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

Period	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	
Jurassic	Parmelia Group		Otorowiri aquitard	Extensive aquitard below Dandaragan Plateau (includes shaley part of the Carnac Formation)
Jurassic	Parmelia Group	Otorowiri Formation	Shale and siltstone, minor sandstone	
Jurassic	Yarragadee Formation		Yarragadee aquifer	
Jurassic	Yarragadee Formation	Unit D	Local aquitard	Major regional aquifer Mostly fresh
Jurassic	Yarragadee Formation	Unit D	Shale, siltstone and clayey sandstone	
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
Triassic	Lesueur Sandstone	Sandstone	Fresh to brackish
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
Permian (Early)	High Cliff Sandstone	Sandstone, minor siltstone	Saline
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 / Ordovician		Tumblagooda aquifer	
	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	
	Moora Group	Chert, siltstone, sandstone and arkose	Potential poor aquifer Local aquifer in Noondine Chert Mostly saline, locally fresh
		Yandanooka aquifer	
	Yandanooka Group	Sandstone, siltstone, conglomerate and arkose	Potential poor aquifer Mostly saline
		Mullingarra fractured-rock aquifer	
	Mullingarra Inlier	Gneissic rocks	Local fractured-rock aquifer Salinity unknown
		Northampton fractured-rock aquifer	
	Northampton Inlier	Gneissic rocks	Local fractured-rock aquifer Fresh to brackish

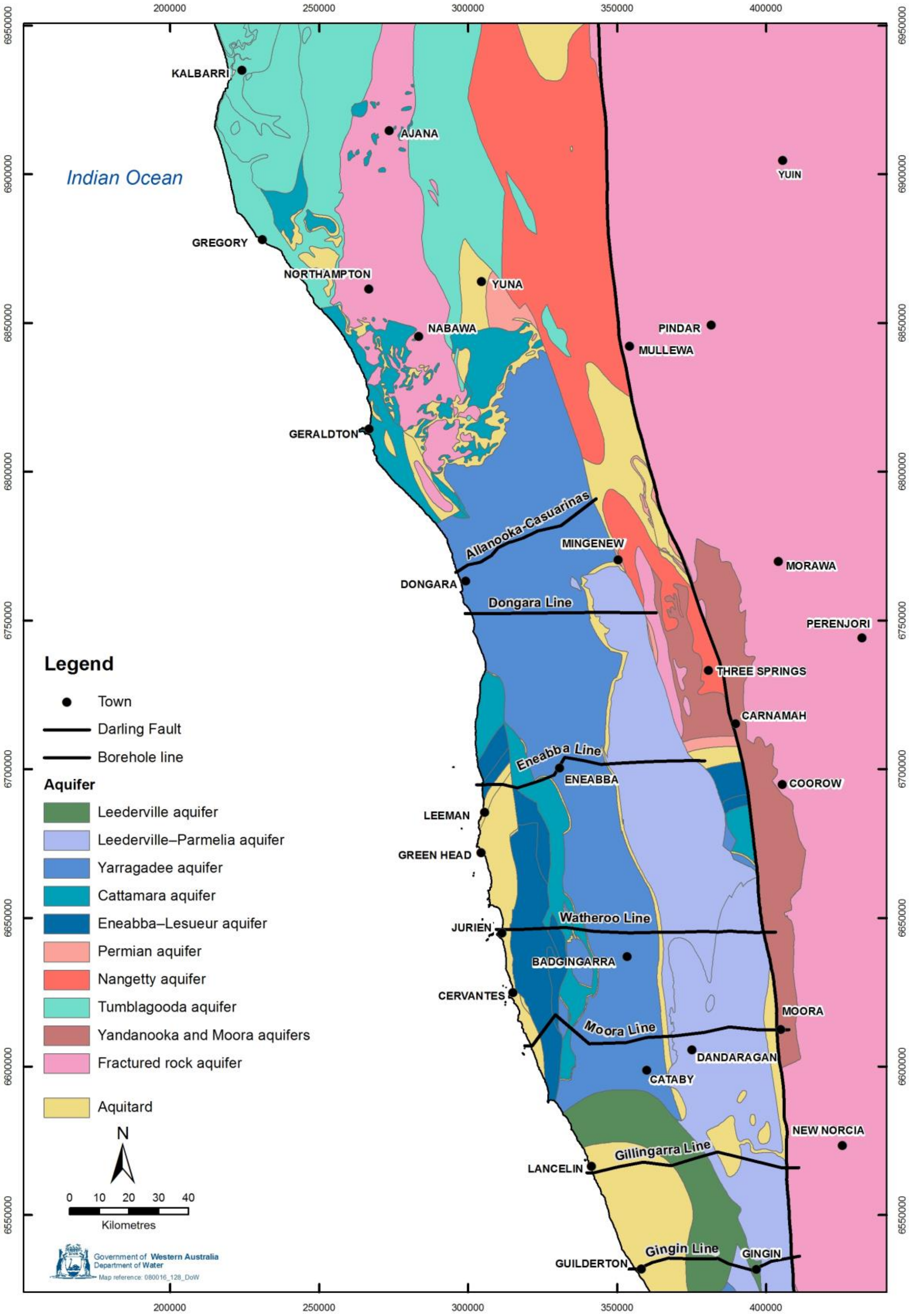


Figure 53 Aquifers and aquitards below the superficial formations or surficial deposits

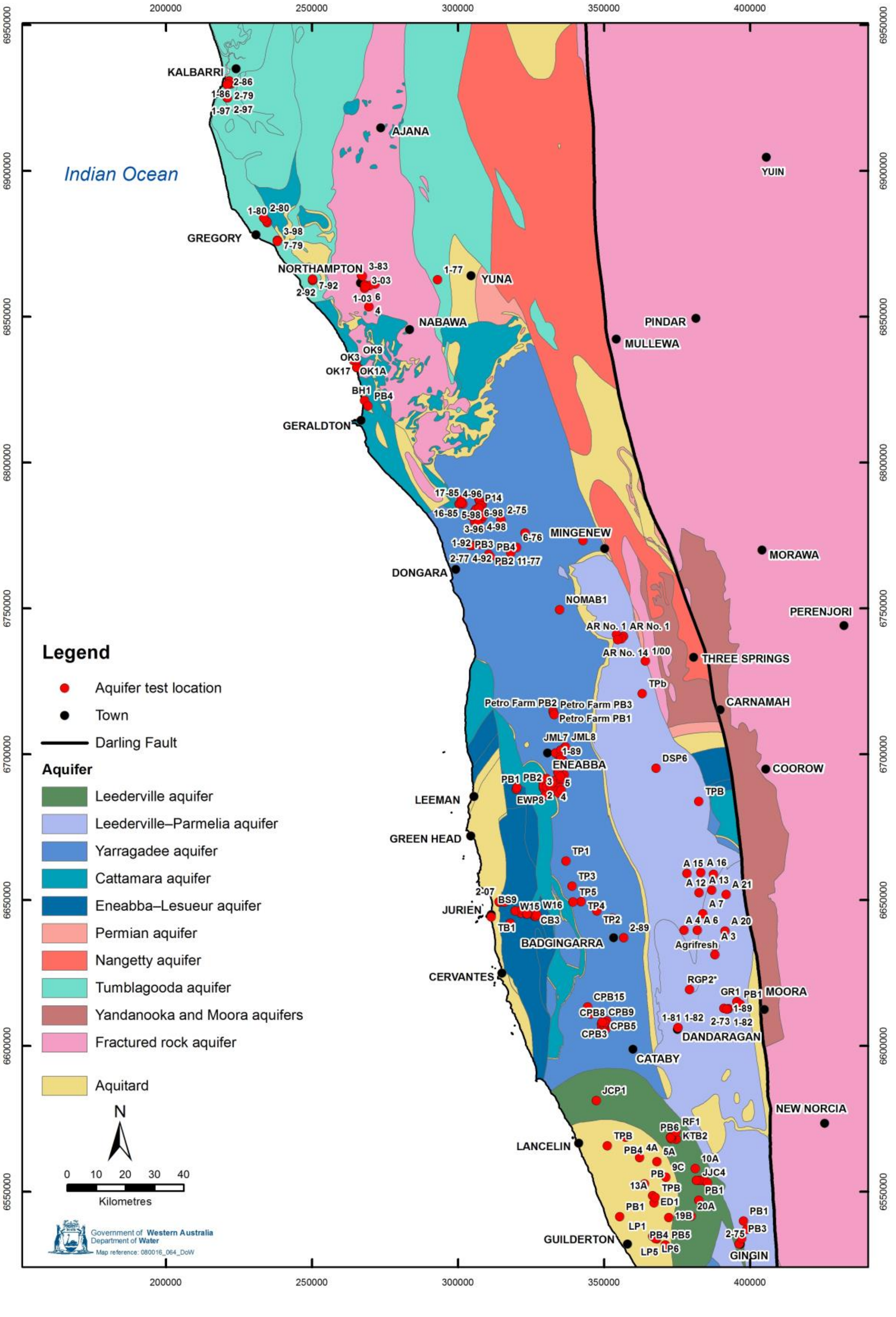


Figure 54 Bore sites with aquifer test data (bores in the Guilderton–Lancelin area are within the Superficial aquifer)

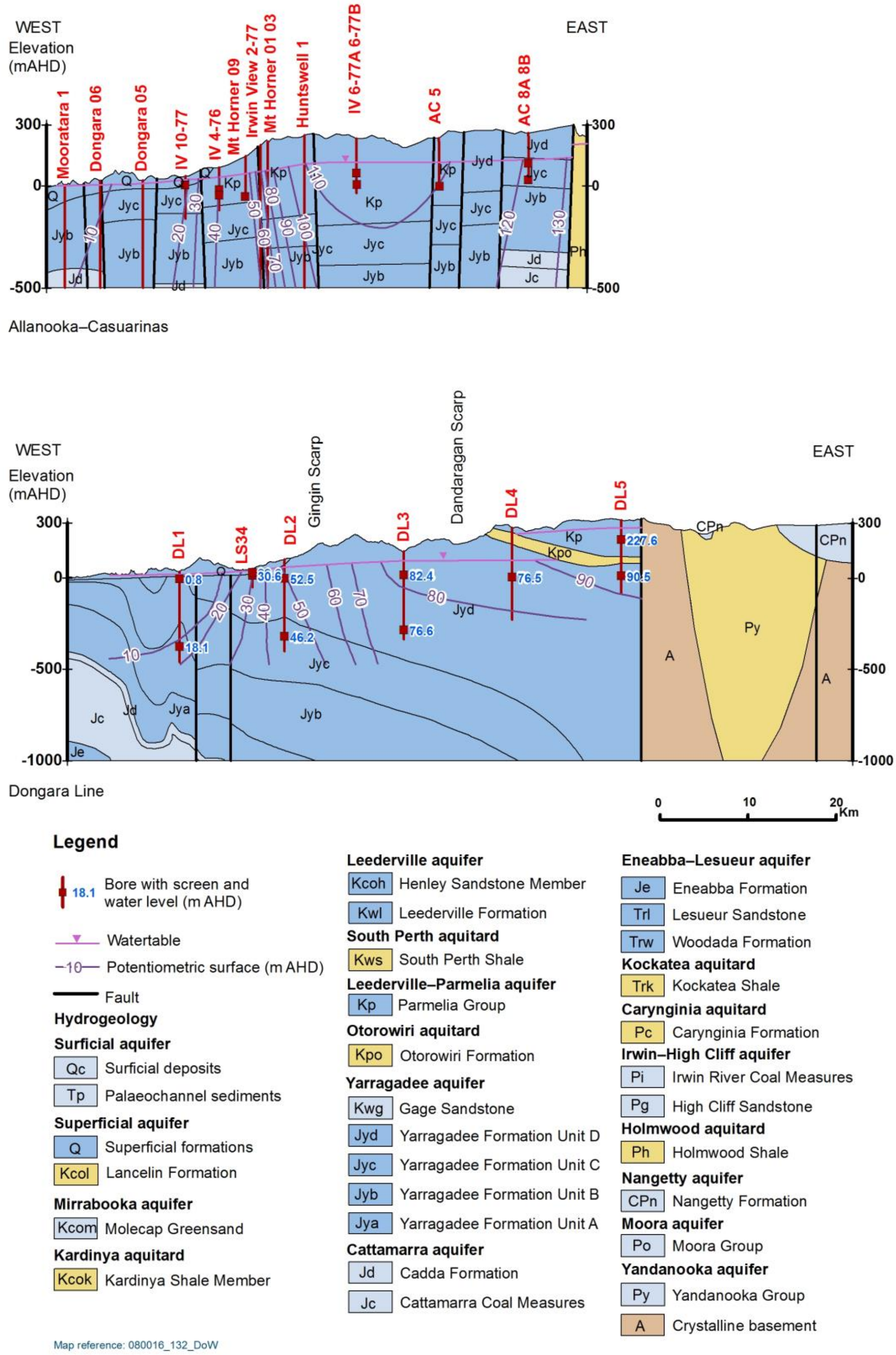


Figure 55 Hydrogeological cross-sections (hydraulic head)

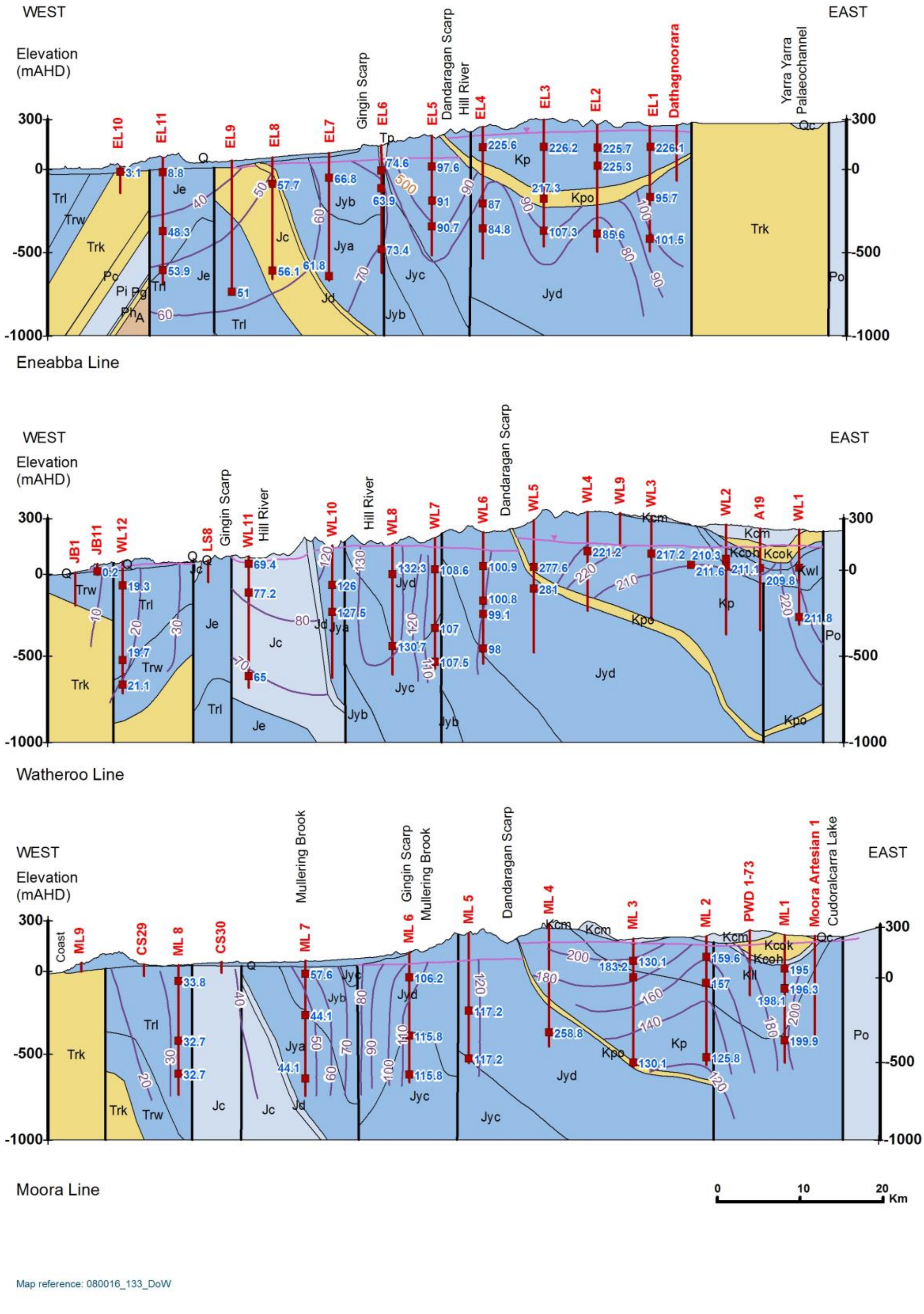


Figure 55 Hydrogeological cross-sections (hydraulic head) (continued)

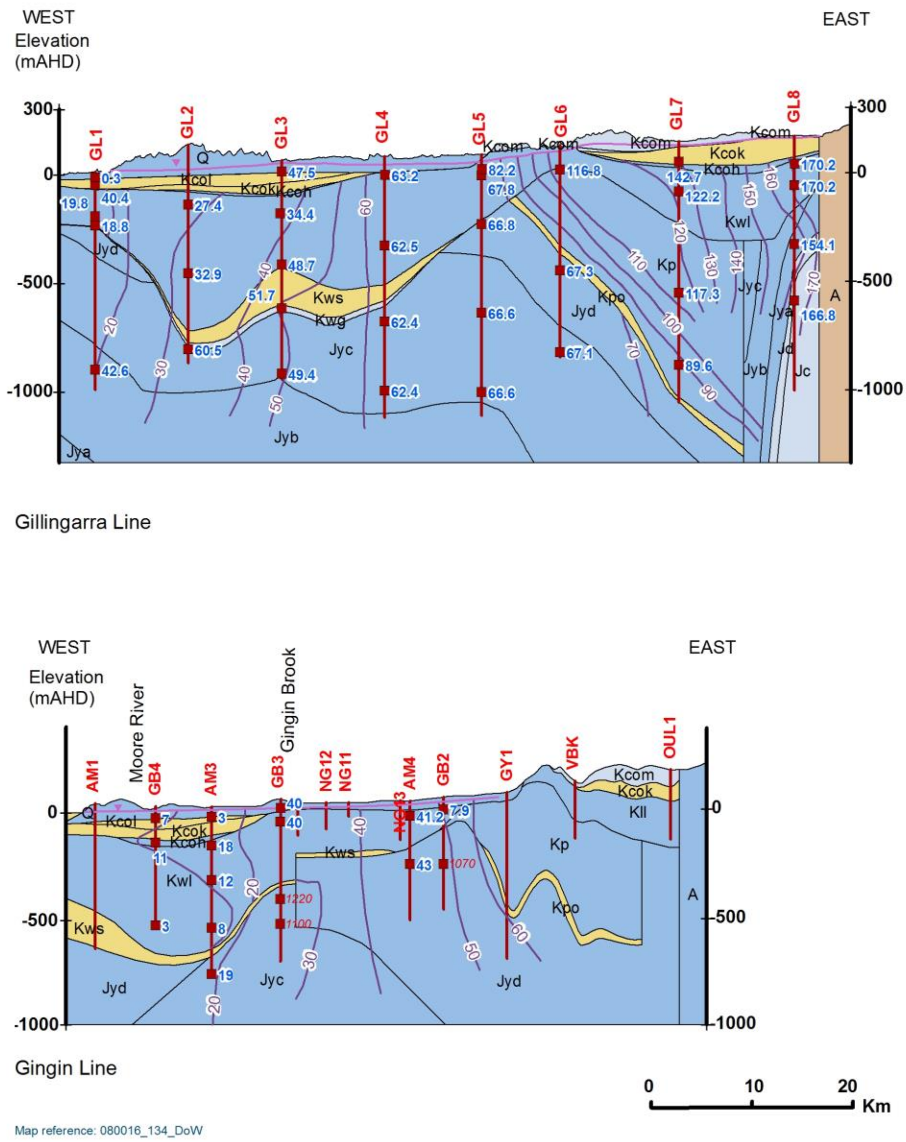


Figure 55 Hydrogeological cross-sections (hydraulic head) (continued)

