagle Fault. Groundwater is also brackish within the Eneabba Formation component beneath the central to eastern portion of the coastal plain, where the elevated salinity may be the result of brackish groundwater leaking from the overlying Superficial aquifer or westward flow across the Wedge Fault from the Cattamarra aquifer.

Hydrochemistry

A hydrochemical trilinear diagram for the Eneabba–Lesueur aquifer is shown in Figure 95. Groundwater in the Eneabba–Lesueur aquifer is sodium chloride type. Its hydrochemistry is similar to the Cattamara and Yarragadee aquifers, reflecting the similar derivation from rainfall recharge (Commander 1978) and hydraulic connection between the aquifers.

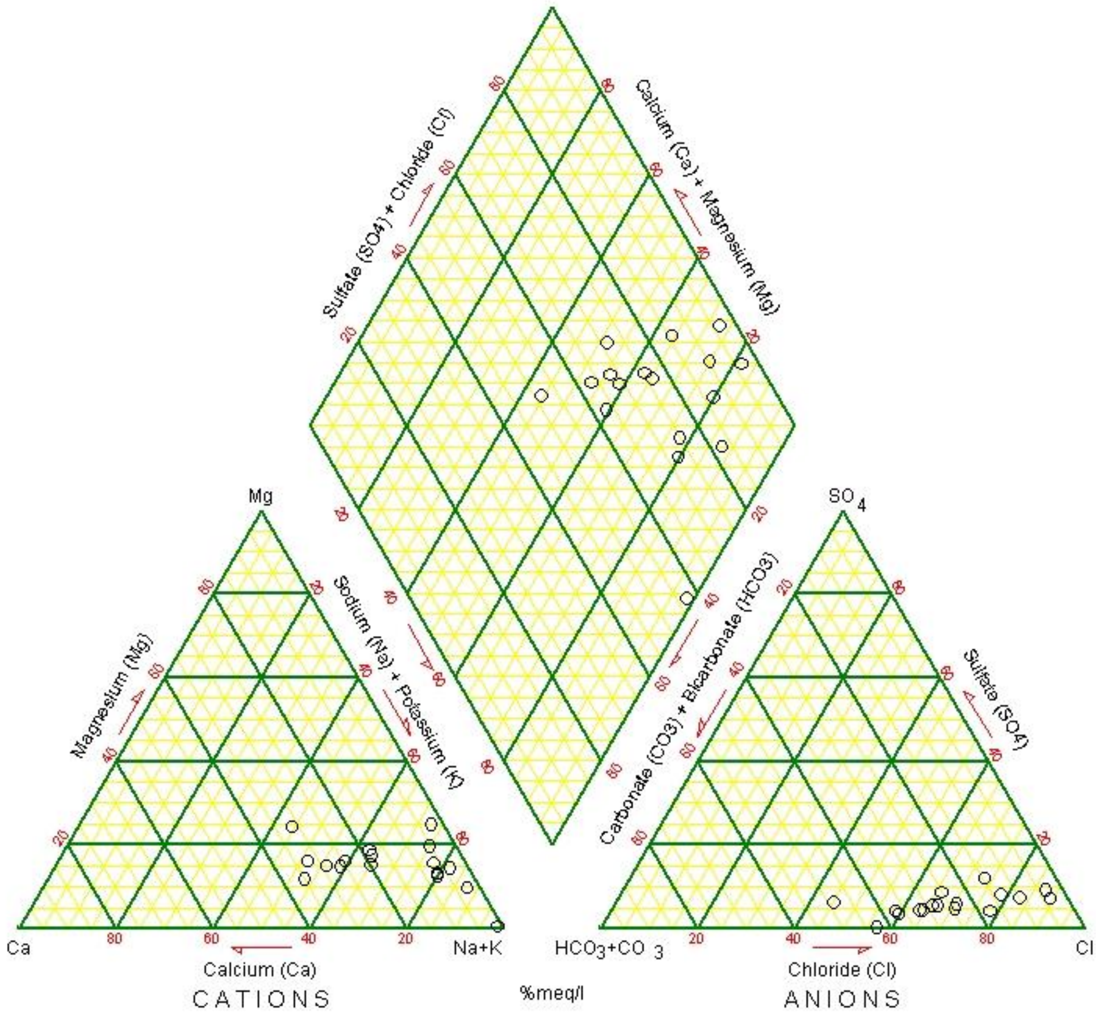


Figure 95 Eneabba–Lesueur aquifer: hydrochemical trilinear diagram

Groundwater isotopic composition and age

Table 17 presents carbon-14 and carbon-13 isotope data for samples collected during 1993 from Watheroo Line bore WL12 and Eneabba Line bore EL11 (Egis 1999), and in the Jurien Bay area from Water Corporation exploration holes and some of the Leeman Shallow monitoring bores during 2002 (Leaney 2002).

There is significant variation in groundwater age ranging from modern to more than 30 000 years BP, with a general increase along the flow path (Baddock & Lach 2003). Relatively old groundwater near the base of the aquifer in Jurien 28/01 (19 000 years) may reflect a long groundwater flow path from the Mt Lesueur area. Leeman Shallow LS5A and Jurien 13/01 may include a component of older groundwater from the Cattamarra aquifer (Baddock & Lach 2003).

Based on these groundwater ages, groundwater flow rates of 3–8 m/year were calculated for the more permeable upper part of the Lesueur Sandstone component, which was less than expected for these sands (Baddock & Lach 2003). It was postulated that diffusion of old groundwater from neighbouring aquitards (Sandford 1997) and cross-formational flow

(Bethke & Johnson 2002) might be responsible for the apparent older groundwater ages. As such, groundwater ages derived from carbon-14 isotopes may provide an upper limit for groundwater ages in the Eneabba–Lesueur aquifer (Baddock & Lach 2003).

Table 17 *Groundwater isotope data for the Eneabba–Lesueur aquifer*

Project / Town	Bore	Screen interval (m bgl)	14C (pmC)	14C error (pmC)	14C age, corrected (yr BP)	14C age error (yr BP)	δ13C (‰ PDB)	Sample date
Eneabba Line	EL11D	438–444	16.3	0.3	15 000	150	–13.2	1993
Jurien Bay	5/01	165.7–177.7	65.3	1.2	2900	–	–13.2	2002
Jurien Bay	7/01	77.7–89.7	66.1	1.2	2800	–	–20.9	2002
Jurien Bay	13/01	111.7–117.7	<2%	–	>30 000	–	–19.7	2002
Jurien Bay	22/01	116.7–128.7	86.2	1.3	600	–	–14.7	2002
Jurien Bay	24/01	99.7–111.7	80.1	1.3	1200	–	–15.0	2002
Jurien Bay	26/01	153.7–165.7	74.2	1.2	1900	–	–15.7	2002
Jurien Bay	28/01	269.7–275.8	9.7	0.9	19 000	–	–16.0	2002
Watheroo Line	WL12A	135.0–142.0	40.1	1.0	7000	–	–18.7	2002
Watheroo Line	WL12	712.0–719.0	5.4	0.3	24 130	450	–20.0	1993
Watheroo Line	WL12A	135.0–142.0	45.0	1.8	6590	320	–	1993
Watheroo Line	WL12B	572.0–579.0	16.4	0.3	14 950	150	–20.2	1993
Leeman Shallow	LS5A	84.0–90.0	25.3	1.0	11 000	–	–14.8	2002
Leeman Shallow	LS6A	93.1–99.1	74.4	1.2	1900	–	–12.0	2002
Leeman Shallow	LS9A	90.0–96.0	73.7	1.2	1900	–	–19.2	2002
Leeman Shallow	LS11A	76.0–88.0	93.1	1.3	Modern	–	–19.7	2002

Data from Egis Consulting (1999)

Notes: 14C – carbon-14; 13C – carbon-13; 18O – oxygen-18; 2H – deuterium; pmC – per cent modern carbon; PDB – 13C standard; δ – ratio of sample to standard; SMOW – standard mean ocean water; ‰ – per mil (parts per thousand) (after Baddock & Lach 2003; Egis 1999). Different correction models have been used to generate 14C age, corrected (yr BP); refer to the original project reports for more information.

5.10 Bookara Sandstone local aquifer

The Bookara Sandstone Member of the Kockatea Shale forms a minor local aquifer, and very little data are available for this resource. Hydraulic conductivities within the Bookara Sandstone local aquifer are likely to be similar to hydraulic conductivities for the Permian aquifers, which have the same lithologies. One salinity measurement of 49 000 mg/L TDS was obtained from the Bookara Sandstone in an exploration bore near Jurien Bay (Milbourne 1967). Water quality throughout the Bookara Sandstone local aquifer is likely to be saline because of low permeability of the Kockatea Shale and limited opportunity for recharge.

5.11 Permian aquifers

The Permian formations form a sequence of local aquifers and aquitards that outcrop on the Irwin Terrace and near Yuna (see Figure 53 and Table 6). The Permian formations include, in order of deposition, the Nangetty Formation, Holmwood Shale, High Cliff Sandstone, Irwin Coal Measures, Carynginia Formation and the Wagina Sandstone. Generally, the Nangetty Formation, High Cliff Sandstone, Irwin Coal Measures and Wagina Sandstone form aquifers, while the Carynginia Formation and Holmwood Shale form aquitards. However, some groundwater is abstracted from these ‘aquitards’ locally to supply water for stock use.

Groundwater levels in the Permian are shown in Figure 58 (see Section 5.1). East of the Urella Fault, groundwater levels are significantly higher than in the Mesozoic aquifers to the west. Groundwater levels vary from about 200 m AHD south of the Greenough River, to over 250 m AHD north of the Irwin River in the less permeable outcrops of the Holmwood Shale. Near Mingenew, groundwater levels are near 150 m AHD and groundwater is discharged into the Lockier River and Green Brook (Commander 1981). In comparison, groundwater levels in the Yarragadee aquifer immediately west of the Urella Fault are about 110 m AHD (see Figure 85).

Salinity in stock bores is highly variable with large differences over relatively small distances probably because of varying salinity of discrete waterbearing horizons. Groundwater salinity in the majority of bores ranges from 1000 to 7000 mg/L TDS with the highest salinity where groundwater is locally discharged into the Lockier River and Green Brook (Commander 1981), and to the north-east of Yuna where it is brackish.

No groundwater storage or throughflow estimates have been published for the Permian aquifers. Individual units within the Permian aquifer sequence are described in more detail below.

Nangetty aquifer

The Nangetty aquifer is a minor aquifer at the base of the Permian sequence. It consists of the Nangetty Formation, which is made up of sandy siltstone, mudstone and sandstone. The aquifer has low permeability and is mainly used as a source for stock water with low yields of 5–50 m^3/day (Commander & McGowan 1991). Groundwater in the Nangetty aquifer is generally brackish to saline ranging from 1500 to more than 5000 mg/L TDS (Commander & McGowan 1991).

Stock water near Yuna is obtained principally from the Nangetty Formation component (locally overlain by Holmwood Shale), with sandy units up to 75 m thick over less permeable units (Berliat 1966). The watertable is typically 40–70 m deep in this area.

Holmwood aquitard

The Holmwood Shale forms the Holmwood aquitard, which overlies the Nangetty Formation. Within the Holmwood aquitard, there are minor sandy horizons with very low yield potential that are developed locally for stock water.

Irwin — High Cliff aquifer

The Irwin – High Cliff aquifer consists of the High Cliff Sandstone and the Irwin River Coal Measures, which are hydraulically connected where both formations are present. The aquifer is present locally at shallow depth in the Locker region and eastern margin of the Victoria Plateau and is considered the most prospective of the Permian units in terms of bore yield and quality. The High Cliff Sandstone comprises interbedded sandstone, conglomerate and minor siltstone that conformably overlies the Holmwood Shale and underlies the Irwin River Coal Measures. The Irwin River Coal Measures comprise alternating beds of siltstone, claystone with subordinate sandstone and minor coal.

Recharge is from direct rainfall to the High Cliff Sandstone and overlying Wagina Sandstone from the Northampton Inlier in the west and north-west, and from lateral discharge from the Greenough River (Swarbrick 1964b).

Groundwater flow within the aquifer is restricted by the 'Wicherina Barrier' where the Holmwood Shale rises above the potentiometric surface of the Irwin – High Cliff aquifer (Swarbrick 1964b). There is limited north–south flow, with hydraulic heads 12 m higher in the northern sub-province than in the south. Groundwater flow south of Wicherina is inferred to be to the south-west, while groundwater flow north of Wicherina is to the south-east (Swarbrick 1964b). Groundwater salinity within the Irwin – High Cliff aquifer beneath outcrops in the Irwin River area ranges from 750 to 1400 mg/L TDS, but can be up to 8000 mg/L TDS where it mixes with more saline groundwater in the shaley overlying Nangetty Formation, underlying Holmwood Shale and Carynginia Formations (Le Blanc Smith & Mory 1995). Groundwater salinity increases to the north-east away from the Northampton Inlier.

The High Cliff Sandstone is the main aquifer component developed in the Wicherina borefield, which historically supplied water to Geraldton and the smaller communities of Mullewa and Eradu (Water Corporation 2004). Groundwater salinity in the Wicherina borefield varies both laterally and vertically (Swarbrick 1964b), which may be due to the distribution of sand and clay facies, and faulting and pumping effects. Abstraction from three operating production bores resulted in a watertable decline of up to 8 m, and an increase in salinity from 220 to 440 mg/L TDS between 1958 and 1963. By 2004, salinity had further increased to about 1200 mg/L TDS (Water Corporation 2004).

Moderate yields of between 50 and 500 m^3/day of variable salinity groundwater have been reported from bores screened across the Irwin River Coal Measures (Commander & McGowan 1991).

Carynginia aquitard

The Carynginia Formation, which consists of micaceous siltstone and claystone with quartz sandstone and thin fine conglomerate beds, forms the Carynginia aquitard. The Carynginia aquitard is considered to be a minor aquitard, and is exploited locally as a water source for stock bores, but yields are generally less than 5 m^3/day (Commander & McGowan 1991).

Wagina aquifer

The Wagina aquifer comprises clayey sandstone and minor beds of siltstone, claystone and low-grade coal. It is used for stock water with bores being less than 30 m deep. The Wagina aquifer, together with the Irwin – High Cliff aquifer, forms the groundwater source for the Wicherina borefield. Moderate bore yields of 50–500 m^3/day are possible from sandy horizons with variable salinity (Commander & McGowan 1991).

5.12 Tumblagooda aquifer

The Tumblagooda aquifer is a significant groundwater resource that extends from the Perth Basin into the southern Carnarvon Basin. The Tumblagooda Sandstone and the overlying Cretaceous Winning Group comprise the Tumblagooda aquifer. The Winning Group sediments are likely to be minor and mainly unsaturated, but where they are saturated, there is good hydraulic connection with the underlying Tumblagooda Sandstone (Berliat 1966). Groundwater is present within the primary porosity of the sandstone and secondary porosity associated with fractures (Kern 1993b).

Groundwater recharge and discharge

Recharge to the Tumblagood aquifer is associated with rainfall infiltration through overlying formations or directly to the aquifer in outcropping areas (AGC 1987). The aquifer is also recharged by the infiltration of floodwater from the Murchison River, and by groundwater flow from the Northampton Inlier. Yerina Spring, 13 km north-east of Port Gregory, may be maintained by groundwater discharge from the Tumblagooda aquifer (Koomberi 1996).

Groundwater levels and flow

Groundwater levels and flow in the Tumblagood aquifer are strongly influenced by the Northampton Inlier, which forms a hydraulic barrier resulting in groundwater mounding of up to 250 m (see Figure 58). West of the Northampton Inlier, water levels fall rapidly towards the coast. East of the Northampton Inlier, groundwater flows to the south-west and north-west with a groundwater divide east of Yuna. At Port Gregory, beneath the Hutt Lagoon, a dense brine plume is also likely to form an impediment to groundwater movement (GMA Garnet 1998).

Hydraulic parameters

Bore yield and permeability estimations are available from investigations associated with town water supplies for Kalbarri (Water Corporation 2000), Port Gregory (Boyd 1980; Rockwater 1993), Horrocks (Ventriss 1994), and Yuna (WAWA 1978), which are summarised in Appendix H. Bore yields range from 55 to 1311 m^3/day with transmissivity between 8 and 111 m^2/day, and hydraulic conductivity generally less than 1 m/day.

Groundwater salinity

Groundwater salinity in outcropping areas of the Tumblagood aquifer is shown in Figure 59 (see Section 5.1). Fresh to brackish groundwater is restricted to areas of outcrop (Playford et al. 1970). Groundwater is freshest near the recharge area at the contact with the Northampton Inlier (Playford et al. 1970). Groundwater salinities between 320 and 2340 mg/L TDS have been recorded in the Hutt Lagoon area near Port Gregory (Boyd 1980; Rockwater 1993). In the Kalbarri town water supply, groundwater salinity is less than 400 mg/L TDS (Kern 1993b; Water Corporation 2000). However, a shallow brackish lens associated with permeability variations is present in some bores (Hocking et al. 1982).

Groundwater salinity in the Tumblagood aquifer increases with distance from the recharge areas. In many areas, groundwater is too saline for domestic use but is adequate for stock watering (Playford et al. 1970). Groundwater salinities increase east of the Northampton Inlier. West of Balla, groundwater salinity ranges from 1700 to 3100 mg/L TDS (Berliat 1966). At Yuna, groundwater salinity is about 1500 mg/L TDS (Laws 1977; AGC 1987). Near Balla, groundwater salinity is 3300–6900 mg/L TDS. In the Dartmoor area, about 50 km north-east of Northampton, groundwater salinities are greater than 10 000 mg/L TDS (Berliat 1966).

5.13 Yandanooka and Moora aquifers

The Yandanooka and Moora aquifers have similar geological and hydrogeological characteristics. These local aquifers are found along the margin of the northern Perth Basin and adjacent Yilgarn Craton.

Yandanooka aquifer

The Yandanooka aquifer is formed by the sediments of the Yandanooka Group, a thick sequence of low-permeability sandstone, siltstone and conglomerate. Groundwater is present within the weathering profile and fracture zones of the Yandanooka Group. The primary porosity is very low because these rocks have been metamorphosed. The aquifer has very low to low bore yields ranging from less than 5 to 50 m^3/day (Commander & McGowan 1991).

Watertable configuration in the Yandanooka aquifer is closely related to topography (Commander & McGowan 1991). Groundwater flow is towards the Yarra Yarra Lakes, as well as the Lockier and Arrowsmith rivers (Commander & McGowan 1991).

Groundwater salinity in the Yandanooka aquifer varies considerably over short distances as bores can intersect various local waterbearing formations within the Yandanooka Group. Groundwater salinity is typically between 1000 and 5000 mg/L TDS but salinities are elevated in low-lying areas near Yarra Yarra Lakes, Lockier River and Green Brook (Commander & McGowan 1991). Siltstone horizons also tend to have higher groundwater salinities than sandy layers (Commander 1981).

Moora aquifer

The Moora aquifer is formed by the sediments of the Moora Group east of the Darling Fault. Groundwater is sourced predominantly from the Noondine Chert, which is fractured to depths of at least 60 m. The Moora aquifer may provide a conduit for deep groundwater flow along the Darling Fault, where it is in geological contact with the Leederville–Parmelia aquifer.

Aquifer parameter data is sparse and variable. High bore yields of up to 1000 m^3/day have been recorded (WRC 1998b). Early estimates of transmissivity are by contrast quite low (130–320 m^2/day) (Wall 1968).

Groundwater salinity in the Moora aquifer is also highly variable. Low-salinity groundwater (<1000 mg/L) is present within sand-filled hollows in the chert south of Marchagee and along the Darling Scarp (Wall 1968). South-west of Gunyidi, salinity rises to 8000 mg/L (Wall 1968). At Moora, the groundwater salinity distribution is erratic and unrelated to the topography (Wall 1968).

5.14 Mullingarra and Northampton fractured-rock aquifers

The Mullingarra and Northampton fractured-rock aquifers consist of gneissic basement rocks. Groundwater in these aquifers is generally restricted to fractures. The most intense fracturing is usually found along faults and shear zones, with other fracturing resulting from joint sets and opening bedding plane partings. Groundwater is sometimes found in the weathered gneiss profile but, because these profiles are often clayey, permeability is low.

Mullingarra fractured-rock aquifer

The Mullingara Inlier comprises Archean pelitic, quartzofeldspathic and semipelitic gneisses (Baxter & Lipple 1985). It is commonly weathered to clay that overlies decomposed or fractured rock (Commander 1981). Groundwater is obtained from fractures, joints, faults and shears that are locally discontinuous and commonly widely spaced (Commander & McGowan 1991).

Groundwater levels are close to the surface and significantly higher than in the adjacent Leederville–Parmelia aquifer. The watertable elevation ranges from 150 m AHD south of Mingenew to 250 m AHD in the Three Springs area, compared to levels of about 220 m AHD in the Leederville–Parmelia aquifer. Depth to groundwater is generally less than 10 m and the watertable subtly reflects the topography. Near the Urella Fault, depth to watertable is up to 25 m (Commander 1981), which suggests some potential for groundwater flow across the fault.

The permeability of the Mullingarra aquifer is very low with bore yields of between 5 and 50 m^3/day (Commander & McGowan 1991). Groundwater salinity is highly variable but tends to range from 2000 to 6000 mg/L TDS (Commander & McGowan 1991). Groundwater salinity is not well known, but generally increases towards drainage lines. Variations in lithology are likely to affect salinity with quartz-rich horizons having lower salinity than amphibolite horizons (Commander 1981).

Northampton fractured-rock aquifer

Hydrogeological information for the Northampton Inlier is limited to town water supply investigations for Northampton and Horrocks, and limited data from stock and private bores.

Groundwater in the Northampton Inlier is predominantly in granulite bedrock within fractures and joints. Open fractures have been delineated up to a depth of 60 m (Kern 1994) and are commonly associated with dolerite dyke intrusions (Boyd 1979; Laws 1978). Prospective areas are likely where basement rocks are weathered, intruded by quartz veins and pegmatites, in shear zones, or in feldspathic quartzites where open fractures are evident (Kern 1994).

Swarbrick (1964a) suggested that the quartzite unit might be a reasonable target for additional water supplies for Northampton. However, investigations of the quartzite encountered no significant groundwater resource. Test drilling in granulites south and west of Wheal May Creek, north of Northampton, indicated some potential for water supply. Swarbrick (1964a) highlighted potentially high concentrations of copper and lead in groundwater within dolerite dykes.

Recharge to the Northampton fractured-rock aquifer is via direct rainfall infiltration and downward leakage of surface water from creeks (Kern 1994). Groundwater is discharged from fractures into the Tumblagooda aquifer.

Water levels in the Northampton aquifer exceed 250 m AHD north-west of Northampton near Hutt River, and decrease to less than 50 m AHD south-west of Northampton (see Figure 58).

Groundwater salinities in town water supply bores in the Northampton aquifer range from 700 to 1450 mg/L TDS (WAWA 1989), increasing in the groundwater flow direction (Kern 1994) becoming brackish to saline towards the end of the aquifer extent (see Figure 59). Bore yields from the Northampton aquifer are highly variable, ranging from less than 100 m^3/day up to 500 m^3/day in bores associated with the Northampton town water supply (Kern 1994; Swarbrick 1964a; WAWA 1989). Aquifer test results for the Northampton town water supply are presented in Appendix I. Transmissivity is generally 5–50 m^2/day, with hydraulic conductivity of less than 1 m/day.

5.15 Geothermal resources

In the northern Perth Basin, temperatures have been measured within several of the deep borehole lines drilled by GSWA and in many of the exploratory petroleum wells. Differential temperature wire-line logs were undertaken in cased holes of the Eneabba (Commander 1978), Moora (Briese 1979) and Gillingarra (Moncrieff 1989) lines. These logs were completed at least several weeks after construction to ensure that temperatures had adjusted to the ambient geothermal conditions. Temperature logging in the Dongara Line bores indicated that temperatures had not adjusted at the time of logging, and were not suitable for analysis (Irwin 2007). Available downhole temperatures from petroleum wells in the Perth Basin have been collated and geothermal gradients calculated by Bestow (1982), and also by Mory and Iasky (1996).

At the watertable, temperatures increase from about 20 ºC in the south along the Gillingarra Line (Moncrieff 1989) to 24 ºC in the north along the Eneabba Line (Commander 1978). The highest temperature of 158 ºC was recorded from 3791 m depth in petroleum well Mount Adams 1 on the Donkey Creek Terrace, about 29 km south-east of Dongara (Mory & Iasky

1996). In the deep groundwater monitoring bores, a maximum temperature of 56 ºC was measured in Gillingarra Line GL6A at 974 m (Moncrieff 1989).

Figure 96 shows the interpreted geothermal gradient across the northern Perth Basin and southern Carnarvon Basin. A low geothermal gradient of typically less than 2.5 ºC per 100 m is present in the Dandaragan Trough (Bestow 1982), probably due to the high thermal conductance of sandstone that forms thick sequences in this part of the basin (particularly associated with the Yarragadee Formation). To the west of the Beagle Ridge and on the margins of the Northampton Inlier there is a higher geothermal gradient, in excess of 4 ºC per 100 m (Commander 1979; Bestow 1982; Mory & Iasky 1996). In these areas, significant intervals of less conductive shale (Kockatea Shale, Carynginia Formation and Holmwood Shale) present at shallower depths may contribute to the elevated geothermal gradients (Thomas 1984). There are lower gradients through the sandstone-dominated beds of the Eneabba Formation and Lesueur Sandstone. Geothermal gradients of 1.7 – 5.5 ºC per 100 m were recorded in the Eneabba Line bores (Commander 1978).

Temperatures within the deep-water monitoring bores display distinctive geothermal gradients through the various formations. In the Leederville Formation, there is a geothermal gradient of about 3 ºC per 100 m. Temperatures reach about 45 ºC at the base of the formation in Gillingarra Line GL2B (Moncrieff 1989). There is a higher geothermal gradient throughout most of the Parmelia Group, with a gradient of 4.8 ºC per 100 m through clayey sediments in the Carnac Formation, and 3.7 ºC per 100 m in the Otorowiri Formation (Briese 1979). Temperatures reach 46 ºC near the base of the Carnac Formation in Moora Line ML2B at 730 m bgl (Briese 1979) and may exceed 45 ºC in ML3A at 760 m bgl.