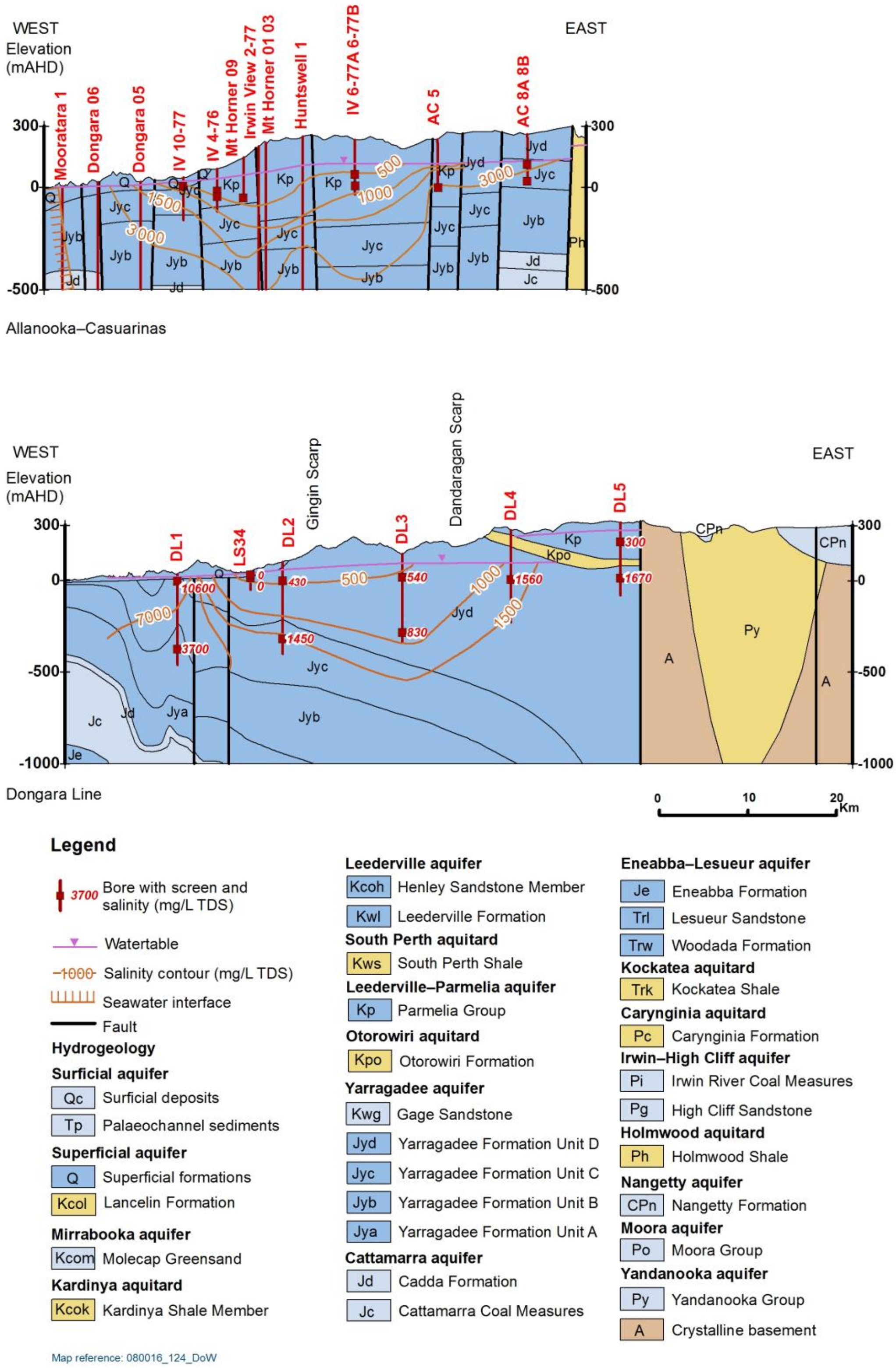
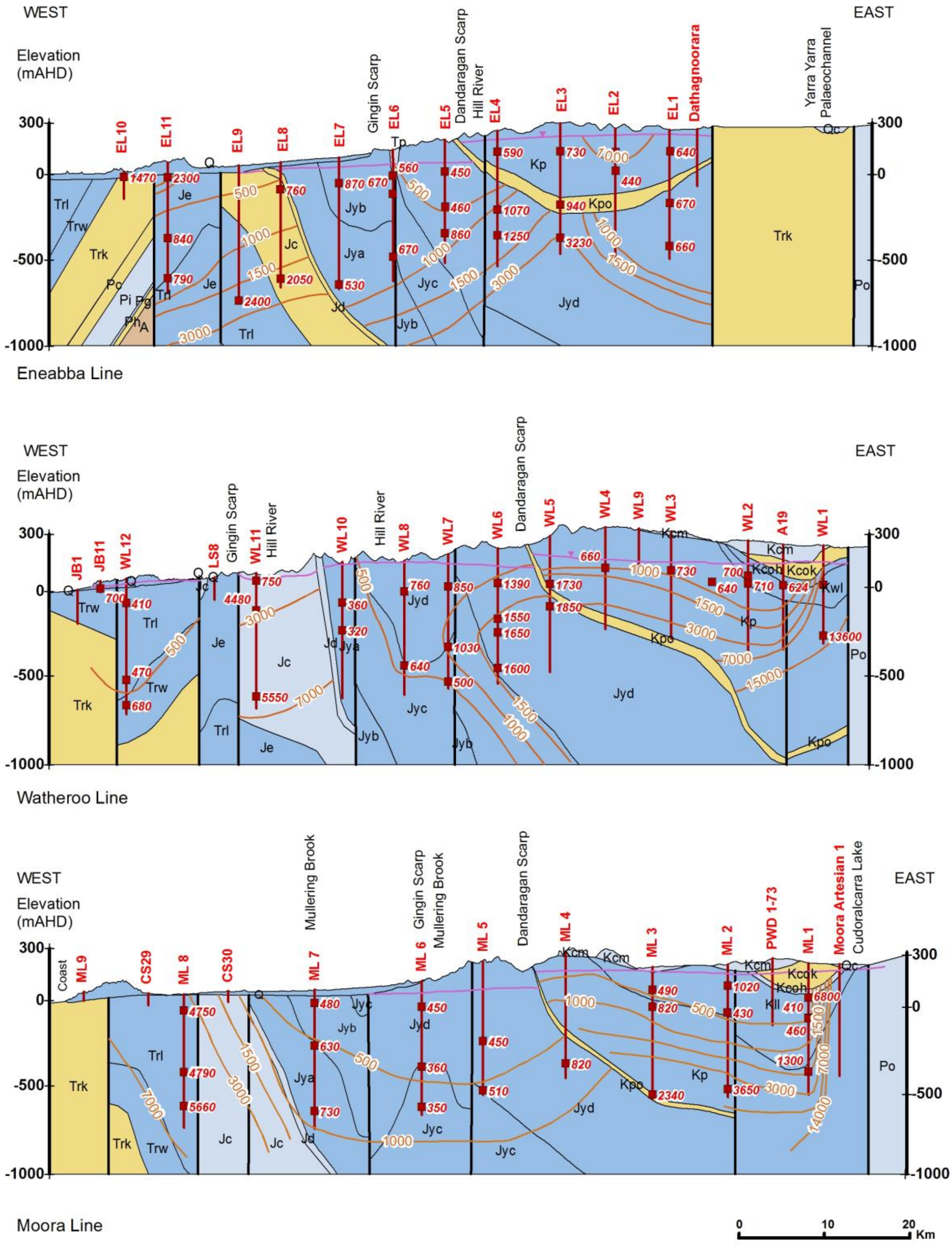
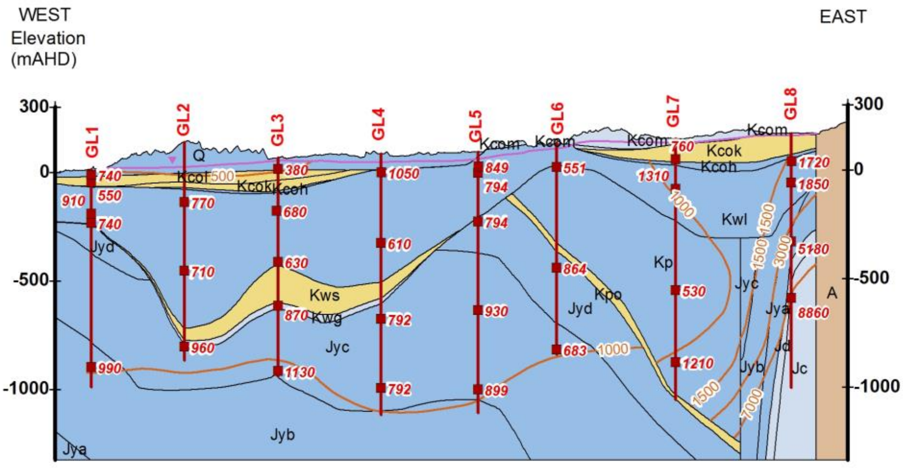


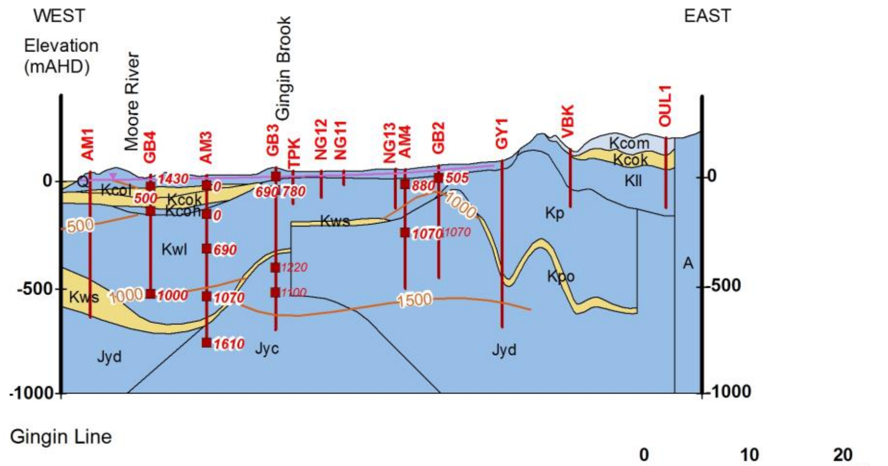
Figure 56 Hydrogeological cross-sections (salinity)



Map reference: 080016_125_DoW

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





Map reference: 080016_126_DoW

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

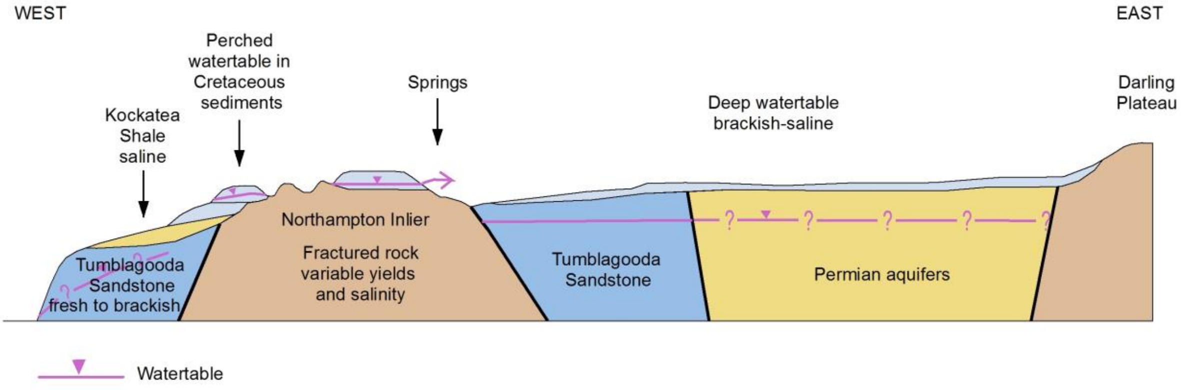


Figure 57 Hydrogeological setting across the Northampton Inlier

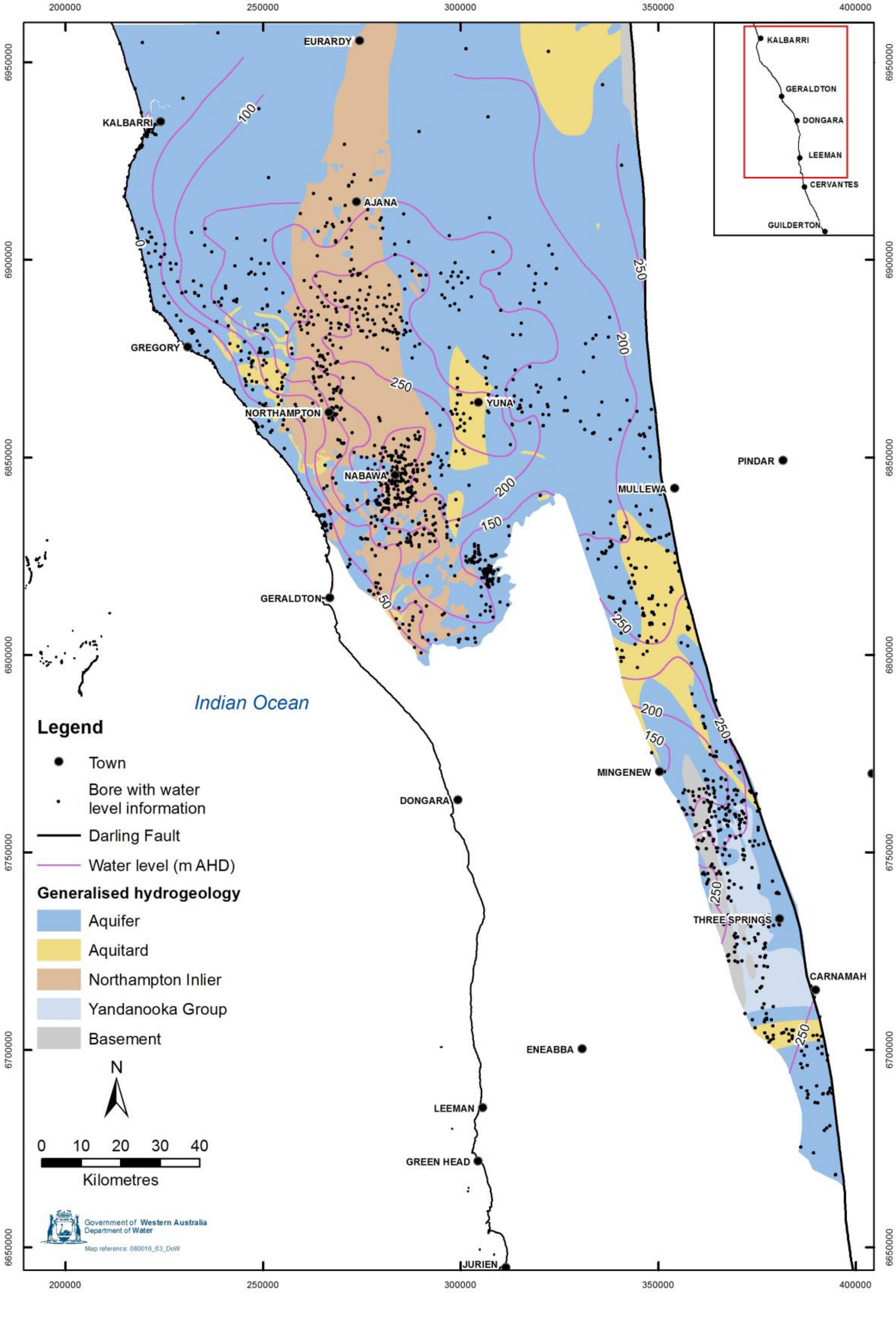


Figure 58 Northern region: hydrogeology and potentiometric surface

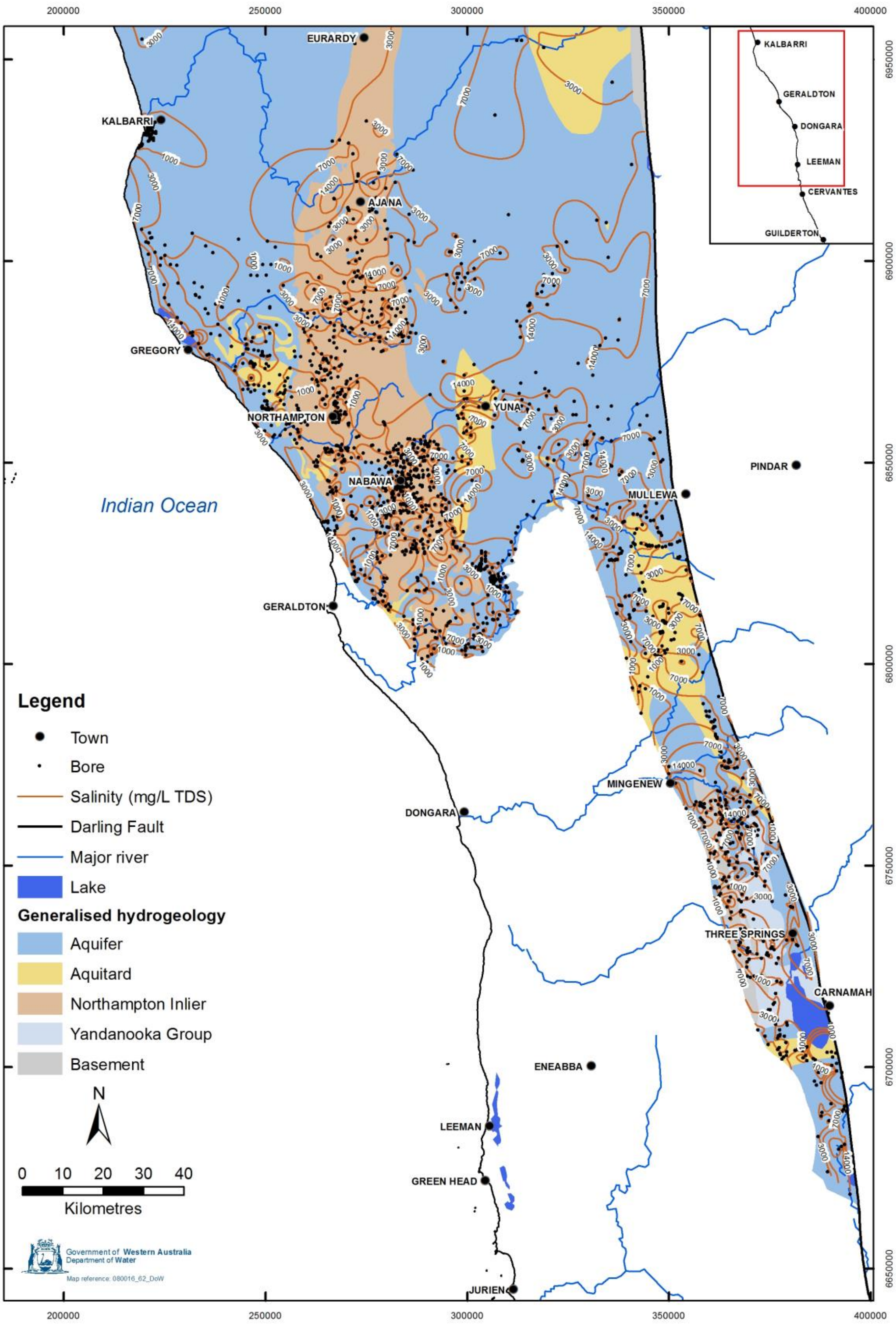


Figure 59 Northern region: groundwater salinity

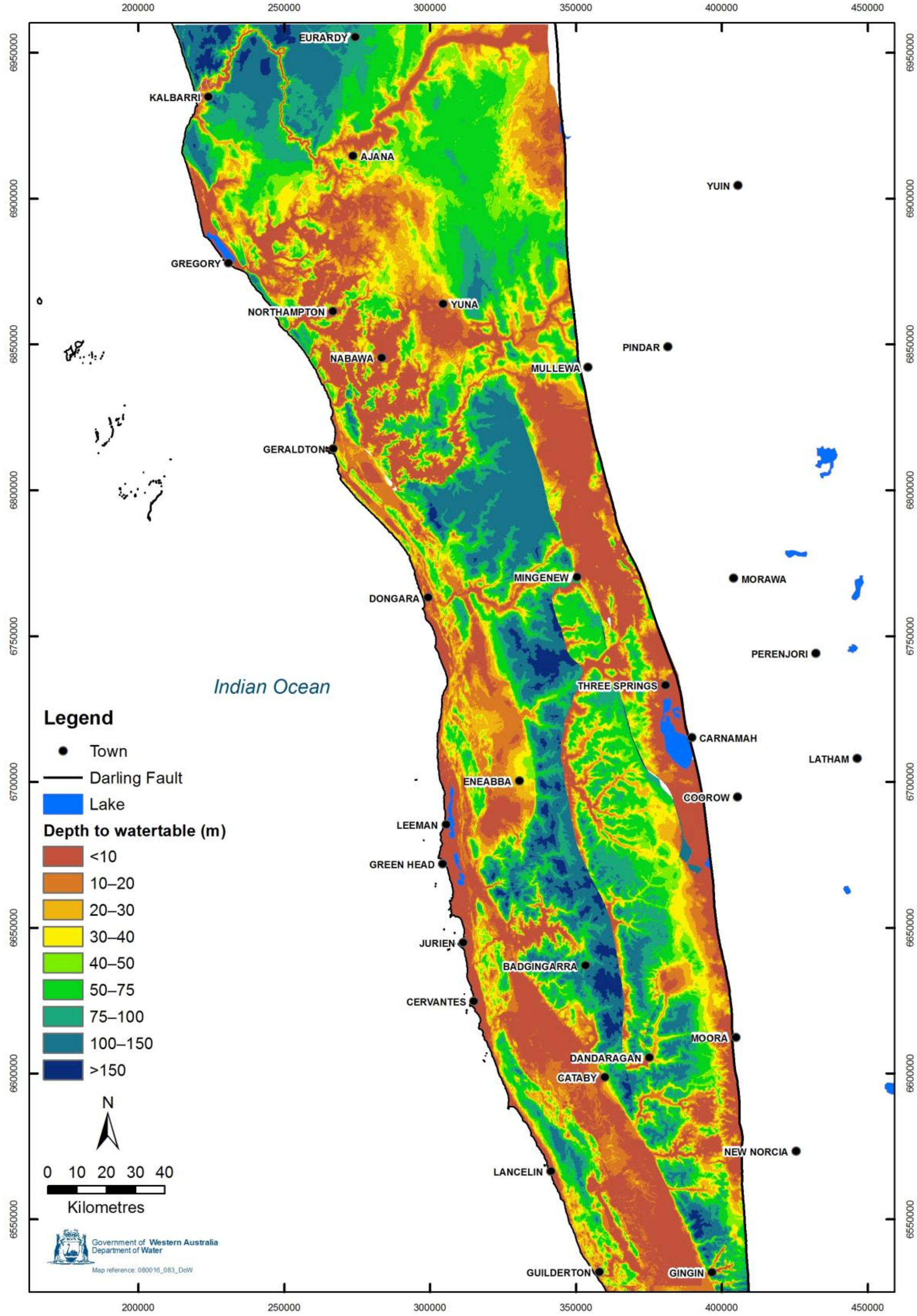


Figure 60 Representative depth to watertable (2015)

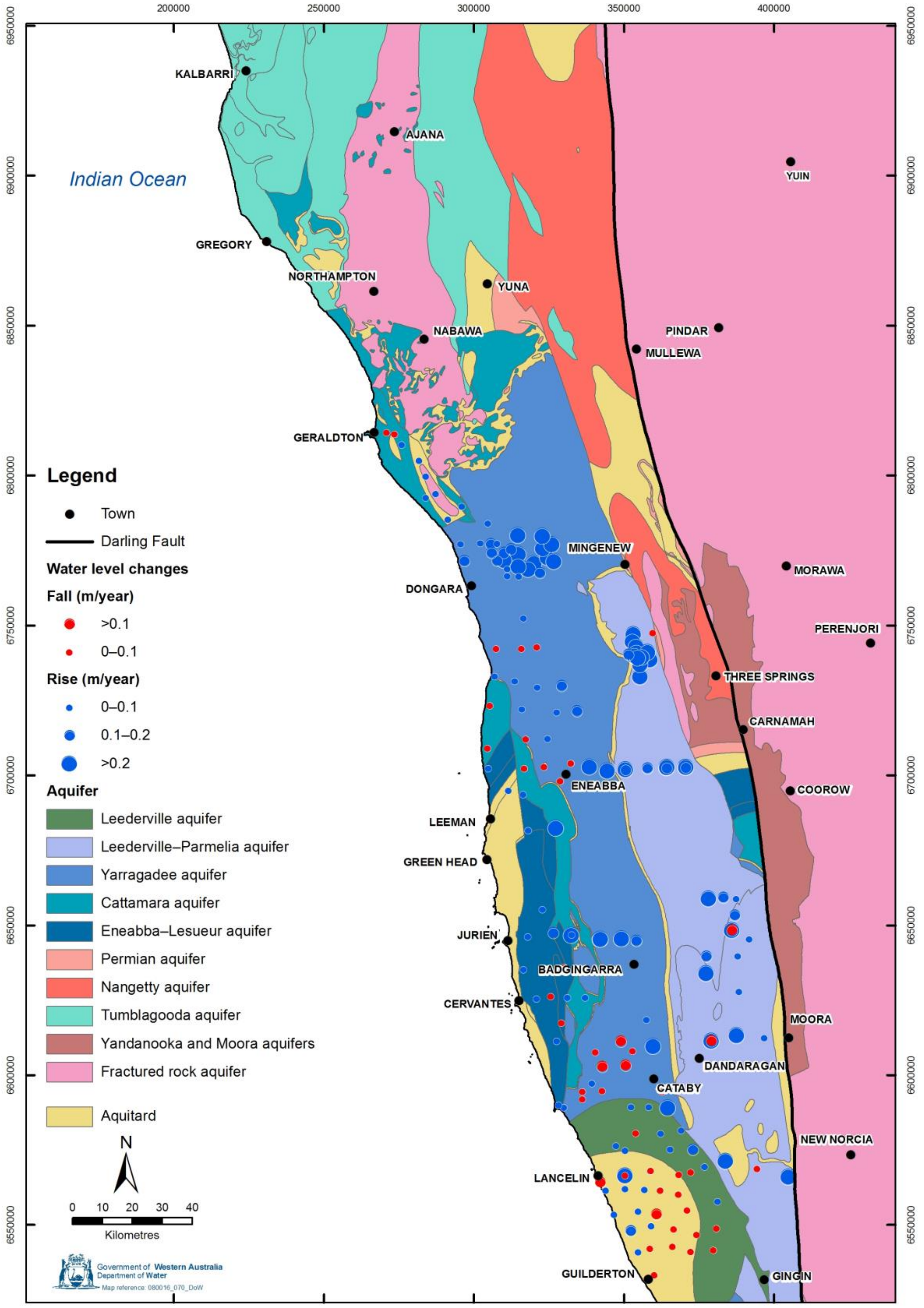


Figure 61 Water level change between mid-1980s and mid-2000s

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.