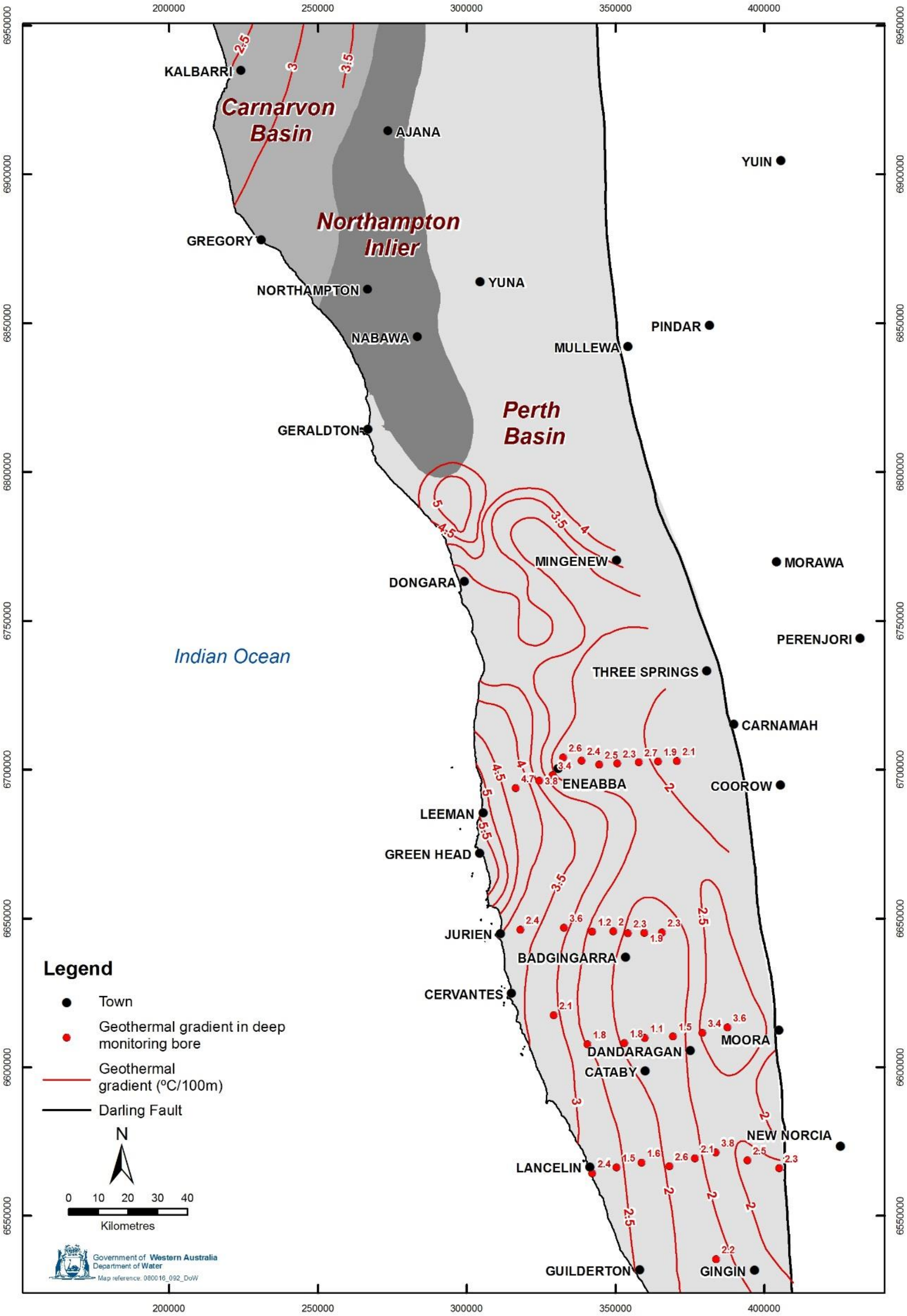
Geothermal gradients in the Yarragadee Formation range from 1.7 to 2.7 ºC per 100 m (Commander 1978; Moncrieff 1989), and are typically 1.4 ºC (ML5) to 1.8 ºC (ML7) per 100 m through sandy intervals. A maximum groundwater temperature of 55 ºC was measured at 970 m bgl in Gillingarra Line GL6A (Moncrieff 1989). In the petroleum wells screened across the Yarragadee aquifer, the groundwater temperature reached 125 ºC at about 4370 m bgl in petroleum well Warro 1. Groundwater temperatures reached 160 ºC in the deepest portion of the aquifer at about 5450 m near Moora (Bestow 1982).

The high shale content of the Cattamarra Coal Measures provides thermal insulation, resulting in a temperature gradient of up to 5.5 ºC per 100 m. In the Lesueur Sandstone, a geothermal gradient of 2 ºC per 100 m was measured in Moora Line bore ML8A (Briese 1979) and it is anticipated that the geothermal gradient through the Eneabba Formation component may be slightly higher. Relatively high geothermal gradients probably occur through the deeper Kockatea Shale and Permian formations component due to the high portion of shale.

Bestow (1978) considered that development of geothermal energy was technically viable in the Perth Basin at depths of between 3000 and 3500 m, where temperatures are likely to be between 65 and 120 ºC. Below these depths, the porosity and permeability of formations are probably too low to yield appreciable quantities of water without hydraulic fracturing to enhance permeability (Bestow 1982). Heat flow in the northern Perth Basin is estimated to be between 45 and 60 MW/m^2 (Bestow 1982).

The geothermal gradient is generally greater in the Carnarvon Basin where an average gradient of 3.3 ºC per 100 m has been derived from petroleum exploration wells (Moors 1980). However, there is a large range between wells. Gradients are highest along the eastern margin of the Carnarvon Basin, where the basin is shallowest and thick shale units are present.

The search for Enhanced Geothermal Systems (EGS) or direct-use heat plays begin with identification of anomalously high heat occurrence at accessible depths. The Department of Mines and Petroleum recently developed a steady state, 3D conductive heat model of the northern Perth Basin (Gibson et al. 2010). Modelled temperatures were relatively high in areas of the northern Perth Basin containing relatively shallow basement, together with a significant cover of sediments to act as a thermal insulator. The highest modelled thermal gradients were at the bounding edges of the model domain between deep sedimentary troughs and shallow basement zones.



(after Moors 1980; Mory & Iasky 1996)

Figure 96 Geothermal gradient in the northern Perth Basin region

6 Groundwater resource availability and management

The hydrogeological information presented in this bulletin provides the most up-to-date understanding of groundwater resources of the northern Perth Basin at the regional scale. This chapter explains how the Department of Water applies this understanding to determine and manage the volume of groundwater that is available for licensing at the management area and subarea scale. This includes considering economic, environmental and community factors together with the hydrogeological understanding. This chapter also discusses the importance of the department's regional-scale monitoring data in building hydrogeological knowledge and how numerical modelling informs the management of groundwater resources.

People seeking to abstract or disturb groundwater need to consider other factors at the local scale that will inform the department's decisions to grant a groundwater licence or approvals for other regulatory agencies. Section 6.2 outlines these factors and provides guidance to aid proponents in designing a viable, approvals-ready proposals for taking and using groundwater in the northern Perth Basin.

The groundwater resources of the northern Perth Basin have supported the growth and development of the region for many decades. Groundwater is a vital water source for the region's towns and is also important for irrigated agriculture and mining. This final chapter concludes with a summary of current groundwater use across the northern Perth Basin and prospects for future groundwater source development.

6.1 Managing groundwater at the regional scale

The northern Perth Basin covers four legislatively proclaimed groundwater resource management areas: the Gascoyne, Arrowsmith, Jurien and Gingin groundwater areas (Figure 97). The department manages three of these areas (Arrowsmith, Jurien and Gingin) using allocation plans. These plans set the amount of groundwater that can be taken each year (the allocation limit). They guide how the department licenses water use at the local-scale by defining the local rules to be applied for each aquifer by subarea (WRC 2002a, b, c; DoW 2010a, 2010b, 2015c). The department manages groundwater in the Gascoyne area using allocation limits and statewide licensing policies without an allocation plan. The department's *Water resources inventory 2014* (DoW 2014) provides an overview of the volumes of groundwater available for licensing across the state.

Water licences are the regulatory instrument that grant groundwater entitlements and authorise people to take water, under specific conditions. The department uses allocation plans and water licensing to administer the *Rights in Water and Irrigation (RIWI) Act 1914* on behalf of the state.

Allocation plans are designed to achieve specific water resource objectives and to contribute to broader, water-related outcomes such as economic development or protecting environmental features. The department establishes the objectives and outcomes of each allocation plan using a process of scientific assessment, policy analysis, consultation, and considering (sometimes competing) water demands. At the most fundamental level, this means deciding how much water should remain in the system to maintain the integrity of the water resource and to support GDEs.

Groundwater allocation limits are based on hydrogeological calculations but also take account of a range of environmental, social, cultural and economic factors. For example, a limit may take into account estimates of recharge or throughflow as well as the sensitivity of a groundwater-dependent wetland to fluctuations in groundwater level.

Allocation limits are generally in place for the life of an allocation plan (usually 7–10 years) and are adjusted periodically as plans and water resource objectives are revised or new water resource challenges need to be addressed. The department will generally review allocation limits when the hydrogeological foundations upon which they are based change or the demand on the resource approaches the allocation limit. As in other parts of the south-west, the drying climate trend in the northern Perth Basin is a significant factor that may drive future changes in allocation limits.

Using regional groundwater monitoring and numerical models

Groundwater is a hidden resource that moves very slowly. Collecting long-term monitoring data is the most direct way to build an understanding of aquifers and their response to changes in abstraction, land use and climate.

The department's network of over 700 regional monitoring bores provides a data source for interpreting the long-term groundwater responses of the aquifers in the northern Perth Basin. Monitoring data also underpins the sustainable management of groundwater resources and are an important measure of the effectiveness of the department's approach to resource management. The department strives to align the frequency of groundwater monitoring to levels of resource use, taking into account predicted future demand so that data needed for adaptive management is available.

Groundwater level data are stored in the department's databases that can be publicly accessed through the Water Information Reporting (WIR) system at www.wir.water.wa.gov.au. Groundwater levels in regional monitoring bores are generally measured two to six times a year but some are continuously monitored using data loggers. The deepest monitoring bore (North Gingin 2A) is about 1000 m deep.

Monitoring data are the basis for building a conceptual understanding of a hydrogeological system and are essential for the development and application of numerical groundwater models. The department builds numerical groundwater models to aid water resource management in situations where careful planning is needed to account for multiple effects of abstraction, land-use change and shifts in climate. Outputs from groundwater models are used in this context to:

- assess the availability of water and inform allocation limit decisions
- make licence and allocation planning decisions
- formulate advice to government and other decision makers
- inform policy development
- review water resource response to actual conditions.

Much of the data collated and presented in this report was used as the basis for developing a regional numerical groundwater model of the northern Perth Basin between Guilderton to the south and Geraldton to the north (Pennington Scott 2010; GHD 2011). Identified as GARAMS (Gingin Arrowsmith Regional Aquifer Modelling System), the model overlaps with the Perth Regional Aquifer Modelling System (PRAMS) in the area between Gingin Brook and the Moora Line (De Silva et al. 2013). GARAMS simulates major hydraulic processes, using MODFLOW (Harbaugh et al. 2000) at a regional scale based on simplified geology and hydrogeology.

6.2 Factors to consider for groundwater development at the local scale

People planning a development that is likely to affect groundwater-dependent features or will require a new groundwater source should carefully consider a range of factors. These considerations should include the potential for a development to impact other water users, the water requirements of GDEs as well as the suitability of the aquifer to supply the required quantity and quality of groundwater. The following section provides proponents with guidance for designing viable approvals-ready proposals.

Regulatory framework for licensing

The Department of Water regulates groundwater abstraction and provides advice to other regulators so that the integrity of the water resource, including the water-dependent environment, is maintained. It considers both the take and the use of water when assessing licence applications. This includes assessing environmental risk from abstracting and using water and whether this falls under the provisions of environmental legislation, such as the *Environment Protection and Biodiversity Conservation Act 1999* and the *Environmental Protection Act 1986* (which cover social, cultural and heritage considerations as well as ecological factors). Gaining regulatory approval to abstract groundwater is generally straightforward for proposals which demonstrate they:

- can be met within existing allocation limits
- maintain resource integrity and quality
- avoid impacts on other water users
- avoid impacts to sites of high ecological, cultural or social value.

Where a groundwater activity (such as abstraction, excavation or managed aquifer recharge) poses a risk to a water resource, other water users or the environment, the department (or another regulatory agency) may ask proponents to undertake a hydrogeological assessment A well-planned and executed hydrogeological assessment should predict impacts to the water resource and characterise or quantify the risks to other users and the environment.

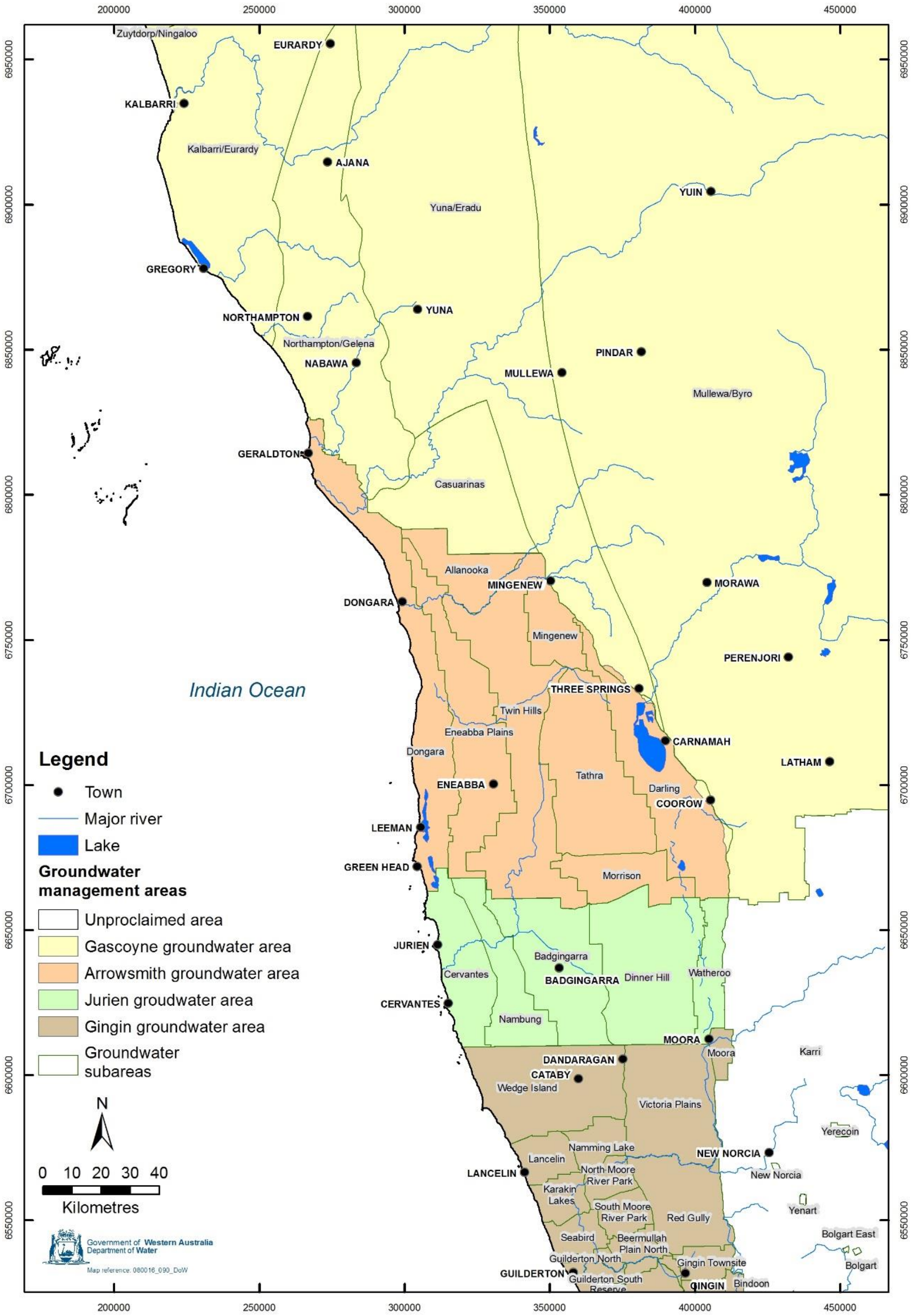


Figure 97 *Groundwater management areas*

Using local-scale groundwater monitoring and modelling

Regional groundwater flow models are generally not suited to investigating and designing site-specific groundwater operations such as excavations, dewatering and water supply abstraction. This is because of limitations in the resolution and calibration of regional models in simulating small-scale changes in groundwater flow and levels at discrete sites of interest. Subregional or local-scale models are better suited to these applications. Similarly, site-specific numerical models or analytical approaches are best applied to designing pumping infrastructure and determining bore specifications.

As part of gaining regulatory approvals, a proponent for a new development or new groundwater source may need to provide a groundwater modelling assessment to the Department of Water, Environmental Protection Authority and other regulators. This is most likely when large volumes of groundwater will be abstracted relative to the allocation limit, or where there is high risk of impact to the environment or other groundwater users. The Department of Water may also request groundwater modelling or monitoring information where developments are proposed for locations where the potential and nature of the local aquifers are not well known (Department of Water operational policy 5.12).

A proponent can use subregional, local-scale or site-specific modelling to quantify:

- the change to the water regime supporting each high-value water-dependent ecosystem
- the change to the water regime at other users' bores or to the water resource used by other users (e.g. a riparian user who accesses water from a river pool that receives groundwater discharge)
- the change to the water regime and describe what the impacts are to the water resource
- benchmarks that will be used by the regulator to make the assessment, set approvals conditions and monitor compliance
- benchmarks that will be used by the proponent to establish a monitoring and management framework.

Aquifer suitability

The suitability of aquifers to supply water for different developments varies with groundwater quality, bore yields and depth to groundwater. In the northern Perth Basin, typical factors that affect the aquifer's capacity to yield an ongoing supply of fit-for-purpose groundwater include water-level trends (and the associated impacts to water quality), the potential for saline intrusion (seawater interface, saltwater up-coning) and potential disturbance or exposure of acid sulfate soils.

Groundwater level trends

Water level trends across the northern Perth Basin vary in response to seasonal weather patterns, land-use change, local hydrogeology and abstraction. Water levels are also affected by a drying climate trend, more pronounced in the southern parts of the northern Perth Basin. The drying climate trend is predicted to continue into the future and will present challenges to managing the groundwater resources in the northern Perth Basin (see Section 3.3).

Groundwater levels in the unconfined aquifers of the northern Perth Basin are mostly stable or falling but water levels in northern parts of the Yarragadee and Leederville–Parmelia aquifers (DoW 2011), and in the Superficial aquifer at the base of the Gingin Scarp (Groundwater Consulting Services 2006), are generally rising due to land clearing. Rising water levels can lead to waterlogging and drainage issues. Waterlogging occurs locally on the Dandaragan and Victoria plateaus (Reed & Associates 2008; Raper et al. 2014) and on the Swan Coastal Plain along the Gingin Scarp. In some areas, declining rainfall or abstraction have offset the effects of land clearing so that some hydrographs that showed rising trends have now plateaued or begun to decline (DoW 2011).

Although rising groundwater levels may offer some groundwater abstraction opportunities, they could also be important for increasing the resilience of GDEs to climate change. Water levels in completely unconfined aquifers (Superficial, Mirrabooka and Surficial aquifers), may be relatively responsive to declining rainfall. In contrast, reliable discharge from aquifers that have experienced groundwater rise or are confined and therefore have reliable discharge, may be vital to the persistence of GDEs in a drier future.

Depth to groundwater also has economic implications for capital, maintenance and energy costs. Persistent drawdown can cause a groundwater development to become uneconomic. Changes in the depth to groundwater under anticipated pumping rates must be considered when evaluating viability of projects. These effects may be local or widespread, depending on the number of bores, bore yields and physical properties of the aquifer. A high density of production bores can produce cumulative impacts and therefore exacerbate the impact on the environment and other users.

Groundwater quality

Groundwater quality has important implications concerning the suitability of water for agriculture, industry and public drinking water supplies. Changes in water quality, such as increased salinity or nutrient concentrations and the presence of other chemicals in the soil and groundwater, can threaten the viability of irrigation schemes.

In the northern Perth Basin, groundwater quality is generally good but it can be affected by changes in land use, depth to the watertable and long-term water-level trends. Agricultural land use has historically affected groundwater quality in some areas of the northern Perth Basin through the leaching of chemicals and increasing nitrate and sulfate concentrations (Hirschberg & Appleyard 1996). More recent baseline chemistry surveys show that nitrate levels within the Superficial aquifer are low compared to the greater Perth area, though some pockets of elevated nitrate (e.g. Woodridge near Guilderton) remain (Astron 2012).

In areas where water levels have risen, natural salts stored in the unsaturated soil profiles have been mobilised. The rising groundwater brings salt close to the surface, where it can be concentrated by evaporation, resulting in secondary soil salinity. Secondary salinity can prevent crops and other vegetation from growing. In addition, higher salinity in groundwater can be discharged to rivers, which may impact other aquifers that these rivers recharge. For example, during winter, the Moore River’s south-flowing reach discharges saline water, derived from salinised soils in the upper catchment, into the Superficial aquifer (Stelfox 2001).

Low-lying and valley floor areas on the Dandaragan Plateau and on the northernmost portion of the Victoria Plateau that are prone to waterlogging are also at high risk from rising salinity (Reed & Associates 2008; Raper et al. 2014).

Seawater intrusion and saline up-coning

A natural interface between low-salinity groundwater and seawater is usually present within any unconfined aquifer, either onshore or offshore near the coast. The interface is often described as a ‘wedge’ because saltwater, which is denser than fresh water, forms a tapering saltwater wedge-shaped profile below the fresh groundwater. The location of the interface is dynamic and will shift in response to changes in groundwater flow and water levels. If fresh groundwater throughflow is reduced by abstraction or reduced rainfall recharge, the seawater wedge will move inland. If the saltwater wedge moves landward past the coast, we refer to this as seawater intrusion. As a consequence, bores located in fresh groundwater above the seawater wedge or near the inland toe of the wedge may become saline by up-coning or inland movement of the seawater wedge.

Seawater intrusion is known in bores in unconfined aquifers at Lancelin, Jurien Bay, Port Denison – Dongara and Kalbarri (Kern 1993b; Baddock & Lach 2003). While most instances of seawater intrusion appear not to be a significant problem at the basin scale, it is a risk to coastal communities that depend on locally sourced groundwater for their water supply.

Acid sulfate soils

Acid sulfate soils are naturally occurring soils, sediments or organic substrates (e.g. peat) that are formed under waterlogged conditions. These soils contain iron sulfide minerals (predominantly as the mineral pyrite) or their oxidation products. In an undisturbed state below the watertable, acid sulfate soils are benign. However, if the soils are drained, excavated or exposed to air by a lowered watertable, the sulfides react with oxygen to form sulfuric acid. Release of this sulfuric acid from the soil can in turn release iron, aluminium and other heavy metals (particularly arsenic) within the soil. Once mobilised, the acid and metals can create a variety of adverse impacts, affecting the suitability of the aquifer for abstraction and use, impacting vegetation and aquatic organisms, and degrading concrete and steel structures in the ground to the point of failure.

Acid sulfate soils have been recorded in coastal regions,and are also locally associated with freshwater wetlands and sulfate-rich groundwater in some agricultural areas. Datasets that show the risk of potential acid sulfate soils are not comprehensive for the northern Perth Basin. However, risk mapping of the Swan Coastal Plain, Geraldton and Western Australian estuaries covers the very south of the northern Perth Basin, the area around Geraldton and Hutt Lagoon. Point sampling of soils and sediments at eight wetlands identified potential acid sulfate soils at Coomallo Creek and Wongonderrah Nature Reserve (Ryan 2012b). The paucity of risk mapping means that some simple generalisations may assist in assessing the risk of acid sulfate soils for development sites in the northern Perth Basin.

Environmental water requirements

The northern Perth Basin is a hot, dry landscape of mostly low-level and scrubby vegetation. Nature-based recreation activities and ecotourism often rely on lush GDEs such as lakes, estuaries, rivers, wetlands, tall shady trees and caves. The rarity of these verdant sites in the landscape of the northern Perth Basin means these features are often socially and culturally significant and have high ecological value because of their biodiversity.

This section provides guidance on concepts relevant to the assessment of impacts to GDEs in the northern Perth Basin at the scale of individual development proposals. This includes how to locate potential GDEs, how to define the environmental outcomes that will aid regulatory approvals, and some considerations for assessing drawdown risk.

Numerous methods are used to identify potential GDEs. For example, depth to groundwater is a good indicator of potential for groundwater dependency, with tree roots known to access groundwater up to 15 m deep in the northern Perth Basin (N Lauritsen 2013, pers. comm.). Another way is to combine estimates of groundwater depth with ecosystem mapping, aerial photography and satellite imagery. Useful mapping datasets include wetland mapping (e.g. the Department of Parks and Wildlife's geomorphic wetland mapping datasets (Department of Parks and Wildlife 2014)), watercourse mapping and native vegetation mapping. The location of areas of dense vegetation or water visible on aerial photography and thermal or spectral satellite imagery may also be used in conjunction with depth-to-groundwater mapping to identify potential GDEs.

To identify sites of ecological, cultural and social value, and their management objectives, the standard environmental assessment legislation, tools and policies apply. These measures guide proponents and consultants in understanding what levels of environmental impact are acceptable at which sites, without the need for monitoring commitments or referral to an environmental regulator for assessment (such as the requirement to refer proposals likely to have a significant environmental effect, under the *Environmental Protection Act 1986*).

Robust drawdown impact assessments are required to address differences in drawdown vulnerability between various parts of an ecosystem. For example, in the case of a watertable wetland with an aquatic habitat of 0.2 m depth and fringed by groundwater-dependent trees, the impact assessment has to consider the different vulnerability of the water body and the trees. A 0.2 m drawdown might result in complete loss of the aquatic habitat but the trees may be able to extend their roots to follow a falling watertable (Canham et al. 2012). Drawdown risk graphs (e.g. DoW 2009a) may be useful in evaluating risk to vegetation but not to the aquatic system.

Conversely, for a wetland where the aquatic habitat is sustained by perched groundwater (see Section 3.5), drawdown in the regional aquifer may pose negligible risk to the aquatic habitat but cause risk to fringing trees that may have their roots accessing the regional watertable. A wetland with these characteristics is known from near Eneabba (A Lam 2013, pers. comm.).

Guidance on impact assessment for perched wetlands is available in Richardson et al. (2011). This guidance is highly relevant to the northern Perth Basin, where there are many wetlands underlain by clay or laterite aquitards. As described in Section 3.5, unless there is an unsaturated zone between the wetland aquitard and the regional watertable, drawdown in the regional watertable may pose wetland risk. Conversely, ecosystems reliant on truly perched groundwater, while at low risk from drawdown in the regional watertable, might instead be affected by activities that cause the perched groundwater to drain away, such as excavation for a mine pit (Jacobs 2015).

The Superficial aquifer is important for maintaining many GDEs but other aquifers also play a vital role in supporting GDEs across the northern Perth Basin. The Surficial, Mirrabooka, Leederville–Parmelia, Yarragadee, Cattamarra and Eneabba–Lesueur aquifers all sustain GDEs directly. In some areas, groundwater levels in the Superficial aquifer are also supported by significant upward flow from the Leederville, Yarragadee, Cattamarra and Eneabba–Lesueur aquifers. Of 89 sites considered by Rutherford et al. (2005) to be GDEs, 76 were assessed to be in hydraulic connectivity with aquifers other than the Superficial aquifer, either directly, or via hydraulic connectivity with the Superficial aquifer (Table 18). Viewed in the regional and long-term context (decades and longer), maintaining potentiometric head in confined and semi-confined aquifers such as the Leederville, Leederville–Parmelia, Yarragadee, Cattamarra and Eneabba–Lesueur aquifers is an important mechanism in making GDEs more resilient to the effects of a drying climate.

The physiographic features of the northern Perth Basin have a strong influence on GDE location, distribution (Figure 98), type and hydrogeology. Figure 99 provides a hypothetical cross-section from the coast (west) and inland to the Dandaragan Plateau (east) to depict the physiographic positions in which GDEs are typically found. Appendix J shows the location of 105 potential GDEs and Rutherford et al. (2005) propose conceptual models for individual GDEs. These references are a useful starting point for locating and assessing likely groundwater dependence and are not exhaustive. The following sections describe known GDEs, ordered by their physiographic position.

Table 18 Number of GDEs connected to aquifers of the northern Perth Basin

	Other aquifers in hydraulic connectivity							
Aquifer hosting the ecosystem	No other aquifer	Mirrabooka	Leederville	Yarragadee	Cattamarra	Eneabba	Lesueur	Total
Surficial	2							2
Superficial	13		2	10	3	3	9	40
Mirrabooka	7		2					9
Leederville		1						1
Leerderville–Parmelia	17							17
Yarragadee	14							14
Cattamarra	4							4
Eneabba	1							1
Lesueur	1							1
Total	59	1	4	10	3	3	9	89

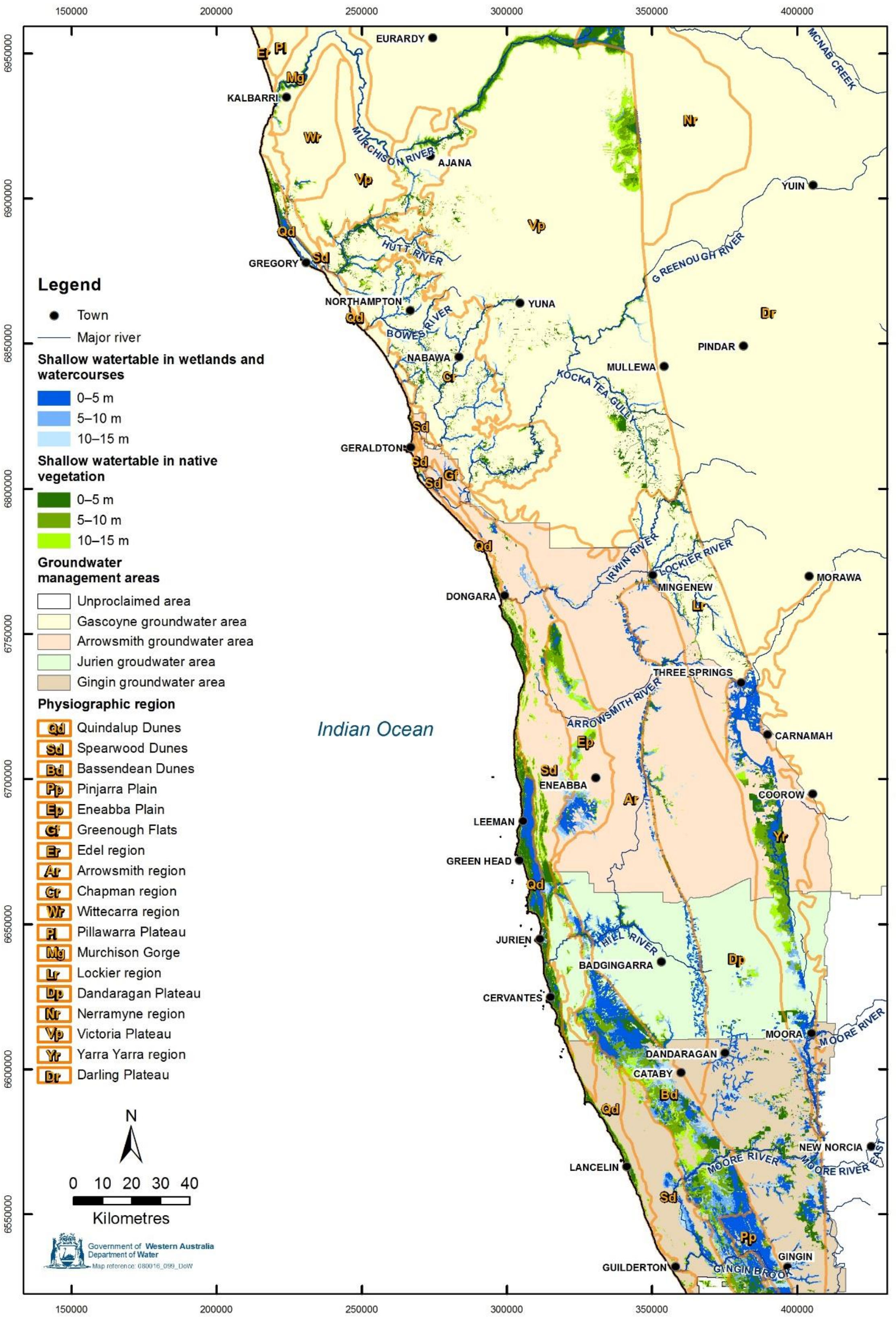


Figure 98 Potential GDEs of the northern Perth Basin and southern Carnarvon Basin

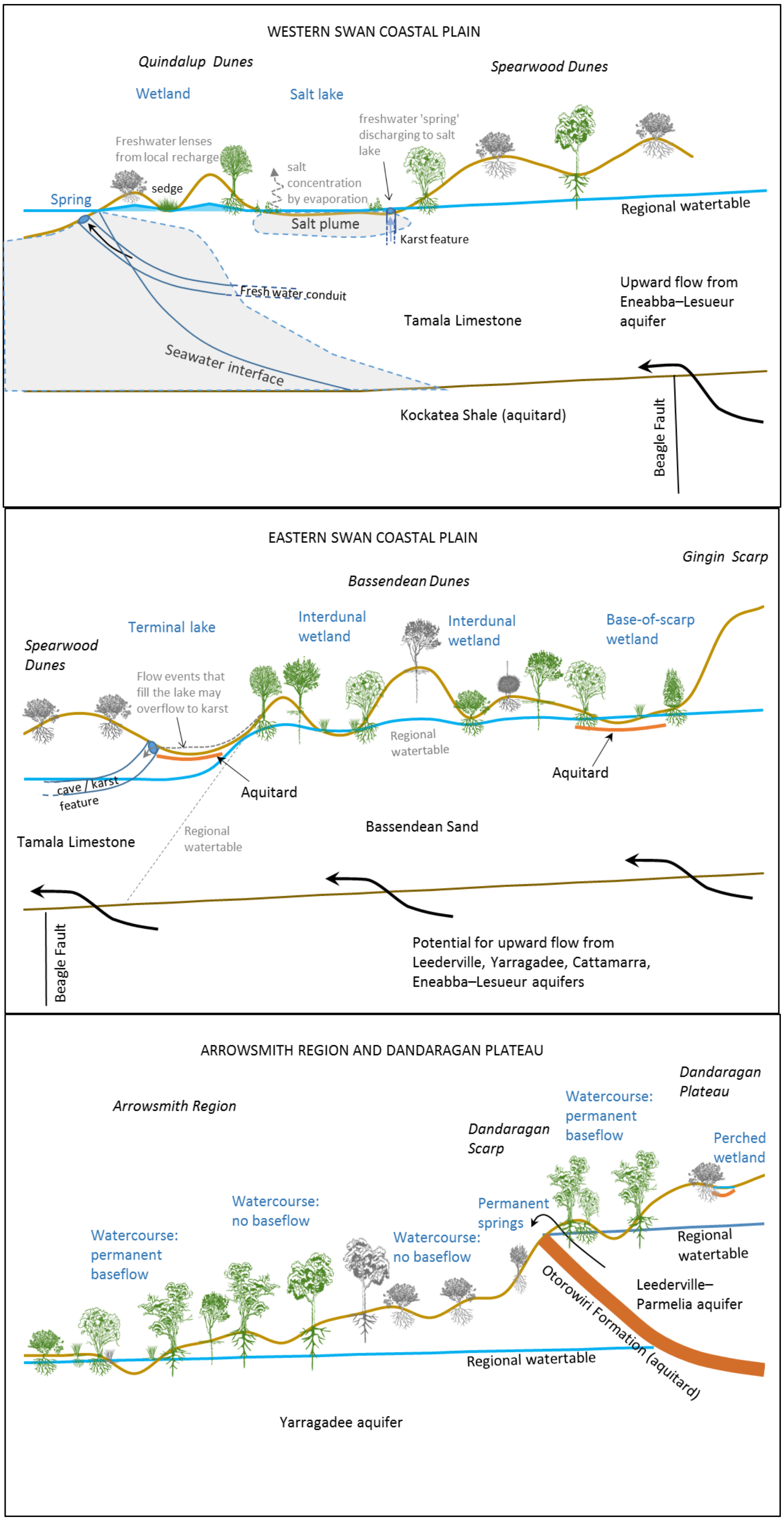


Figure 99 Schematic diagram showing common GDE types and local hydrogeology

GDEs of the Swan Coastal Plain

GDEs on the Swan Coastal Plain depend primarily on the Superficial aquifer. As such, abstraction from the Leederville, Yarragadee, Eneabba–Lesueur or Cattamarra aquifers may also pose a tangible risk to them in areas of hydraulic connection between aquifers (Table 19). For example, overstorey deaths of Banksia woodland supported by the Superficial aquifer have been observed in response to abstraction from the Yarragadee aquifer (Zencich 2003).

For GDEs closest to the coast, the potential for drawdown is minimised by the influence of sea level and high transmissivity in the Tamala Limestone. Here, abstraction risk may be primarily from the landward movement of the seawater interface, the horizontal movement of saline plumes under salt lakes or from saline up-coning. This may increase the salinity of groundwater delivered to ecosystems.

Further inland, drawdown may pose the greatest risk to GDEs. On the Gnangara Mound near Perth, wetlands on the boundary between the Tamala Limestone and the Bassendean Sands have proven highly sensitive to lowered groundwater levels within the Tamala Limestone (Kretschmer & Kelsey 2016). Acidification from drawdown may also be a risk for wetlands of both the Tamala Limestone (Groundwater Consulting Services 2013) and the Bassendean Sand.

From the Hill River southward, where the watertable has risen in response to increased recharge from vegetation clearing, new lakes have formed, such as Minty’s Lake south of Cataby (Groundwater Consulting Services 2006). In these areas, standing dead trees are visible across some lakes (e.g. Crackers Swamp Main Lake) (Halse et al. 1993). The trees may have died due to waterlogging and salinity. The wetlands in this landscape position tend to be throughflow features, recharging saline groundwater into the aquifer to the west. These and similar sites pose a challenge in determining appropriate environmental water objectives, and would require individual assessment of current habitat value.

Table 19 Areas of hydraulic connectivity between the Superficial aquifer and underlying aquifers

Area	Aquifer(s)
Areas of Tamala Limestone of the Superficial aquifer from Eneabba Creek to south of the Hill River	Cattamarra, Eneabba–Lesueur aquifers
Areas of Tamala Limestone between the Arrowsmith and Greenough rivers	Yarragadee aquifer
Bassendean Dune System between Cataby and Bibby Creek	Yarragadee aquifer
Bassendean Dune System in the southern Swan Coastal Plain	Leederville aquifer

GDEs of the Arrowsmith region

The Yarragadee aquifer is the main aquifer supporting GDEs in the Arrowsmith region, along with the Cattamarra, Eneabba and Lesueur aquifers (Rutherford et al. 2005). Groundwater discharge is primarily associated with incised watercourses and springs in places where the land surface is below the hydraulic head in the aquifer, mainly in the western part of region. In the central parts of the Arrowsmith region, isolated springs may receive groundwater from perched aquifers (Rutherford et al. 2005). Abstraction from the Yarragadee, Eneabba–Lesueur and Cattamarra aquifers in the western parts of the Arrowsmith region may also affect GDEs in the Swan Coastal Plain to the west due to hydraulic connectivity between aquifers.

Near Badgingarra, vertical hydraulic conductivity in the Yarragadee aquifer may be relatively low, potentially allowing abstraction from deep bores without implications for ecosystems dependent on shallow groundwater. In this same area, the Eneabba Fault may provide a horizontal boundary, so that abstraction on one side of the fault may not cause drawdown on the other side of the fault (Pennington Scott 2014). In this and similar cases where drawdown impacts are assumed to be spatially constrained, monitoring and adaptive management is typically required, to account for uncertainty in the assumptions.

In the southern Arrowsmith region, Mullering Brook and the Mount Jetty and Bibby creeks receive groundwater discharge from the Yarragadee aquifer as baseflow, springs and pools, which in turn support riparian vegetation and aquatic habitats (Rutherford et al. 2005). Hill River and its tributaries, Coomallo and Munbinea creeks, form an extensive system receiving baseflow and spring discharge from the Yarragadee and Cattamarra aquifers as they cross the Arrowsmith region. Water levels in the Yarragadee aquifer near Hill River have been rising since 1980. This has resulted in greater volumes of groundwater discharge to the river, and the upstream migration of springs (Lindsay 2004).

North of Hill River, Cockleshell Gully receives discharge from the Eneabba–Lesueur aquifer, and Erindoon and Bindoon creeks receive water from the Cattamarra aquifer. Springs and pools associated with the Irwin River, and tributaries such as Springy Creek and the Lockier River, are supported by the Yarragadee aquifer. The Lockier River also receives discharge from the Parmelia aquifer upstream of its confluence with the Irwin River (Rutherford et al. 2005).

GDEs of the Dandaragan Plateau

Much of the northern and western boundaries of the Dandaragan Plateau are marked by outcropping Otorowiri Siltstone. Along the outcrop, multiple short watercourses and permanently flowing contact springs are supported by groundwater discharge from the Leederville–Parmelia aquifer. The orientation of the Otorowiri Siltstone suggests that its springs have probably been sites of reliable discharge from the Leederville–Parmelia aquifer over geological timescales. Discharge zones would have expanded and contracted many times before recent decades of rising groundwater and increased discharge due to land clearing. In this context, it may not be correct to assume that the recent rising groundwater levels are inherently damaging to ecosystems, and that rebalancing groundwater levels through abstraction will have ecological benefits. On the contrary, if groundwater levels are managed carefully, these springs may provide an opportunity to maintain farm water supplies and regionally significant aquatic refuges in a drying climate.

South of Moora and Dandaragan, the Leederville–Parmelia aquifer is overlain in various places by patches of the Mirrabooka and surficial aquifers. Wetlands, watercourses and vegetation over shallow groundwater are found in the valleys of the Moore River and Gingin, Mullering and Minyulo brooks. These GDEs are sustained by the Mirrabooka and Surficial aquifers in the centre of the Dandaragan Plateau, and by the Leederville–Parmelia aquifer closest to the Gingin Scarp (Johnson 2000; Rutherford et al. 2005; Tuffs 2011).

Abstraction has led to substantial declines in hydraulic head in parts of the Leederville–Parmelia aquifer (Johnson 2000) and may have reduced the linear extent or rate of groundwater discharge in watercourses that this aquifer supports. Also in this southern part of the Dandaragan Plateau, the Yallalie Basin contains lakes over shallow groundwater, and is underlain by lacustrine sediments that are Pliocene in age (Rutherford et al. 2005).

South-east of Moora, shallow aquifers are prone to waterlogging due to poorly developed external drainage and the near-surface presence of an aquitard. The geology is also somewhat patchy, so that the watertable is discontinuous and difficult to map at regional scale (Rutherford et al. 2005). These patchy conditions highlight the need for local-scale assessments to verify regional generalisations and ground-truth regional-scale mapping of geological formations.

GDEs of the Lockier region

The springs on the western boundary of the Lockier region have been used for farm water supplies (Borger 2010) and town water supplies (e.g. Three Springs), and also form regionally rare habitats with water and tall trees. Some of these springs may receive discharge from the Parmelia aquifer, where its sediments overtop the Urella Fault and onlap onto the Mullingarra Gneiss (R Speed 2016, pers. comm.).

GDEs of the Yarra Yarra region (Monger Palaeochannel)

The Yarra Yarra region includes a naturally saline system of salt lakes that is also affected by secondary salinity (Stelfox 2001). Water levels in the Yarra Yarra Lakes appear to be close to the potentiometric surface in the Leederville–Parmelia aquifer to the west, and may be maintained by shallow discharge from the Surficial aquifer or by upward flow from the Leederville–Parmelia aquifer (Yesertener 1999b). The salt lakes dry in summer and are inundated in winter. South and downstream of Yarra Yarra Lakes, the Coonderoo River receives discharge from a palaeochannel aquifer (the Surficial aquifer) and the Eneabba–Lesueur aquifer. Lakes Eganu and Pinjarrega, related to the Coonderoo River, are watertable features. Further downstream, salt lakes at Watheroo, Namban, Coomberdale Road and Moora may be sustained by groundwater discharge from an elevated watertable over the Yilgarn Craton to the east (Stelfox 2001).

GDEs of the Chapman region, Victoria Plateau, Wittecarra region and Murchison Gorge

GDEs of the Chapman region, Victoria Plateau, Wittecarra region and Murchison Gorge are associated with the Greenough, Chapman, Bowes, Hutt and Murchison rivers and their springs. River baseflow and shallow groundwater support river pools, wetlands and riparian vegetation. Each of these rivers receives groundwater discharge from various aquifers as they cross them.

In the east of the Victoria Plateau, the Greenough River and its tributary, the Kockatea Gully, may receive groundwater discharge from the Permian aquifers within the Nangetty Formation and the Holmwood Shale. As it crosses into the Chapman region, the Greenough River gains groundwater from the Yarragadee aquifer at Ellendale Pool (Schafer 2016).

Based on the distribution of geological formations and depth to groundwater, the Chapman River may receive groundwater from the Tumblagooda Sandstone and Northampton Inlier. Further downstream, the Chapman River receives spring discharge from the Cattamarra aquifer at the base of the Nabawa Sandplain, where Jurassic sediments overlie the crystalline rocks of the Northampton Inlier (Koomberi 1994a; Hundi 1999a, 1999b). In particular, perennial springs are known along a tributary of the Chapman River near the Nanson–Howatharra Road, west of Chapman Road (K Foster 2010, pers. comm.). Some springs of the Chapman River system have experienced reduced discharge since 2001 (A Kern 2016, pers. comm.).

The Bowes and Hutt rivers arise over the fractured rock of the Northampton Inlier. The Bowes River supports river pools and dense river gums in this area (A Lam 2016, pers. comm.). Tributaries of the middle and lower reaches of the Hutt River have perennial flows that are maintained by sandplain seeps. These tributaries include Yerina Springs, Yarder Gully, Swamp Gully, the unnamed creek (on which Harry Springs is located), Simkin Creek and Bishop Gully (Department of Environment 2005). Yerina Spring receives groundwater discharge from the sands of the Surficial aquifer and the underlying Tumblagooda aquifer (Koomberi 1996), and ecologically significant springs within a proclaimed water reserve (Wilson and Harmsworth 2007).

The Murchison River receives groundwater discharge within the area of the Kalbarri National Park (Kern 1993b; Mory & Hocking 2008), where a number of small springs emerge from bedding planes below the Ross Graham Lookout (A Kern 2016, pers. comm.). This area corresponds with the fractured rock of the Northampton Inlier. Based on depth to groundwater and aquifer mapping, the Tumblagooda aquifer may also contribute to baseflow in the Murchison River in its course across the Victoria Plateau, Chapman region, Murchison Gorge and Kalbarri townsite. There are known to be a few springs in the backyards of the town of Kalbarri (A Kern 2016, pers. comm.). Some other isolated springs and wetlands are found within the Chapman region, including Wicherina Spring, Sandsprings (Heritage Council of Western Australia 2010) and Utcha Swamp.

6.3 Current and future use of groundwater in the northern Perth Basin

Current groundwater use

Today, about 95 per cent of all water used in the northern Perth Basin is from groundwater. Figure 100 shows the distribution of licensed groundwater entitlements in 2016. Groundwater from the northern Perth Basin provides vital water supplies for all towns in the northern Perth Basin and some nearby towns in basement fractured-rock areas (Figure 101). Town water for Cervantes, Lancelin, Ledge Point and Guilderton are supplied by the Superficial aquifer (Table 20). Around half of current groundwater use from the Leederville aquifer is for town water supply at Seabird and Woodridge.

The Leederville–Parmelia aquifer has a long history of supplying fresh groundwater for many towns across the region. The Arrowsmith Scheme, first developed in 1963, provides water to Arrino, Morawa and Perenjori; the Dathagnoorara Scheme, installed in 1971, supplies water to Carnamah and Coorow; the Dookanooka borefield, established in 1976, provides water to Three Springs; and the Koolbung borefield, established in 1973, provides water for Moora. Dandaragan has obtained its water supply locally since 1982.

The Allanooka borefield, about 50 km south-east of Geraldton, delivers potable water to Geraldton, Dongara, Port Denison, Walkaway, Narngulu, Mullewa, Northampton, Yuna and Eradu from the Yarragadee aquifer. This scheme has been progressively expanded over many decades (Allen 1979; DoW 2008) and supplying the scheme generates one of the largest fresh groundwater demands on the Yarragadee aquifer in the northern Perth Basin. The small townships of Eneabba and Badgingarra also obtain their town water supply from the Yarragadee aquifer. Green Head and Leeman access town water supply from the Eneabba–Lesueur aquifer because water quality in the Superficial aquifer in this area is poor.

In the southernmost portion of the Carnarvon Basin, Kalbarri, Port Gregory and Horrocks use the Tumblagooda aquifer for town water supply. The Northampton fractured-rock aquifer provides town water supply to Nabawa but no longer provides town water supply at Northampton due to poor water quality and low bore yields.

Irrigated agriculture, horticulture, mining and other industries are also supported by groundwater from the major regional aquifers, with use largely governed by groundwater quality.

Groundwater use from the Superificial aquifer where it is brackish supports mineral sands mining at Cooljarloo. South of Lancelin, particularly along Cowalla Road, there are numerous horticultural users that range from small market gardens to significant irrigation operations that abstract several gigalitres each year. There are also numerous domestic and garden users associated with rural estates and ‘lifestyle blocks’.

Stock and domestic use is common throughout the Swan Coastal Plain where groundwater quality permits. Near Jurien Bay, there are numerous domestic garden and industrial users. However, between Jurien Bay and Lancelin there is minimal groundwater use as most land is national parks and nature reserves. Groundwater availability from the Superficial aquifer is limited north of Green Head due to poor groundwater quality and the most significant use is for onshore infrastructure related to the Cliff Head offshore gas development.

The growth of irrigated horticulture and pasture has been supported by groundwater from the Leederville–Parmelia aquifer. In the southern parts of the Gingin groundwater area, olive trees, vineyards, tree plantations and pasture are all supported by groundwater from the Leederville–Parmelia. Further north, in the Jurien groundwater area, there are several major horticultural operations that abstract groundwater to grow citrus, mangoes and stone fruit, together with some pasture and other tree plantations. In the Arrowsmith groundwater area, groundwater is used to grow native flowers, olive trees and pasture, and is being piped east into the Yilgarn region for iron ore mining.

Fresh to brackish groundwater in the Yarragadee and Cattamarra aquifers has supported mineral sands mining in the Eneabba area since the 1970s. In the 2000s, the Yarragadee aquifer has also supported pasture operations near Dongara and Cataby and, more recently, olive and almond tree plantations near Badgingarra and Eneabba. Groundwater abstracted from the Yarragadee aquifer is also piped east for use in magnetite processing for iron ore mining. Groundwater in the Cattamarra aquifer is mostly brackish to saline and has been used historically for mineral sands mining at the Eneabba West Mine, which is no longer operational (Rockwater 1990). There is some limited horticultural development where water quality and yields permit, with the remaining use primarily for stock and domestic purposes.

The Surficial, Permian and the Yandanooka, Mullingara and Northampton fractured-rock aquifers are minor water resources with brackish to saline groundwater that are mainly used for stock and domestic purposes.