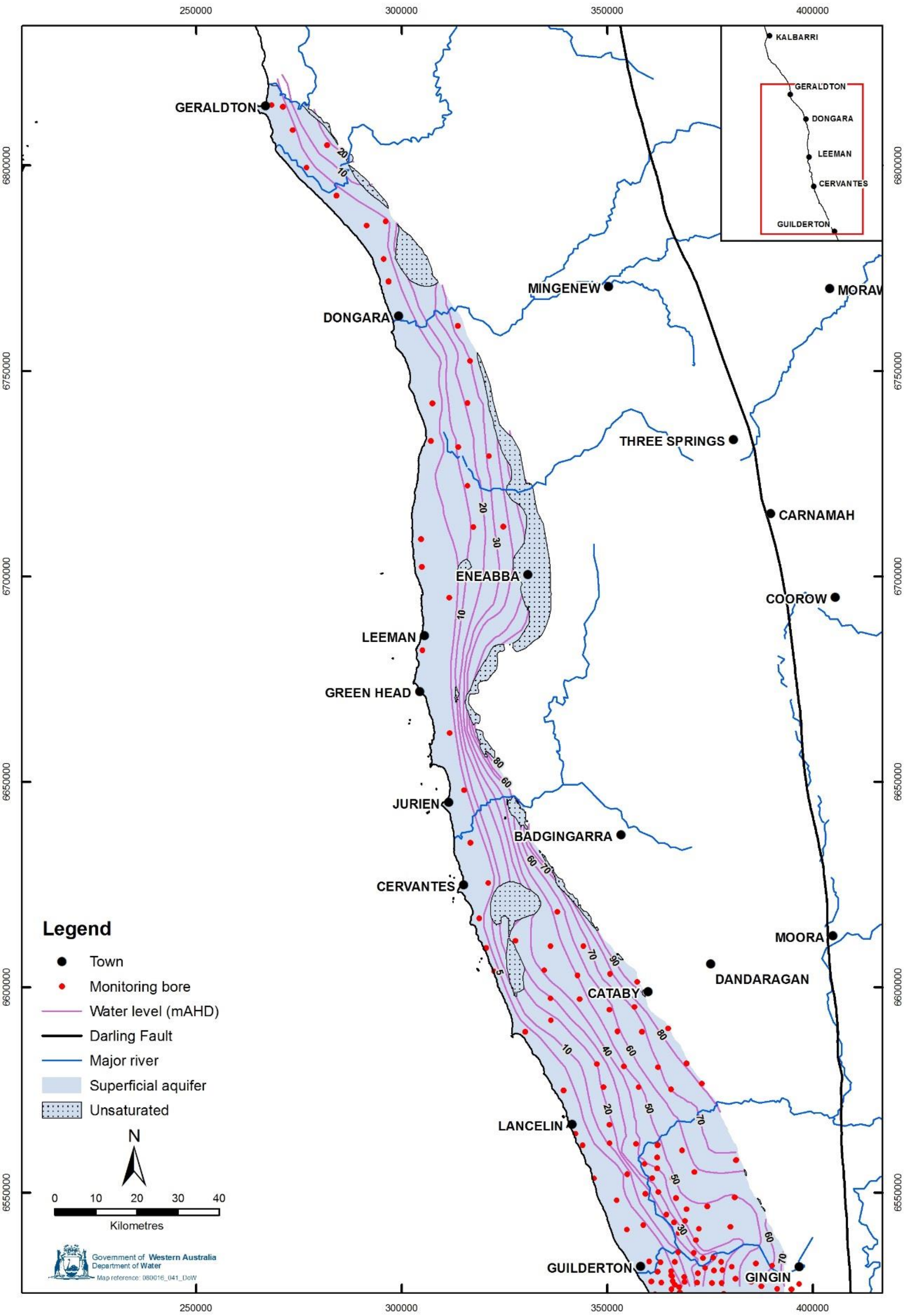


Figure 62 Superficial aquifer: watertable elevation (2015)

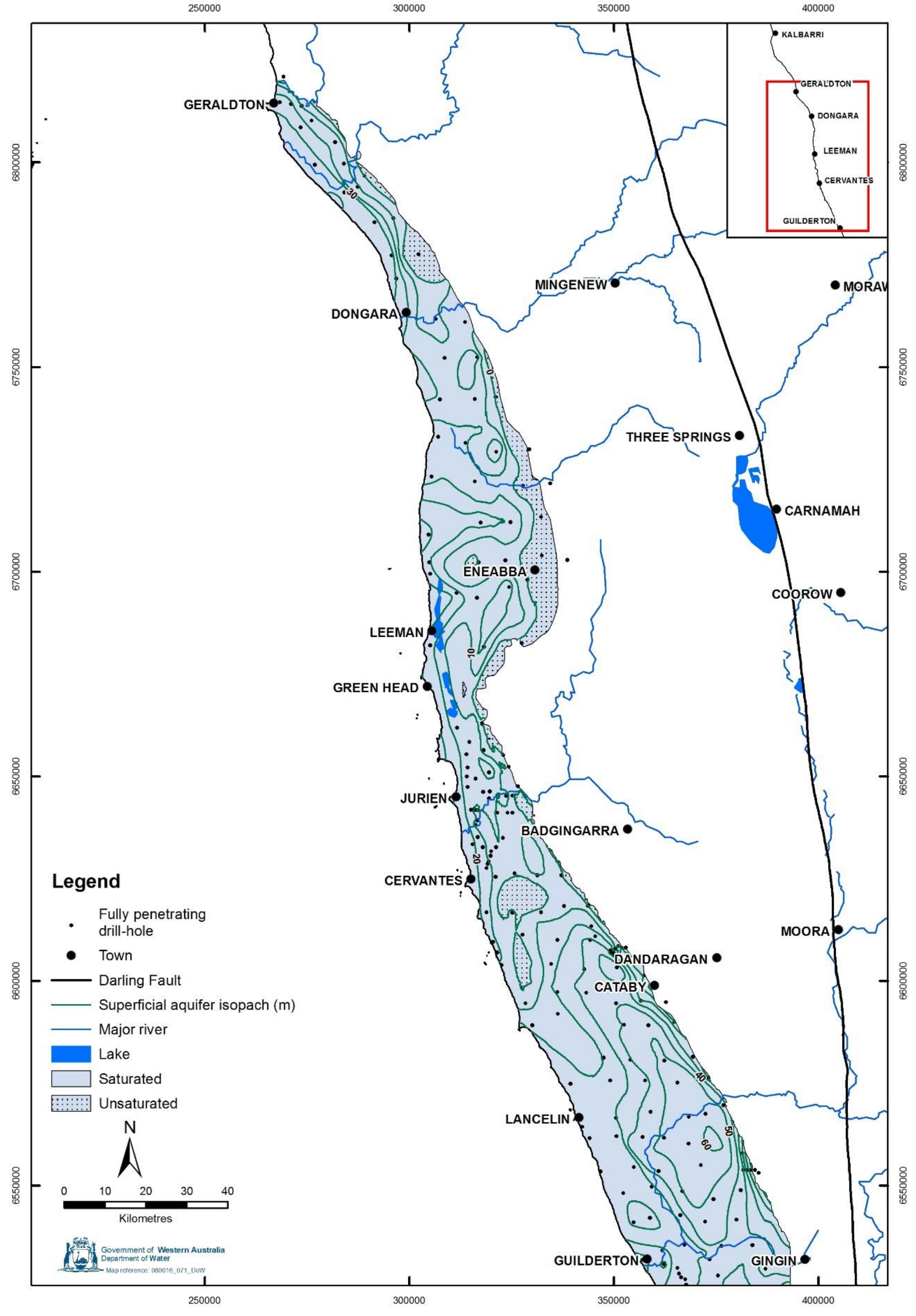


Figure 63 Superficial aquifer: saturated thickness

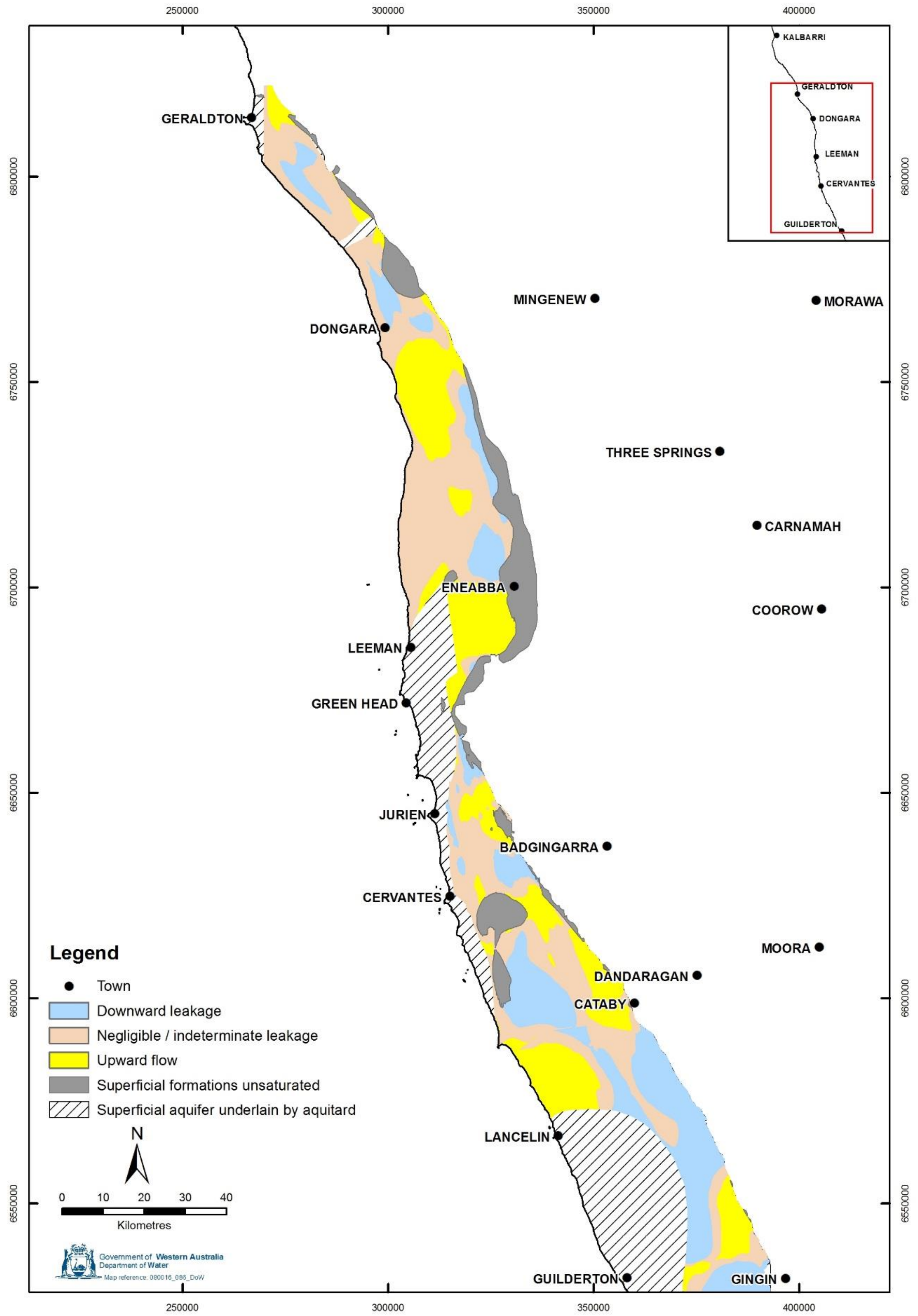
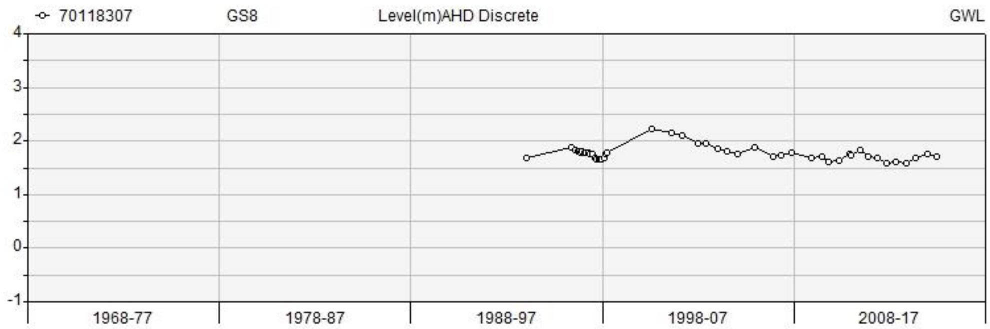
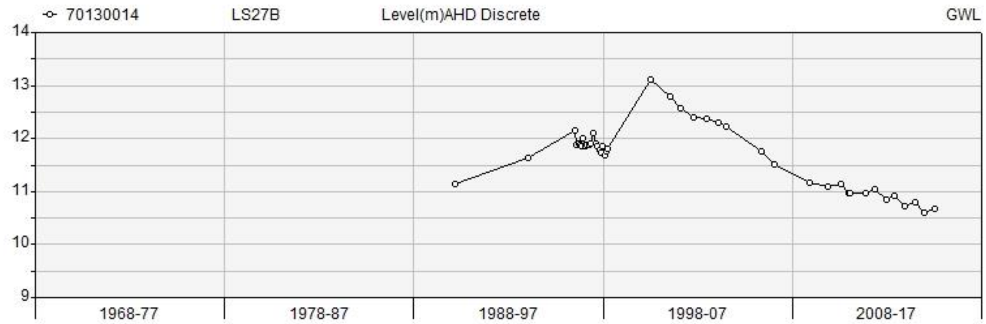


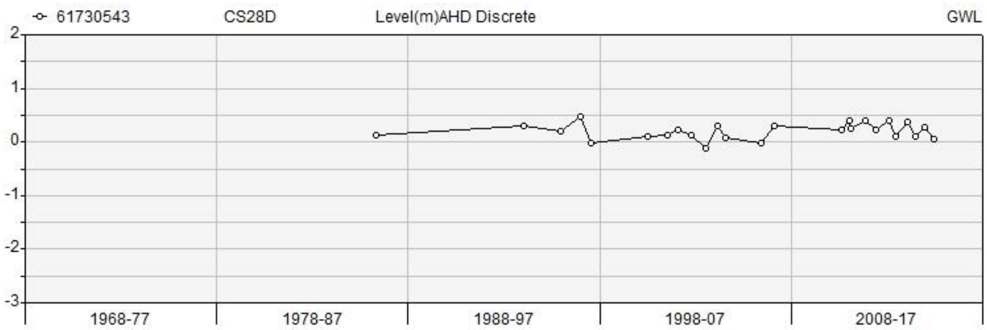
Figure 64 *Direction of vertical leakage between Superficial aquifer and underlying aquifers (Leederville, Yarragadee, Cattamarra and Eneabba–Lesueur)*



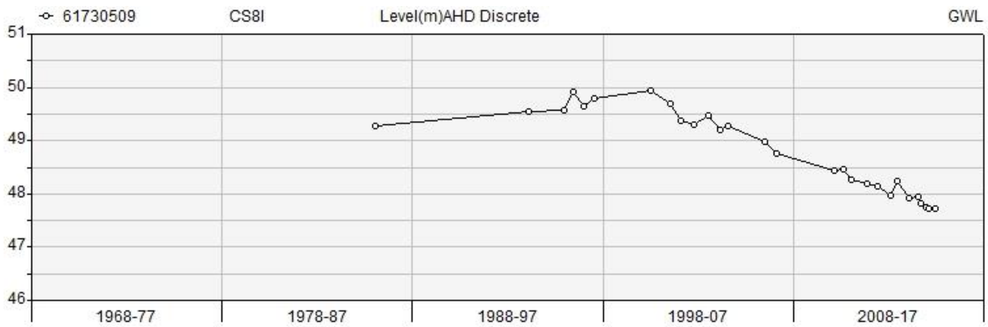
Greenough Shallow 8



Leeman Shallow 27B

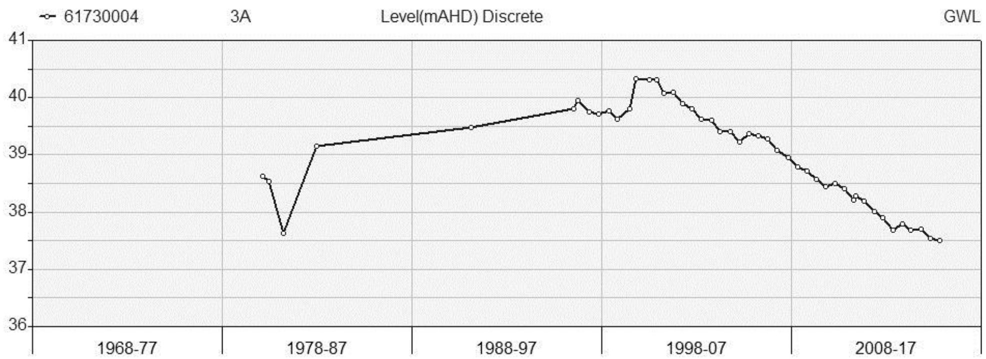


Cataby Shallow 28D

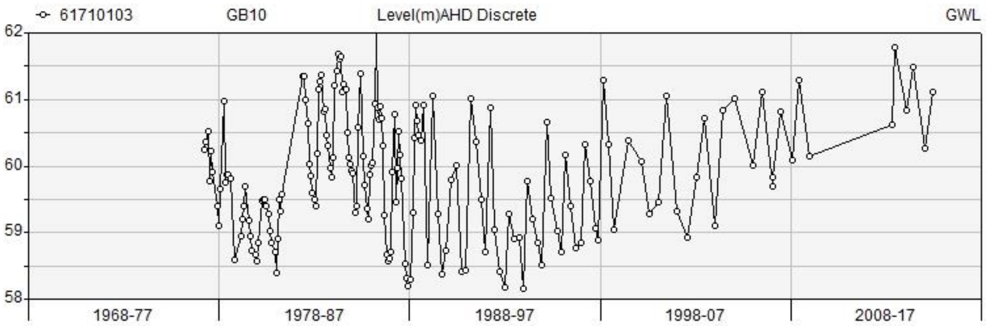


Cataby Shallow 8I

Figure 65 Superficial aquifer: selected bore hydrographs



Salvado 3A



Gingin Brook 10

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).

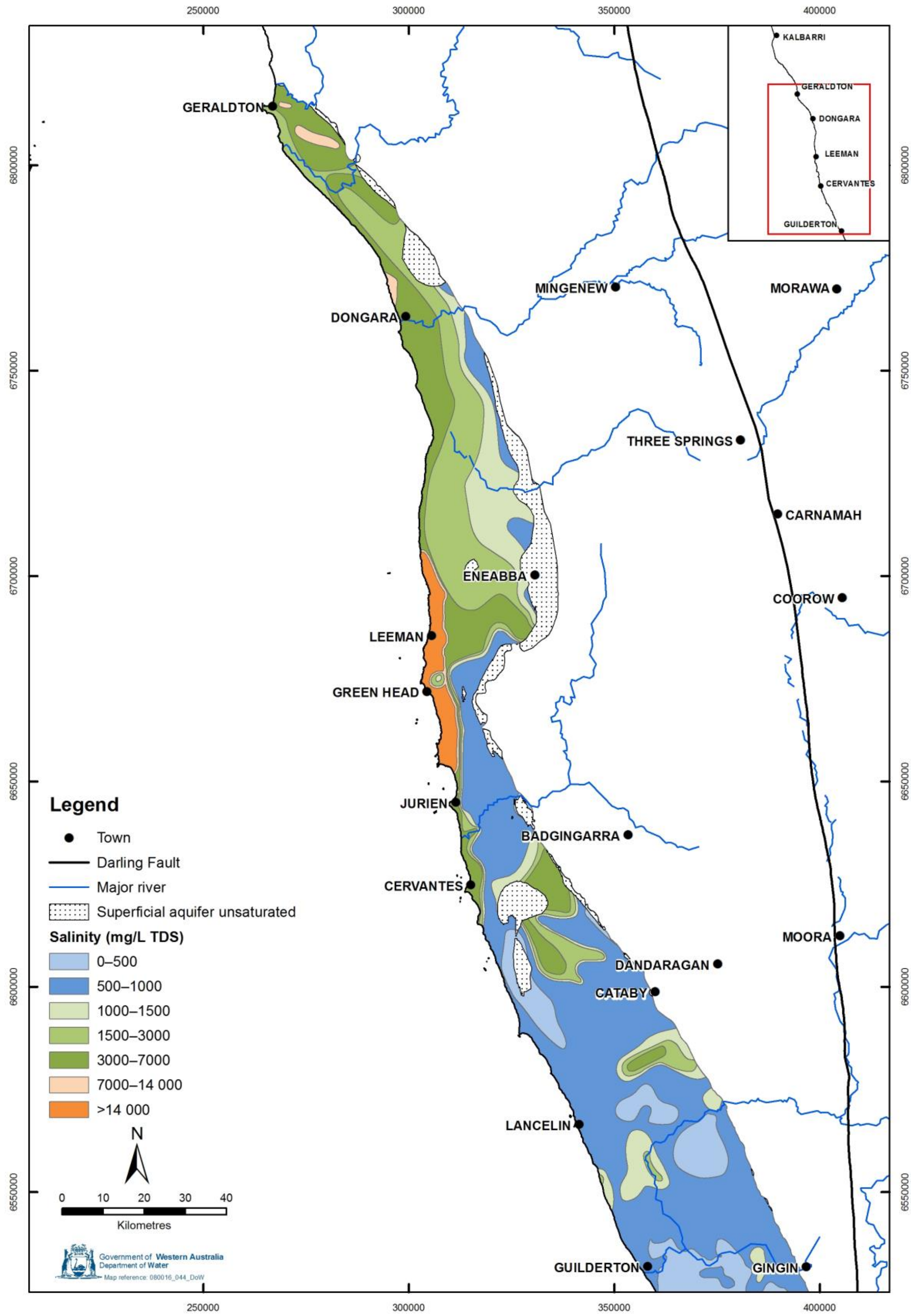


Figure 66 Superficial aquifer: groundwater salinity

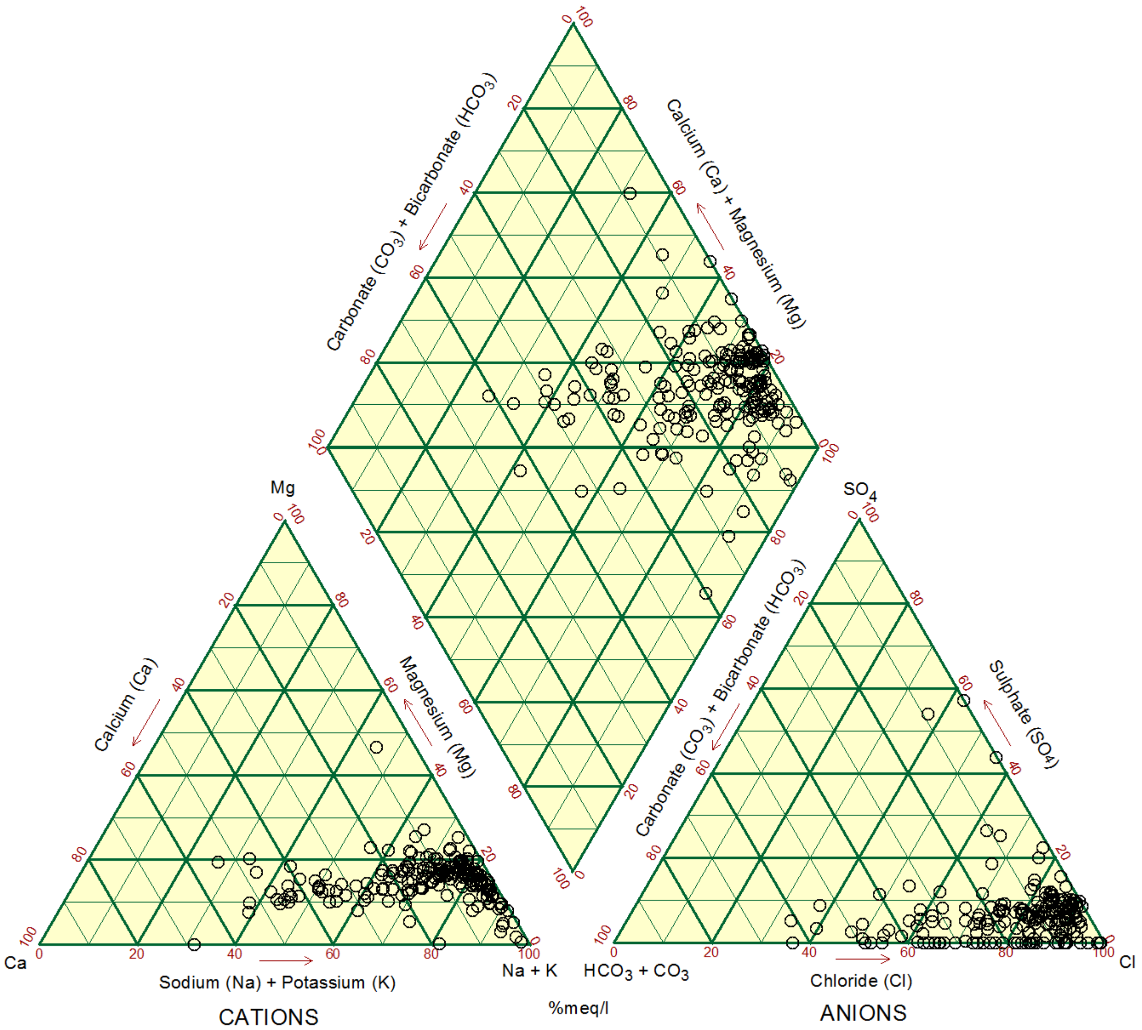


Figure 67 Superficial aquifer: hydrochemical trilinear diagram

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.

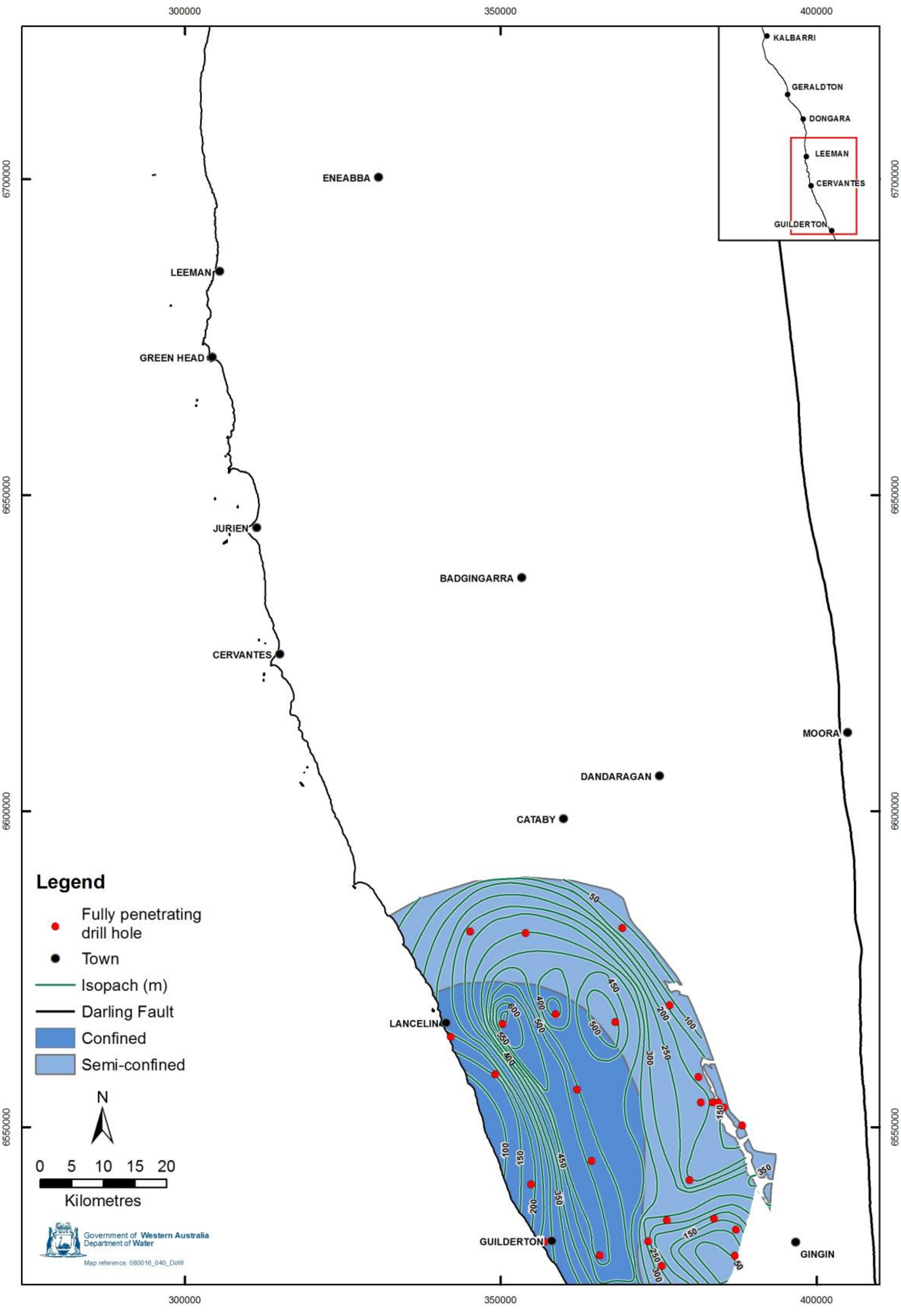


Figure 68 Leederville aquifer: aquifer thickness

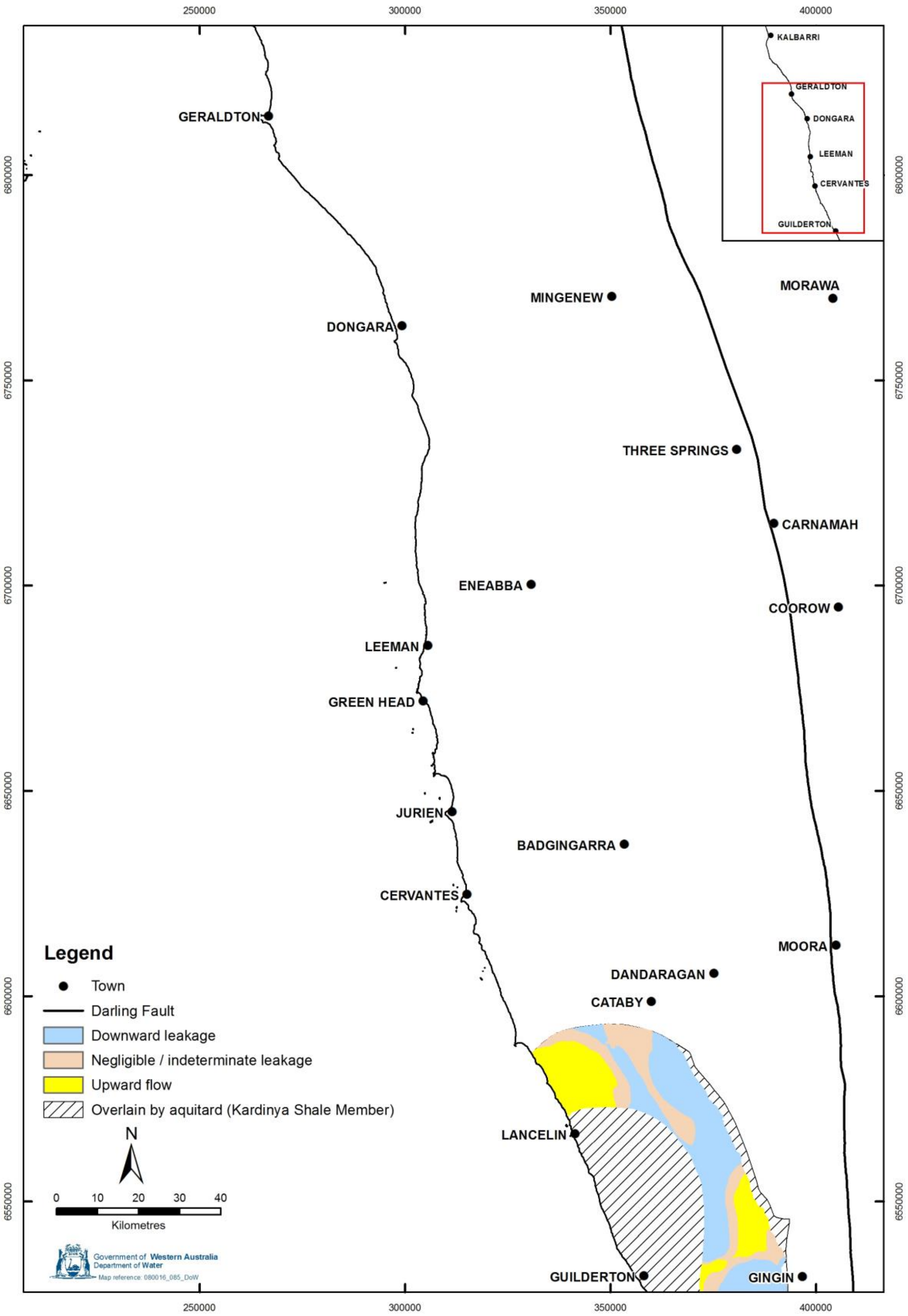


Figure 69 *Groundwater connection between Leederville aquifer and overlying Superficial aquifer*

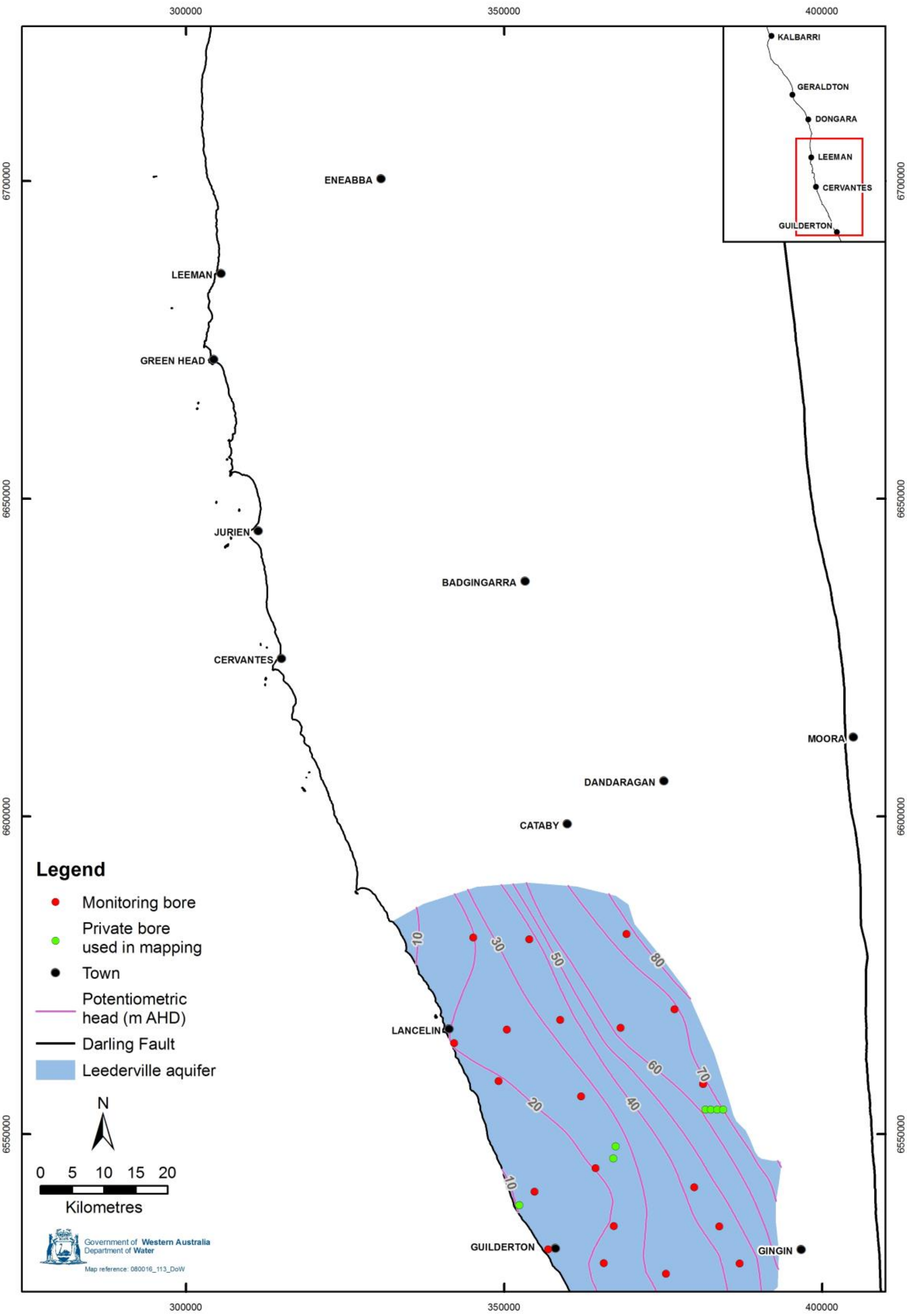


Figure 70 Leederville aquifer: potentiometric surface (2015)

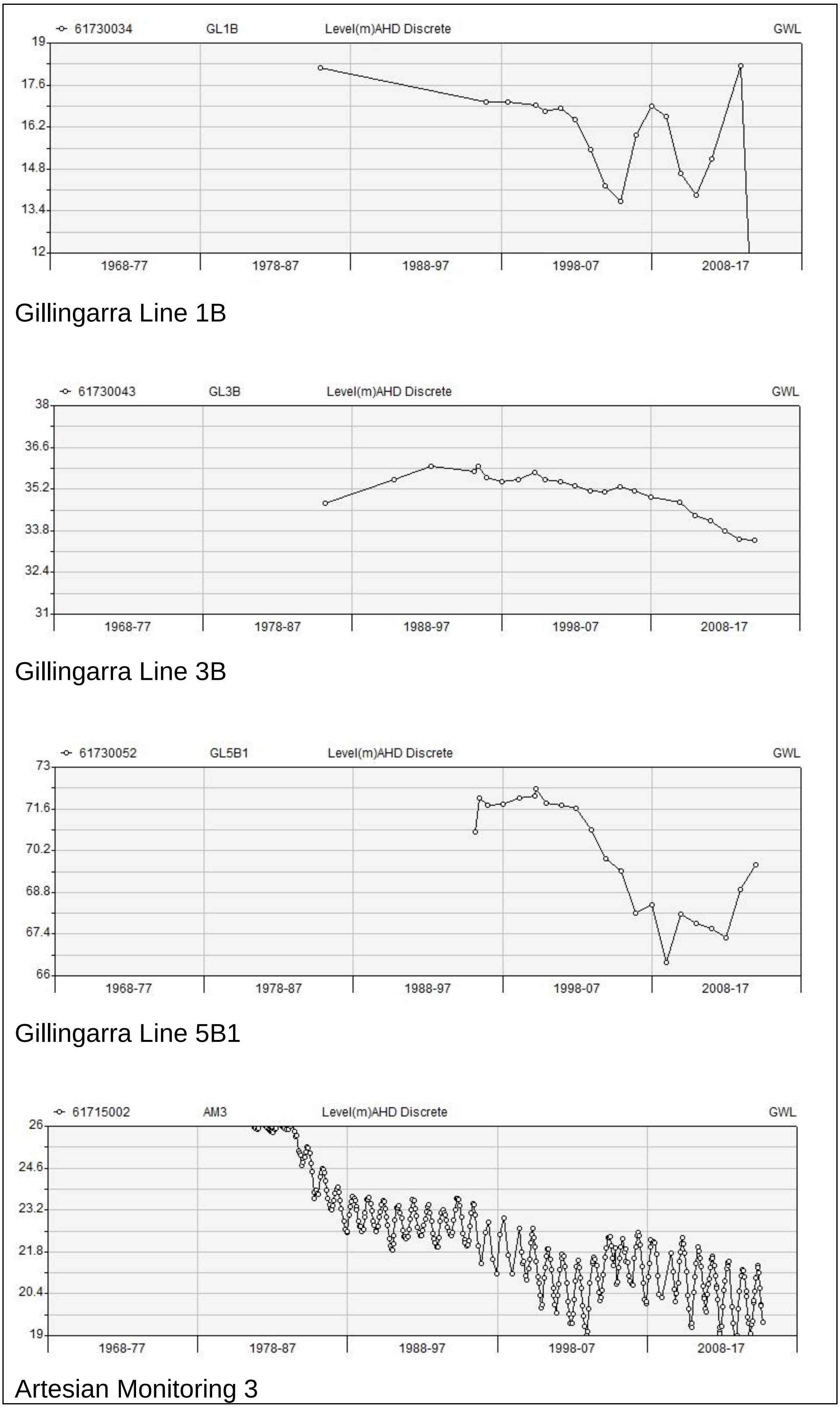


Figure 71 Leederville aquifer: selected bore hydrographs

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.

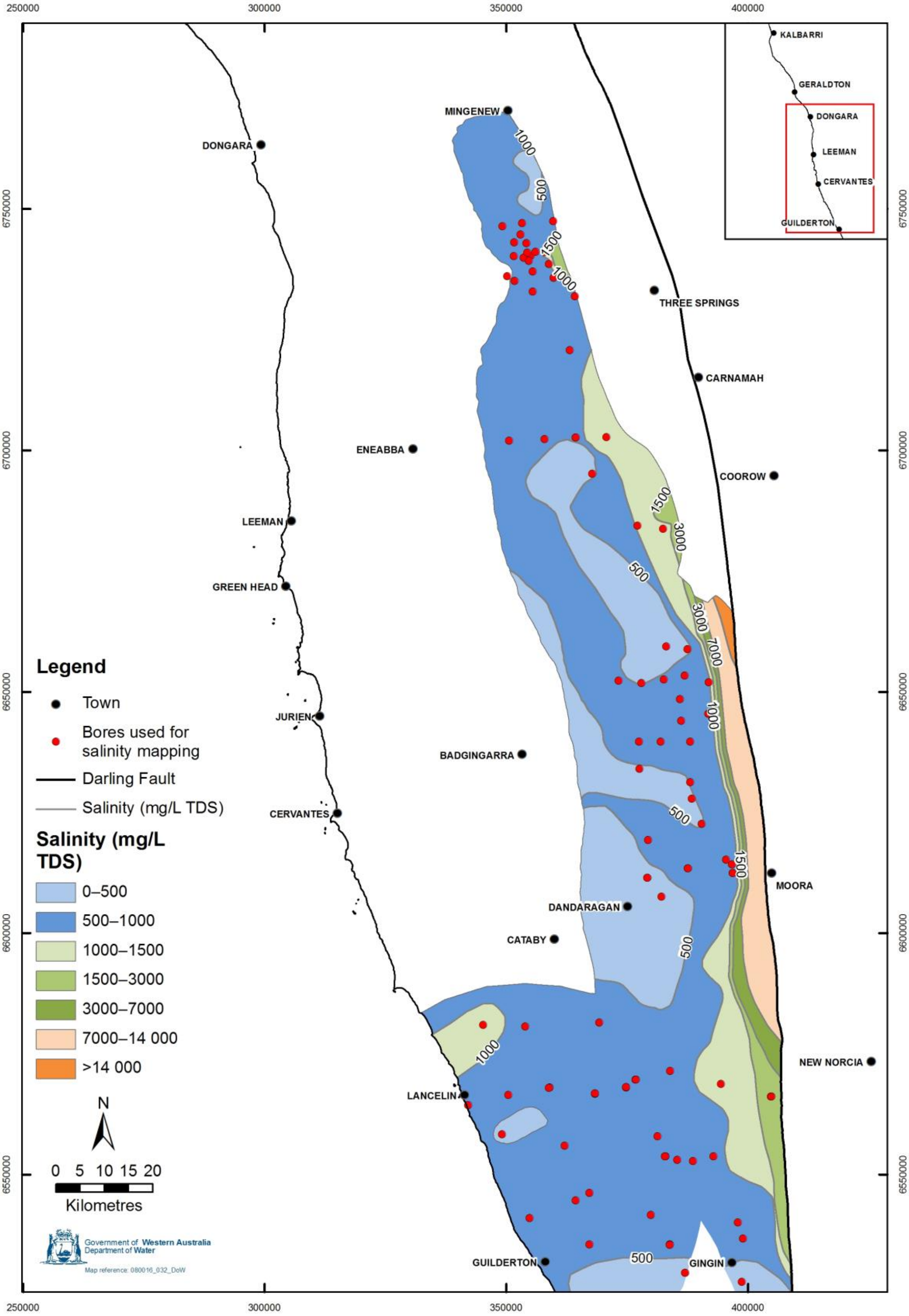


Figure 72 Leederville and Leederville–Parmelia aquifers: groundwater salinity

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).

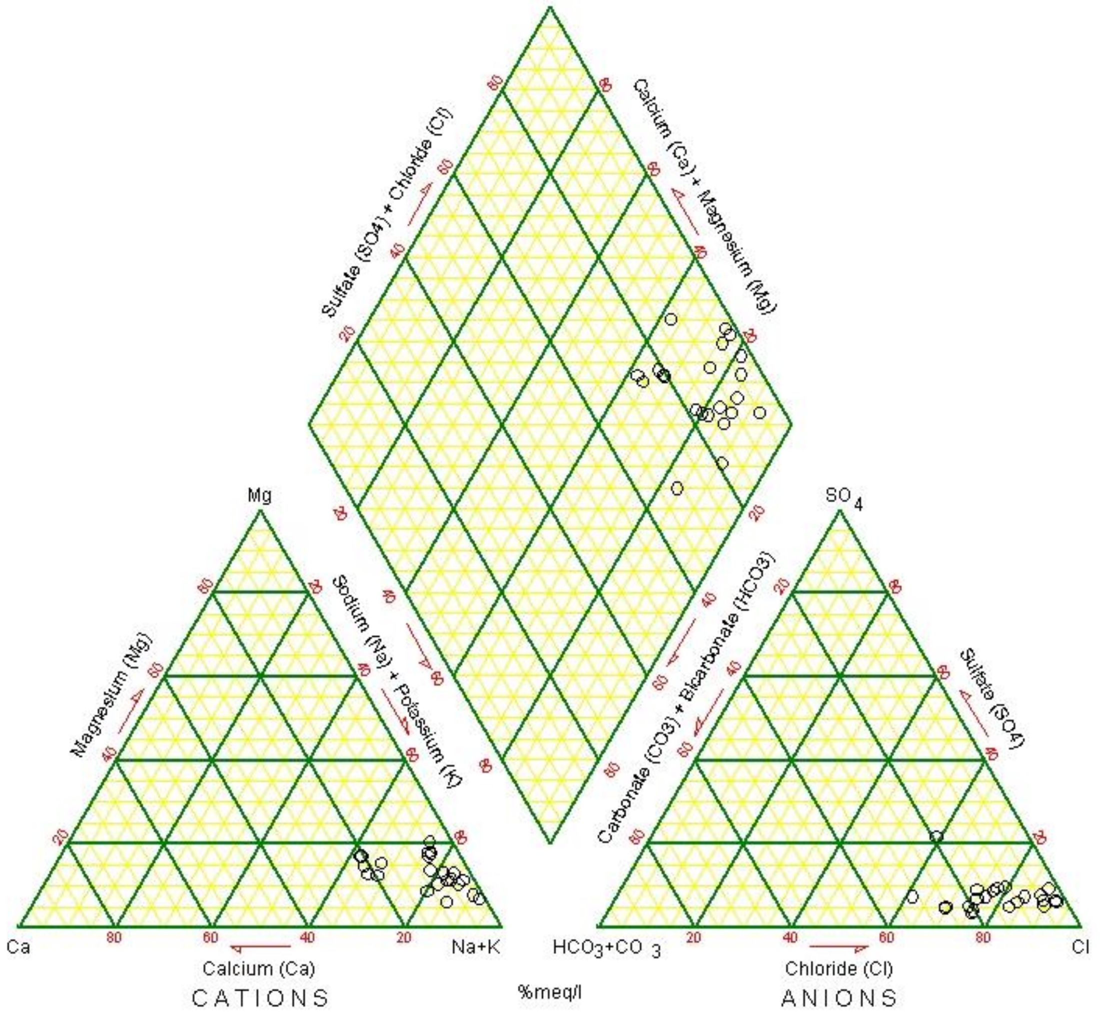


Figure 73   Leederville aquifer: hydrochemical trilinear diagram

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.