Table 20 Town water supplies that use groundwater resources

Town	Aquifer	Scheme
Kalbarri	Tumblagooda	Kalbarri and Port Kalbarri
Gregory	Tumblagooda	Port Gregory (non-potable)
Horrocks	Tumblagooda	Horrocks
Nabawa	Northampton fractured-rock	Supplemented by Allanooka when required
Yuna/Mullewa farmlands	Irwin – High Cliff	Wicherina Rural Water Supply (non-potable)
Mingenew farmlands	Yarragadee	Mingenew Rural Water Supply (non-potable)
Geraldton/Greenough/Walkaway/ Eradu/Mullewa/Northampton/Yuna	Yarragadee	Allanooka
Dongara/Denison	Yarragadee	Wye Springs and Allanooka
Mingenew	Parmelia	Mingenew
Arrino/Morawa/Perenjori/Caron/ Bunjil/Latham and farmlands	Parmelia	Arrowsmith
Three Springs and farmlands	Parmelia	Dookanooka
Carnamah/Coorow and farmlands	Parmelia	Dathagnoorara
Eneabba	Yarragadee	Eneabba
Leeman – Green Head	Lesueur	Mt Peron
Jurien Bay	Superficial	Jurien
Badgingarra	Yarragadee	Badgingarra
Cervantes	Superficial	Cervantes
Watheroo	Moora (Noondine Chert)	Watheroo
Moora	Leederville–Parmelia	Koolbung
Moora farmlands	Surficial	Moora (non-potable)
Ocean Farm	Superficial	Ocean Farms Nilgen
Lancelin	Superficial	Lancelin
Ledge Point	Superficial	Ledge Point
Dandaragan	Leederville–Parmelia	Dandaragan
Sovereign Hill	Superficial	Sovereign Hill
Seabird	Leederville	Seabird
Woodridge	Superficial and Leederville	Woodridge
Guilderton	Superficial	Guilderton

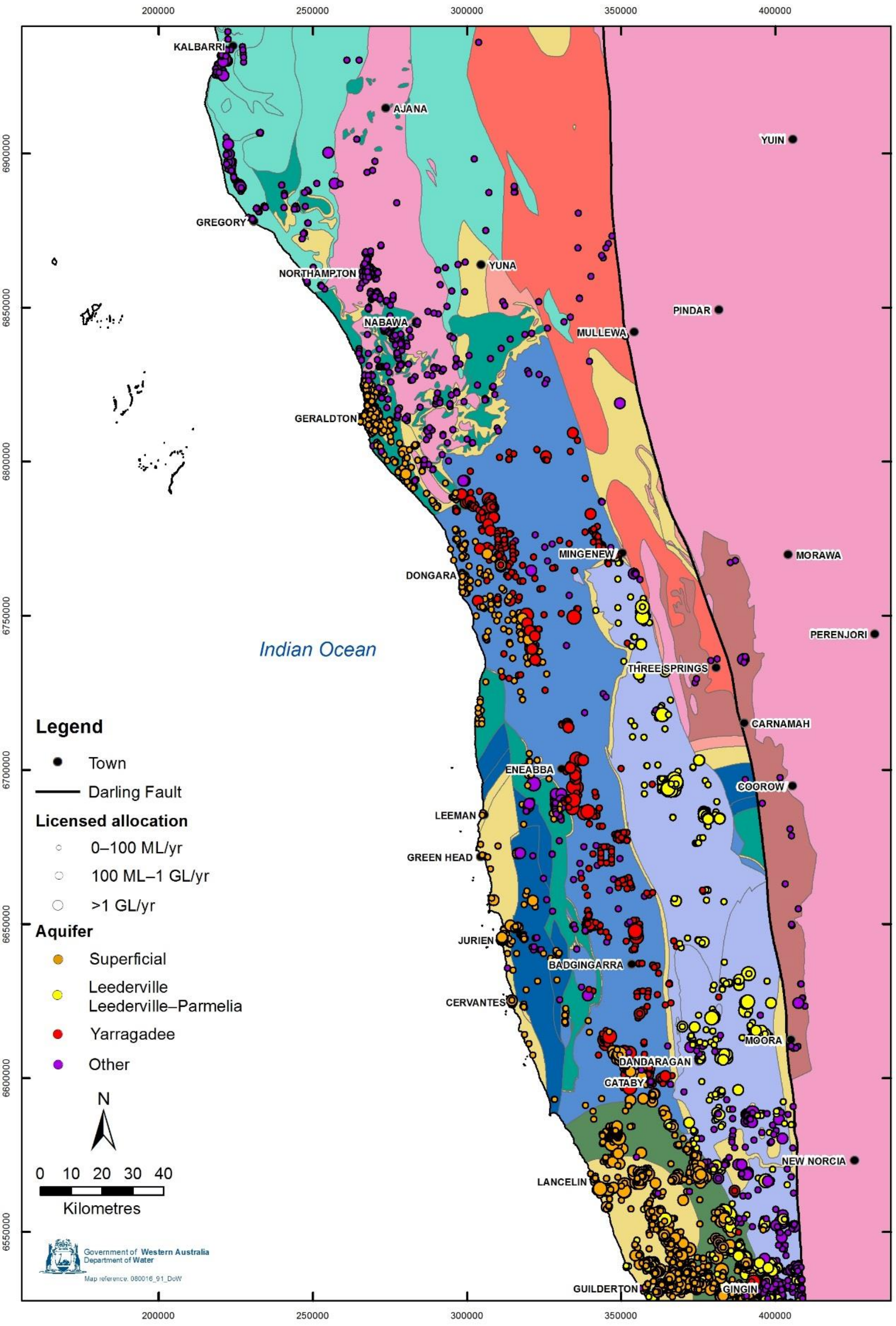


Figure 100 Groundwater allocation by aquifer (2016)

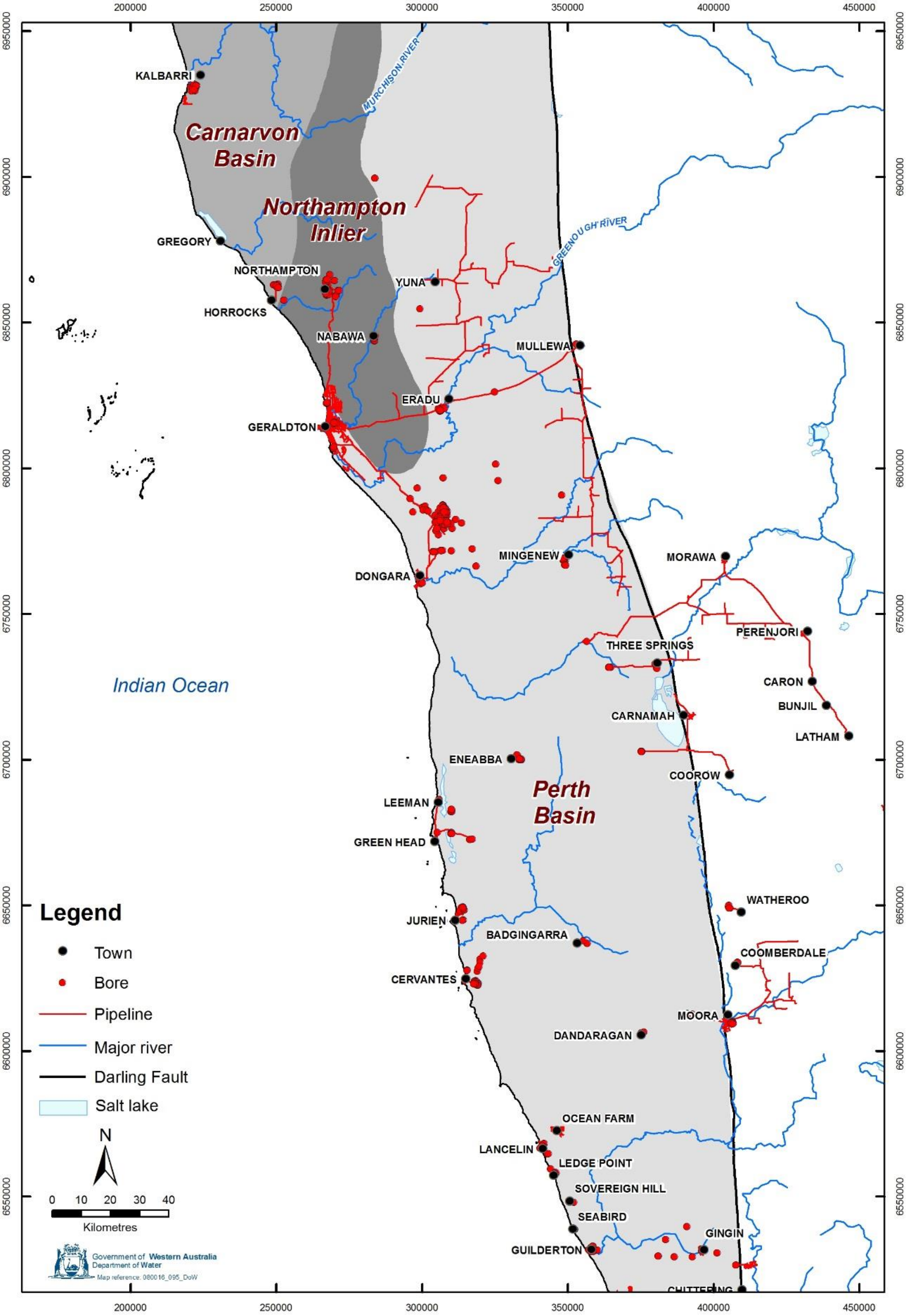


Figure 101 Town water supply bores and pipelines

Projected groundwater demand

There are four main drivers of future water demand in the northern Perth Basin region. These are:

- proposed and planned mining projects, including water sources for mines outside the region covered by this bulletin
- a potential future port facility and industrial estate at Oakajee (24 km north of Geraldton)
- growth of Geraldton and other rural towns, including Jurien Bay and Morawa
- northward expansion of irrigated agriculture and horticulture, including the Water for Food Midlands area between Moora and Dongara.

The Department of Water's 'Mid West regional water supply strategy' (DoW 2015b) provides a long-term outlook for water demand and supply in the Arrowsmith and Jurien groundwater areas of the northern Perth Basin. The strategy indicates that water supplies for Geraldton and the region's other towns (including Jurien Bay and Morawa) are secured until at least 2030. This assumes that about 200 GL/year of groundwater will be available to meet future water demand in the northern Perth Basin, which could more than double over the next 30 years from 75 GL/year to over 180 GL/year.

The total volume of water remaining in the region for licensing is greater than the projected demand but localised shortages and competition for fresh groundwater will increase with rising demand. The proposed water supply options to meet demand for a port and industrial estate at Oakajee include piping water from the Yarragadee aquifer north of the Irwin River (in the Allanooka and Casuarinas subareas) or from the Carnarvon Basin, and desalinating seawater onsite.

The upper bound of projected demand for irrigated agriculture in the Mid West region by 2043 is about 30 GL/year (DoW 2015b). The Midlands groundwater and land assessment, which is part of the state government's Royalties for Regions Water for Food project is investigating groundwater availability, land capability and crop suitability in the area between Gingin and Dongara.

Further growth is also expected to the north of Gingin, in the western part of the Wheatbelt region, where the licensed water entitlements were about 170 GL/year in early 2016. Here too, future water demand could be very high but there is less than 40 GL/year of groundwater available for further allocation.

Scope exists for increased abstraction from today's groundwater sources and for development of major new groundwater sources. Potential new sources are mainly within the Superficial aquifer north-east of Lancelin, the unconfined Yarragadee aquifer between the Hill and Irwin rivers and in the coastal Cattamarra and Eneabba–Lesueur aquifers. These potential new sources are located away from the areas of greatest groundwater demand, but if demand for large groundwater resources arises, the size and the extent of these potential resources should be reassessed. If large fresh–marginal groundwater resources are not present, desalination of brackish or saline groundwater could be practical (provided cheap sources of energy are available).

The current water availability and relatively low cost of groundwater source development means that groundwater will remain the major source of water supply in the northern Perth Basin for the foreseeable future. As the population of the region grows, and mining operations or other developments expand, it is likely that more marginal groundwater sources will need to be accessed to meet future water supply demands. This may drive further hydrogeological investigations of the northern Perth Basin to increase our understanding of the viability of fresh–marginal or brackish–saline groundwater to provide reliable water sources.

Shortened forms

AEM	airborne electromagnetic
AGC	Australian Groundwater Consultants
AHD	Australian Height Datum
Ampol	Australian Motorists Petrol Company
ANZECC	Australian and New Zealand Environment and Conservation Council
API	American Petroleum Institute (API is the unit for gamma-ray logs)
bgl	below ground level
BMR	Bureau of Mineral Resources
BOM	Bureau of Meteorology
BP	before present
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEC	(WA) Department of Environment and Conservation
DoW	(WA) Department of Water
DMP	(WA) Department of Mines and Petroleum
GARAMS	Gingin Arrowsmith Regional Aquifer Modelling System
GDE	Groundwater-dependent ecosystem
GSWA	Geological Survey of Western Australia
ERM	Environmental Resources Management
Ma	million years
MGA	Map Grig of Australia
MODFLOW	modular finite-difference flow model
NPB	northern Perth Basin
NACC	Northern Agricultural Catchments Council
RMS (error)	root-mean-square (error)
PRAMS	Perth Regional Aquifer Modelling System
PWD	Public Works Department
TDS	total dissolved solids
TWS	town water supply
WAPET	West Australian Petroleum Pty Ltd
WAWA	Water Authority of Western Australia
WIR	Water Information Reporting system
WRC	Water and Rivers Commission
WRM	Wetland Research Management

Glossary

abstraction	the withdrawal of water by pumping from an aquifer
AHD	Australian Height Datum; equivalent to Mean Sea Level (MSL) + 0.026 m, and Low Water Mark Fremantle (LWMF) + 0.756 m
alkaline	any of various soluble mineral salts that have a pH greater than 7 and which is found in water and soil
allocation limit	annual volume of water set aside for consumptive use from a water resource
alluvium (alluvial)	detrital material that is transported by streams and rivers and deposited
anion	a negative-charged ion that migrates to an anode (such as in electrolysis)
annual licensed water entitlement	the quantity of water that a person is entitled to take on an annual basis in accordance with the *Rights in Water and Irrigation Act 1914*
anticline	type of fold that is an arch-like shape and has its oldest sedimentary strata at its core
aquifer	a geological formation or group of formations able to receive, store and transmit significant quantities of water
artesian aquifer (bore)	a confined aquifer under sufficient pressure that the water would rise in a bore above the ground surface
confined aquifer	an aquifer lying between confining strata of low permeability so that the water in the aquifer cannot flow vertically
perched aquifer	an unconfined aquifer separated from an underlying body of groundwater by an unsaturated zone (contains a perched watertable)
unconfined aquifer	an aquifer near the surface with a free watertable or phreatic level at atmospheric pressure
semi-confined aquifer	An aquifer that is underlain by an impermeable stratum and bounded at the top by soil layers of relatively low permeability (hydraulic conductivity), especially in a horizontal sense. These layers form the semi-confining layer (the aquitard) in which a free watertable is found

aquifer system	intercalated permeable and poorly permeable materials that comprise two or more permeable units separated by aquitards, which impede vertical groundwater movement but do not affect the regional hydraulic continuity of the system
aquitard	a geologic formation, group of formations, or part of a formation through which virtually no water moves
Archean	the earliest part of Precambrian, between 4000 Ma and 2500 Ma
baseflow	the portion of river and stream flow coming from groundwater discharge
basin (geological)	a depression of large size, which may be of structural or erosional origin (contains sediments)
bed (geological)	a subdivision of a formation, smaller than a member
bedrock	lithified rock that lies under the loose, softer material (regolith) at the ground surface
bore	small diameter well, usually drilled with machinery
brackish (water)	with a salinity ranging between 1000 mg/L TDS (fresh water) and 3000 mg/L TDS (saline water)
Breakup unconformity	unconformity formed after the breakup of Gondwana during the Early Cretaceous
brine	water that contains more than 35 000 mg/L TDS
Cenozoic	Cenozoic era covers the earth's history during the last 66 million years. It is subdivided into the Tertiary and Quaternary (last 2 million years) periods
Cambrian	the first geological period of the Paleozoic Era, lasting from 541 to 485 million years ago
clastic	composed of fragments, or clasts, of pre-existing minerals and rocks, and that have been transported from their place of origin
coffee rock	colloquial term for iron oxide (limonite) cemented sand grains
colluvium (colluvial)	material transported by gravity down hill slopes
confining bed	sedimentary bed of very low hydraulic conductivity

confluence	meeting of two or more water courses; the place where a tributary joins the main stream
conformably	sediments deposited in a continuous sequence with a break
conformity	the stratigraphic continuity of adjacent sedimentary strata, i.e. they have deposited in an orderly series without evident time lapses
craton	part of the continental crust that has been stable (no orogeny activity) for at least 1000 Ma
Cretaceous	final period of the Mesozoic era occurring 65–135 million years ago
delta (deltaic)	sediments deposited at the mouth of a river where it enters a lake or the ocean
dewatering	removing underground water for construction or other activity. It is often required in mining below the watertable or as a preliminary step to developments in an area
diachronous	varying in age from place to place
diffusion	net movement of molecules or atoms from a region of high concentration (or high chemical potential) to a region of low concentration (or low chemical potential)
discharge (groundwater)	all water leaving the saturated part of an aquifer
disconformity	unconformity between parallel layers of rocks that represents a period of erosion or non-deposition (see unconformity)
dispersion	the extent to which a liquid substance introduced into a groundwater system spreads as it moves through the system
divertible resource	amount of surface water or groundwater that can economically be diverted from groundwater resource or catchment each year
downhole	occurring in the drilled borehole
drawdown (s)	difference between the elevation of the initial potentiometric surface and its position after pumping
drawdown per log cycle (Δs)	Δs is the change in drawdown (s) given by the straight line plot over one log cycle of time (t) or distance (r) during a pumping test when plotting drawdown data on a semilogarithmic graph

ephemeral stream	a stream or part of a stream that flows only in direct response to precipitation and whose channel is above the watertable
eolian	windblown; deposit formed by wind action
estuary (estuarine)	the seaward or tidal mouth of a river where fresh water comes into contact with seawater
evapotranspiration	a collective term for evaporation and transpiration
facies	a mappable lithostratigraphic unit, differing in lithology from adjacent units deposited at the same time and in lithologic continuity
fault	a fracture in rocks or sediments along which there has been an observable displacement
flow path	an underground route for groundwater movement, extending from a recharge zone to a discharge zone
fluvial	pertaining to streams and rivers
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 whose flow is being increased by inflow of groundwater
gamma-ray (logging)	measurement of natural radiactivity from rocks, useful in distiguishing high radation shale from low radation quatz sand
Gondwana	Late Palaeozoic continent of the Southern Hemisphere
groundwater	water that occupies the pores and crevices of rock or soil beneath the land surface
groundwater area	groundwater/surface water area: An area proclaimed under the *Rights in Water and Irrigation Act 1914* for the purposes of licensing and managing water use
groundwater barrier	rock or formation which has a relatively low permeability and which occurs below the land surface where it impedes the movement of groundwater and consequently causes a difference in the hydraulic head on either sides of it
groundwater discharge	flow of groundwater from the zone of saturation

groundwater divide	a ridge in the watertable or other potentiometric surface from which groundwater moves away in both directions normal to the ridge line
groundwater flow	movement of water in the saturated zone
groundwater isotopes	Isotopes of hydrogen (e.g. deuterium, tritium) and oxygen (e.g. oxygen-18) in water and in constituent (e.g. carbon-14) that can be used to determine characteristics of recharge and groundwater age
groundwater management unit (GMU)	discrete aquifer within a groundwater management area (GMA)
groundwater mound	a raised area in a watertable or other potentiometric surface caused by groundwater recharge
groundwater recharge	hydrologic process where water moves downward from surface water to groundwater. Recharge is the primary method that water enters an aquifer
groundwater system	an aquifer (groundwater reservoir) and its contained water. Also, the collective hydrodynamic and geochemical processes at work in the aquifer
groundwater travel time	the time required for groundwater to travel between two locations
group (geological)	includes two or more contiguous or associated formations with significant lithologic features in common
heterogeneous	the state of being non-uniform in structure or composition throughout
hydraulic	pertaining to groundwater motion
hydraulic barrier	a general term referring to modifications of a groundwater flow system to restrict or impede movement of water
hydraulic conductivity (permeability)	the flow through a unit cross-sectional area of aquifer under a unit hydraulic gradient
hydraulic downward head	the hydraulic head decreases with depth indicating potential for downward groundwater flow

downward hydraulic gradients	decreasing heads with depth
hydraulic gradient	rate of change of hydraulic head per unit distance, at a given point and in a given direction
hydraulic head	height of a free surface of a body of water above a given point beneath the surface
upward hydraulic head	the hydraulic head increasing with depth indicating potential for upward groundwater flow
upward hydraulic gradients	increasing heads with depth
homogeneous	the state of being uniform in structure and composition throughout
hypersaline	excessively saline; with a salinity substantially greater than that of sea water (>35 000 mg/L TDS)
igneous rocks	igneous rock is formed through the cooling and solidification of magma or lava
impermeable	a characteristic of some geologic material that limits its ability to transmit significant quantities of water under head differences found in the subsurface
infiltration	movement of water from the land surface to below ground level
inlier	area of older rocks surrounded by younger rocks. Inliers are typically formed by the erosion of overlying younger rocks to reveal a limited exposure of the older underlying rocks
interbedded (of strata)	being positioned between, or alternated with, other layers of dissimilar character
interface	contact zone between two fluids (groundwater) of different chemical and physical composition
interfinger	lithological facies being conformably and alternatively deposited
ion	a positively or negatively charged atom or groups of atoms
major ions	constituents commonly present in grouwater in concentrations exceeding 1.0 mg/L. Major cations are calcium, magnesium, sodium and potatsium; the major cations are sulfate, chloride,

	fluoride, nitrate, and those contributing to alkalinity, most generally assumed to be bicarbonate and carbonate
isoline	contour line
isopach	a contour line joining points of equal thickness of geological unit
Jurassic	the second period of the Mesozoic era occurring 135–190 million years ago
juxtaposition	side by side
karst	a type of topography that is formed on limestone by dissolution, and that is characterised by sinkholes, caves, dolines, solution channels and underground drainage
lacustrine	pertaining to, produced by, or formed in a lake
lateritised (lateritic)	a surficially formed deposit consisting mostly or entirely of iron or aluminium oxides and hydroxides
leach (leaching)	removal of soluble matter by percolation of water
leakage	the flow of water from one aquifer to another
licence	a formal authorisation that entitles the licence holder to ‘take’ water from a watercourse, wetland or underground source for a specified quantity and period of time
lithology	description of the physical characteristcs of a rock unit
losing stream	a stream or that loses water to groundwater as it flows downstream
Map Grid of Australia	a metric rectangular grid system (i.e. east and north), comparable to the AMG grid in use since the 1980s. It is a Cartesian coordinate system based on the Universal Transverse Mercator projection and the Geocentric Datum of Australia 1994
member (geological)	minor rock stratigraphic unit comprising some portion of a formation
metamorphic rocks	sedimentary and igneous rocks that were subjected to more intense pressure or heat and as a result underwent a complete change
Mesozoic	an era of geological time occurring 66–252 million years ago

model (modelling system)	a groundwater flow model simulates hydraulic heads (and watertable elevations in the case of unconfined aquifers) and groundwater flow rates within and across the boundaries of the groundwater system under consideration
analytical model	an analytical model makes simplifying assumptions (e.g. properties of the aquifer are considered to be constant in space and time) to enable solution of a given problem. Analytical models are usually solved rapidly, sometimes using a computer, but sometimes by hand
conceptual model	a conceptual (hydrogeological) model is a descriptive representation of a groundwater system that incorporates an interpretation of the geological and hydrological conditions. It consolidates the current understanding of the key processes of the groundwater system, including the influence of stresses, and assists in the understanding of possible future changes
numerical model	numerical model divides space and time into discrete pieces. Features of the governing equations and boundary conditions (e.g. aquifer geometry, hydrogeological properties, pumping rates or sources of solute) can be specified as varying over space and time
microplankton	microscopic, drifting organism that inhabits the open water, or pelagic zone, of ocean or fresh water
miospore	collective term for microspore and pollen grains
Neocomian	European stage of geological time at base of Cretaceous
non-potable	water that is not of drinking quality, but may be suitable for other purposes
orogen	the process responsible for the development of mountainous terrain, and for deformation of rock within the mountains
overburden	the loose soils, silt, sand, gravel or other unconsolidated material overlying bedrock, and which is either transported or formed in place. Also termed ‘regolith’
oxidation	a chemical change in which electrons are lost by an atom or group of atoms
palaeochannel	a channel that is no longer part of the contemporary fluvial system, i.e. has been abandoned or buried

palaeovalley	a valley that is no longer part of the contemporary fluvial system, i.e. has been abandoned or buried
Palaeozoic	the era of geological time extending from about 541 to 252 million years ago
palynology	study of plant pollen, spores and certain microscopic plankton organisms (collectively termed palynomorphs) in both living and fossil form
paralic	laid down on the landward side of a coast
pelagic	part of the open sea or ocean that is not near the coast or sea floor
permeable	ability to permit water movement
permeability	the property or capacity of a porous rock, sediment or soil for transmitting water
phreatic	term used in hydrology to refer to aquifers
plain	tract of flat or level terrain
plateau	an extensive land region considerably elevated (more than 150 m in altitude) above the adjacent country or above sea level
porosity	the percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected
potable	fresh and marginal water generally considered suitable for human consumption
potentiometric surface	a surface of equal hydraulic heads or potentials, typically depicted by a map of equipotentials such as a map of watertable elevations
Precambrian	the era of geological time extending from about 4600 to 541 million years ago
Proterozoic	the later of the two major subdivisions of the Precambrian
aquifer test	one of a series of techniques to evaluate the hydraulic properties of an aquifer by observing how water levels change with space and time when water is pumped from the aquifer
Quaternary	relating to the most recent period in the Cenozoic era

recharge (groundwater)	all water reaching the saturated part of an aquifer (natural or artificial), such as rainfall recharge, induced recharge from other aquifers or throughflow
renewable resource (groundwater)	Groundwater extracted from an aquifer that receives recharge from rivers, rainfall or from other aquifers
resistivity (logging)	Measurement of electrical resistivity in the formation immediately surrounding a borehole, useful for estimation of salinity in clean sands
ridge	a tectonic subdivision of a geological basin having relatively shallow basement
runoff	part of the precipitation flowing to surface streams
salinity	a measure of the concentration of total dissolved solids (TDS) in water (DoW 2014) 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
saturated	all open spaces are filled with water under pressure equal to or greater than that of the atmosphere
saturated zone	the area in an aquifer, below the watertable, in which relatively all pores and fractures are saturated with water
scarp	a line of cliffs (steep slopes) produced by faulting or by erosion
scheme	water diverted from a source or sources by a water authority or private company and supplied via a distribution network to customers for urban and industrial use or for irrigation
seawater interface	a diffusion zone in which fresh water and saltwater mix and which is maintained near the coast
seawater intrusion	the invasion of fresh water by seawater. This can be caused by excessive groundwater abstraction from coastal aquifers, or upward movement from deeper saline zones due to up-coning near coastal discharge/pumping wells
seawater wedge	a wedge-shaped intrusion of salty ocean water into a freshwater estuary, tidal river or aquifer; it slopes downward in the upstream/upgradient direction, and salinity increases with depth

secondary salinity	salinisation of soil, surface water or groundwater due to human activity such as urbanisation and agriculture (irrigated and dryland)
sedimentary basin	a low area in which permeable sediments laid down at various times in the past have accumulated
sedimentary rock	sedimentary rocks are formed on the surface of the Earth, either in water or on land. They are called secondary, because they often result from the accumulation of small pieces broken off from pre-existing rocks
seepage	water that seeped or oozed through a porous soil
self-supplied	water users (individuals or organisations) who divert from a source for their own individual requirements
shelf	shallow, marginal part of a sedimentary basin
solution channel	tubular or planar channel formed by the solution of calcium carbonate in limestone
specific capacity (of a bore)	the pumping rate (yield) divided by the drawdown. It is a valuable number that can be used to provide the design pumping rate or maximum yield for the well
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 is expressed as a percentage
spring	place where discharge of groundwater flows at the ground surface
stage	succession of rock strata laid down in a single age on the geologic timescale, which usually represents millions of years of deposition
storage	the estimated volume of water contained in an aquifer
storativity or storage coefficient	the volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer
stratigraphy	the science of rock strata. Concerned with original succession and age relations of rock strata and their form, distribution, lithology, fossil content, geophysical and geochemical properties

stygofauna	name used for any fauna that live in groundwater systems or aquifers, such as caves, fissures and vugs. Stygofauna are made up predominantly of many kinds of crustaceans but includes worms, snails, insects, other invertebrate groups, and, in Australia, two species of blind fish
subarea	a subdivision, within a surface or groundwater area, defined to better manage water allocation. Subarea boundaries are not proclaimed and can therefore be amended without being gazetted
sub-basin	a geological basin within a larger geological basin
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
surface water area	an area proclaimed under the *Rights in Water and Irrigation Act 1914* for the purposes of licensing and managing water use
sustainable (yield)	level of groundwater extraction measured over a specified planning timeframe that should not be exceeded to protect the higher value social, environmental and economic uses associated with the aquifer
swale	a slight depression, sometimes filled with water, in the midst of generally level land
syncline	a basin-shaped fold with younger sedimentary strata closer to the centre of the structure
tectonic	pertaining to the forces involved in, or the resulting structures or features, of rocks
Tertiary	the first period of the Cenozoic era occurring 2–65 million years ago
throughflow	groundwater flow within an aquifer
total dissolved solids	a term that expresses the quantity of dissolved material in a sample of water, either the residue on evaporation, dried at 180oC or, for many, water that contain more than about 1000 mg/L, the sum of chemical constituents

transmissivity	the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer thickness
trough (geological)	a linear depression or basin that subsides as it recieves clastic material, located not far from the source supplying the sediment
type (locality, section)	the place at which a stratotype is situated and from which it derives its name
unconformably	time break in sequence of deposition
unconformity	break in a sequence of strata in an area that represents a period of time during which no sediments were deposited
unconsolidated	loosely bound (sediments)
unit (geological)	is a volume of rock of identifiable origin and age range that is defined by the distinctive and dominant, easily mapped and recognisable petrographic, lithologic or palaeontologic features (facies) that characterise it
unsaturated	the area above the watertable where soil pores are not fully saturated, although some water may be present
watertable	the surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere
weathering	the in-situ physical disintegration and chemical decomposition of rock material at or near the earth’s surface
well	large diameter bore, usually dug by hand; also petroleum bore
wetland	area permanently, seasonally or intermittently waterlogged or inundated with water that may be fresh, saline, flowing or static
WIR	the Department of Water’s self-service water information system that provides online access to a range of scientific data from the department’s water information databases
yield	sustainable rate at which a bore or well can be pumped