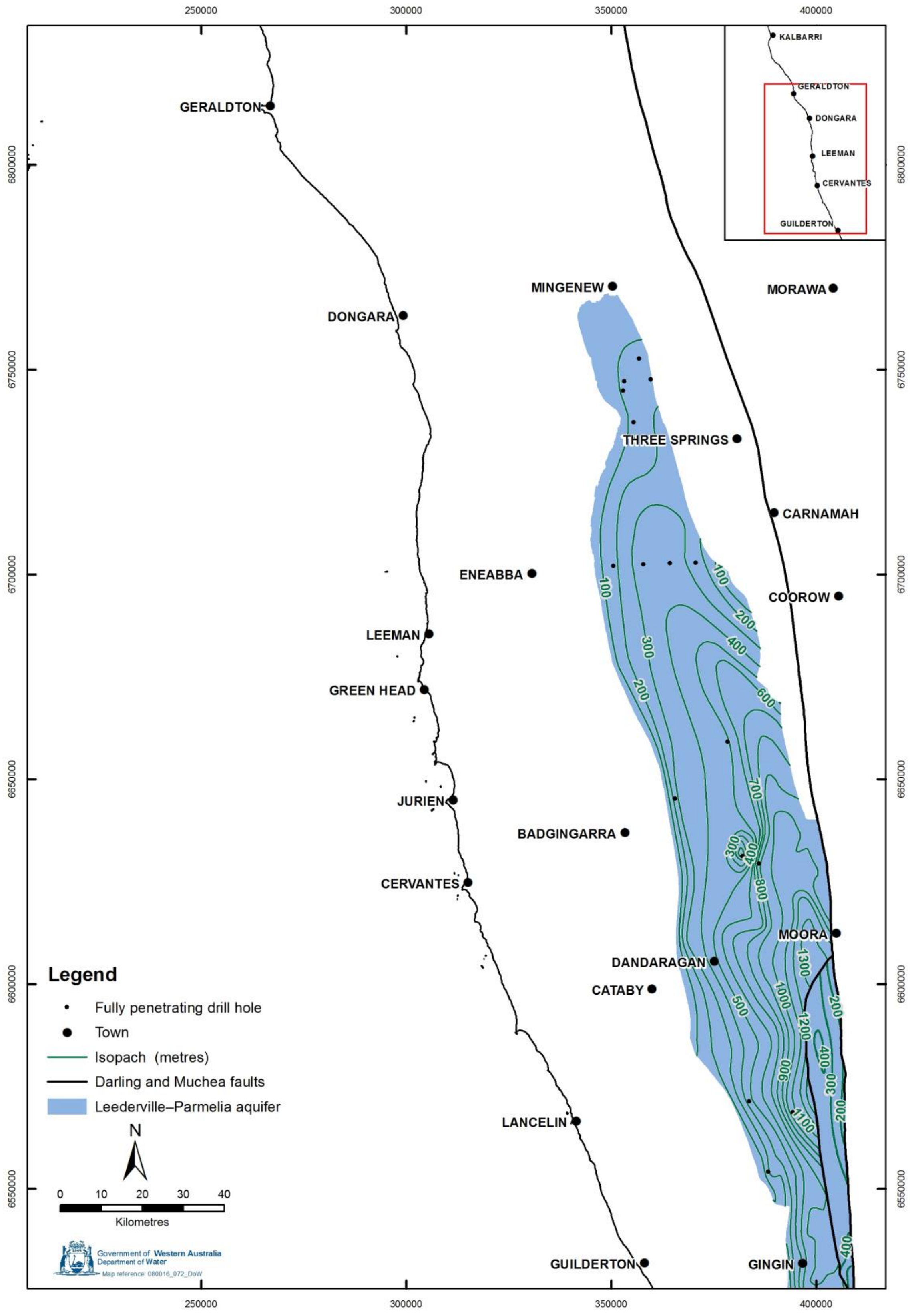


Figure 74 Leederville–Parmelia aquifer: aquifer thickness

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.

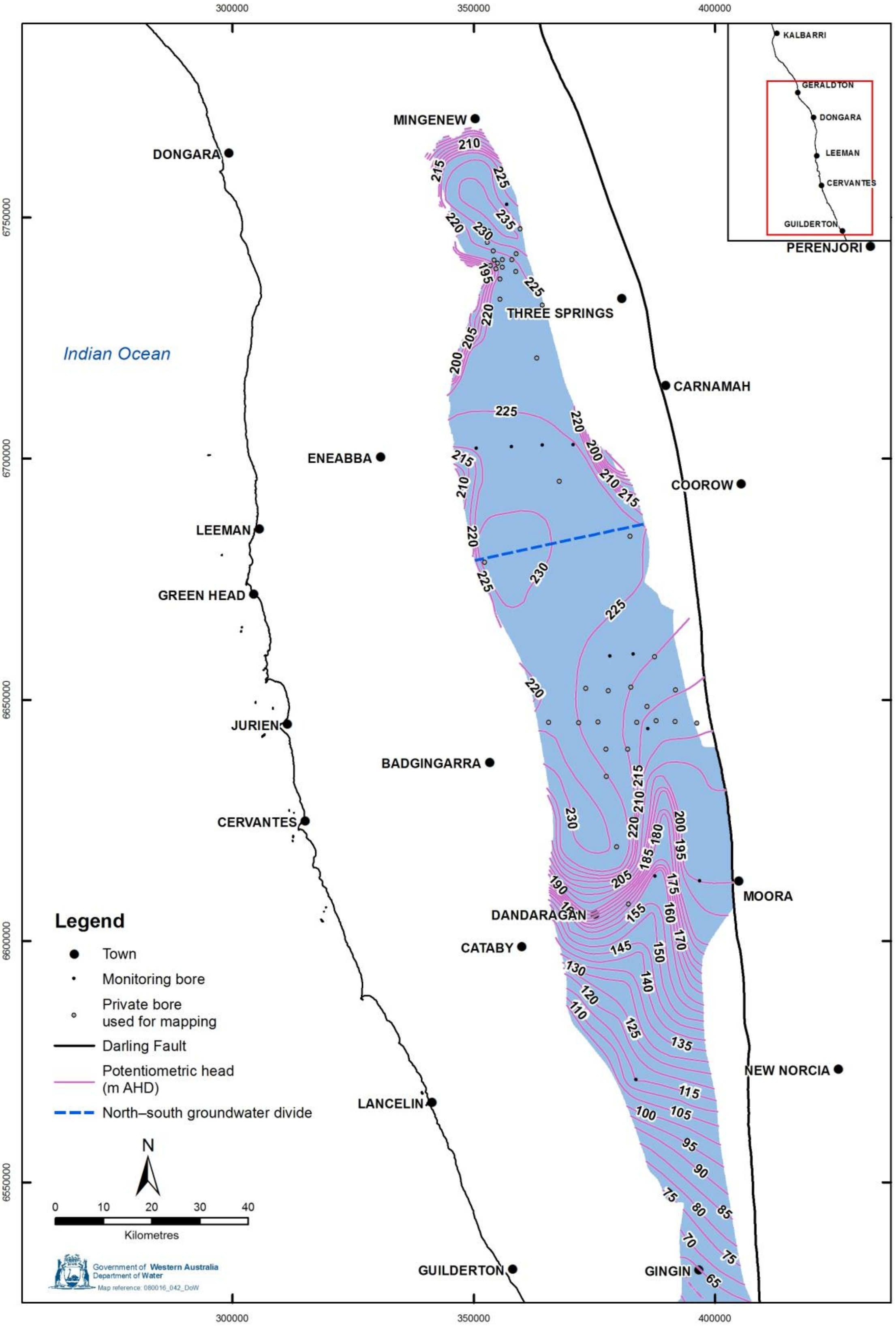


Figure 75 Leederville–Parmelia aquifer: potentiometric surface (Parmelia Group component) (2015)

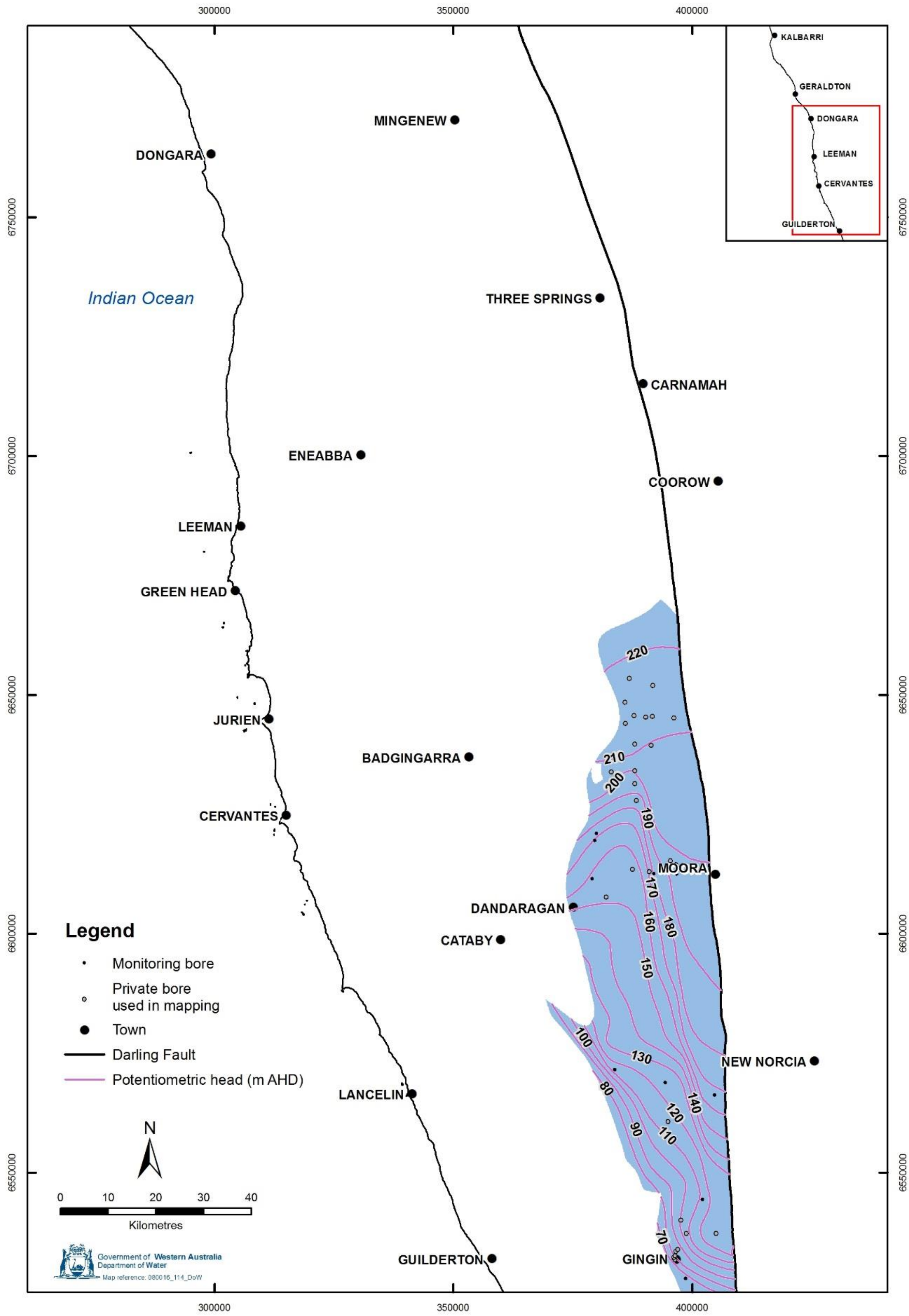
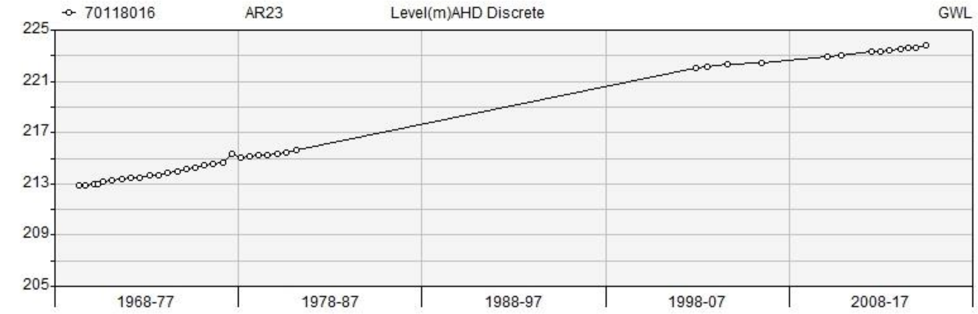
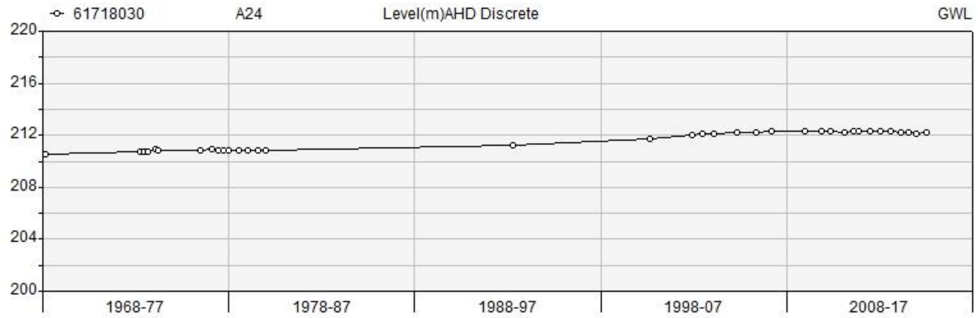


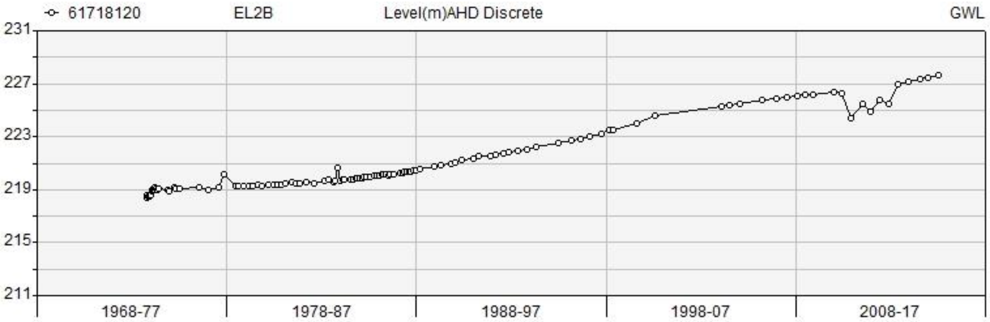
Figure 76 *Leederville–Parmelia aquifer: potentiometric surface (Leederville Formation component) (2015)*



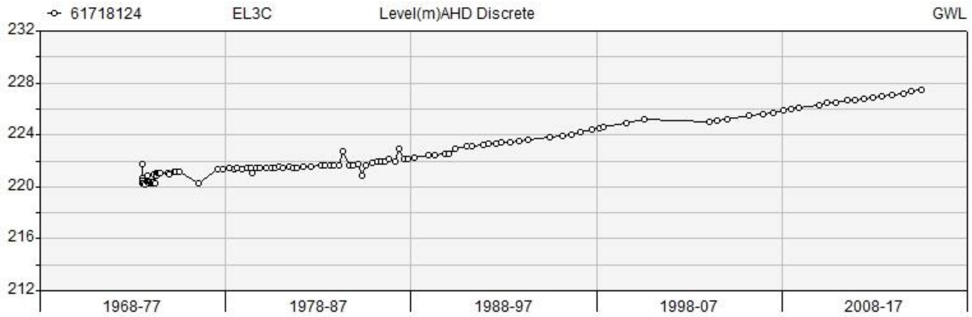
Arrowsmith River 23



Arrowsmith River 24

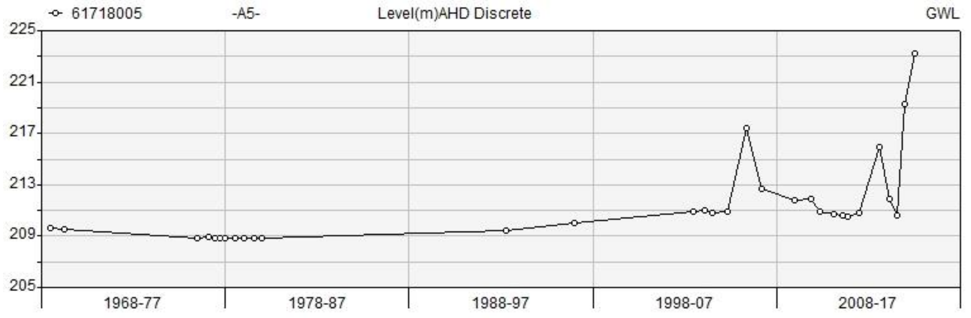


Eneabba Line 2B

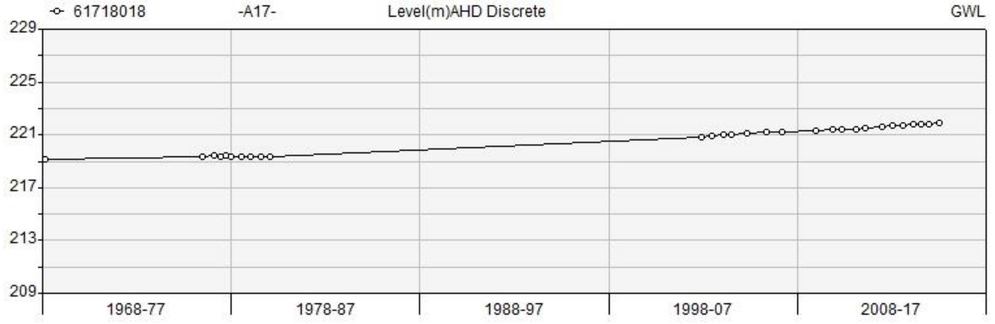


Eneabba Line 3C

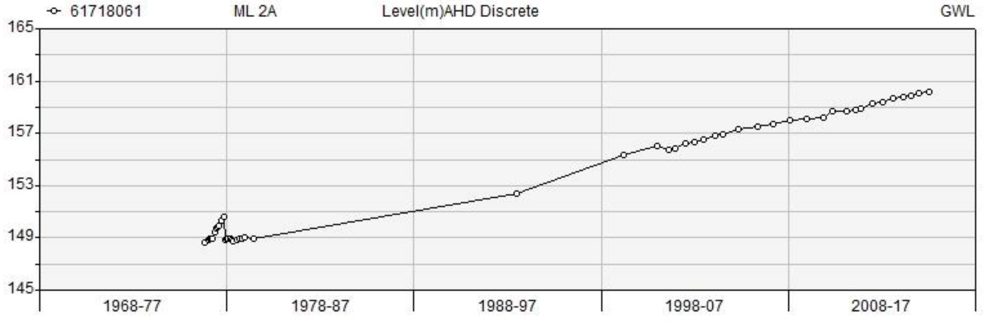
Figure 77　　Leederville–Parmelia aquifer: selected bore hydrographs



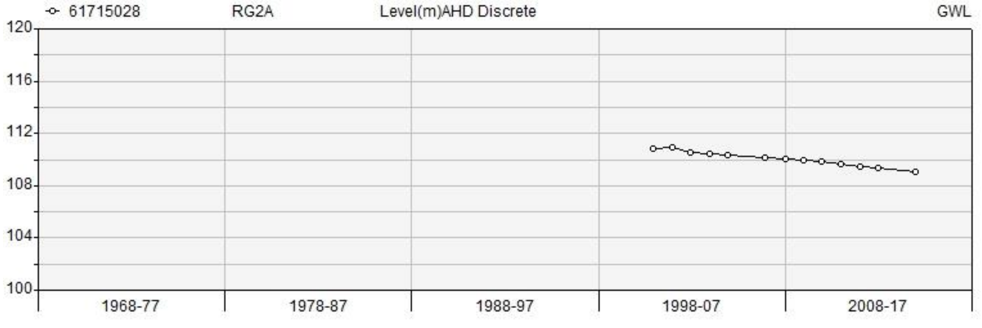
Agaton 5



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).

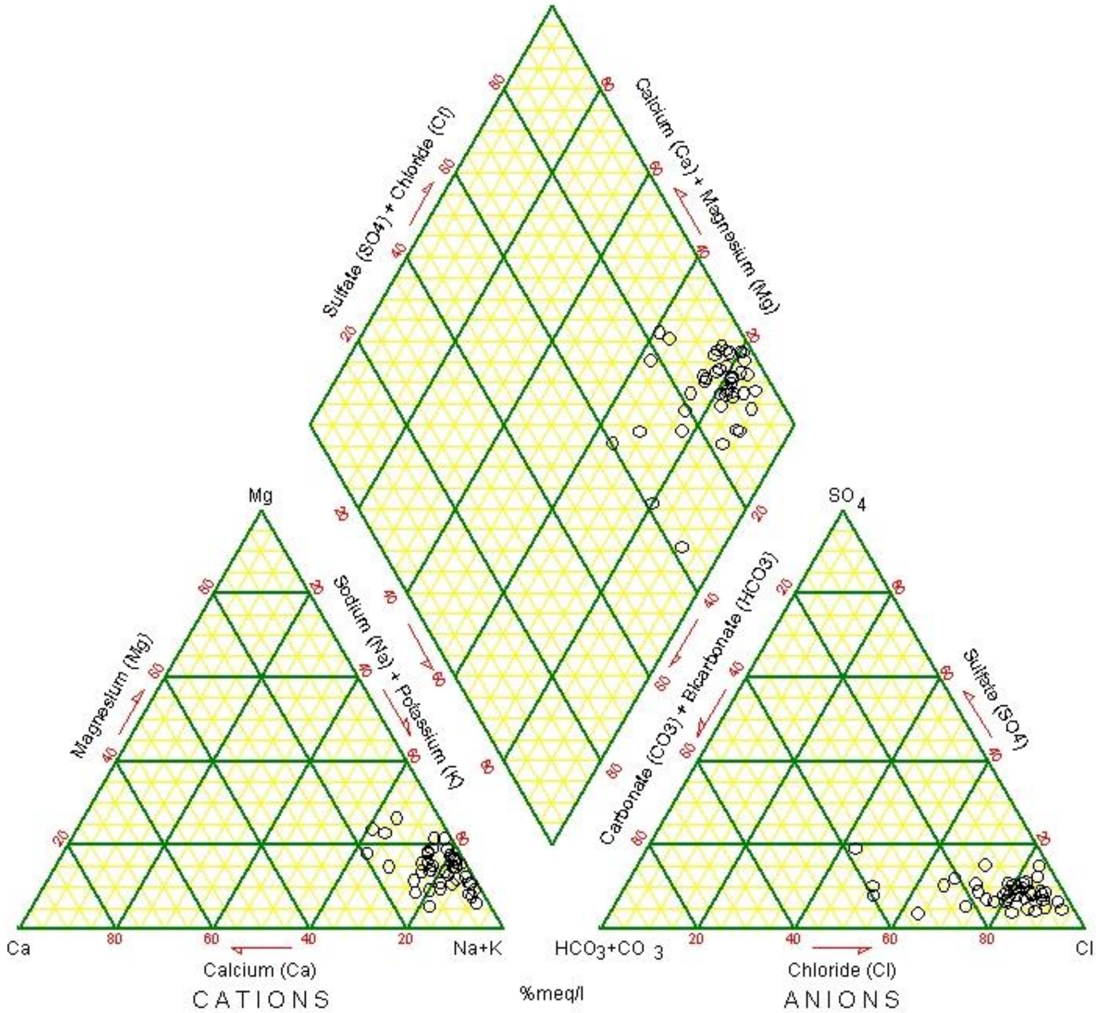


Figure 78   Leederville–Parmelia aquifer: hydrochemical trilinear diagram

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.

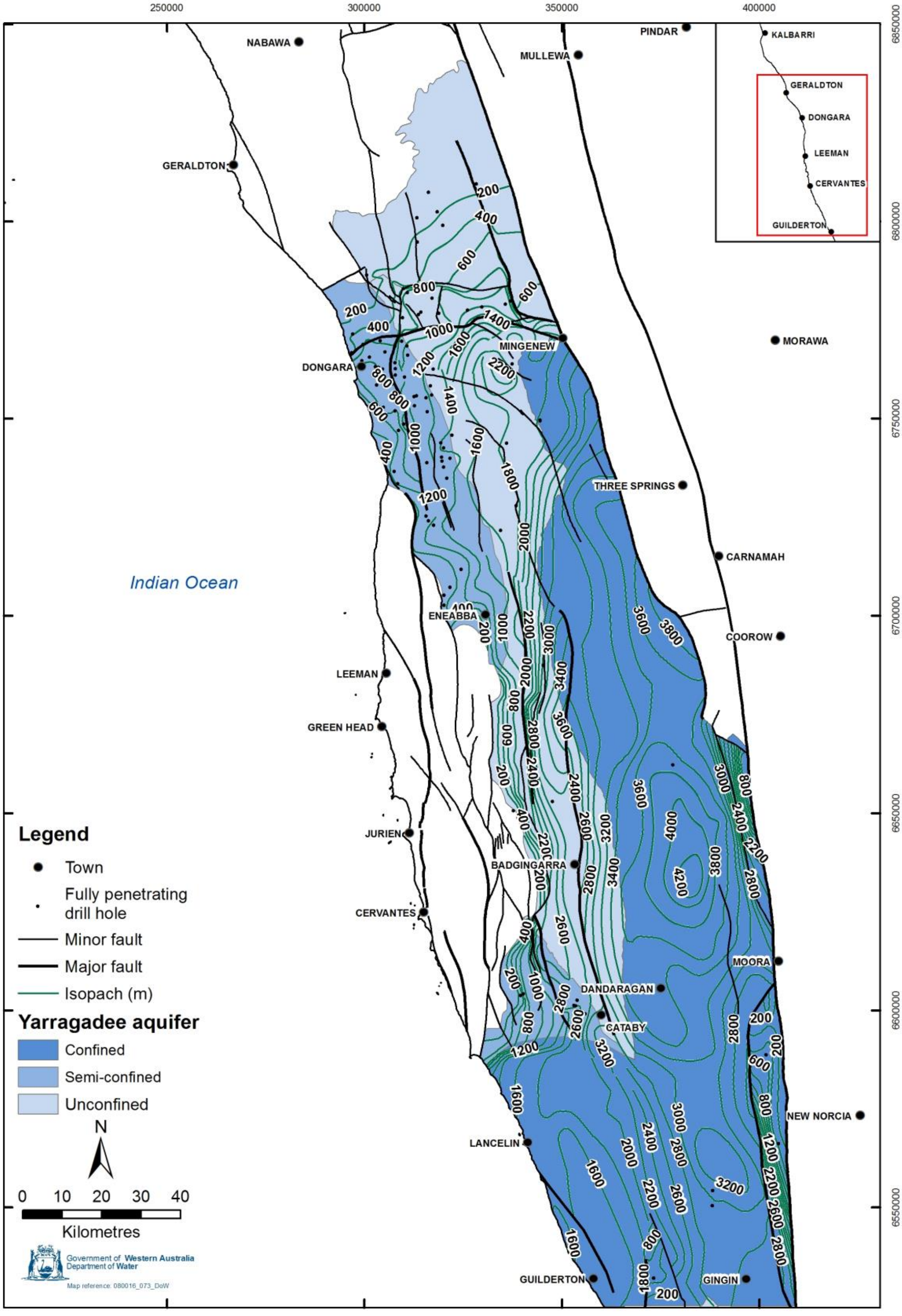


Figure 79 Yarragadee aquifer: saturated aquifer thickness

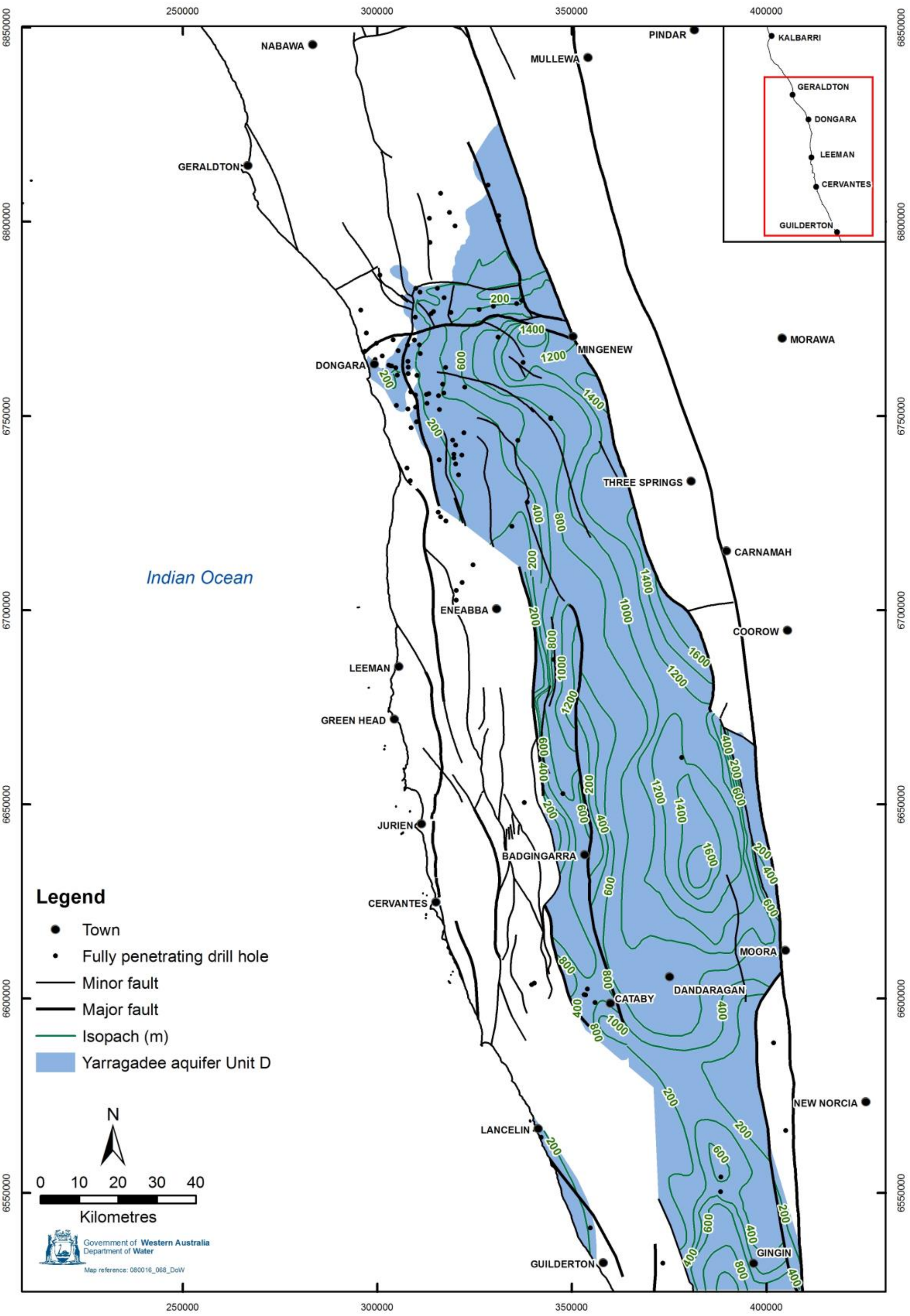


Figure 80 Yarragadee aquifer Unit D: aquifer thickness

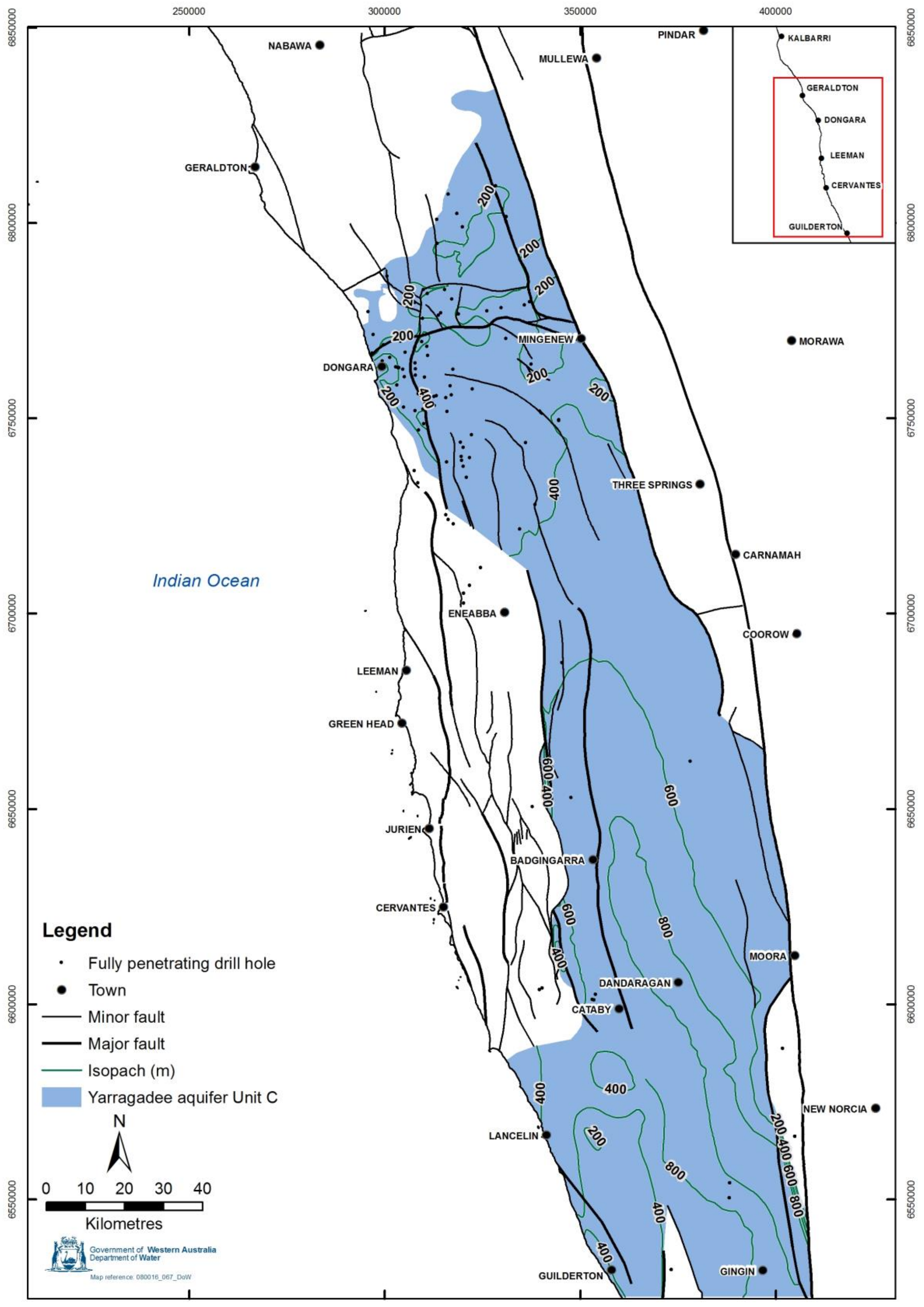


Figure 81 Yarragadee aquifer Unit C: aquifer thickness

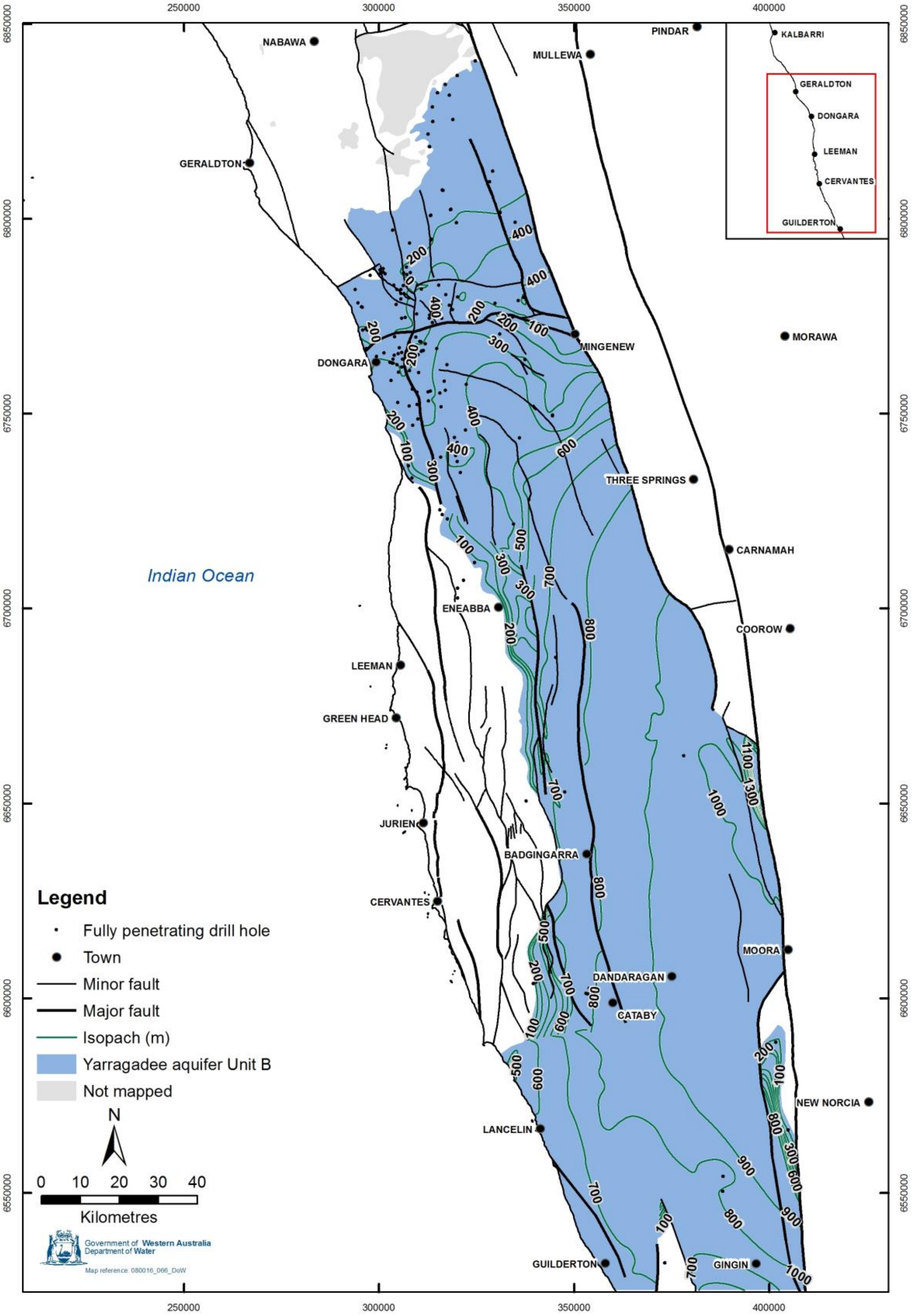


Figure 82 Yarragadee aquifer Unit B: aquifer thickness

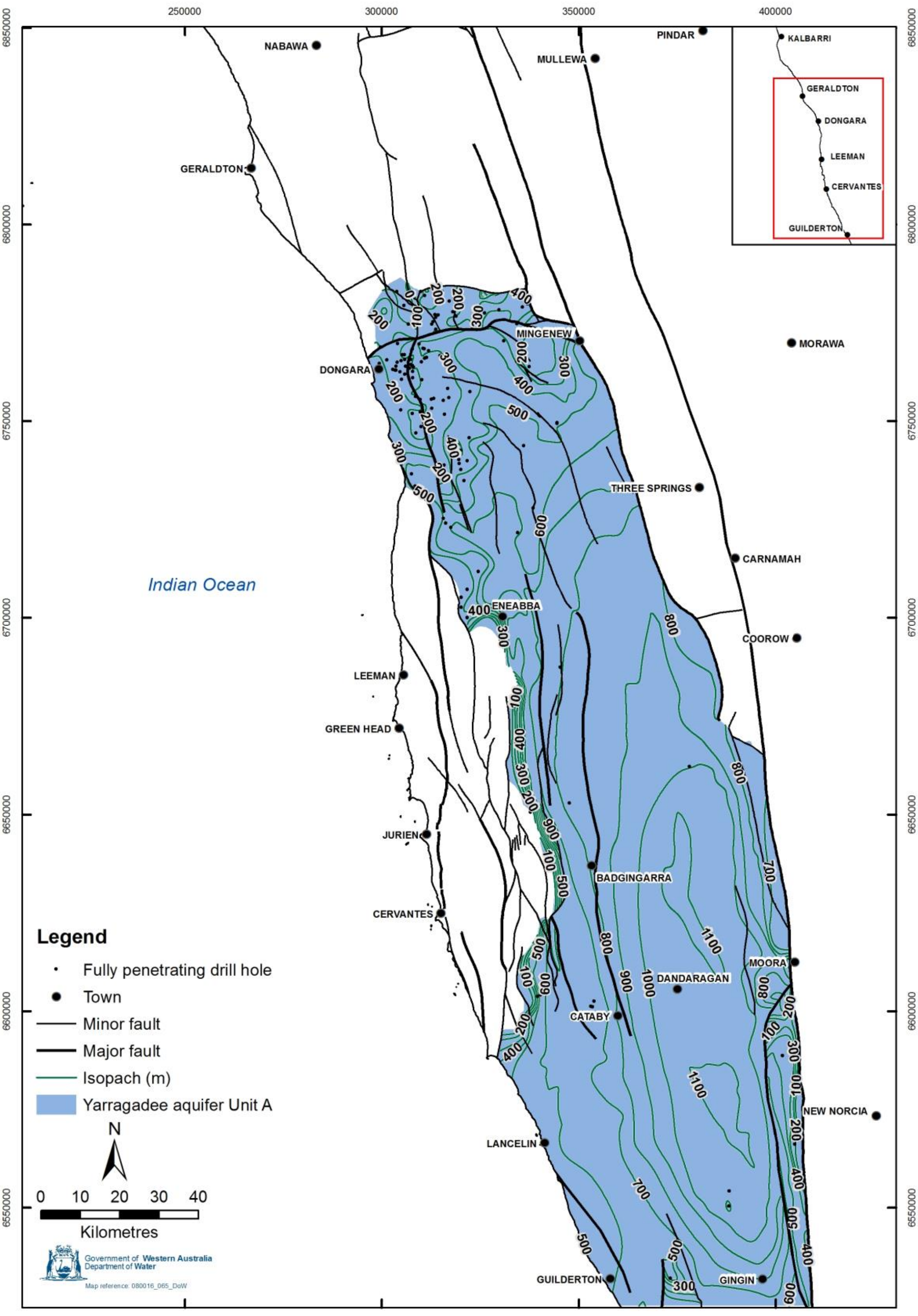


Figure 83 Yarragadee aquifer Unit A: aquifer thickness

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.

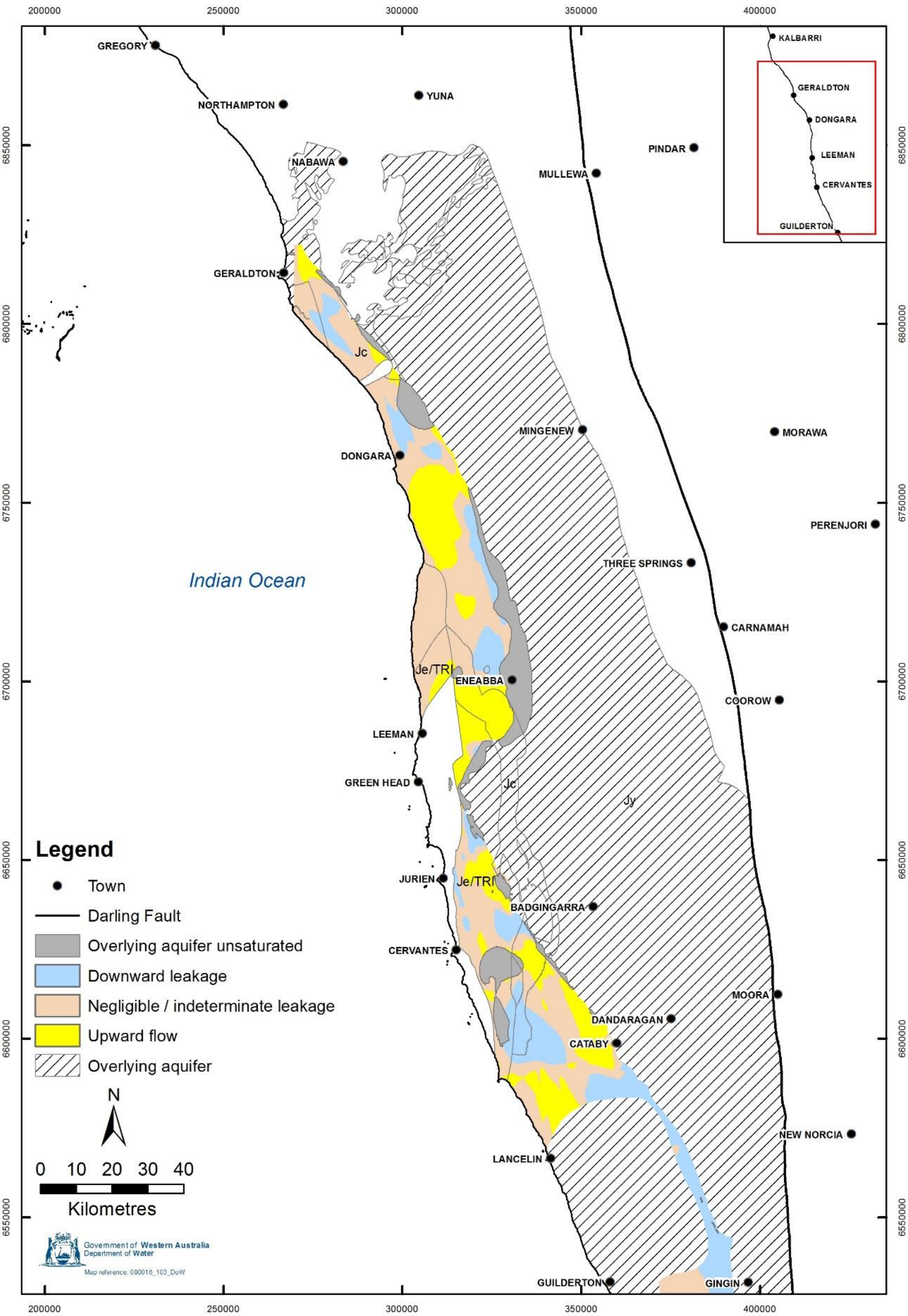


Figure 84 Vertical leakage between Yarragadee, Cattamarra and Eneabba–Lesueur aquifers and overlying Superficial and/or Leederville aquifer(s)