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Appendices

Appendix A Stratigraphic data from key bores

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Abbarwardoo 1	320170	6836620	m AHD	222	-378															199						166
			m bgl	0	600															23						56
Agaton A1	377518	6633972	m AHD	271	-269		246							-269												
			m bgl	0	540		25							540												
Agaton A10	373260	6652250	m AHD	275	-30									115												
			m bgl	0	305									160												
Agaton A11	377966	6651767	m AHD	294	104									218												
			m bgl	0	190									76												
Agaton A12	382608	6652478	m AHD	275	-434						213			-365	-434											
			m bgl	0	709						62			640	709											
Agaton A13	386904	6653310	m AHD	248	-65				102	35	-65															
			m bgl	0	312				146	213	312															
Agaton A14	388387	6627812	m AHD	232	-72		127		89	64	-72															
			m bgl	0	304		105		143	168	304															
Agaton A15	378439	6659080	m AHD	296	-438									-225	-307	-354				-354						
			m bgl	0	734									521	603	650				650						
Agaton A16	383291	6659749	m AHD	263	-185		223			221	113			-70												
			m bgl	0	447		40			42	150			332												
Agaton A17	387510	6658783	m AHD	254	-496		178			105	-20			-237												
			m bgl	0	750		76			149	274			491												
Agaton A18	390408	6645266	m AHD	256	-26		176		110	67	-16															
			m bgl	0	282		80		146	189	272															
Agaton A19	391784	6645363	m AHD	237	-351		153		64	19	-77			-351												
			m bgl	0	588		84		173	218	314			588												

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Agaton A2	381970	6634040	m AHD	224	153						-81															
			m bgl	0	71						305															
Agaton A20	391509	6639344	m AHD	257	-48		89																			
			m bgl	0	305		168																			
Agaton A21	391855	6651892	m AHD	231	-74		146		42	6	-49			-71												
			m bgl	0	305		85		189	225	280			302												
Agaton A23A	385994	6648317	m AHD	258	-40		231		203	167	104			-40												
			m bgl	0	298		27		55	91	154			298												
Agaton A24	386177	6643930	m AHD	262	-109		228			193	149			-101												
			m bgl	0	371		34			69	113			363												
Agaton A3	388040	6634040	m AHD	228	-479		111			88	-150			-266												
			m bgl	0	707		117			140	378			494												
Agaton A4	377467	6639628	m AHD	295	126									175												
			m bgl	0	169									120												
Agaton A5	388041	6639604	m AHD	265	-40		143			102	-6															
			m bgl	0	305		122			163	271															
Agaton A7	383822	6645235	m AHD	257	-48									34												
			m bgl	0	305									223												
Agaton A9A	390392	6622557	m AHD	268	-281		170		68		-144			-281												
			m bgl	0	549		98		200		412			549												
Agrifresh PB1	388060	6631320	m AHD	223	22	208		159	60		8															
			m bgl	0	215	15		64	163		215															
Allanooka 1	306848	6774597	m AHD	51	-1136	9											-104	-278		-321	-348	-651				-806
			m bgl	0	1187	42											155	329		433	463	702	?	?	?	857
Allanooka 1-82	307146	6787499	m AHD	147	29											132	-53			-53						
			m bgl	0	118											15	94			94						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Allanooka 1-87	307679	6783281	m AHD	75	-38											21				-35						
			m bgl	0	113											54				110						
Allanooka 2	305000	6779296	m AHD	67	-940															-321	-348	-684				-684
			m bgl	0	1006															387	414	?750	?	?	?	750
Allanooka 2-89	306400	6784090	m AHD	107	6															16						
			m bgl	0	101															91						
Allanooka 2-92	306179	6781721	m AHD	81	-73															-69						
			m bgl	0	154															150						
Allanooka A1	307608	6785082	m AHD	103	-202															-202						
			m bgl	0	305															305						
Allanooka A13	307510	6782819	m AHD	88	-49															-49						
			m bgl	0	137															137						
Allanooka A14	306184	6781192	m AHD	83	-54															-54						
			m bgl	0	137															137						
Allanooka A15	313598	6781388	m AHD	177	25															25						
			m bgl	0	152															152						
Allanooka A18	305669	6777362	m AHD	58	-79															-79						
			m bgl	0	137															137						
Allanooka A19	308664	6783938	m AHD	93	-59															-59						
			m bgl	0	152															152						
Allanooka A20	305702	6785344	m AHD	140	-12															-12						
			m bgl	0	152															152						
Allanooka A21	304694	6784120	m AHD	159	-33															-33						
			m bgl	0	192															192						
Allanooka NO. 4	305135	6795597	m AHD	244	16															16						
			m bgl	0	228															228						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Allanooka NO.8	306469	6802136	m AHD	199	148															148						
			m bgl	0	52															52						
Allanooka P 1-76	304895	6781517	m AHD	104	-40												-40			-40						
			m bgl	0	144												144			144						
Allanooka P 1-77	305142	6779510	m AHD	79	-141												-99	-141		-141						
			m bgl	0	220												178	220		220						
Allanooka P 2-76	305348	6781821	m AHD	105	-102												-53	-102		-102						
			m bgl	0	207												158	207		207						
Allanooka P 2-77	306062	6781042	m AHD	82	-151															-151						
			m bgl	0	233															233						
Allanooka P 3-76	306225	6782237	m AHD	19	-112															-112						
			m bgl	0	131															131						
Allanooka P 3-77	307644	6781036	m AHD	96	-129												-129			-129						
			m bgl	0	225												225			225						
Allanooka P 4-76	307635	6782016	m AHD	90	-121															-121						
			m bgl	0	211															211						
Allanooka P 4-77	308856	6781092	m AHD	100	-103											15	-103			-103						
			m bgl	0	203											85	203			203						
Allanooka P 4-82	308149	6780771	m AHD	25	-153											-28	-153			-153						
			m bgl	0	178											53	178			178						
Allanooka P 4-98	307750	6777417	m AHD	0	33											33				33						
			m bgl	0	51											51				51						
Allanooka P 5-76	308563	6782029	m AHD	97	-137											16	-137			-137						
			m bgl	0	234											81	234			234						
Allanooka P 5-77	304854	6778667	m AHD	63	-124												-124			-124						
			m bgl	0	187												187			187						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Allanooka P10	308082	6786321	m AHD	132	64												64			64						
			m bgl	0	68												68			68						
Allanooka P11	307526	6786732	m AHD	143	41															41						
			m bgl	0	102															102						
Allanooka P12	307397	6787387	m AHD	145	48															48						
			m bgl	0	97															97						
Allanooka P1-82	307149	6787501	m AHD	67	-47															-47						
			m bgl	0	114															114						
Allanooka P2	307423	6785518	m AHD	125	42											89	42			42						
			m bgl	0	83											36	83			83						
Allanooka P2-73	305541	6783335	m AHD	129	2															2						
			m bgl	0	127															127						
Allanooka P2-74	307246	6784073	m AHD	90	-252											20	-65	-252		-252						
			m bgl	0	342											70	155	342		342						
Allanooka P3-74	307076	6782570	m AHD	86	-196												-180	-196		-196						
			m bgl	0	282												266	282		282						
Allanooka P4-74	307797	6783215	m AHD	89	-108															-108						
			m bgl	0	197															197						
Allanooka P5	308573	6784903	m AHD	110	57															57						
			m bgl	0	53															53						
Allanooka P7	307611	6785274	m AHD	116	52															52						
			m bgl	0	64															64						
Allanooka P9	308734	6785412	m AHD	177	40															40						
			m bgl	0	137															137						
Allanooka PW2	307582	6785881	m AHD	138	76															76						
			m bgl	0	62															62						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Allanooka-Casuarinas 1A	303607	6796965	m AHD	250.93	-51													35		35	-24	-51				
			m bgl	0	302													216		216	275	302				
Allanooka-Casuarinas 10A	325134	6795532	m AHD	255.50	-15											185	-15			-15						
			m bgl	0	270											70	270			270						
Allanooka-Casuarinas 11BA	325433	6800185	m AHD	236.16	32											170	32			32						
			m bgl	0	204											66	204			204						
Allanooka-Casuarinas 12A	330912	6798246	m AHD	268.55	89									89												
			m bgl	0	180									180												
Allanooka-Casuarinas 13A	335047	6799009	m AHD	273.54	80											184	133	80		80						
			m bgl	0	194											90	141	194		194						
Allanooka-Casuarinas 14A	322687	6807434	m AHD	213.36	75												125	75		75						
			m bgl	0	138												88	138		138						
Allanooka-Casuarinas 15A	329243	6812105	m AHD	213.36	27											113	51	27		27						
			m bgl	0	186											100	162	186		186						
Allanooka-Casuarinas 2A	307952	6793677	m AHD	245.90	-60													4		4	-60					
			m bgl	0	306													242		242	306					
Allanooka-Casuarinas 3A	314514	6788637	m AHD	224.87	-65												126	-65		-65						
			m bgl	0	290												99	290		290						
Allanooka-Casuarinas 4A	321721	6784961	m AHD	216.94	-89											76	-81			-89						
			m bgl	0	306											141	306			306						
Allanooka-Casuarinas 5A	331132	6781799	m AHD	229.07	-11									-11						-11						
			m bgl	0	240									240						240						
Allanooka-Casuarinas 6A	322879	6790598	m AHD	257.73	-29											143	-29			-29						
			m bgl	0	287											115	287			287						
Allanooka-Casuarinas 7A	331002	6790767	m AHD	262.82	23									188		23				23						
			m bgl	0	240									75		240				240						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Allanooka-Casuarinas 8A	338330	6787340	m AHD	259.35	19											134	31	19		19						
			m bgl	0	240											125	228	240		240						
Allanooka-Casuarinas 9A	312937	6800821	m AHD	243.90	74													82		82	74					
			m bgl	0	170													162		162	170					
Artesian Monitoring AM1	356924	6531829	m AHD	54	-740	-45	-164				-445	-463		-740												
			m bgl	0	794	99	218				517	517		794												
Artesian Monitoring AM11	406614	6525106	m AHD	190	-620	187	77		-39	-80	-524			-620												
			m bgl	0	810	3	113		229	270	714			810												
Artesian Monitoring AM2	365659	6529664	m AHD	36	-871		-87		-174		-739	-767	-793							-845						
			m bgl	0	907		123		210		775	803	829							881						
Artesian Monitoring AM3	367230	6535516	m AHD	27	-702		-43		-137		-702															
			m bgl	0	729		70		164		729															
Artesian Monitoring AM4A	383765	6535457	m AHD	50	-499						-150	-154	-282				-499			-499						
			m bgl	0	549						200	204	332				549			549						
Artesian Monitoring AM5	375465	6527980	m AHD	52	-250						-225									-250						
			m bgl	0	302						277									302						
Artesian Monitoring AM6	387030	6529634	m AHD	64	-236						-16									-236						
			m bgl	0	300						80									300						
Artesian Monitoring AM7	398727	6527718	m AHD	102	-619	99			82		-204			-619												
			m bgl	0	721	3			20		306			721												
Artesian Monitoring AM8	369282	65522397	m AHD	52	-758				-288		-758															
			m bgl	0	810				340		810															
Apium1	312677	6755457	m AHD	107	-1032											-183	-518	-755	-1004	-1004	-1032					
			m bgl	0	1139											290	625	862	1111	1111	1139					
Arradale 1	335856	6778911	m AHD	270	-1980											-372	-480	-618	-985	-985	-1043					
			m bgl	0	2250											642	750	888	1255	1255	1313					

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Arramall 1	315691	6725165	m AHD	34	-2216														-501	-501	-558	-1199	-1478	-1646	-1754	-2187
			m bgl	0	2250														535	535	592	1133	1512	1680	1788	2221
Arrowsmith No 1	356649	6740424	m AHD	209	15									42	15											
			m bgl	0	194									167	194											
Arrowsmith No 2	359206	6742469	m AHD	256	154									154												
			m bgl	0	102									102												
Arrowsmith No 25	358301	6730642	m AHD	311	-241									204	36	-229				-229						
			m bgl	0	552									107	275	540				540						
Arrowsmith No 3	360479	6739524	m AHD	228	121									121												
			m bgl	0	107									107												
Arrowsmith No 4	350894	6739317	m AHD	203	66										172	66				66						
			m bgl	0	137										31	137				137						
Arrowsmith 1	317638	6722898	m AHD	51	-3395													-69	-702	-702	-751	-1307	-1656	-1869	-2049	-2638
			m bgl	0	3446													120	753	753	802	1358	1707	1920	2100	2689
Arrowsmith Scheme 10	355047	6740366	m AHD	201	29									29												
			m bgl	0	172									172												
Arrowsmith Scheme 11	356027	6741138	m AHD	222	81									85												
			m bgl	0	141									137												
Arrowsmith Scheme 12	354316	6741005	m AHD	208	21									25												
			m bgl	0	187									183												
Arrowsmith Scheme 13	355982	6739543	m AHD	227	21									32												
			m bgl	0	206									195												
Arrowsmith Scheme 14	354668	6739238	m AHD	218	59									66												
			m bgl	0	159									152												
Arrowsmith Scheme 15	358794	6738631	m AHD	222	112									112												
			m bgl	0	110									110												

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Arrowsmith Scheme 16	355503	6737076	m AHD	272	48									77	50											
			m bgl	0	224									195	222											
Arrowsmith Scheme 17	354145	6742933	m AHD	265	18									18												
			m bgl	0	247									247												
Arrowsmith Scheme 18	351540	6740261	m AHD	222	16										155	21				16						
			m bgl	0	206										67	201				206						
Arrowsmith Scheme 19	351633	6743138	m AHD	276	32									182	127	32				32						
			m bgl	0	244									94	149	244				244						
Arrowsmith Scheme 20	351752	6735088	m AHD	184												-57				-57						
			m bgl	0	241											241				241						
Arrowsmith Scheme 21	352933	6744727	m AHD	283	38									100	42	38				38						
			m bgl	0	245									183	241	244				244						
Arrowsmith Scheme 22	353233	6747056	m AHD	267	-38									108	38	-38				-38						
			m bgl	0	305									159	229	305				305						
Arrowsmith Scheme 23	355488	6732904	m AHD	306	50									102	70											
			m bgl	0	256									204	236											
Arrowsmith Scheme 24	359690	6747520	m AHD	287	-18									107	54					-18						
			m bgl	0	305									180	233					305						
Arrowsmith Scheme 26	362383	6720858	m AHD	280	-23									-23												
			m bgl	0	302									302												
Arrowsmith Scheme 27	349202	6746453	m AHD	258	-45									173	121	-45				-45						
			m bgl	0	303									85	137	303				303						
Arrowsmith Scheme 8	350163	6736093	m AHD	169	-52											-52				-52						
			m bgl	0	221											221				221						
Arrowsmith Scheme 9	359750	6735766	m AHD	231	72									73												
			m bgl	0	159									158												

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Astrik PB2	310550	6768030	m AHD	55	-101	22										-101				-101						
			m bgl	0	156	33										156				156						
Astrik PB3	310500	6768510	m AHD	47	-103	21										-103				-103						
			m bgl	0	150	26										150				150						
Astrik PB4	311095	6767570	m AHD	64	-77	32										-77				-77						
			m bgl	0	141	32										141				141						
Badaminna 1	373355	6531874	m AHD	37	-2393	-6	-38				-252								-784	-784	-837	-2393				
			m bgl	0	2430	43	75				289								821	821	874	2430				
Badgingarra 1-89	356775	6637010	m AHD	93	-187											-26	-187			-187						
			m bgl	0	280											119	280			280						
Barberton 1	401845	6588555	m AHD	215	-3199		177	165	115	104	-228							-350	-718	-718	-740					
			m bgl	0	3414		38	50	100	111	443							565	933	933	955					
Barragoon 1	365645	6529649	m AHD	36	-2290												-1033	-1739	-2290	-2290						
			m bgl	0	2326							803					1069	1775	2326	2326						
Bartsia 1	303190	6758392	m AHD	41	-888											-210	-432	-674	-871	-871	-888					
			m bgl	0	929											251	473	715	912	912	929					
Beekeeper 1	324596	6711615	m AHD	46	-2966													-73	-430	-430	-516	-1134	-1656	-1880	-2058	-2681
			m bgl	0	3012													120	477	477	562	1180	1702	1926	2104	2727
Beharra Spring North 1	320115	6742469	m AHD	52	-1525											-258	-615	-979	-1410	-1410	-1525					
			m bgl	0	1577											310	667	1031	1462	1462	1577					
Beharra Spring South 1	320935	6734790	m AHD	45	-1241											-265	-561	-950	-1241	-1241						
			m bgl	0	1286											310	606	995	1286	1286						
Beharra Springs 1	319724	6739154	m AHD	42	-3658											-165	-478	-898	-1265	-1265	-1361	-1986	-2644	-2722	-2903	-3241
			m bgl	0	3700											207	520	940	1307	1307	1403	2028	2686	2764	2945	3283
Beharra Springs 2	320126	6737614	m AHD	50	-3444											-206	-481	-941	-1259	-1259	-1341	-2143	-2705	-2764	-2895	-3252
			m bgl	0	3493											255	530	990	1308	1308	1390	2193	2755	2814	2945	3302

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Beharra Springs 3	319684	6740132	m AHD	42	-3463											-193	-488	-938	-1297	-1297	-1414					
			m bgl	0	3505											235	530	980	1339	1339	1456					
Beharra 1	307636	6736528	m AHD	23	-2033													-156	-703	-703	-835	-1147	-1383	-1558	-1658	-1738
			m bgl	0	2056													179	726	726	858	1170	1406	1571	1671	1751
Beharra 2	308500	6733309	m AHD	29	-1895													-58	-607	-607	-704	-628	-705	-853	-990	-1413
			m bgl	0	1924													87	636	636	?	657	734	882	1019	1442
BF10-1	341210	6691431	m AHD	193	-7											-7				-7						
			m bgl	0	200											200				200						
Bonniefield 1	297179	6771348	m AHD	18	-994															-328	-371				-659	-890
			m bgl	0	1012															346	389				677	908
Bootine 1	388223	6550242	m AHD	166	-3037						-15				-89	-524	-1137	-1962	-2899	-2899		-3037				
			m bgl	0	3203						181				255	690	1303	2128	3065	3065		3203				
BS5	321519	6641020	m AHD	51	-406	9																		-325	-406	
			m bgl	0	457	42																		376	457	
BS6	321539	6645470	m AHD	35	-440	17																		-433	-440	
			m bgl	0	475	18																		468	475	
BS7	319649	6646270	m AHD	61	-518	13																		-491	-518	
			m bgl	0	579	48																		552	579	
Bullsbrook 1	390061	6516984	m AHD	86	-2765						-74					-1191	-1882	-2224	-2721	-2721	-2765					
			m bgl	0	2851						160					1277	1968	2310	2807	2807	2851					
Bunjong 1	299492	6764518	m AHD	8	-816												-378	-575	-790	-790	-816					
			m bgl	0	823												385	582	797	797	823					
Casuarina	325395	6800166	m AHD	237	34														34	34						
			m bgl	0	203														203	203						
Casuarinas 1	319992	6798872	m AHD	240	-1238														-89	-89		-146				
			m bgl	0	1478														329	329		386				

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Cataby 1	340386	6603965	m AHD	58	-2240													-65	-664	-664	-712	-1814	-1994			
			m bgl	0	2298													123	722	722	770	1872	2052			
CEB1	349300	6605990	m AHD	87	-213											-213				-213						
			m bgl	0	300											300				300						
Connolly 1	300678	6786237	m AHD	108	-370															-76	-118					
			m bgl	0	478															184	226					
Coomallo 1	347731	6652726	m AHD	253	-3267											-547	-1160	-1911	-2719	-2719	-2801	-3253				-3267
			m bgl	0	3520											800	1413	2164	2972	2972	3054	3506				3520
Corybas 1	310853	6768323	m AHD	56	-1032											-164	-494	-672	-1001	-1001	-1032					
			m bgl	0	1088											220	550	728	1057	1057	1088					
CPB10	349130	6607475	m AHD	84	36	52														36						
			m bgl	0	48	32														48						
CPB11	349220	6606770	m AHD	86	31	56														31						
			m bgl	0	55	30														55						
CPB12	350510	6605640	m AHD	91	36	50														36						
			m bgl	0	55	41														55						
CPB13	349930	6606310	m AHD	89	32	59														32						
			m bgl	0	57	30														57						
CPB14	350000	6606780	m AHD	77	19	45														19						
			m bgl	0	58	32														58						
CPB15	344433	6613335	m AHD	73	-115	51										3	-115			-115						
			m bgl	0	188	22										70	188			188						
CPB17	345395	6610835	m AHD	71	-129	46											-129			-129						
			m bgl	0	200	25											200			200						
CPB3A	350989	6608481	m AHD	97	43	82														43						
			m bgl	0	54	15														54						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
CPB6	352820	6608210	m AHD	115	-185															-185						
			m bgl	0	300															300						
CPB7	351935	6608015	m AHD	100	52	83														52						
			m bgl	0	48	17														48						
CPB8	350255	6607885	m AHD	97	-203	77														-203						
			m bgl	0	300	20														300						
Cypress Hill 1	386064	6629311	m AHD	212	-778						-111			-722	-772											
			m bgl	0	990						323			934	984											
Dandaragan 1-77	376260	6606564	m AHD	174	18						81			18												
			m bgl	0	156						93			156												
Dandaragan 1-81	376300	6606650	m AHD	130	6						13			6												
			m bgl	0	124						117			124												
Dandaragan 1	385808	6614516	m AHD	267	-836										-588	-836				-836						
			m bgl	0	1103										855	1103				1103						
Dathagnoorara 1/91	375330	6702880	m AHD	276	90									90												
			m bgl	0	186									186												
Dathagnoorara 2-86	375240	6702880	m AHD	276	46									-221	190					46						
			m bgl	0	230									55	86					230						
Denison 1	301330	6765421	m AHD	27	-2273												-378	-566	-728	-728	-766	-1099	-1260	-1390	-1486	-1746
			m bgl	0	2300												405	593	755	755	793	1126	1287	1417	1513	1773
Depot Hill 1	337131	6779723	m AHD	263	-2210											-183	-244	-333	-392	-392					-522	-699
			m bgl	0	2473											446	507	596	655	655					785	962
Diamond Soak 1	331187	6800211	m AHD	264	-499													78	-258	-258	-315	-499				
			m bgl	0	763													186	522	522	579	763				
Dinner Hill No 1	367169	6645409	m AHD	349	44									263	184	44				44						
			m bgl	0	305									86	165	305				305						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Dinner Hill No 2	366282	6645338	m AHD	322	-44									286	214	-44				-44						
			m bgl	0	366									36	108	366				366						
DOH 1	382154	6607521	m AHD	275	-23		173				-23															
			m bgl	0	298		102				298															
Dominion Downs TP1	382439	6683800	m AHD	251	114									114												
			m bgl	0	137									137												
Dongara 8	307977	6762556	m AHD	49	-1850											-60	-351	-548		-691	-736	-1107	-1185	-1307	-1396	-1660
			m bgl	0	1899											109	400	597		740	785	1156	1234	1356	1445	1709
Dongara 1	304739	6762409	m AHD	45	-2116															-777	-808	-1021	-1217	-1309	-1363	-1626
			m bgl	0	2161															822	853	1066	1262	1347	1408	1671
Dongara 12	307844	6764032	m AHD	26	-1987															-774	-824	-1068	-1171	-1271	-1315	-1599
			m bgl	0	2013															800	850	1094	1197	1297	1341	1625
Dongara 13	305366	6766792	m AHD	84	-1949															-682	-751	-1077	-1266	-1394	-1457	-1712
			m bgl	0	2033															766	835	1161	1350	1478	1541	1796
Dongara 16	305125	6760501	m AHD	25	-1899															-746	-815	-1075	-1170	-1293	-1359	-1627
			m bgl	0	1924															771	840	1100	1195	1318	1384	1652
Dongara 19	310229	6760443	m AHD	110	-2069															-1081	-1136				-1551	-1663
			m bgl	0	2179															1191	1246	?	?	?	1661	1773
Dongara 2	303516	6762819	m AHD	23	-1722															-705	-765	-983	-1273	-1318	1391	-1659
			m bgl	0	1745															728	788	1006	1296	1341	1414	1682
Dongara 20	307924	6760892	m AHD	76	-1863															-626	-688	-1013	-1167	-1294	-1360	-1633
			m bgl	0	1939															702	764	1089	1243	1370	1436	1709
Dongara 22	303705	6762849	m AHD	32	-1768															-666	-728	-1046	-1199	-1316	-1407	-1669
			m bgl	0	1800															698	760	1078	1231	1348	1439	1701
Dongara 26	302942	6763057	m AHD	18	-1812															-754	-802	-1179	-1286	-1370	-1452	-1670
			m bgl	0	1830															772	820	1199	1304	1388	1474	1686

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Dongara 27	307823	6768185	m AHD	34	-1696															-650	-671	-998	-1076	-1141	-1185	-1448
			m bgl	0	1730															684	705	1032	1110	1175	1219	1482
Dongara 5	304075	6769572	m AHD	28	-1780															-555	-615	-898		-1100	-1221	-1503
			m bgl	0	1808															583	643	926		1128	1249	1531
Dongara 6	299794	6768697	m AHD	25	-1534															-610	-649	-918	-1154	-1255	-1298	-1423
			m bgl	0	1559															635	674	943	1179	1280	1323	1448
Dongara 7	308652	6756162	m AHD	43	-2121															-743	-815	-1079	-1411	-1569	-1628	-2051
			m bgl	0	2164															786	858	1122	1454	1612	1671	2094
Dongara Line DL1A	308668	6752317	m AHD	18	-474												-234	-482		-482						
			m bgl	0	492												252	500		500						
Dongara Line DL2A	320106	6752422	m AHD	86	-415											-228	-417			-417						
			m bgl	0	501											314	503			503						
Dongara Line DL3A	333143	6752581	m AHD	128	-353											-356				-356						
			m bgl	0	481											484				484						
Dongara Line DL4B	344970	6752754	m AHD	258	-243									233	168	-250				-250						
			m bgl	0	501									25	90	511				511						
Dongara Line DL5A	356890	6752577	m AHD	299	-100									100	70	-100				-100						
			m bgl	0	399									199	229	399				399						
Donkey Creek 1	334610	6721529	m AHD	107	-3746											-113	-506	-905		-1535	-1606	-2401	-3256	-3455	-3636	-3746
			m bgl	0	3853											220	613	1012		1642	1713	2508	3363	3562	3743	3853
Dookanooka 1-75	364146	6731712	m AHD	288	21									21												
			m bgl	0	267									267												
Dookanooka 1-00	364147		m AHD	288	-11									-11												
			m bgl	0	299									299												
DSO5	367798	6695215	m AHD	280	210									210												
			m bgl	0	70									70												

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
DSP6	367807	6695161	m AHD	281	176									176												
			m bgl	0	105									105												
E. Lake Logue 1	321711	6698281	m AHD	49	-2381																	-472				
			m bgl	0	2430																	521				
E. Lake Logue 2	321826	6699961	m AHD	43	-2260															-307	-349					
			m bgl	0	2303															350	392					
East Heaton 1	329835	6778210	m AHD	252	-2268															-1123	-1167	-1398		-1515	-1569	-1789
			m bgl	0	2520															1375	1419	1650		1767	1821	2041
EC60	328740	6688530	m AHD	59	-91	30																-91				
			m bgl	0	150	30																150				
ED1	367172	6546146	m AHD	55	-285	12	-44		-185		-285															
			m bgl	0	340	43	99		240		340															
Eganu 1	386924	6682465	m AHD	233	-367																	-367				
			m bgl	0	600																	600				
Ejarno 1	313277	6755704	m AHD	73	-2795														-996	-996	-1077	-1728	-1982	-2152	-2261	-2654
			m bgl	0	2868														1069	1069	1150	1801	2055	2225	2334	2727
Emu Downs MP1	347513	6625199	m AHD	189	9											9				9						
			m bgl	0	180											180				180						
Emu Downs PB1	347415	6625633	m AHD	193	13											13				13						
			m bgl	0	180											180				180						
Eneabba Line EL10	311522	6694803	m AHD	11	-148	-25																		-145		
			m bgl	0	159	36																		156		
Eneabba Line EL11	316462	6693611	m AHD	66	-36																	-630	-696			
			m bgl	0	102	66																696	762			
Eneabba 40125-2	334547	6688137	m AHD	113	-370	86												-237	-370	-370						
			m bgl	0	483	27												350	483	483						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Eneabba 1-75	333647	6699931	m AHD	106	-134													-134		-134						
			m bgl	0	240													240		240						
Eneabba 40125-1	334367	6687531	m AHD	118	-350													58	-350	-350						
			m bgl	0	468													60	468	468						
Eneabba 40125-3	334392	6689828	m AHD	98	-470	76												-270	-470	-470						
			m bgl	0	568	22												368	568	568						
Eneabba 40125-4	333110	6687462	m AHD	114	-286	104												74	-286	-286						
			m bgl	0	400	10												40	400	400						
Eneabba 40125-5	334491	6686659	m AHD	134	-268	86												-56	-268	-268						
			m bgl	0	402	48												190	402	402						
Eneabba Line EL1A	370634	6702762	m AHD	257	-494									-34	-100	-493				-493						
			m bgl	0	751									291	357	750				750						
Eneabba Line EL2A	364325	6702687	m AHD	264	-498									-114	-216	-496				-496						
			m bgl	0	762									378	480	760				760						
Eneabba Line EL3A	357884	6702360	m AHD	295	-467									-139	-233	-465				-465						
			m bgl	0	762									434	528	760				760						
Eneabba Line EL4	350593	6702012	m AHD	254	-538									38	-42	-493				-493						
			m bgl	0	792									216	296	747				747						
Eneabba Line EL5	344497	6701564	m AHD	201	-517											-515				-515						
			m bgl	0	718											716				716						
Eneabba Line EL6	338577	6702915	m AHD	139	-624													-279	-621	-621						
			m bgl	0	763													418	760	760						
Eneabba Line EL7	332354	6703890	m AHD	96	-669													-264	-669	-669						
			m bgl	0	765													360	765	765						
Eneabba Line EL8A	328854	6698052	m AHD	69	-661	44													3	3	-31	-675				
			m bgl	0	730	25													66	66	100	744				

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Eneabba Line EL9	324341	6696211	m AHD	52	-745	6																-284	-743			
			m bgl	0	797	46																336	795			
Eneabba 1	338583	6727776	m AHD	123	-4056											-201	-442	-1045	-1627	-1627	-1734	-2187	-2855	-3132	-3279	-4056
			m bgl	0	4179											324	565	1168	1750	1750	1857	2310	2978	3255	3402	4179
ERA71	328150	6692600	m AHD	56	-117	31																-117				
			m bgl	0	173	24																173				
ERA73	329850	6685740	m AHD	80	-101	62																-101				
			m bgl	0	181	18																181				
ERA74	329755	6685810	m AHD	78	-41	66																-41				
			m bgl	0	119	12																119				
ERA75	329980	6685760	m AHD	80	-83	63																-83				
			m bgl	0	163	17																163				
ERA76	329770	6685800	m AHD	79	-91	66																-91				
			m bgl	0	170	13																170				
Eremia 1	307513	6756147	m AHD	27	-807													-592	-782	-782	-807					
			m bgl	0	834													619	809	809	834					
Erregulla 1	344612	6749291	m AHD	233	-4011											-567	-979	-1302	-1786	-1786	-1825	-2571			-3129	-2672
			m bgl	0	4244											800	1212	1535	2019	2019	2058	2804			3362	3905
Erregulla 2	344609	6749507	m AHD	241	-3336															-1782	-1843	-1849	-2553	-3150	-3291	-3336
			m bgl	0	3577															2023	2084	2090	2794	3391	3532	3577
Eurangoa 1	318961	6776624	m AHD	250	-2027															-823	-859			-1058	-1203	-1446-1414
			m bgl	0	2277															1073	1109			1308	1453	1696
Evandra 1	307860	6751797	m AHD	17	-832												-372	-594	-783	-783	-832					
			m bgl	0	849												389	611	800	800	849					
EWP1	329187	6691571	m AHD	57	-76	37																-76				
			m bgl	0	133	20																133				

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
EWP2	329171	6691002	m AHD	54	-83	36																-83				
			m bgl	0	137	18																137				
EWP3	329190	6690481	m AHD	56	-82	36																-82				
			m bgl	0	138	20																138				
EWP4	329149	6690181	m AHD	56	-109																	-109				
			m bgl	0	165																	165				
EWP5	329153	6689133	m AHD	54	-82	29																-82				
			m bgl	0	136	25																136				
EWP6	330372	6690236	m AHD	61	-163	44																-163				
			m bgl	0	224	17																224				
EWP7	330378	6691608	m AHD	64	-171																	-171				
			m bgl	0	235																	235				
EWP8	330361	6688784	m AHD	60	-150																	-150				
			m bgl	0	210																	210				
GG1 75	396282	6532092	m AHD	124	-155		18	-22	-115		-155															
			m bgl	0	279		106	146	239		279															
GG1 85	396511	6531630	m AHD	92	13		13																			
			m bgl	0	79		79																			
Gillingarra Line GL1	348000	6564250	m AHD	4	-998	-28	-74		-79		-233	-249	-276			-504	-991			-991						
			m bgl	0	1002	32	78		83		237	253	280			508	995			995						
Gillingarra Line GL2	350300	6566300	m AHD	130	-874	-12	-53		-78	-87	-727	-778	-798				-874			-874						
			m bgl	0	1004	143	184		208	217	857	908	928				1004			1004						
Gillingarra Line GL3	358700	6567800	m AHD	59	-948	27	-45		-95	-103	-438	-616	-635				-940	-948		-948						
			m bgl	0	1007	32	104		154	162	497	675	694				999	1007		1007						
Gillingarra Line GL4	368150	6566600	m AHD	77	-1125	3					-518	-592	-619			-782	-1123			-1123						
			m bgl	0	1202	74					595	669	696			859	1200			1200						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Gillingarra Line GL5	376750	6569250	m AHD	85	-1117	62					-140	-155	-215			-380	-1055	-1115		-1115						
			m bgl	0	1202	23					225	240	300			465	1140	1200		1200						
Gillingarra Line GL6	383700	6571200	m AHD	128	-847						27			-330	-379	-701	-847			-847						
			m bgl	0	975						101			458	507	829	975			975						
Gillingarra Line GL7	394350	6568600	m AHD	145	-1056		120		40	26	-227			-1033	-1056											
			m bgl	0	1201		25		105	119	372			1178	1201											
Gillingarra Line GL8	405000	6566000	m AHD	172	-1000				77	59	-151							-261	-411	-411	-490	-993				
			m bgl	0	1172				95	113	323							433	583	583	662	1165				
Gingin Line 1	401660	6530940	m AHD	117	-495	103	39	17			-203			-495												
			m bgl	0	612	14	78	100			320			612												
Gingin Line 2	387246	6533723	m AHD	58	-451	3					-112						-447			-447						
			m bgl	0	509	55					170						505			505						
Gingin Line 3	376315	6535236	m AHD	32	-689	-36					-296	-346	-408						-628	-628	-663	-689				
			m bgl	0	720	67					327	377	440						659	659	694	720				
Gingin Line 4	361830	6534070	m AHD	10	-525	-30			-155	-182	-313															
			m bgl	0	535	40			165	192	323															
Gingin Line 5	395400	6531470	m AHD	104	-412	86	49	24	-23		-292			-414												
			m bgl	0	516	18	55	80	127		396			518												
Gingin Line 6	367390	6535764	m AHD	19	-777	-6	-45		-136		-335								-777	-777						
			m bgl	0	796	25	64		156		354	?	?						796	796						
Gingin No1	388342	6554087	m AHD	198	-4346						83			-102	-158	-781	-1500	-2054	-3149	-3149	-3268	-4293				
			m bgl	0	4544						115			300	356	979	1698	2252	3347	3347	3466	4491				
GR1	395515	6615136	m AHD	233	142		205		-30	-60	142															
			m bgl	0	375		28		263	293	375															
Heaton 1	326223	6777352	m AHD	186	-2252											-341	-530	-817	-1084	-1084	-1121	-1414		-1673	-1733	-1944
			m bgl	0	2438											527	716	1003	1270	1270	1307	1600		1859	1919	2130

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Hill River 1	337808	6650473	m AHD	109	-470														40	40	-43	-470				
			m bgl	0	579														69	69	152	579				
Hill River HRA	338883	6649346	m AHD	91	-5														-5	-5						
			m bgl	0	96														96	96						
Hill River HRB	339504	6649335	m AHD	85	-11														-11	-11						
			m bgl	0	96														96	96						
Hill River HRC	339048	6649951	m AHD	84	-12														-12	-12						
			m bgl	0	96														96	96						
Hill River HRD	340832	6648390	m AHD	96	0													0		0						
			m bgl	0	96													96		96						
Hill River HRF	339647	6649333	m AHD	85	-11	57													-11	-11						
			m bgl	0	96	28													96	96						
Hill River HRG	340096	6649448	m AHD	85	-11	59													-11	-11						
			m bgl	0	96	26													96	96						
Hill River HR H	342137	6649168	m AHD	99	3											3				3						
			m bgl	0	96											96				96						
Hill River HRI	341145	6649394	m AHD	96	0													0		0						
			m bgl	0	96													96		96						
Hill River HRK	342248	6649360	m AHD	99	3											3				3						
			m bgl	0	96											96				96						
Hill River HRL	342461	6649334	m AHD	100	4											4				4						
			m bgl	0	96											96				96						
Hill River HRM	342958	6649697	m AHD	105	5											5				5						
			m bgl	0	100											100				100						
Hill River No.1	337816	6650473	m AHD	111	-468														40	40	-43	-470				
			m bgl	0	579														69	69	152	579				

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Hill River No.4	330294	6636682	m AHD	93	-215																			-140	-215	
			m bgl	0	308																			233	308	
Horner West 1	309740	6775434	m AHD	95	-1356															-691	-741					
			m bgl	0	1451															786	836					
Hovea1	309876	6755321	m AHD	60	-1194	-24										-145	-622	-860	-1122	-1122	-1194					
			m bgl	0	1254	84										205	682	920	1182	1182	1254					
HR TP4	342191	6649376	m AHD	99	-6	84											-6			-6						
			m bgl	0	105	15											105			105						
HR TP5	339412	6649334	m AHD	85	-11	58													-11	-11						
			m bgl	0	96	27													96	96						
HRC MP2	347599	6646250	m AHD	130	-270											-203	-270			-270						
			m bgl	0	400											333	400			400						
HRC MP3	339039	6654818	m AHD	110	-197													-58	-197	-197						
			m bgl	0	307													168	307	307						
HRC TP1	337039	6663350	m AHD	135	-210													50	-210	-210						
			m bgl	0	345													85	345	345						
HY J	341752	6649512	m AHD	96	0											0				0						
			m bgl	0	96											96				96						
IRWIN VIEW 0B2-75	314735	6780248	m AHD	149	-72									39		-25	-51			-51						
			m bgl	0	221									110		174	200			200						
IRWIN VIEW 0B4-75	309991	6777448	m AHD	101	-56											-55				-55						
			m bgl	0	157											156				156						
IRWIN VIEW OB10-77	307775	6771858	m AHD	47	-161															-158						
			m bgl	0	208															205						
IRWIN VIEW OB11-77	318146	6768980	m AHD	110	-102											-105				-105						
			m bgl	0	212											215				215						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
IRWIN VIEW OB12-77	326748	6771614	m AHD	177	-38											-37				-37						
			m bgl	0	215											213				213						
IRWIN VIEW OB13-77	322996	677996	m AHD	180	-23									92		-19				-19						
			m bgl	0	203									88		199				199						
IRWIN VIEW OB1-76	326148	6777242	m AHD	181	-72											-69				-69						
			m bgl	0	253											250				250						
IRWIN VIEW OB1-77	307773	6777350	m AHD	80	-141											68	-135	-137		-137						
			m bgl	0	221											12	215	217		217						
IRWIN VIEW OB2-76	324597	6772850	m AHD	149	-58											-55				-55						
			m bgl	0	207											204				204						
IRWIN VIEW OB2-77	312443	6775651	m AHD	145	-63											-37	-62			-62						
			m bgl	0	208											182	207			207						
IRWIN VIEW OB3-76	322027	6767710	m AHD	112	-194											-194				-194						
			m bgl	0	306											306				306						
IRWIN VIEW OB3-77	314984	6766364	m AHD	58	-162											-159				-159						
			m bgl	0	220											217				217						
IRWIN VIEW OB4-75	309991	6777448	m AHD	102	-55											-45				-45						
			m bgl	0	157											147				147						
IRWIN VIEW OB4-76	310045	6774430	m AHD	88	-120											-69	-249			-249						
			m bgl	0	208											245	425			425						
IRWIN VIEW OB4-77	311163	6766560	m AHD	53	-150											-149				-149						
			m bgl	0	203											202				202						
IRWIN VIEW OB5-76	311166	6768879	m AHD	85	-137											-134				-134						
			m bgl	0	222											219				219						
IRWIN VIEW OB5-77	318654	6766652	m AHD	87	-127											-125				-125						
			m bgl	0	214											212				212						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
IRWIN VIEW OB6-76	320146	6770860	m AHD	173	-66											-67				-67						
			m bgl	0	239											240				240						
IRWIN VIEW OB6-77	322950	6779918	m AHD	228	-42									111		-41				-41						
			m bgl	0	270									117		269				269						
IRWIN VIEW OB7-77	313110	6771923	m AHD	140	-55											-50				-50						
			m bgl	0	195											190				190						
IRWIN VIEW OB8-77	317234	6772450	m AHD	147	-79											-63				-63						
			m bgl	0	226											210				210						
IRWIN VIEW OB9-77	305917	6774390	m AHD	37	-178												-129	-173		-177						
			m bgl	0	215												166	210		214						
Jay1	310954	6781841	m AHD	130	-1165											-75	-412	-557	-783	-783	-846					
			m bgl	0	1295											205	542	687	913	913	976					
JBM1	351200	6565652	m AHD	140	-12	67	18		10	2	-12															
			m bgl	0	152	73	122		130	138	152															
JE2	337204	6663318	m AHD	135	-110														-110	-110						
			m bgl	0	245														245	245						
JE3	352890	6657620	m AHD	232	12											128	12			12						
			m bgl	0	220											104	220			220						
JE4	349240	6645524	m AHD	145	-105											-105										
			m bgl	0	250											250										
JE5	337915	6634844	m AHD	145	-95														-95	-95						
			m bgl	0	240														240	240						
Jingemia 1	304943	6752723	m AHD	8	-979											-96	-452	-678	-920	-920	-979					
			m bgl	0	987											104	460	686	928	928	987					
JJC1	384440	6553850	m AHD	105	-146	63					-123			-146												
			m bgl	0	251	42					228			251												

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
JJC2	383490	6553850	m AHD	76	-175	54					-152			-175												
			m bgl	0	251	22					228			251												
JJC3	382490	6553850	m AHD	63	-76	42					-76															
			m bgl	0	139	21					139															
JJC4	381640	6553850	m AHD	62	-190	28					-190															
			m bgl	0	252	34					252															
JML7	336804	6703343	m AHD	126	-282													-282		-282						
			m bgl	0	408													408		408						
Jurien 28-01	316132	6649426	m AHD	42	-263	-3																		-235	-263	
			m bgl	0	305	45																		277	305	
Karara PB1	342807	6773234	m AHD	149	-151											-101	-151			-151						
			m bgl	0	300											250	300			300						
Killarney PB1	396670	6614340	m AHD	236	-122				3	-31	-122															
			m bgl	0	358				233	267	358															
Kingia1	308719	6746906	m AHD	25	-728												-270	-505	-682	-682	-728					
			m bgl	0	753												295	530	707	707	753					
Lakelands PB1	319989	6688930	m AHD	40	-430	8																	-430			
			m bgl	0	470	32																	470			
Lakelands PB2	320239	6688550	m AHD	40	-380	-5																	-380			
			m bgl	0	420	45																	420			
LSS B1	405115	6537084	m AHD	175	92	155	126	97	92																	
			m bgl	0	83	20	50	78	83																	
MAB1	334872	6749575	m AHD	148	-192											-192				-192						
			m bgl	0	340											340				340						
Mondarra 1	317106	6755872	m AHD	77	-2986											-330	-630	-956		-1211	-1286	-1792	-2103	-2238	-2307	-2608
			m bgl	0	3063											407	707	1033		1288	1363	1869	2180	2315	2384	2685

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Mondarra 2	316013	6751603	m AHD	27	-2827											-266	-554	-875		-1153	-1208	-1800	-2281	-2447		-2699
			m bgl	0	2854											293	581	902		1180	1235	1827	2308	2474		2726
Mondarra 3	316824	6758175	m AHD	91	-2896													-906		-1152	-1209					
			m bgl	0	2987													997		1243	1300					
Mondarra 4	315766	6755171	m AHD	45	-2850															-1147	-1251	-1695	-2008	-1199	-2338	-1756
			m bgl	0	2895															1192	1296	1740	2053	2244	2363	2801
Moora 1-73	392656	6612759	m AHD	239	-181		193		29	20	-181															
			m bgl	0	420		46		210	219	420															
Moora 1-89	393340	6612750	m AHD	238	-117		191		26	16	-117															
			m bgl	0	355		47		212	222	355															
Moora 2-73	391109	6612886	m AHD	221	-128		60		14	2	-128															
			m bgl	0	349		161		207	219	349															
Moora Line ML1A	396862	6612400	m AHD	213	-543				26	-1	-417			-537												
			m bgl	0	756				187	214	630			750												
Moora Line ML2A	387600	6613340	m AHD	206	-556	203					-92			-554												
			m bgl	0	762	3					298			760												
Moora Line ML3A	379166	6611416	m AHD	193	-569	187	161				2			-572												
			m bgl	0	762	6	32				191			765												
Moora Line ML4A	369274	6610253	m AHD	285	-447									-135	-215	-437				-437						
			m bgl	0	732									420	500	722				722						
Moora Line ML5A	359774	6609733	m AHD	204	-568											-517	-568			-568						
			m bgl	0	772											721	772			772						
Moora Line ML6A	352901	6608040	m AHD	116	-656	95										-369	-644			-644						
			m bgl	0	772	21										485	760			760						
Moora Line ML7A	340607	6607557	m AHD	70	-731													-228	-719	-719						
			m bgl	0	801													298	789	789						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Moora Line ML8A	329190	6617329	m AHD	39	-731																		-114	-731		
			m bgl	0	770																		153	770		
Moora Line ML9A	321499	6606980	m AHD	9	-16	-11																				-11
			m bgl	0	25	20																				25
Mooratara 1	296852	6766622	m AHD	4	-1626															-343	-387					
			m bgl	0	1630															347	391					
Mountain Bridge 1	316301	6724015	m AHD	39	-3377														-538	-538	-599	-1235	-1729	-1945	-2120	-2608
			m bgl	0	3416														577	577	638	1274	1768	1984	2159	2647
MP-1	337039	6663350	m AHD	135	-265													55	-265	-265						
			m bgl	0	400													80	400	400						
MP3	339039	6654750	m AHD	110	-197													-30	-197	-197						
			m bgl	0	307													140	307	307						
MRS 1-01	340130	6782832	m AHD	216	42											85	49	42		42						
			m bgl	0	174											131	167	174		174						
Mt Adams 1	322257	6745667	m AHD	86	-3705											-259	-579	-951	-1334	-1334	-1440	-1955	-2581	-2666	-2849	-3442
			m bgl	0	3791											345	665	1037	1420	1420	1526	2041	2667	2752	2935	3528
Mt Hill 1-77	295990	6789730	m AHD	30	-120																	-120				
			m bgl	0	150																	150				
Mt Hill 16-85	301139	6787131	m AHD	131	-7															-7						
			m bgl	0	138															138						
Mt Hill 17-85	301169	6786171	m AHD	123	-21															-21						
			m bgl	0	144															144						
Mt Horner 1	313829	6776295	m AHD	195	-2057															-878	-917			-1133	-1192	-1382
			m bgl	0	2252															1073	1112			1328	1387	1577
Mt Horner 7	314443	6776864	m AHD	213	-1635															-849	-883	-115		-1265	-1361	-1574
			m bgl	0	1848															1062	1096	1328		1478	1574	1787

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Mullering 1	339697	6603614	m AHD	57	-1609														-218	-218		-1609				
			m bgl	0	1666														275	275		1666				
Mungarra 1	316283	6807251	m AHD	191	-419														17	17						
			m bgl	0	609														174	174						
Mungarra 2	313431	6800837	m AHD	232	-381															54		-994				
			m bgl	0	613															178		1226				
Mungarra 3	313532	6794643	m AHD	246	-385														35	35		-85				
			m bgl	0	631														211	211		331				
Mungarra 4	331172	6801554	m AHD	262	-381													7	-167	-167		-258				
			m bgl	0	643													255	429	429		520				
Mungarra 5	318577	6802360	m AHD	233	-389															-54		-175				
			m bgl	0	622															287		408				
Narkarino 1	295792	6777233	m AHD	27	-573															-183	-224				-457	-573
			m bgl	0	600															210	251				484	600
Narlingue 1	315454	6782850	m AHD	193	-1937															-753	-794					
			m bgl	0	2130															946	987					
NEE B1	367551	6548014	m AHD	54	-15	28	-4		-15																	
			m bgl	0	69	26	58		69																	
NEE B2	369493	6549996	m AHD	60	-12	33	-5		-12																	
			m bgl	0	72	27	65		72																	
No7	385262	6590616	m AHD	179	123				123																	
			m bgl	0	56				56																	
North Erregulla 1	337485	6763780	m AHD	163	-3282											-1104	-1291	-1580	-1735	-1735	-1860	-2224	-2623		-2639	-3058
			m bgl	0	3444											1266	1453	1742	1897	1897	2022	2387	2786		2802	3221
North Gingin NGG1	354794	6540935	m AHD	29	-869	-23			-71		-266	-426	-686			-869										
			m bgl	0	898	52			100		295	455	715			898										

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
North Gingin NGG10	340832	6588847	m AHD	38	-330	-1							-202				-330									
			m bgl	0	368	39							240				368									
North Gingin NGG11	352559	6590849	m AHD	70	-170	18							-56				170									
			m bgl	0	240	52							126				240									
North Gingin NGG12	364476	6591073	m AHD	122	-142								10				-142									
			m bgl	0	264								112				264									
North Gingin NGG2	364382	6544635	m AHD	27	-995	-10			-183		-673	-753	-893				-995									
			m bgl	0	1022	37			210		700	780	920				1022									
North Gingin NGG3	379896	6541610	m AHD	46	-530	11					-194	-214	-404				-530									
			m bgl	0	576	35					240	260	450				576									
North Gingin NGG4	349125	6558311	m AHD	37	-475	-19			-98		-223	-278	-423				475									
			m bgl	0	512	56			135		260	315	460				512									
North Gingin NGG5	362096	6555911	m AHD	45	-723	-1			-150		-605	-695	-723													
			m bgl	0	768	46			195		650	740	768													
North Gingin NGG6	381279	6557868	m AHD	70	-266	44					-140		-243				-266									
			m bgl	0	336	26					210		313				336									
North Gingin NGG7	345177	6580914	m AHD	70	-520	3					-260		-475				-520									
			m bgl	0	590	67					330		545				590									
North Gingin NGG8	353959	6580652	m AHD	58	-529	4					-352		-482				-529									
			m bgl	0	587	54					410		540				587									
North Gingin NGG9	369231	6581466	m AHD	97	-474	59					-23		-73				-474									
			m bgl	0	571	38					120		170				571									
North Yardanogo 1	315885	6738699	m AHD	35	-2352															-1050	-1100					
			m bgl	0	2387															1085	1135					
North Yardarino 1	309566	6769517	m AHD	56	-2214															-928	-955	-1393	-1641	-1756		
			m bgl	0	2270															984	1011	1449	1697	1812		