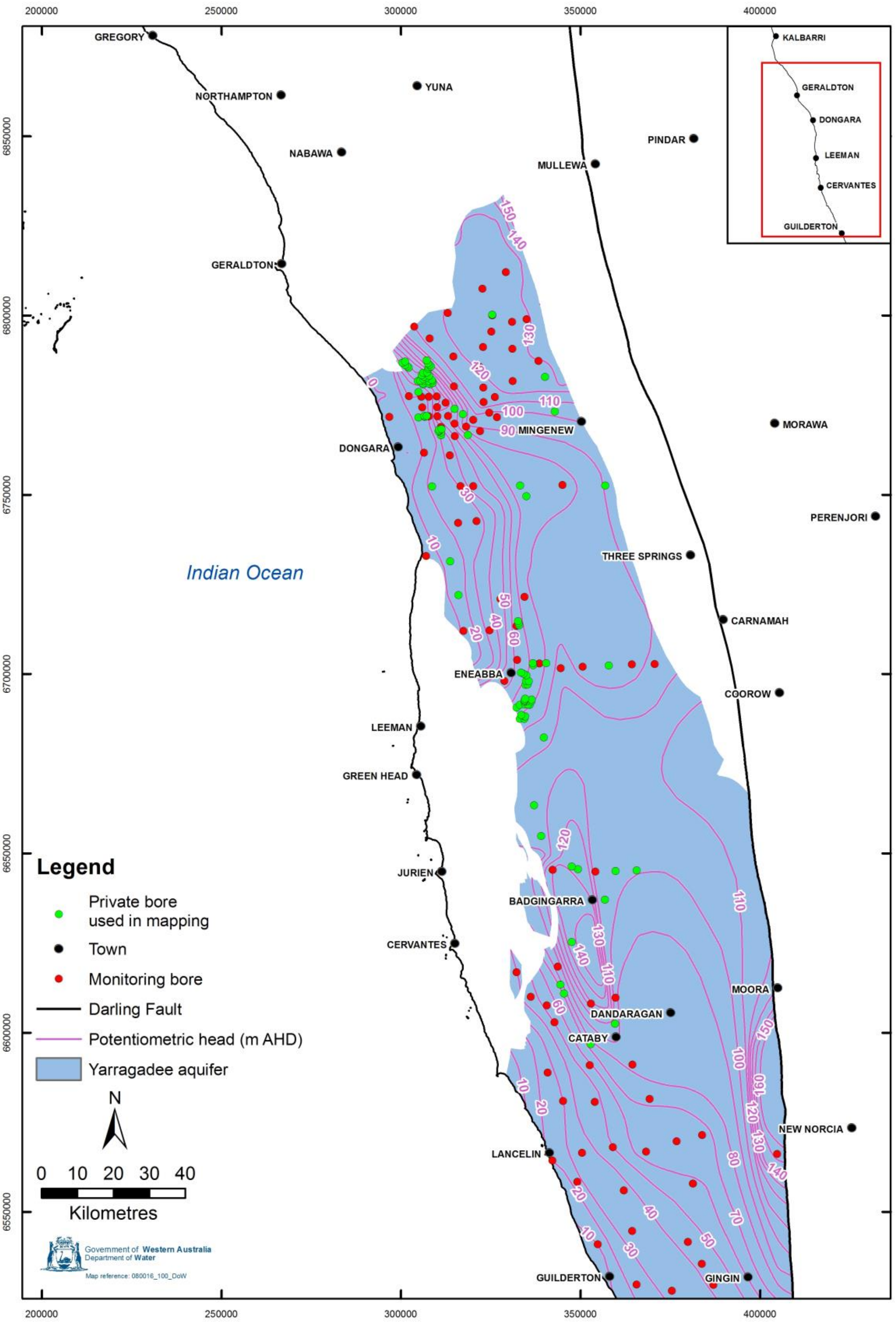


Figure 85 Yarragadee aquifer: potentiometric surface (2015)

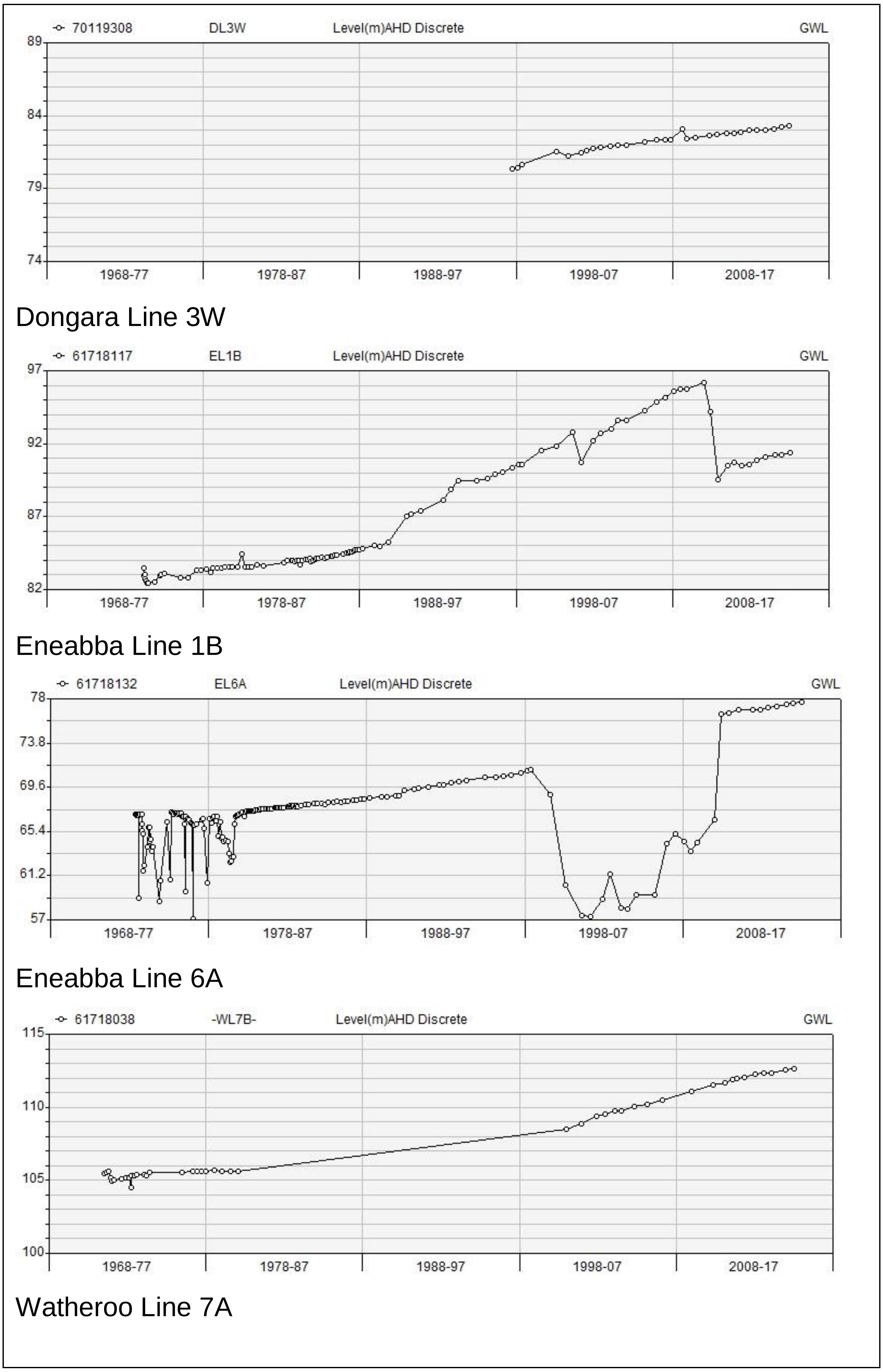
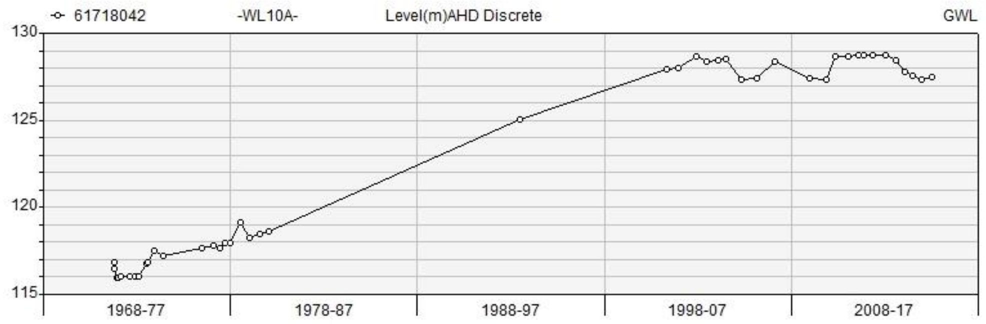
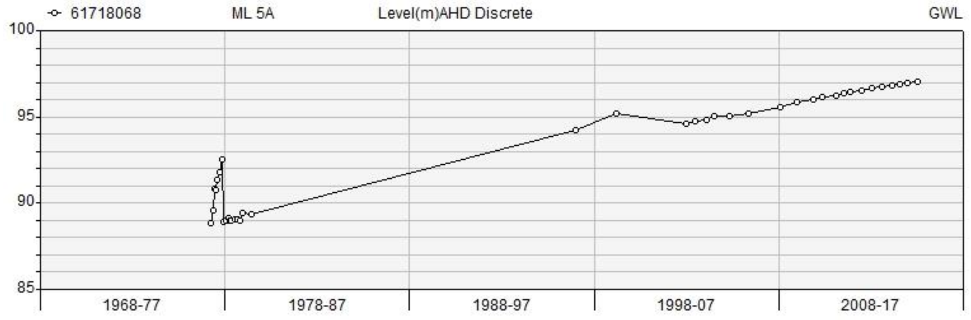


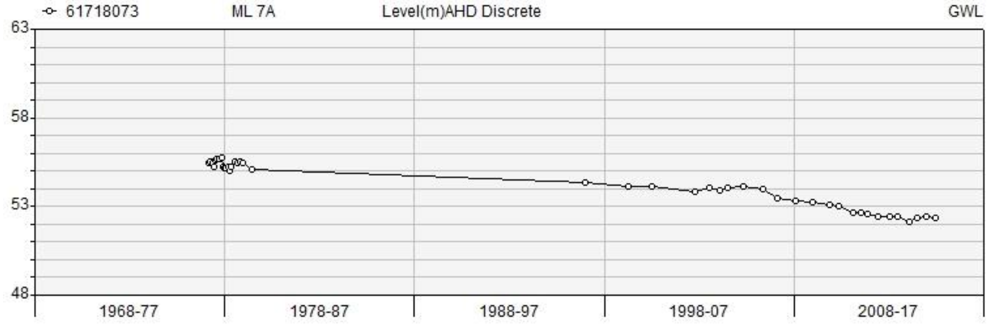
Figure 86 Yarragadee aquifer: selected bore hydrographs



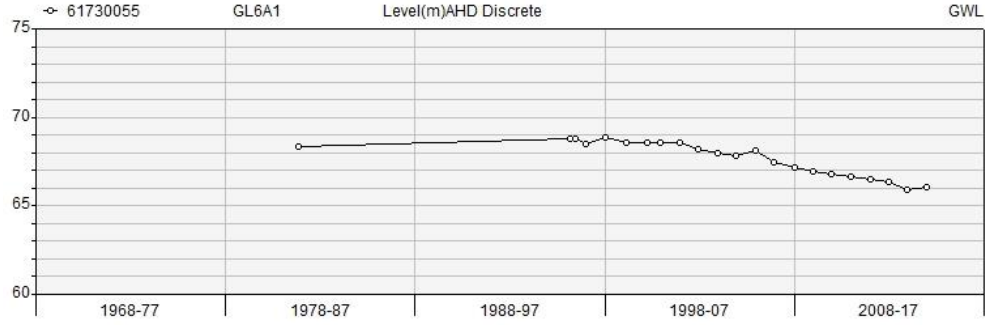
Watheroo Line 10A



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.

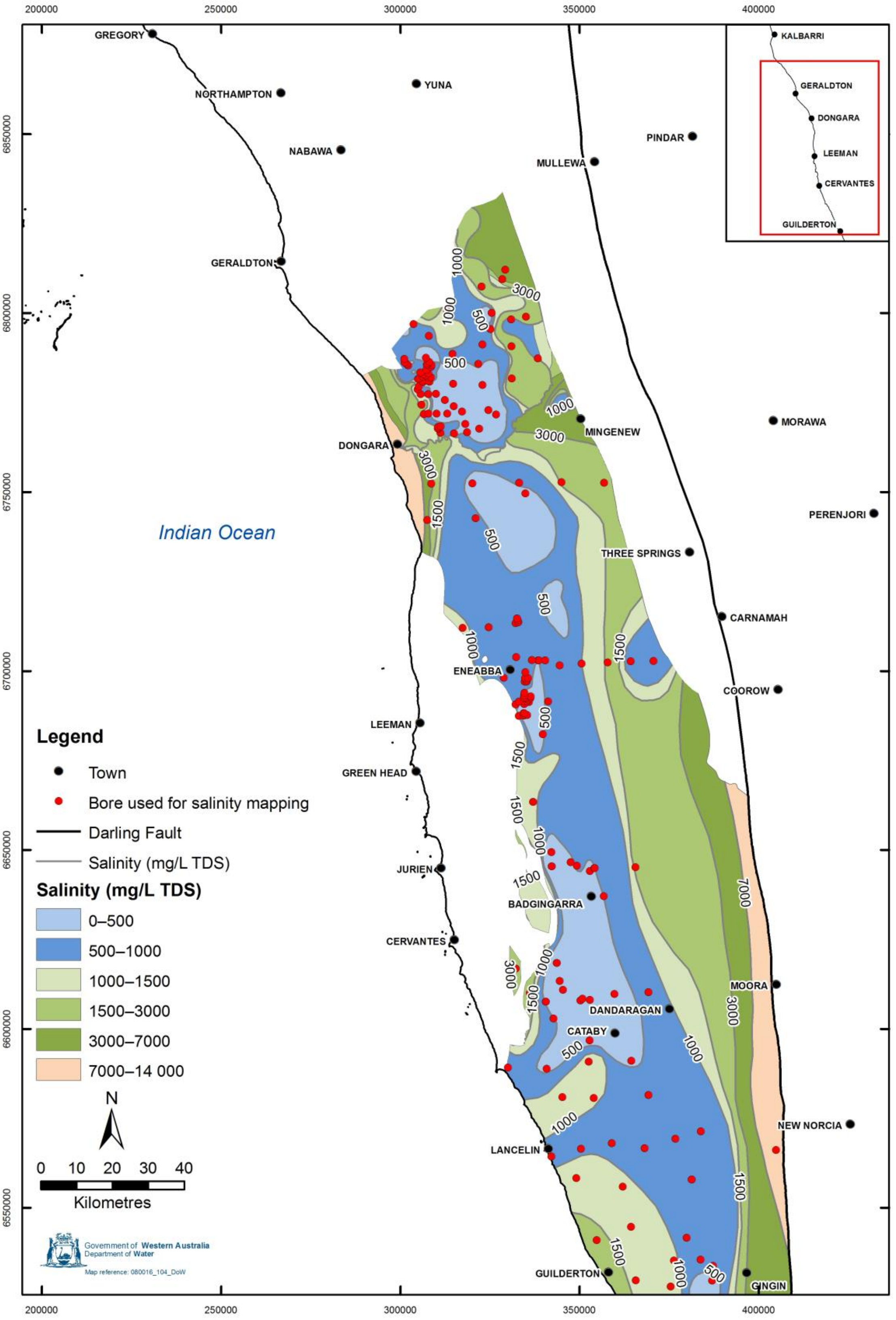


Figure 87 Yarragadee aquifer: groundwater salinity

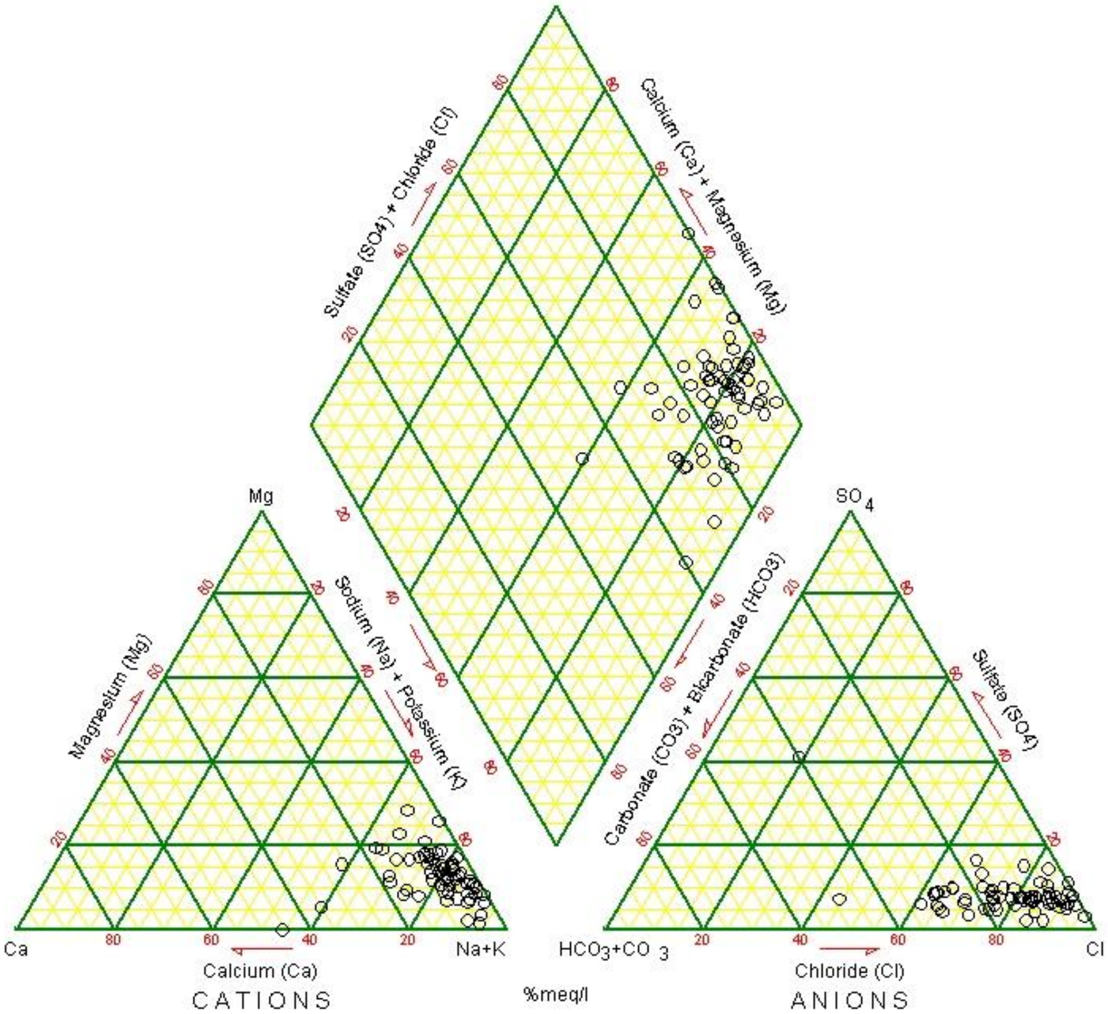


Figure 88 Yarragadee aquifer: hydrochemical trilinear diagram

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).