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Ocean Hill 1	345364	6687264	m AHD	213	-3627											-676	-1233	-1948	-2740	-2740	-3026					
			m bgl	0	3840											889	1446	2161	2953	2953	3239					
Petro PB1	332603	6714704	m AHD	97	-75												-75			-75						
			m bgl	0	172												172			172						
Petro PB2	332760	6714152	m AHD	99	-57												-57			-57						
			m bgl	0	156												156			156						
Petro PB3	332934	6713576	m AHD	104	-37												-37			-37						
			m bgl	0	141												141			141						
Quinns Rock 1	359460	6480637	m AHD	24	-2186						-585	-735	-751			-1109	-1563	-1665	-2181	-2181						
			m bgl	0	2210						611	760	775			1133	1587	1689	2205	2205						
Red Gully RG1A	395019	6560569	m AHD	145	-329	142	123	115	67	49	-285			-329												
			m bgl	0	474	3	22	30	78	96	430			474												
Red Gully RG2A	402223	6544254	m AHD	162	-328	156	112	99	14	-34	-299			-328												
			m bgl	0	490	6	50	63	148	196	461			490												
Red Gully RG3A	402930	6520639	m AHD	101	-98	98	54	5	-73	-85	-98															
			m bgl	0	199	3	47	96	174	186	199															
Red Gully RGP2	379351	6619278	m AHD	194	38						76			38												
			m bgl	0	156						118			156												
Redback 1	321748	6739868	m AHD	65	-1263											-200	-442	-843	-1187	-1187	-1263					
			m bgl	0	1328											265	507	908	1252	1252	1328					
REM1A	335261	6701352	m AHD	115	-376													-306	-376	-376						
			m bgl	0	491													421	491	491						
REM2	334954	6701130	m AHD	113	-395													-283	-395	-395						
			m bgl	0	508													396	508	508						
Rosslyn 1	309922	6782831	m AHD	109	-921											-46	-302	-387	-552	-552	-584					
			m bgl	0	1030											155	411	496	661	661	693					

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
RTO2	348167	6677117	m AHD	206	-194											-194				-194						
			m bgl	0	400											400				400						
RTO4	352298	6678396	m AHD	268	-32									83	45	-32				-32						
			m bgl	0	300									185	223	300				300						
SHTP01	339761	6682267	m AHD	193	-407													-109	-407	-407						
			m bgl	0	600													302	600	600						
Smart Exp1	396600	6539310	m AHD	195	102	185	143	130	109		102															
			m bgl	0	93	10	52	65	86		93															
Smart Exp2	397740	6539900	m AHD	214	115	204	153	142	125		115															
			m bgl	0	99	11	61	72	90		99															
Snottygobble 1	312803	6753195	m AHD	68	-1076											-146	-469	-755	-987	-987	-1076					
			m bgl	0	1144											214	537	823	1055	1055	1144					
Strawberry Hill 1	317565	6762468	m AHD	59	-2845													-1009	-1286	-1286	-1338	-1854	-2188	-2385	-2443	-2676
			m bgl	0	2903													1067	1344	1344	1396	1913	2247	2444	2502	2735
Tabletop 1	317181	6780430	m AHD	220	-1605												-340	-670	-793	-793						
			m bgl	0	1825												560	1110	1013	1013						
Tarantula 1	319418	6743777	m AHD	52	-1400														-1349	-1349	-1400					
			m bgl	0	1451														1400	1400	1451					
Tathra	363140	6720750	m AHD	266	126									126												
			m bgl	0	140									140												
Valley Brook No1	398000	6536000	m AHD	109	47	97	79	76	18	9	47															
			m bgl	0	156	13	30	33	91	100	156															
WAB-T01	354912	6646217	m AHD	190	-410											20	-410			-410						
			m bgl	0	600											170	600			600						
Walyering 1	353182	6601020	m AHD	95	-3549											-561	-1173	-1961	-2592	-2592		-3449				
			m bgl	0	3643											655	1267	2055	2686	2686		3543				

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Walyering 2	353990	6602420	m AHD	100	-4015															-2548		-4015				
			m bgl	0	4115															2648		4115				
Walyering 3	355977	6598964	m AHD	94	-4093														-2672	-2672						
			m bgl	0	4187														2766	2766						
Walyering 4	353551	6600943	m AHD	95	-2543															-2543						
			m bgl	0	2638															2638						
Warradong 1	322525	6757360	m AHD	96	-3621											-404	-674	-1075	-1439	-1439	-1477	-2157	-2474	-2631	-2689	-3082
			m bgl	0	3717											500	770	1171	1535	1535	1573	2253	2569	2727	2785	3178
Warro 1	378470	6662015	m AHD	291	-4094																-4094					
			m bgl	0	4385																4385					
Warro 2	378252	6662053	m AHD	292	-4562									-323	-383	-1601	-2106	-3076	-4076	-4076	-4255	-4558				
			m bgl	0	4854									615	675	1893	2398	3368	4368	4368	4547	4850				
Watheroo Line WL1	396287	6645071	m AHD	225	-327		209		118	94	-107			-196												
			m bgl	0	552		16		107	131	332			421												
Watheroo Line WL10	342223	6645376	m AHD	141	-624														-618	-618						
			m bgl	0	765														759	759						
Watheroo Line WL11	332615	6646698	m AHD	79	-683	71																-651				
			m bgl	0	762	8																730				
Watheroo Line WL12	318029	6646153	m AHD	50	-712	7																		-601	-712	
			m bgl	0	762	43																		651	762	
Watheroo Line WL2	387876	6645551	m AHD	261	-376		185		166	124	5			-96												
			m bgl	0	637		76		95	137	256			357												
Watheroo Line WL3	379215	6645442	m AHD	314	-289		289							-274												
			m bgl	0	603		25							588												
Watheroo Line WL4	371817	6645151	m AHD	335	-239									-234												
			m bgl	0	574									569												

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Watheroo Line WL5	365594	6645180	m AHD	286	-479									-5	-54	-473				-473						
			m bgl	0	765									291	340	759				759						
Watheroo Line WL6	359738	6645008	m AHD	217	-545											-494	-545			-545						
			m bgl	0	762											711	762			762						
Watheroo Line WL7	354138	6644873	m AHD	187	-576											-334	-576			-576						
			m bgl	0	762											520	762			762						
Watheroo Line WL8	349240	6645524	m AHD	149	-606	128										-439	-606			-606						
			m bgl	0	755	21										588	755			755						
Watheroo Line WL9	375800	6645286	m AHD	324	10									10												
			m bgl	0	314									314												
Watheroo Line WL10	342223	6645376	m AHD	141	-624														-624	-624						
			m bgl	0	765														765	765						
WCR1	325169	6645210	m AHD	49	-473	40																		-228	-457	-473
			m bgl	0	522	9																		277	506	522
WCR2	323599	6645150	m AHD	40	-383	17																		-370	-383	
			m bgl	0	423	23																		410	423	
WCR3	325159	6641080	m AHD	55	-105	37																		-105		
			m bgl	0	160	18																		160		
WCR4	324029	6641050	m AHD	60	-308	21																		-240	-308	
			m bgl	0	367	39																		300	367	
West Erregulla 1	336095	6743648	m AHD	220	-3845											-380	-670	-1135	-1686	-1686	-1757					
			m bgl	0	4065											600	890	1355	1906	1906	1977					
West White Pt 1	309825	6752209	m AHD	75	-2173															-878	-954	-1527	-1772		-1822	-2102
			m bgl	0	2248															953	1029	1602	1847		1897	2177
West White Pt 2	310077	6748456	m AHD	32	-2323											-128	-597	-858	-1059	-1059	-1105	2231	-1457	-1596	-1718	-2199
			m bgl	0	2355											160	629	890	1091	1091	1137	1356	1489	1628	1750	2231

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Wicherina 1	328477	6809440	m AHD	263	-1423														-17	-17	-34					-186
			m bgl	0	1686														280	280	297					449
Woodada 1	320284	6702526	m AHD	34	-2512															-337	-426	-731	-1214	-1421	-1613	-1171
			m bgl	0	2546															371	460	765	1248	1455	1647	2205
Woodada 3	321819	6707106	m AHD	42	-2498															-278	-309	-635	-1512	-1755	-1903	-2359
			m bgl	0	2540															320	351	677	1554	1797	1945	2401
Woodada 5	320278	6705088	m AHD	52	-2756															-298						
			m bgl	0	2808															350						
WRCC-T01	352839	6596751	m AHD	81	-419											-419				-419						
			m bgl	0	500											500				500						
WSX3	345428	6674861	m AHD	202	-143											-143				-143						
			m bgl	0	345											345				345						
WTE1	334579	6693080	m AHD	103	-348	82											11	-250	-348	-348						
			m bgl	0	450	21											92	352	450	450						
WTE10	335570	6692350	m AHD	115	-473													-347	-473	-473						
			m bgl	0	588													462	588	588						
WTE2	334579	6691480	m AHD	107	-593	90											40	-390	-593	-593						
			m bgl	0	700	17											67	497	700	700						
WTE3	336379	6692870	m AHD	143	-498	108												-329	-498	-498						
			m bgl	0	641	35												472	641	641						
WTE31	335904	6697874	m AHD	121	-83	89												-83		-83						
			m bgl	0	204	32												204		204						
WTE32	335211	6699159	m AHD	100	-110													-110		-110						
			m bgl	0	210													210		210						
WTE33	335390	6697433	m AHD	106	-98													-98		-98						
			m bgl	0	204													204		204						

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
WTE34	335214	6696769	m AHD	109	-101													-101		-101						
			m bgl	0	210													210		210						
WTE35	334529	6696736	m AHD	106	-104													-104		-104						
			m bgl	0	210													210		210						
WTE36	335100	6698086	m AHD	101	-76													-76		-76						
			m bgl	0	177													177		177						
WTE37s	331625	6689185	m AHD	89	-113	71													-113	-113						
			m bgl	0	202	18													202	202						
WTE38s	333085	6690880	m AHD	93	-132	86												-60	-132	-132						
			m bgl	0	225	7												153	225	225						
WTE39s	332270	6690150	m AHD	93	-127	70													-127	-127						
			m bgl	0	220	23													220	220						
WTE4	336239	6691500	m AHD	138	-561	101												-216	-561	-561						
			m bgl	0	699	37												354	699	699						
WTE5	334581	6690710	m AHD	100	-590													-348	-590	-590						
			m bgl	0	690													448	690	690						
WTE6	335284	6691480	m AHD	106	-588													-330	-588	-588						
			m bgl	0	694													436	694	694						
WTE7	334365	6693440	m AHD	102	-352													-323	-352	-352						
			m bgl	0	454													425	454	454						
WTE8	336100	6691530	m AHD	130	-346													-223	-346	-346						
			m bgl	0	476													353	476	476						
Yallalie No1	382040	6631150	m AHD	215	-3106						-24			-55	-105	-1848	-2432	-3099		-3099						
			m bgl	0	3321						239			270	320	2063	2647	3314		3314						
Yardarino 1	311080	6765996	m AHD	43	-2334											-218	-546	-813	-1031	-1031	-1063					
			m bgl	0	2377											261	589	856	1074	1074	1106					

Bore name	Easting	Northing	Elevation unit	Ground elevation (m AHD)	Dilling depth	Base formation																				
						QTs	Kcm	Kcom	Kcok	Kcoh	Kwl	Kws	Kwg	Kp	Kpo	Jyd	Jyc	Jyb	Jya	Jy	Jd	Jc	Je	Trl	Trw	Trk
Yukich	385330	6553080	m AHD	128	-74	83					-10			-74												
			m bgl	0	202	45					138			202												

Notes

The depth quoted for the deepest formation intersected in each bore represents the total drilling depth. As such, the total depth is generally not the base of that formation.

Some deep petroleum wells penetrate older Permian formations not included in Appendix A.

m AHD metre above Australian Height Datum

m bgl metre below ground level

QTs superficial formations

Kcm Molecap Greensand

Kcom Mirrabooka Member

Kcok Kardinya Shale Member

Kcoh Henley Sandstone Member

Kwl Leederville Formation

Kws South Perth Shale

Kwg Gage Formation

Kp ‘Undifferentiated’ Parmelia Group (see Table 6)

Kpo Otorowiri Formation

Jyd Yarragadee Formation Unit D

Jyc Yarragadee Formation Unit C

Jyb Yarragadee Formation Unit B

Jya Yarragadee Formation Unit A

Jy Yarragadee Formation (i.e. not resolved into units as above)

Jd Cadda Formation

Jc Cattamarra Coal Measures

Je Eneabba Formation

Trl Lesueur Sandstone

Trk Woodada Formation

Trk Kockatea Shale

Appendix B Pumping test analyses for the Superficial aquifer

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	Transmissivity (m^2/day)
OK1A	Oakajee	264290 m E 6834970 m N	33.5	39.5	6.0	20	300	0.10	1200
OK3	Oakajee	265392 m E 6832675 m N	11.6	17.6	6.0	26	150	0.02	1440
OK9	Oakajee	265392 m E 6835168 m N	45.3	49.3	4.0	15	270	1.06	84
OK12	Oakajee	265374 m E 6832571 m N	29.4	35.4	6.0	20	210	0.06	294
OK14	Oakajee	267047 m E 6831855 m N	28.0	36.0	8.0	22	240	0.24	232
OK17	Oakajee	265416 m E 6832858 m N	50.4	55.4	5.0	7	360	1.40	10
PB4	Geraldton	269239 m E 6819376 m N	13.0	16.0	3.0	387	5760	2.85	661
BH1	Geraldton	268034 m E 6821289 m N	6.0	12.0	6.0	246	720	1.99	250
BS7A	Jurien	319649 m E 6646270 m N	46.9	59.0	12.1	300	1140	4.60	1305
WCR2A	Jurien	323629 m E 6645150 m N	13.5	16.4	3.0	400	2880	6.25	600
BS9	Jurien	321859 m E 6646630 m N	24.5	30.5	6.0	190	2280	14.10	21
CB2	Jurien	326239 m E 6644430 m N	6.1	11.3	5.2	150	1560	3.70	71
CB3	Jurien	326118 m E 6644850 m N	1.1	6.3	5.2	350	100	2.75	221
W15	Jurien	326587 m E 6644404 m N	5.5	8.5	3.0	138	2350	2.63	164
W16	Jurien	326976 m E 6644902 m N	4.7	7.7	3.0	184	2600	3.33	144
TB1	Jurien	311396 m E 6644126 m N	14.5	20.5	6.0	432	2880	1.92	633
1-07	Jurien	314132 m E 6649179 m N	10.8	16.8	6.0	2500	480	1.68	11450
2-07	Jurien	314075 m E 6649355 m N	10.8	16.8	6.0	3000	480	0.35	>12000
4A	Jurien	362200 m E 6561620 m N	37.0	55.0	18.0	1183	480	10.36	251
5A	Jurien	368168 m E 6560230 m N	32.2	44.2	12.0	891	480	4.08	876
9C	Jurien	371182 m E 6554946 m N	30.0	42.2	12.0	952	480	3.78	264

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	Transmissivity (m^2/day)
10A	Jurien	381279 m E 6557868 m N	18.0	24.0	6.0	237	480	5.83	129
13A	Jurien	366646 m E 6548606 m N	57.4	75.4	18.0	1072	480	7.68	172
19B	Jurien	372229 m E 6541096 m N	36.0	56.0	20.0	445	480	10.75	894
20A	Jurien	379896 m E 6541610 m N	27.0	39.0	12.0	1345	480	3.25	908
CPB5	Cooljarloo	350087 m E 6607315 m N	6.0	60.0	54.0	–	–	–	900
CPB8B	Cooljarloo	350269 m E 6607885 m N	21.0	39.5	18.5	1400	2880	6.80	430
CPB9	Cooljarloo	349400 m E 6608130 m N	18.0	42.0	24.0	1645	2880	6.40	1000
CPB10	Cooljarloo	349130 m E 6607475 m N	24.0	42.0	18.0	1570	2880	6.10	720
CPB11	Cooljarloo	349220 m E 6606770 m N	24.0	48.0	24.0	1390	2880	4.65	730
CPB12	Cooljarloo	350510 m E 6605640 m N	24.0	48.0	24.0	1496	2880	6.90	680
CPB13	Cooljarloo	349930 m E 6606310 m N	27.0	45.0	18.0	1570	2880	4.50	960
CPB14	Cooljarloo	350000 m E 6606780 m N	24.0	42.0	18.0	1400	2880	24.40	1025
CEB1	Cooljarloo	349300 m E 6605990 m N	24.0	48.0	24.0	1736	2880	3.75	1060
PB2	Regans Ford	373119 m E 6568070 m N	39.5	57.5	18.0	1253	480	15.83	92
PB3	Regans Ford	373119 m E 6568849 m N	40.0	58.0	18.0	1074	4480	27.09	78
RF1	Lancelin	374700 m E 6570500 m N	41.0	59.0	18.0	1105	600	11.30	245
KTB1	Lancelin	374790 m E 6568000 m N	30.0	62.0	32.0	1656	4200	8.03	780
PB4	Lancelin	357401 m E 6568644 m N	58.0	67.0	9.0	1770	1440	–	1750
TPB	Lancelin	351120 m E 6565652 m N	124.0	154.0	30.0	3456	1440	6.87	3000
JCP1	Lancelin	347400 m E 6581213 m N	66.0	84.0	18.0	1693	1440	9.42	926, 175
PB1	Seabird	355400 m E 6541400 m N	33.0	39.0	6.0	1015	480	7.73	142
PB3	Gingin	397201 m E 6533866 m N	36.0	60.0	24.0	2160	480	6.67	429
TPB	Gingin	367551 m E 6548014 m N	40.0	64.0	24.0	3655	1860	25.18	852, 158

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	Transmissivity (m^2/day)
PB3	Gingin	373119 m E 6568849 m N	40.0	54.5	14.5	791	1440	16.79	43
PB5	Gingin	372830 m E 6568658 m N	34.0	46.0	12.0	1283	480	8.87	260
PB6	Gingin	372752 m E 6568583 m N	30.0	42.0	12.0	1283	480	16.79	100
PB	Gingin	363937 m E 6552601 m N	36.0	48.0	12.0	720	1500	12.82	960
PB1	Guilderton	382514 m E 6547049 m N	21.0	27.0	6.0	293	10175	11.39	570
LP1	Guilderton	366667 m E 6534630 m N	42.0	66.0	24.0	800	1440	4.03	366, 227
LP2	Guilderton	367294 m E 6534659 m N	38.0	56.0	18.0	1647	1440	2.89	1212, 574
LP3	Guilderton	367800 m E 6534741 m N	30.0	48.0	18.0	1647	1440	3.78	1178, 501
LP3A	Guilderton	367819 m E 6534767 m N	30.0	48.0	18.0	1296	480	0.26	16848, 5357
LP4	Guilderton	368006 m E 6534232 m N	34.0	52.0	18.0	1296	480	0.74	7300, 1872
LP5	Guilderton	368128 m E 6533803 m N	24.0	42.0	18.0	920	480	13.95	161, 83
LP6	Guilderton	367669 m E 6533827 m N	48.0	66.0	18.0	1244	480	3.37	410, 414
PB4	Guilderton	371043 m E 6531675 m N	21.0	33.0	12.0	648	480	5.85	180
PB5	Guilderton	371024 m E 6531735 m N	16.0	22.0	6.0	335	30	6.14	60

Notes: bgl = below ground level

Where two transmissivities are included, the first is derived from the Cooper–Jacob method and the second from the Theis method.

The pumping test results presented in this appendix have been compiled from third party reports which have used varying analysis approaches; as a result there may be some inconsistencies in derived parameters.

The pumping test results are dependent on the bore screen settings (length and position relative to aquifer lithology), and as such the results may not be representative of the bulk aquifer parameters.

Appendix C Pumping test analyses for the Leederville aquifer

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
JJC1	Beer-mullah	384440 m E 6553711 m N	110.6	195.0	*57.3	3860	2880	5.2	0.63	1100
JJC2	Beer-mullah	383490 m E 6553850 m N	66.0	148.5	*54.3	3860	2880	8.9	1.07	660
JJC3	Beer-mullah	382490 m E 6553850 m N	55.9	211.1	*70.7	4200	2880	6.0	0.54	1400
JJC4	Beer-mullah	381640 m E 6553850 m N	47.8	144.1	*28.1	4130	2880	4.1	0.86	880
Yukich Bore1	Beer-mullah	385403 m E 6552997 m N	75.0	117.0	42.0	1926	1440	4.2	–	460
ED1	Seabird	367173 m E 6546161 m N	253.3	332.6	*58.0	3995	2880	5.1	0.35	2090
KTB2	Regans Ford	374790 m E 6568000 m N	76.0	94.0	18.0	1309	480	18.4	–	200

Notes: bgl = below ground level; ΔS = drawdown per log cycle of time

* Total screen length excluding blank intervals

The pumping test results presented in this appendix have been compiled from third party reports which have used varying analysis approaches; as a result there may be some inconsistencies in derived parameters.

The pumping test results are dependent on the bore screen settings (length and position relative to aquifer lithology), and as such the results may not be representative of the bulk aquifer parameters.

Appendix D Pumping test analyses for the Leederville–Parmelia aquifer

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
Parmelia Group										
Arrow-smith River No. 1	Arrowsmith	356649 m E 6740424 m N	119.2	124.4	5.2	644	1440	41.0	–	1298
Arrow-smith River No. 1	Arrowsmith	356649 m E 6740424 m N	132.0	139.0	7.0	1522	1440	28.2	–	421
Arrow-smith River No. 12	Arrowsmith	354316 m E 6741005 m N	80.8	85.4	4.6	628	1440	29.3	–	126
Arrow-smith River No. 13	Arrowsmith	355982 m E 6739543 m N	140.2	155.5	15.2	1414	1440	7.3	–	386
Arrow-smith River No. 14	Arrowsmith	354668 m E 6739238 m N	105.2	118.0	12.8	1824	1440	15.3	–	731
1/00	Dookanooka	364220 m E 6731898 m N	264.6	288.5	23.9	3003	1440	16.6	–	393
TPb	Tathra	363140 m E 6720750 m N	80.1	134.1	54.0	2333	1800	15.9	–	220, 357
DSP6	Tathra	367806 m E 6695161 m N	174.2	278	*72.8	4320	2640	26.6	4.80	165
TPB	Tathra	382439 m E 6683800 m N	76.0	139.0	63.0	3600	2860	17.1	–	1600
A 4	Agaton	377467 m E 6639628 m N	163.4	167.1	3.7	954	1440	32.9	–	27.8
A 6	Agaton	381981 m E 6639650 m N	173.7	181.1	7.2	873	1440	61.5	–	12.7
A 7	Agaton	383822 m E 6645235 m N	203	212.1	9.1	1200	1440	36.5	–	41.1
A 12	Agaton	382608 m E 6652478 m N	251.2	336.5	*36.6	2180	1440	7.4	–	363
A 15	Agaton	378439 m E 6659080 m N	126.8	166.4	*25.9	1200	1440	26.0	–	57
A 16	Agaton	383115 m E 6659340 m N	310.6	395.9	*45.4	2180	1440	11. 9	–	227
A 17*	Agaton	387510 m E 6658783 m N	182.3	490.7	*70.1	2180	1440	7.1	–	384
A 21	Agaton	391855 m E 6651892 m N	284.7	290.2	5.5	1170	1440	48.6	–	28.4

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
RGP2*	Dinner Hill	379351 m E 6619278 m N	84.1	154.2	70.1	6480	1440	24.1	–	641
Leederville Formation										
A 3	Agaton	388040 m E 6634040 m N	116.1	229.2	*26.2	1640	1440	29.7	–	59.0
A 13	Agaton	386904 m E 6653310 m N	203.6	212.7	9.1	1990	1440	11.9	–	238
A 20	Agaton	391509 m E 6639344 m N	189.0	195.1	6.1	2770	1440	20.9	–	165
Agri-fresh	Badgingarra	388048 m E 6631192 m N	166.0	214.0	48.0	2419	1440	46.1	–	380, 59
1-81	Dandaragan	375364 m E 6606230 m N	105.8	114.0	8.2	550	480	45.5	3.9	25.9
1-82	Dandaragan	375364 m E 6606230 m N	102.3	114.3	12	615	480	39.7	2.4	47.0
PB1	Moora	396669 m E 6614173 m N	342.0	376.0	18.0	1728	1440	8.9	–	646, 220
GR1	Moora	395515 m E 6615136 m N	314.5	374.5	60.0	4360	1440	14.5	–	530
1-82	Moora	392122 m E 6612507 m N	292.0	310.4	*18.4	3564	1380	19.3	1.4	467
1-89	Moora	392102 m E 6612507 m N	298	343	45	4830	1440	12.0	0.6	1475
2-07	Moora		42.7	54.7	12.0	1000	1440	0.9	1.1	174.5
1-73	Moora	392656 m E 6612759 m N	333.0	350.4	17.4	1615	480	19.4	1.0	311.6
2-73	Moora	391109 m E 6612860 m N	331.8	351.2	19.4	1615	480	7.4	0.3	1184
WAZ LIAN 1	Gingin	398883 m E 6537073 m N	164.0	251.0	*69.0	7959	2880	14.6	–	1100
PB1	Gingin	397780 m E 6539860 m N	125.0	147.5	22.5	377	480	22.4	–	100
1-75	Gingin	396282 m E 6532092 m N	162.2	172.2	10.0	1004	30	8.0	2.1	87.6
2-75	Gingin	396282 m E 6532117 m N	161.2	172.7	11.5	2209	420	20.4	4.0	101.2
1-00	Gingin	396282 m E 6532092 m N	114.3	147.3	33.0	3513	1440	22.8	3.5	184.0

Notes: bgl = below ground level; ΔS = drawdown per log cycle of time

* Total screen length excluding blank intervals

^ Bores screened across Parmelia Group and Leederville Formation units

Where two transmissivities are included, the first is derived from the Cooper–Jacob method and the second from the Theis method.

The pumping test results presented in this appendix have been compiled from third party reports which have used varying analysis approaches; as a result there may be some inconsistencies in derived parameters.

The pumping test results are dependent on the bore screen settings (length and position relative to aquifer lithology), and as such the results may not be representative of the bulk aquifer parameters.

Appendix E Pumping test analyses for the Yarragadee aquifer

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
1-74	Allanooka	306296 m E 6782690 m N	120.4	131.3	10.9	1490	–	[a]20.4	13.5	20
2-74	Allanooka	307296 m E 6784040 m N	208.2	218.6	10.8	2130	–	[a]32.8	0.6	610
3-74	Allanooka	307186 m E 6782709 m N	70.6	79.8	9.4	2783	–	[a]11.8	0.2	2429
4-74	Allanooka	307676 m E 6783309 m N	96.3	110.1	13.8	2783	–	[a]19.1	0.4	1186
2-76	Allanooka	305686 m E 6781690 m N	139.9	149.3	9.36	1634	480	[a]38.6	3.1	97
3-76	Allanooka	306686 m E 6781709 m N	124.9	134	9.12	1634	480	[a]20.8	0.6	499
4-76	Allanooka	307696 m E 6781750 m N	148.9	158.3	9.36	1634	480	[a]33.6	2.7	111
2-77	Allanooka	306786 m E 6780690 m N	100.1	161.3	*12.4	2239	480	[a]11.9	0.7	586
3-77	Allanooka	307696 m E 6780670 m N	129.9	142.3	12.5	2190	480	[a]0.7	0.8	515
5-77	Allanooka	305736 m E 6779670 m N	121.9	134.3	12.4	1526	480	[a]38.8	1.8	155
1-82	Allanooka	307149 m E 6787501 m N	83.5	92.8	9.3	1670	480	20.8	0.5	612
2-82	Allanooka	308349 m E 6785761 m N	48.5	57.3	8.8	1636	480	17.2	0.3	1200
3-82	Allanooka	305749 m E 6783371 m N	90.8	99.3	8.5	1410	480	13.5	0.2	1300
4-82	Allanooka	308149 m E 6780771 m N	116.4	125.6	9.2	1636	480	11.4	1.1	286
2-83	Allanooka	307679 m E 6781741 m N	88.1	116.1	18.0	3755	1440	28.1	0.3	2752
2-83	Allanooka	307679 m E 6781741 m N	88.1	116.1	18.0	1583	480	11.6	0.8	363
3-85	Allanooka	307799 m E 6786271 m N	47.9	77.95	30.0	2041	480	3.9	0.1	3116
1-87	Allanooka	307679 m E 6783281 m N	86.0	98.0	12.0	2041	480	19.3	0.6	623
1-89	Allanooka	307778 m E 6785529 m N	42.7	54.7	12.0	1547	480	[a]4.2	0.2	1890
2-89	Allanooka	306286 m E 6784030 m N	76.3	88.2	11.9	3180	1440	9.8	0.1	5824
1-92	Allanooka	304699 m E 6781671 m N	71.6	80.8	9.2	3019	480	9.3	0.6	950

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
2-92	Allanooka	306286 m E 6784030 m N	69.0	142.0	*49.0	3821	480	9.7	0.9	780
5-95	Allanooka	307484 m E 6786667 m N	76.0	99.7	23.7	5000	1440	11.5	–	415
1-96	Allanooka	308100 m E 6785168 m N	45.1	63.1	18.0	5000	1440	20.4	0.4	2290
2-96	Allanooka	307649 m E 6785186 m N	52.3	76.3	24.0	5000	1440	17.5	0.4	2290
3-96	Allanooka	308709 m E 6781726 m N	101.0	130.1	29.9	3551	1440	8.2	0.3	2600
4-98	Allanooka	307750 m E 6777417 m N	82.0	106.0	24.0	2002	1440	14.4	0.4	917
5-98	Allanooka	306693 m E 6778581 m N	77.7	107.0	29.3	4202	1440	23.2	3.5	220
6-98	Allanooka	306751 m E 6779311 m N	72.5	96.5	24.0	1984	1440	26.5	1.8	202
15-85	Mt Hill	300442 m E 6785833 m N	87.6	99.6	12.0	3333	1740	19.2	1.9	321
16-85	Mt Hill	301139 m E 6787131 m N	112.8	133.0	20.2	3407	1440	13.0	0.3	2080
17-85	Mt Hill	301169 m E 6786171 m N	88.7	97.9	9.2	3180	1440	20.8	2.1	277
4-96	Mt Hill	301679 m E 6785791 m N	102.0	119.6	17.6	2022	1470	18.2	1.1	336
P14	Allanooka	307163 m E 6784392 m N	82.0	91.7	9.7	2160	480	8.4	0.3	1319
2-75	Irwin View	314735 m E 6780248 m N	188.0	196.0	8.0	893	480	[a]18.0	1.1	149
6-76	Irwin View	320146 m E 6770860 m N	104.2	109.3	5.1	524	480	[a]10.1	0.7	134
1-77	Irwin View	307773 m E 6777350 m N	81.6	106.3	*12.4	1145	480	[a]6.2	0.4	525
3-77	Irwin View	314984 m E 6766364 m N	92.3	101.63	9.3	1145	480	[a]23.5	2.2	95
11-77	Irwin View	318146 m E 6768980 m N	81.0	90.3	9.3	1244	480	[a]9.9	0.7	351
13-77	Irwin View	322996 m E 6775855 m N	111.2	144.3	*9.2	895	480	[a]5.1	0.2	684
Karara_PB1	Mingenew	342807 m E 6773234 m N	144.0	290.0	*96.0	2160	2040	3.2	–	1530
PB2	Dongara	310550 m E 6768030 m N	76.0	106.0	*18.0	3276	480	–	–	145
PB3	Dongara	310500 m E 6768510 m N	70.0	106.0	*18.0	4286	300	–	–	262
PB4	Dongara	311095 m E 6767570 m N	77.0	127.0	*21.0	3273	2880	–	–	114

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
2-75	Dongara	304825 m E 6771583 m N	50.6	93.4	*12.2	2793	300	[a]9.9	0.6	806
1-79	Dongara	307172 m E 6771998 m N	49.2	61.38	12.2	2454	480	[a]9.1	1.1	409
1-92	Dongara	306524 m E 6771956 m N	32.4	57.6	*15.0	3019	540	9.7	1.2	461
4-06	Dongara	304285 m E 6771594 m N	45.4	54.4	9.0	3000	480	6.6	0.9	610
NOMAB 1	Mt Adams	334872 m E 6749575 m N	162.2	329.6	*160.0	8640	4320	17.9	–	1200
1	Eneabba	334363 m E 6687527 m N	280.0	419.0	*61.0	4573	2880	22.3	–	290
2	Eneabba	334553 m E 6688136 m N	275.7	458.1	*62.3	2536	2880	34.2	–	103
3	Eneabba	334392 m E 6689828 m N	436.6	562.8	*62.3	3610	2850	13.8	–	550
4	Eneabba	333115 m E 6687459 m N	197.0	342.0	*61.0	3043	2800	30.9	–	99
5	Eneabba	334491 m E 6686659 m N	221.9	387.0	*62.3	4364	2880	15.1	–	347
2-75	Eneabba	334081 m E 6700004 m N	81.7	91.0	9.3	2361	420	25.7	5.7	76
1-89	Eneabba	333415 m E 6700389 m N	72.0	81.0	9.0	1640	720	21.6	0.4	752
3C	Eneabba	335371 m E 6687656 m N	391.7	528.5	*90.0	3200	2170	–	1.2	476
JML7	Eneabba	336653 m E 6702325 m N	173.7	403.4	*67.3	2730	2160	9.5	–	480
JML8	Eneabba	336800 m E 6702470 m N	153.5	310.8	*63.3	2400	1800	11.6	–	264
Petro Farm PB1	Eneabba	332603 m E 6714704 m N	108.0	168.5	60.5	1165	900	10.73	–	280
Petro Farm PB2	Eneabba	332760 m E 6714152 m N	96.0	150.0	54.0	1165	840	9.4	–	325
Petro Farm PB3	Eneabba	332934 m E 6713576 m N	78.0	138.0	60.0	1165	840	8.8	–	330
REM1A	Eneabba	335261 m E 6701352 m N	241.7	483.1	*63.4	4693	1240	19.5	1.2	738
WTE1	Eneabba	334579 m E 6693080 m N	164.5	447.5	*60.0	3300	2880	27.5	5.5	110
WTE10	Eneabba	335570 m E 6692359 m N	197.9	534.0	*60.0	3330	2880	21.8	4.8	127
WTE11s	Eneabba	334532 m E 6693135 m N	12.2	97.6	*79.3	1800	2880	13.9	–	410

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
WTE13s	Eneabba	334267 m E 6693877 m N	12.2	73.3	61.1	1330	2880	6.5	–	540
WTE2	Eneabba	334579 m E 6691481 m N	262.5	678.0	*58.5	3300	2880	19.5	3.3	186
WTE3	Eneabba	336379 m E 6692870 m N	182.0	342.0	*51.0	3800	2880	19.7	9.3	75
WTE31s	Eneabba	335904 m E 6697874 m N	74.1	200.5	*78.0	3240	2880	14.5	2.0	297
WTE32s	Eneabba	335211 m E 6699159 m N	48.5	205.0	*54.0	3974	4320	15.0	1.3	560
WTE33s	Eneabba	335390 m E 6697433 m N	69.6	190.2	*72.0	3436	2880	17.0	1.6	395
WTE34s	Eneabba	335214 m E 6696769 m N	99.5	160.0	60.5	3020	2880	24.0	1.9	290
WTE35s	Eneabba	334529 m E 6696736 m N	114.4	192.6	*72.2	1900	2880	17.5	3.7	90
WTE36s	Eneabba	335100 m E 6698086 m N	92.9	207.0	*90.1	3890	2880	18.0	1.4	510
WTE37s	Eneabba	331625 m E 6689185 m N	59.4	197.7	*132.0	4750	2880	18.8	–	390
WTE38s	Eneabba	333085 m E 6690880 m N	47.1	221.1	*128.0	4579	1260	16.5	–	400
WTE39s	Eneabba	332270 m E 6690150 m N	53.5	215.7	*146.0	2851	2880	48.3	–	60
WTE6	Eneabba	335284 m E 6691481 m N	130.8	266.1	*36.0	3300	2880	25.0	6.4	94
WTE7	Eneabba	334365 m E 6693440 m N	163.5	384.0	*48.0	3300	2580	21.0	–	274
WTE8	Eneabba	336100 m E 6691530 m N	155.4	471.0	*69.0	3640	2100	9.3	1.0	660
WTE9s	Eneabba	334981 m E 6692407 m N	18.0	90.0	*69.0	2455	2880	–	–	560
TP1	Jurien	337038 m E 6663350 m N	165.0	318.2	*127.0	3500	14400	56.0	–	100
TP2	Jurien	347539 m E 6646250 m N	169.4	398.0	*115.0	4000	10080	40.0	–	230
TP3	Jurien	339039 m E 6654750 m N	167.0	321.9	*121.0	1050	14400	61.0	–	120
TP4	Jurien	342191 m E 6649376 m N	61.0	93	32	1000	14400	48.5	–	45
TP5	Jurien	339412 m E 6649334 m N	65.0	93	28	1000	14400	44.0	–	50
2-89	Badgin-garra	356775 m E 6637010 m N	193.9	221.25	27.32	556	240	7.6	0.5	204
BF11/2	Badgin-garra	352829 m E 6643724 m N	85.4	207.5	67.3	1800	2880	30.2	–	100

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
CPB15	Cataby	344433 m E 6613335 m N	43.0	146.0	*97.0	3000	5760	42.8	–	78
CPB17	Cataby	345395 m E 6610835 m N	41.8	187.6	*151.3	4000	6480	23.0	3.6	203
CPB3	Cataby	350989 m E 6608481 m N	168.0	201.4	33.0	–	–	–	–	60
CPB8	Cataby	350255 m E 6607885 m N	123.0	195.0	*54.0	620	2340	51.3	–	10
CPB8A	Cataby	350260 m E 6607890 m N	50.0	89.9	*33.9	345	2880	39.5	–	6

Notes: bgl = below ground level; ΔS = drawdown per log cycle of time

* Total screen length excluding blank intervals

a Drawdown reported for 10 hours duration rather than end of test

The pumping test results presented in this appendix have been compiled from third party reports which have used varying analysis approaches; as a result there may be some inconsistencies in derived parameters.

The pumping test results are dependent on the bore screen settings (length and position relative to aquifer lithology), and as such the results may not be representative of the bulk aquifer parameters.

Appendix F Pumping test analyses for the Cattamarra aquifer

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
ERA70	Eneabba	329248 m E 6688365 m N	58.2	175.2	*20.0	790	2800	25.0	–	45
ERA73	Eneabba	329850 m E 6685740 m N	53.4	166.5	*21.0	600	2800	19.0	–	65
EWP1	Eneabba	329187 m E 6691571 m N	50.0	103.8	*36.0	600	2880	23.0	–	84
EWP2	Eneabba	329171 m E 6691066 m N	51.3	119.8	*36.0	500	2880	22.0	–	48
EWP3	Eneabba	329190 m E 6690481 m N	37.3	96.8	*30.0	500	2880	23.0	–	34
EWP4	Eneabba	329149 m E 6690181 m N	37.6	88.8	*30.0	680	2880	24.0	–	66
EWP5	Eneabba	329153 m E 6689133 m N	59.2	98.5	*27.0	700	2880	24.0	–	9
EWP6	Eneabba	330372 m E 6690236 m N	50.7	145.4	*49.0	900	2880	15.0	2.5	66
EWP7	Eneabba	330378 m E 6691608 m N	47.4	179.8	*42.0	1000	2880	11.0	–	153
EWP8	Eneabba	330361 m E 6688784 m N	57.8	205.8	*60.0	1350	3780	17.0	3.0	145

Notes: bgl = below ground level; ΔS = drawdown per log cycle of time

* Total screen length excluding blank intervals

The pumping test results presented in this appendix have been compiled from third party reports which have used varying analysis approaches; as a result there may be some inconsistencies in derived parameters.

The pumping test results are dependent on the bore screen settings (length and position relative to aquifer lithology), and as such the results may not be representative of the bulk aquifer parameters

Appendix G Pumping test analyses for the Eneabba-Lesueur aquifer

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
29/01	Jurien	315833 m E 6649219 m N	189.8	249.8	60.0	1805	2880	–	–	20.8
1/91	Jurien	317960 m E 6642000 m N	121.5	152.0	30.5	2002	600	–	–	73.4
WCR2	Jurien	323599 m E 6645150 m N	87.9	370.2	*60.2	1680	2880	33.0	6.5	47
BS6	Jurien	321539 m E 6645470 m N	233.14	378.14	*64.3	4500	2760	48.0	–	137
PB1	White Lake	319988 m E 6687950 m N	264.0	300.0	*30.0	4587	1440	47.0	–	140
PB2	White Lake	320238 m E 6688550 m N	294.0	372.0	*45.0	7000	5760	27.0	3.5	366

Notes: bgl = below ground level; ΔS = drawdown per log cycle of time

* Total screen length excluding blank intervals

The pumping test results presented in this appendix have been compiled from third party reports which have used varying analysis approaches; as a result there may be some inconsistencies in derived parameters.

The pumping test results are dependent on the bore screen settings (length and position relative to aquifer lithology), and as such the results may not be representative of the bulk aquifer parameters.

Appendix H Pumping test analyses for the Tumblagooda aquifer

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
1/79	Kalbarri	222184 m E 6930279 m N	17.0	161.68	144.7	982	480	51.3	–	14.88
2/79	Kalbarri	221293 m E 6929940 m N	26.0	158.08	132.1	544.3	480	29.5	–	29.33
1/86	Kalbarri	221650 m E 6930933 m N	65.87	179.8	113.9	1087	480	37.3	–	33.2
2/86	Kalbarri	220994 m E 6929579 m N	60.11	179.3	119.2	1087	480	17.3	–	28.1
3/86	Kalbarri	222262 m E 6929785 m N	56.11	176.2	120.1	1087	480	20.3	–	110.7
1/98	Kalbarri	221805 m E 6930175 m N	60.0	178.4	118.4	1311	1440	19.1	6.3	38
1/97	Port Kalbarri	220964 m E 6925101 m N	17.13	131.13	114.0	305	1440	28.0	5.6	10
2/97	Port Kalbarri	221080 m E 6925037 m N	17.14	131.14	114.0	360	1440	22.0	3.63	18.2
3/79	Port Gregory	238134 m E 6875825 m N	3.2	36.4	33.2	103	480	9.6	2.60	7.26
7/79	Port Gregory	238211 m E 6876194 m N	1.5	35.7	27.7	160	480	7.2	–	45.12
11/79	Port Gregory	234669 m E 6882231 m N	51.9	65.9	*7.5	149	2400	5.8	–	
1/80	Port Gregory	234449 m E 6882841 m N	55.2	58.3	3.1	55	480	5.8	–	50.50
2/80	Port Gregory	233504 m E 6883824 m N	51.0	53.7	2.7	56	480	4.3	–	20.60
1/77	Yuna	293024 m E 6862743 m N	19.7	35.7	16.0	218.2	480	–	5.1	7.84
1/92	Horrocks	250259 m E 6862411 m N	57.0	108	51.0	338	570	14.5	1.1	56
2/92	Horrocks	250259 m E 6862841 m N	48.3	100.3	52.0	200	510	24.7	2.9	12.6
7/90	Horrocks	250259 m E 6862861 m N	36.1	100.8	64.7	253	2880	24.5	2.7	17.2

Notes: bgl = below ground level; ΔS = drawdown per log cycle of time

* Total screen length excluding blank intervals

The pumping test results presented in this appendix have been compiled from third party reports which have used varying analysis approaches; as a result there may be some inconsistencies in derived parameters.

The pumping test results are dependent on the bore screen settings (length and position relative to aquifer lithology), and as such the results may not be representative of the bulk aquifer parameters.

Appendix I Pumping test analyses for the Northampton Inlier aquifer

Bore	Location	Approx. coordinates (MGA Zone 50)	Top screen (m bgl)	Bottom screen (m bgl)	Screen length (m)	Test rate (m^3/day)	Duration (min)	Drawdown (m)	ΔS (m)	Transmissivity (m^2/day)
4	Northampton	269543 m E 6853418 m N	19.0	49.0	*24.0	–	–	–	–	16.8, 37.1
6	Northampton	269484 m E 6853416 m N	14.0	50.0	*18.0	–	–	–	–	8.4, 11.1
1/03	Northampton	269836 m E 6860735 m N	9.4	63.4	54.0	150	1440	19.0	11.4	2.41
3/03	Northampton	268309 m E 6860292 m N	21.5	63.5	42.0	280	1440	7.2	4.75	10.8
2/94	Northampton	271654 m E 6861201 m N	–	–	–	150	2820	38.8	9.0	
1/88	Northampton		32.0	50.0	18.0	200.4	480	27.8	6.8	5.4
2/88	Northampton		19.5	43.5	24.0	991	480	–	7.9	23
3/88	Northampton		–	–	–	302	480	11.0	6.0	9.2
1/83	Northampton	268039 m E 6859751 m N	47.9	37.9	12.0	396	480	6.1	0.3	242
2/83	Northampton	266889 m E 6864151 m N	12.3	60.3	48.0	302.6	480	18.2	8.0	6.93
3/83	Northampton	267289 m E 6863851 m N	4.1	44.5	40.4	206.2	480	13.3	4.5	8.4
1/87	Northampton	268126 m E 6860903 m N	11.0	44.7	33.7	379	480	1.9	1.04	66.8
2/79	Northampton	268126 m E 6860903 m N	0.0	25.0	25.0	227	2880	11.0	1.40	29.72

Notes: bgl = below ground level; ΔS = drawdown per log cycle of time

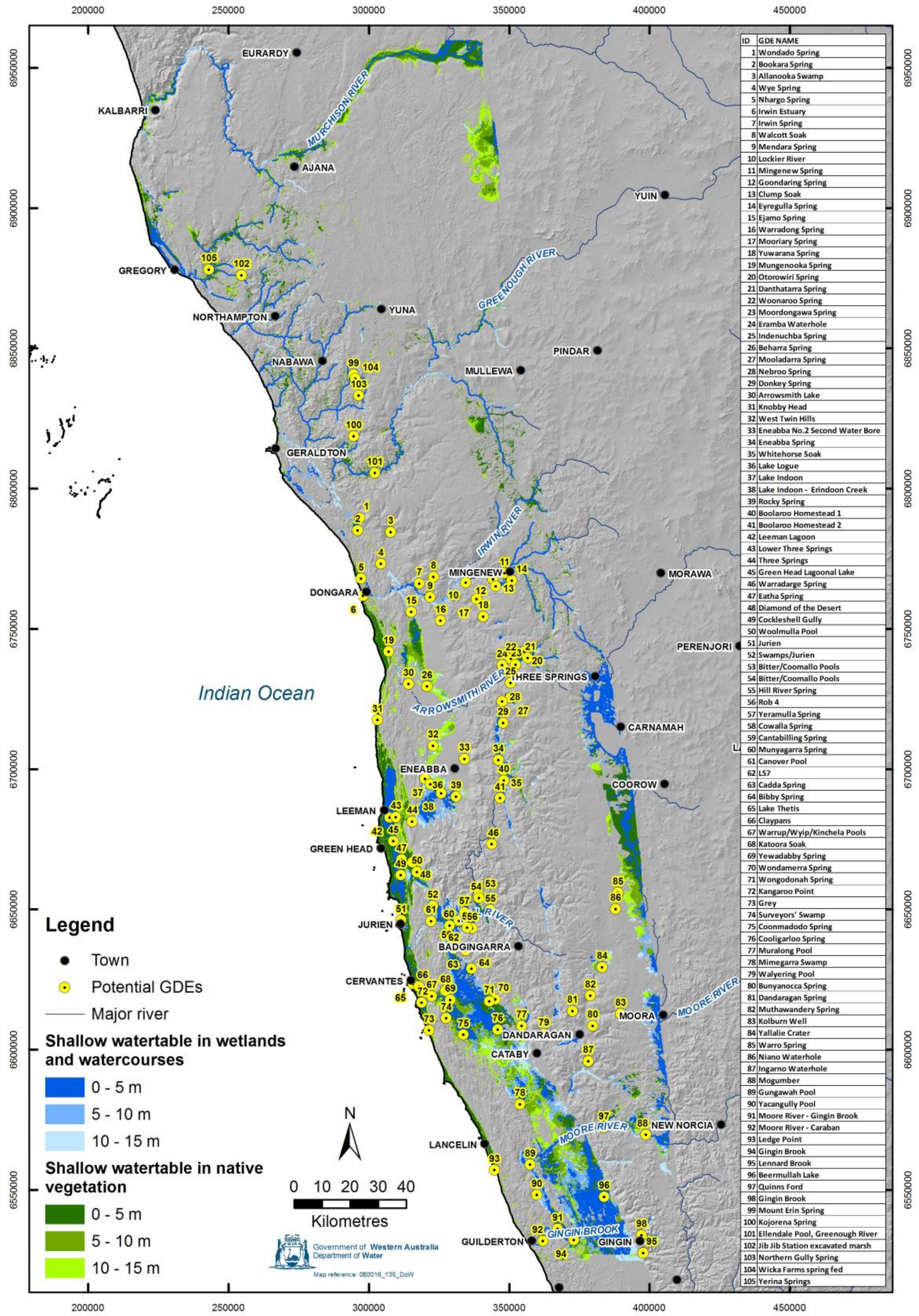
* Total screen length excluding blank intervals

Where two transmissivities are included, the first is derived from the Cooper–Jacob method and the second from the Theis method.

The pumping test results presented in this appendix have been compiled from third party reports which have used varying analysis approaches; as a result there may be some inconsistencies in derived parameters.

The pumping test results are dependent on the bore screen settings (length and position relative to aquifer lithology), and as such the results may not be representative of the bulk aquifer parameters.

Appendix J Potential groundwater-dependent ecosystems in the northern Perth Basin



ID	GDE NAME
1	Wondado Spring
2	Bookara Spring
3	Allanooka Swamp
4	Wye Spring
5	Nhargo Spring
6	Irwin Estuary
7	Irwin Spring
8	Walcott Soak
9	Mendara Spring
10	Lockier River
11	Mingenew Spring
12	Goondaring Spring
13	Clump Soak
14	Eyregulla Spring
15	Ejamo Spring
16	Warradong Spring
17	Mooriary Spring
18	Yuwarana Spring
19	Mungenooka Spring
20	Otorowiri Spring
21	Danthatarra Spring
22	Woonaroo Spring
23	Moordongawa Spring
24	Eramba Waterhole
25	Indenuchba Spring
26	Beharra Spring
27	Mooladarra Spring
28	Nebroo Spring
29	Donkey Spring
30	Arrowsmith Lake
31	Knobby Head
32	West Twin Hills
33	Eneabba No.2 Second Water Bore
34	Eneabba Spring
35	Whitehorse Soak
36	Lake Logue
37	Lake Indoon
38	Lake Indoon - Erindoon Creek
39	Rocky Spring
40	Boolaroo Homestead 1
41	Boolaroo Homestead 2
42	Leeman Lagoon
43	Lower Three Springs
44	Three Springs
45	Green Head Lagoonal Lake
46	Warradarge Spring
47	Eatha Spring
48	Diamond of the Desert
49	Cockleshell Gully
50	Woolmulla Pool
51	Jurien
52	Swamps/Jurien
53	Bitter/Coomallo Pools
54	Bitter/Coomallo Pools
55	Hill River Spring
56	Rob 4
57	Yeramulla Spring
58	Cowalla Spring
59	Cantabilling Spring
60	Munyagarra Spring
61	Canover Pool
62	LS7
63	Cadda Spring
64	Bibby Spring
65	Lake Thetis
66	Claypans
67	Warrup/Wyip/Kinchela Pools
68	Katoora Soak
69	Yewadabby Spring
70	Wondamerra Spring
71	Wongodonah Spring
72	Kangaroo Point
73	Grey
74	Surveyors' Swamp
75	Coonmadodo Spring
76	Cooligarloo Spring
77	Muralong Pool
78	Mimegarra Swamp
79	Walyering Pool
80	Bunyanocca Spring
81	Dandaragan Spring
82	Muthawandery Spring
83	Kolburn Well
84	Yallalie Crater
85	Warro Spring
86	Niano Waterhole
87	Ingarno Waterhole
88	Mogumber
89	Gungawah Pool
90	Yacangully Pool
91	Moore River - Gingin Brook
92	Moore River - Caraban
93	Ledge Point
94	Gingin Brook
95	Lennard Brook
96	Beermullah Lake
97	Quinns Ford
98	Gingin Brook
99	Mount Erin Spring
100	Kojorena Spring
101	Ellendale Pool, Greenough River
102	Jib Jib Station excavated marsh
103	Northern Gully Spring
104	Wicka Farms spring fed
105	Yerina Springs

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