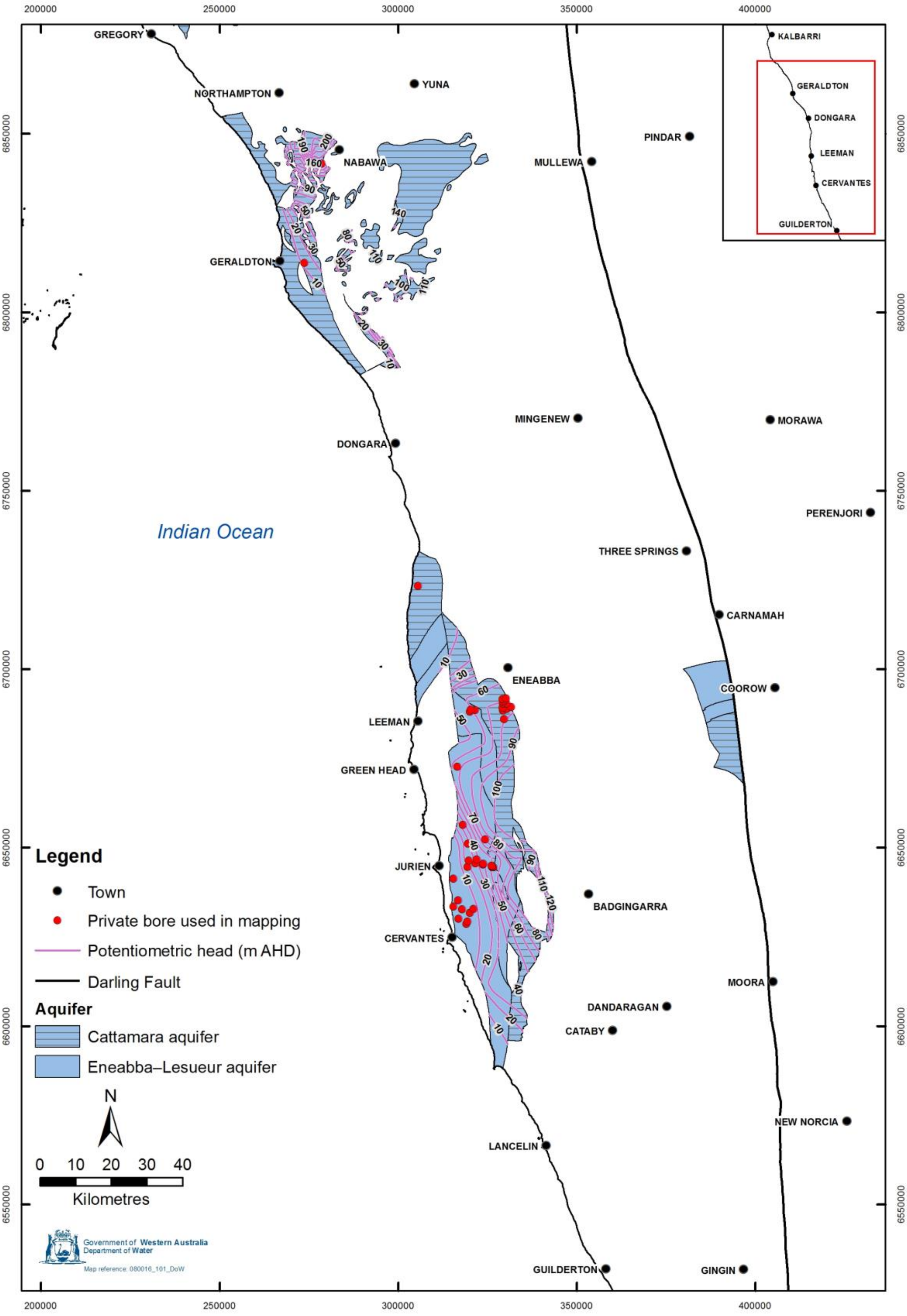


Figure 89 Cattamarra and Eneabba–Lesueur aquifers: potentiometric surface

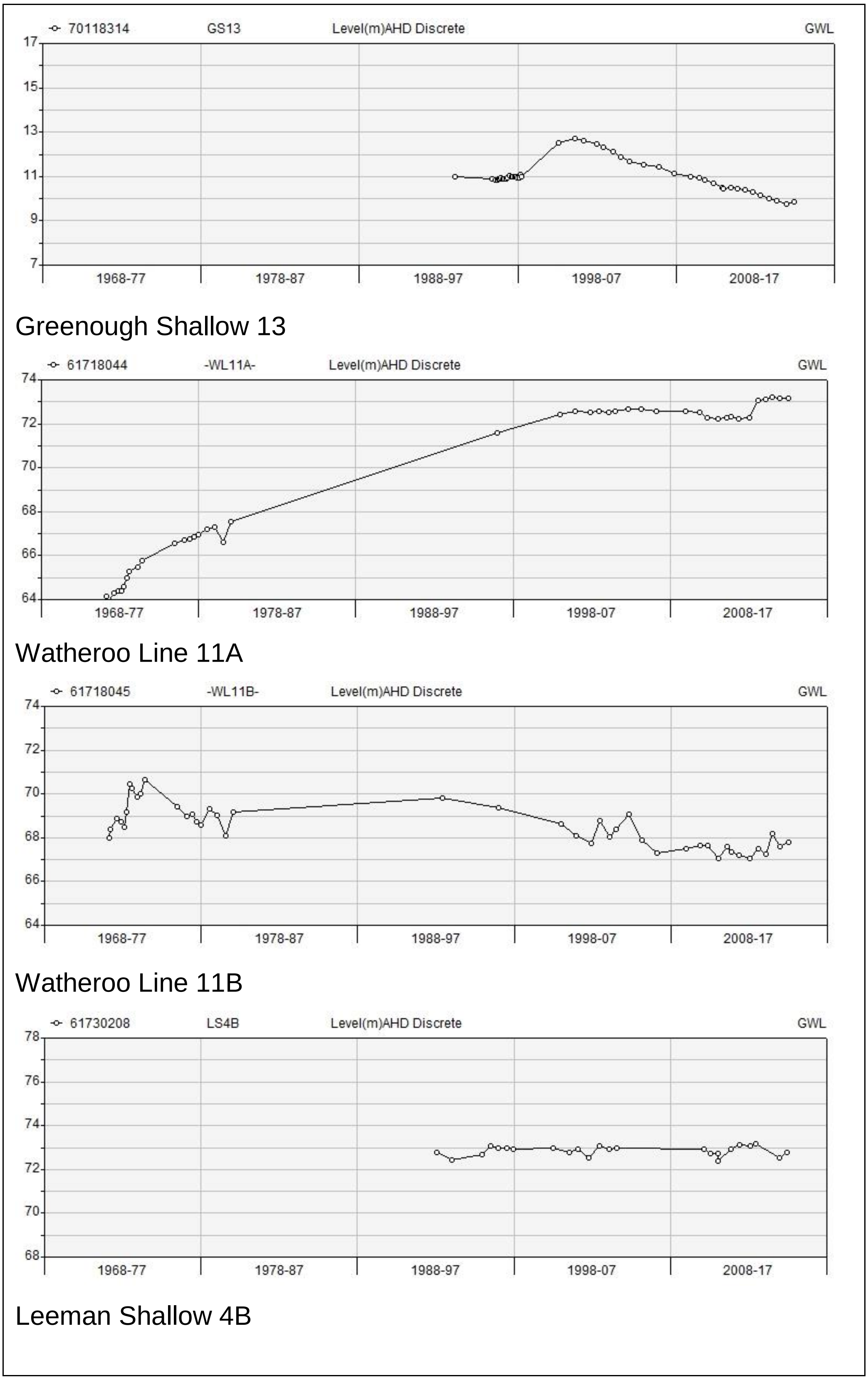


Figure 90 Cattamarra aquifer: selected bore hydrographs

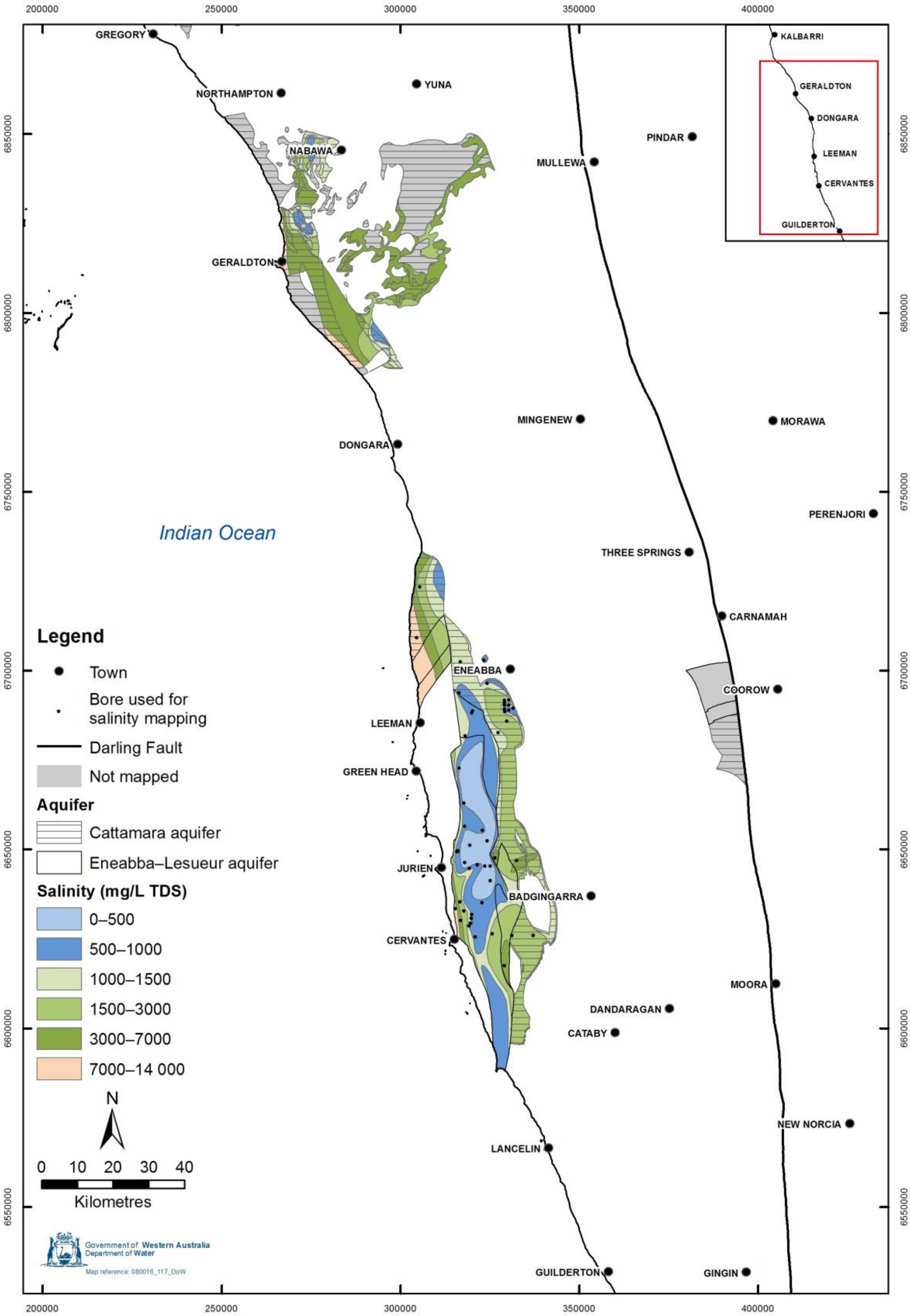


Figure 91 Cattamarra and Eneabba–Lesueur aquifers: groundwater salinity

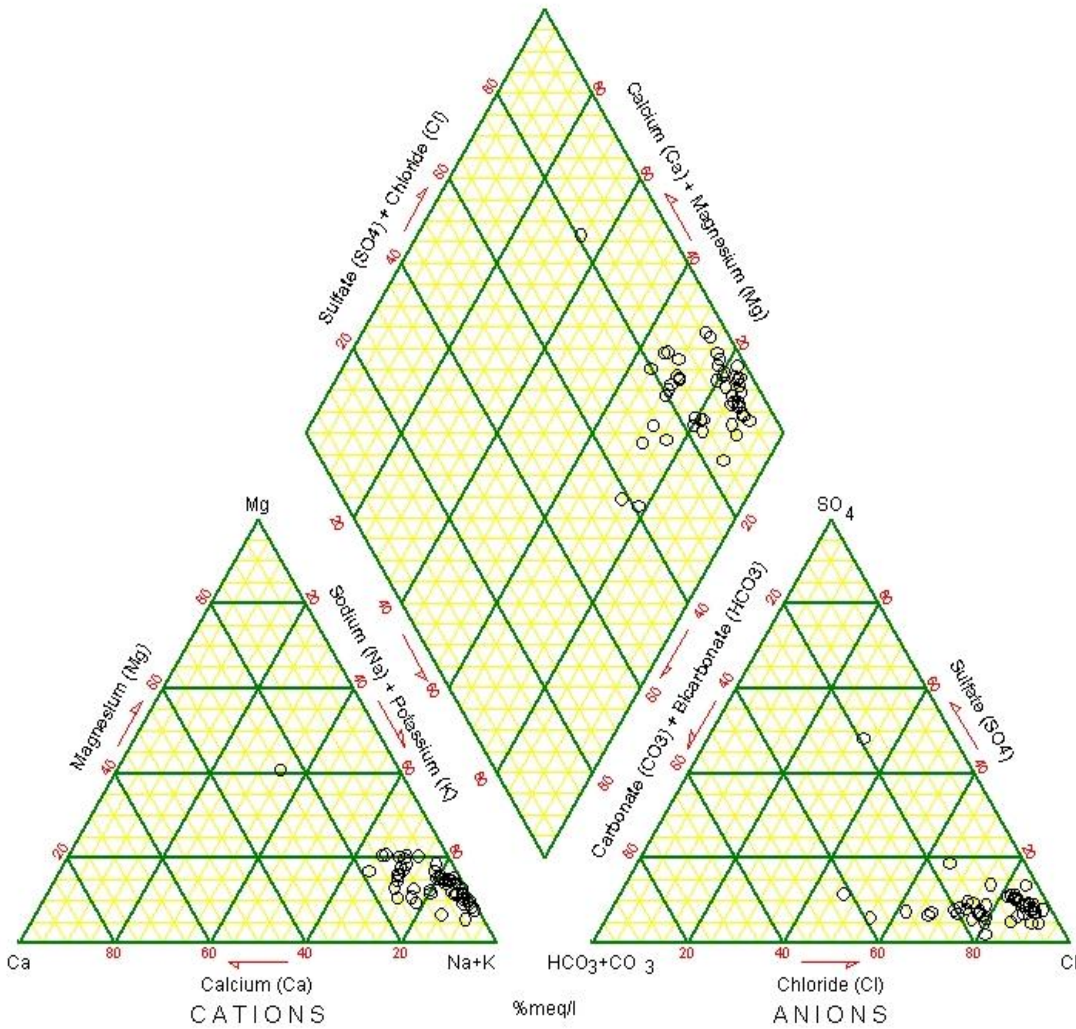


Figure 92 Cattamarra aquifer: hydrochemical trilinear diagram

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.

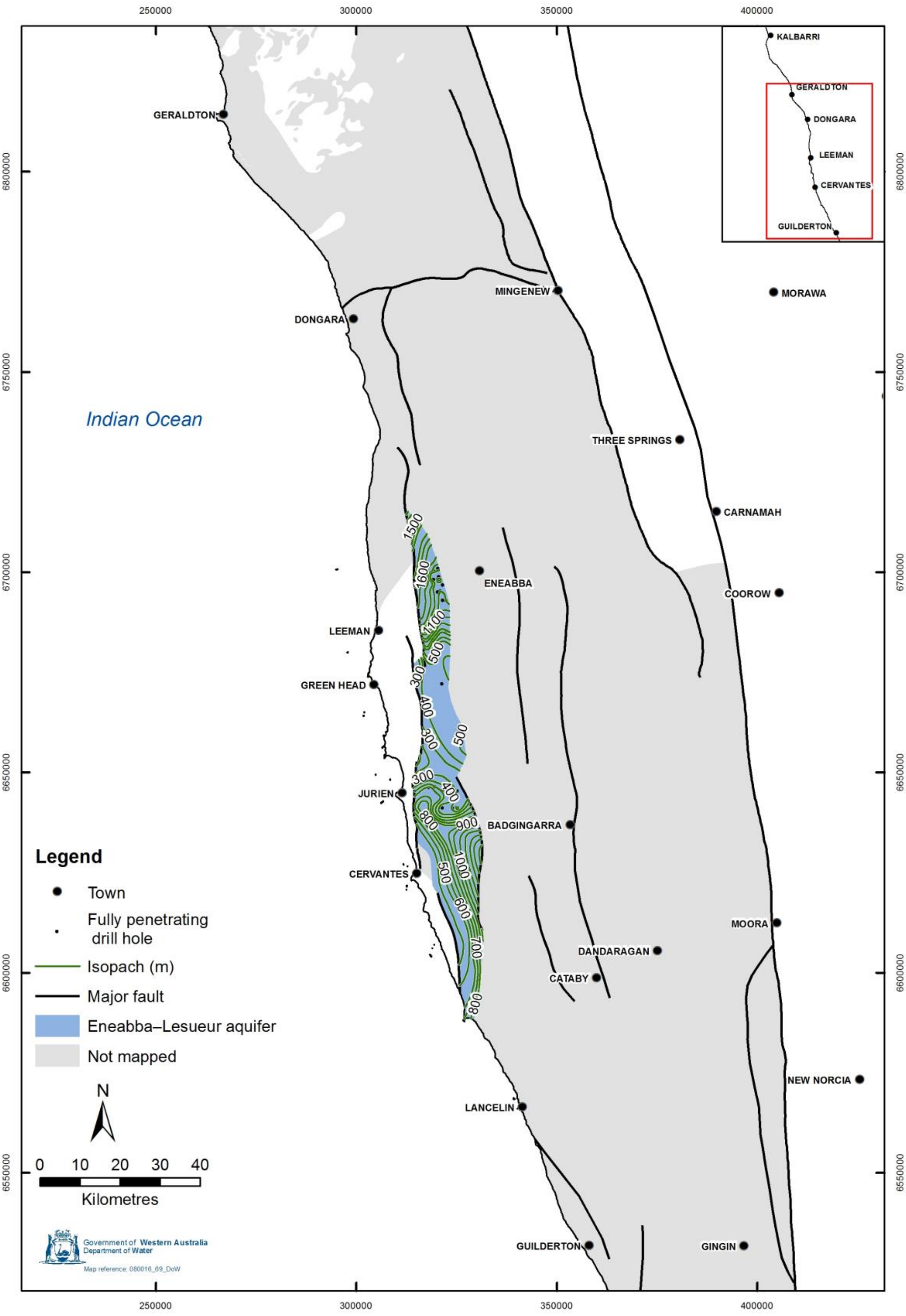
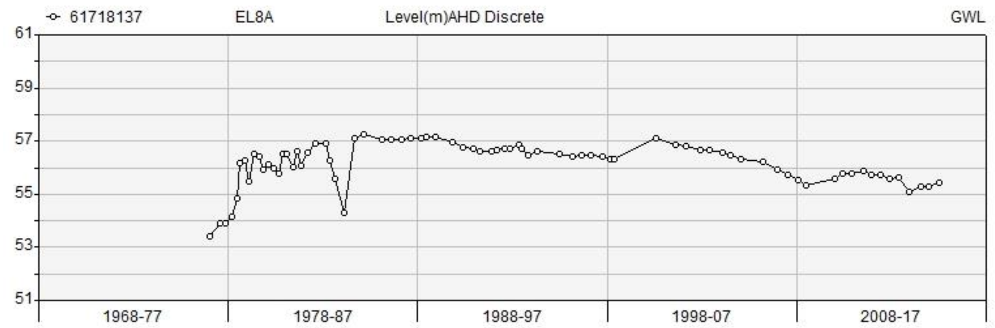
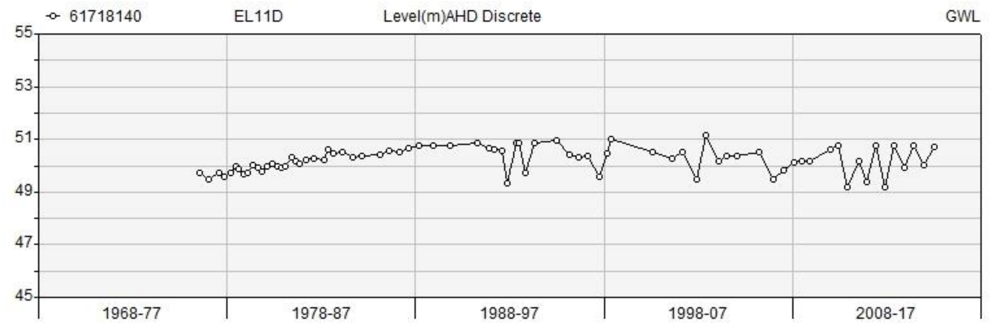


Figure 93 Eneabba–Lesueur aquifer: aquifer thickness



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 x 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.

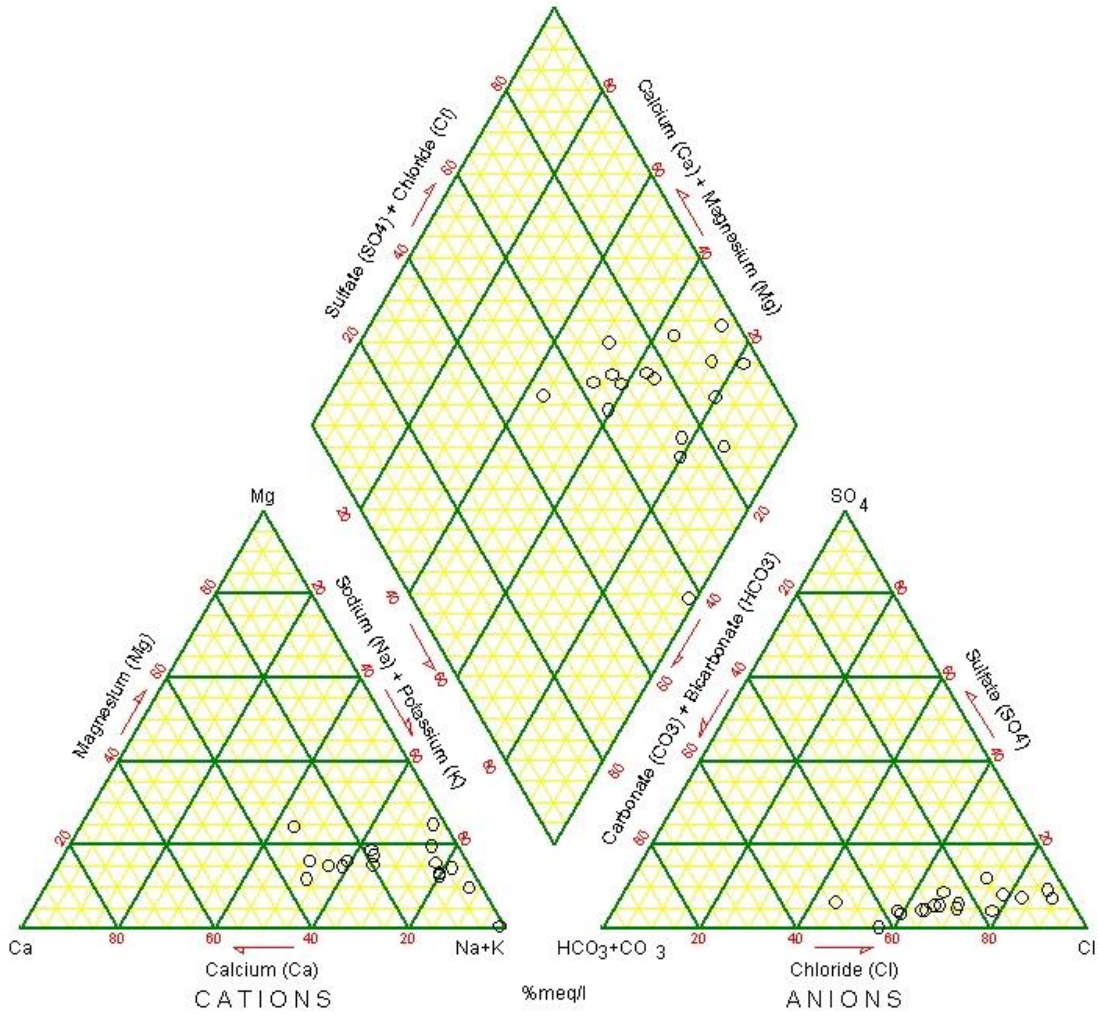


Figure 95 Eneabba–Lesueur aquifer: hydrochemical trilinear diagram

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.

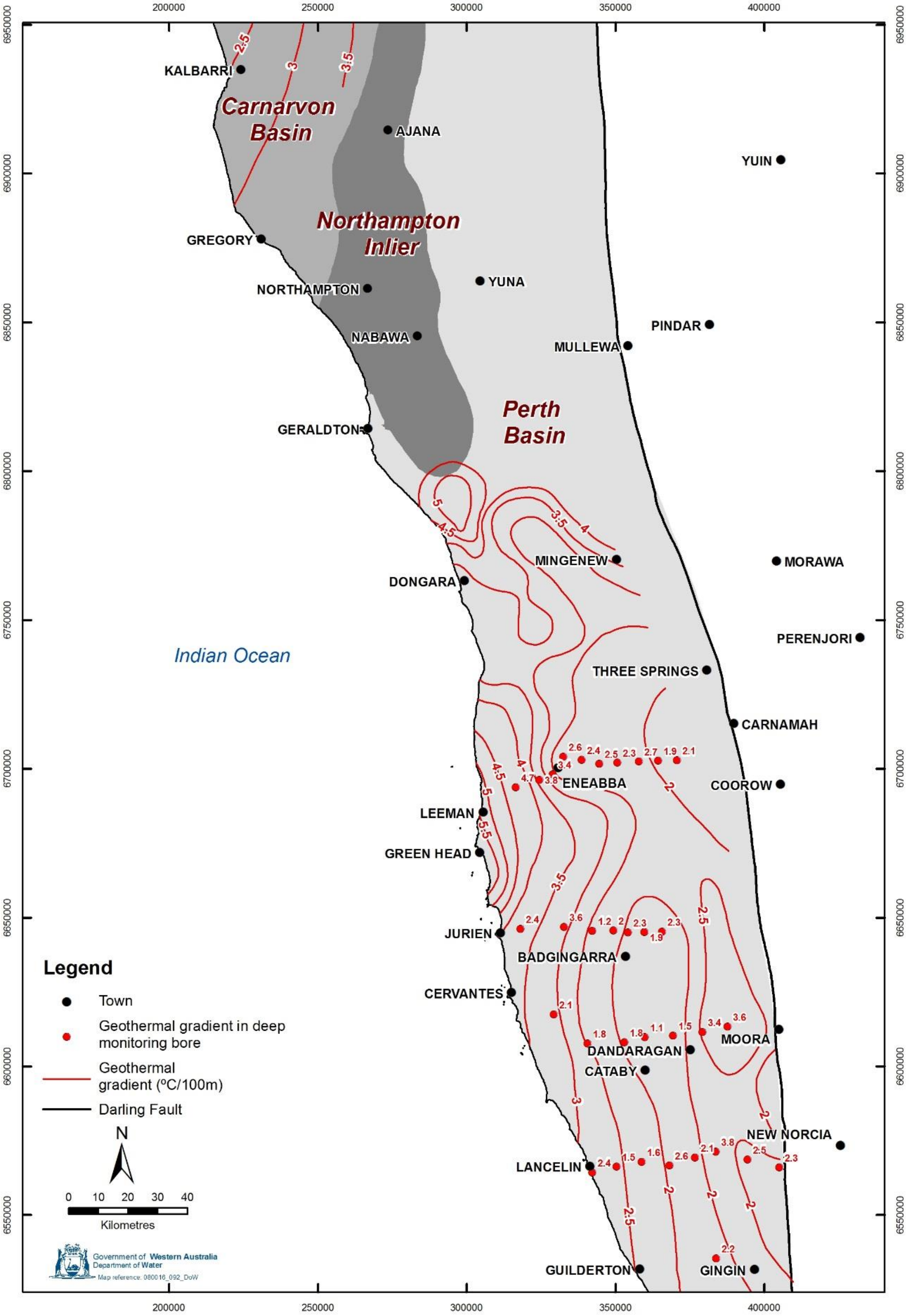
Geothermal gradients in the Yarragadee Formation range from 1.7 to 2.7 ºC per 100 m (Commander 1978; Moncrieff 1989), and are typically 1.4 ºC (ML5) to 1.8 ºC (ML7) per 100 m through sandy intervals. A maximum groundwater temperature of 55 ºC was measured at 970 m bgl in Gillingarra Line GL6A (Moncrieff 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