3 Biogeophysical setting

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

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

3.1 Physiography and topography

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

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

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

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

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

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

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

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

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

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

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

3.2 Vegetation and land use

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

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

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

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

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

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

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

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

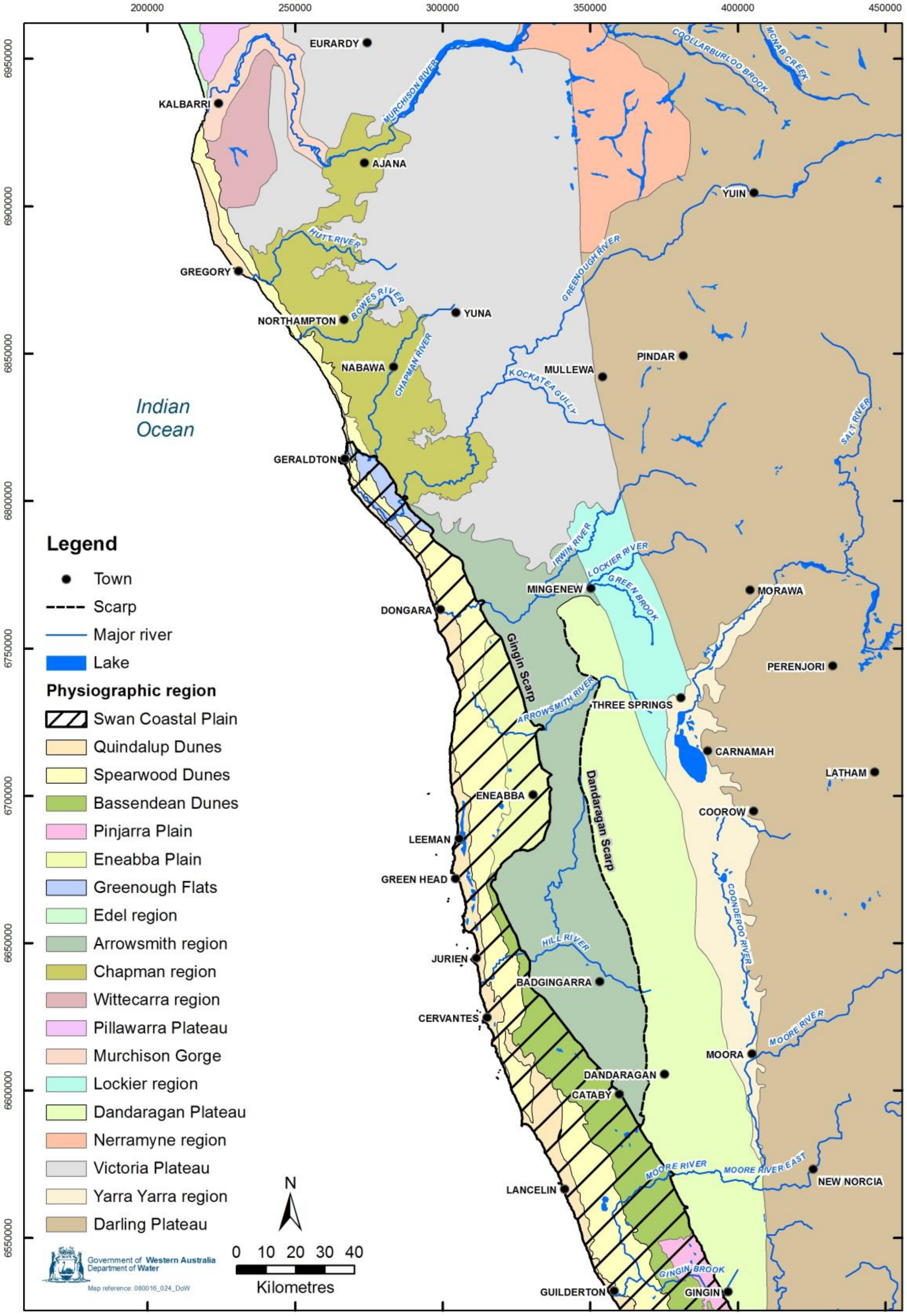


Figure 5 Physiography and topography of the northern Perth Basin

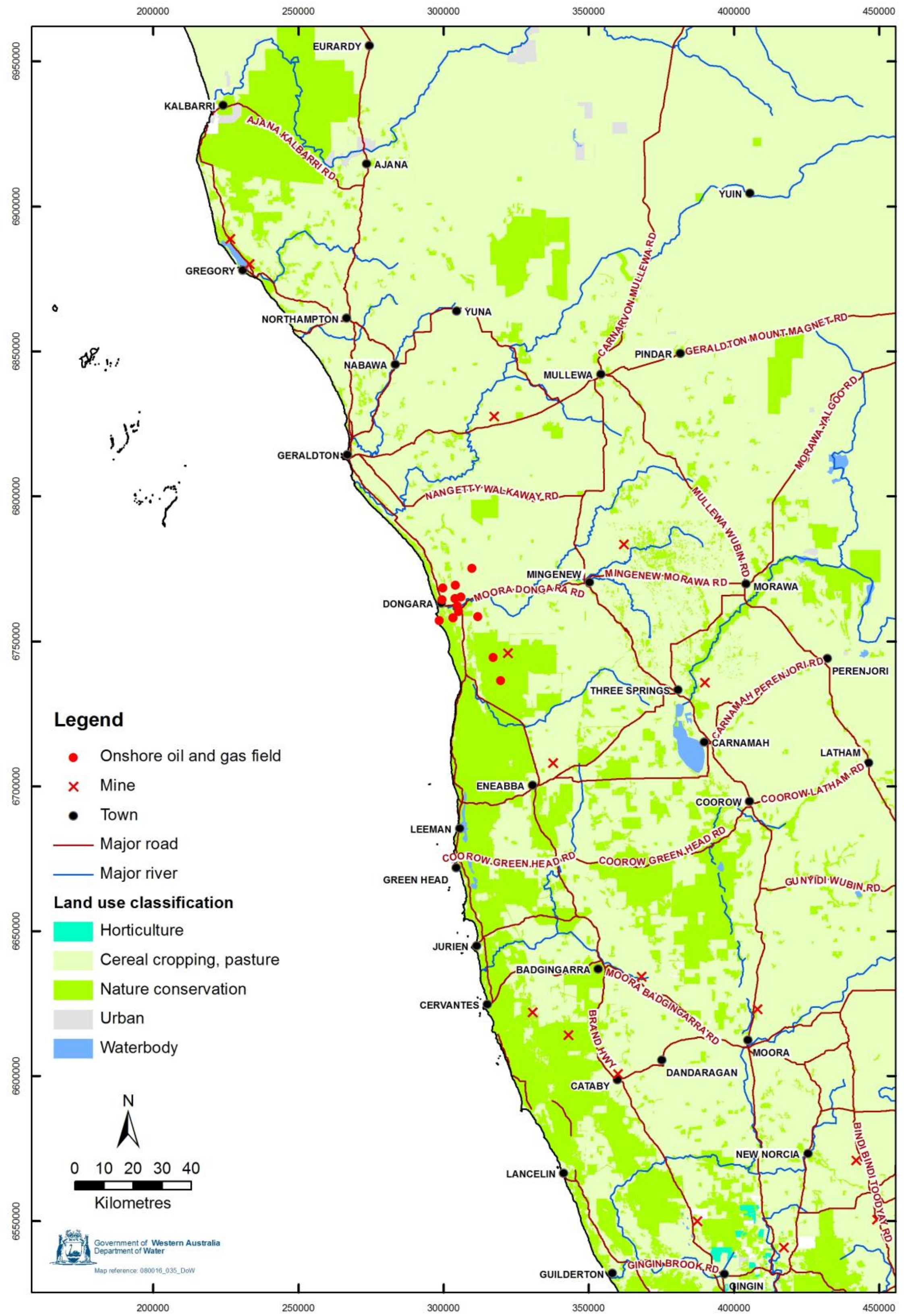


Figure 6 Land use

3.3 Climate: past, present and future

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

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

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

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

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

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

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

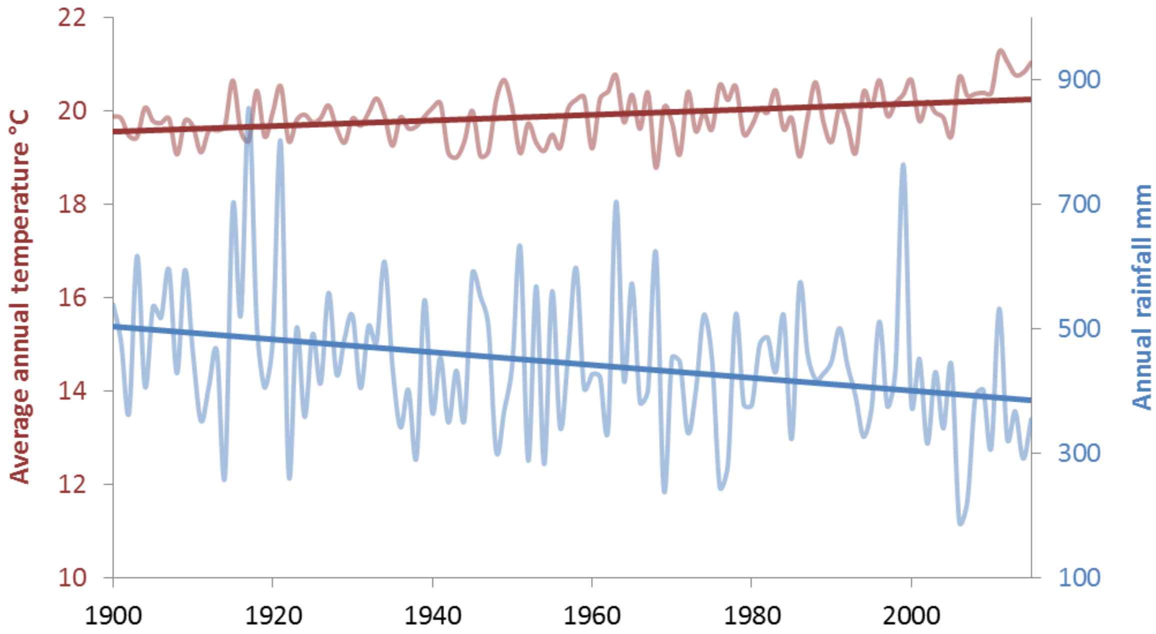
Climate change is projected to result in increased temperature and evaporation throughout Western Australia, coupled with a decline in winter and spring rainfall in the south-west. There is high confidence in these climate projections as there is a good understanding of the atmospheric circulation patterns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

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

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

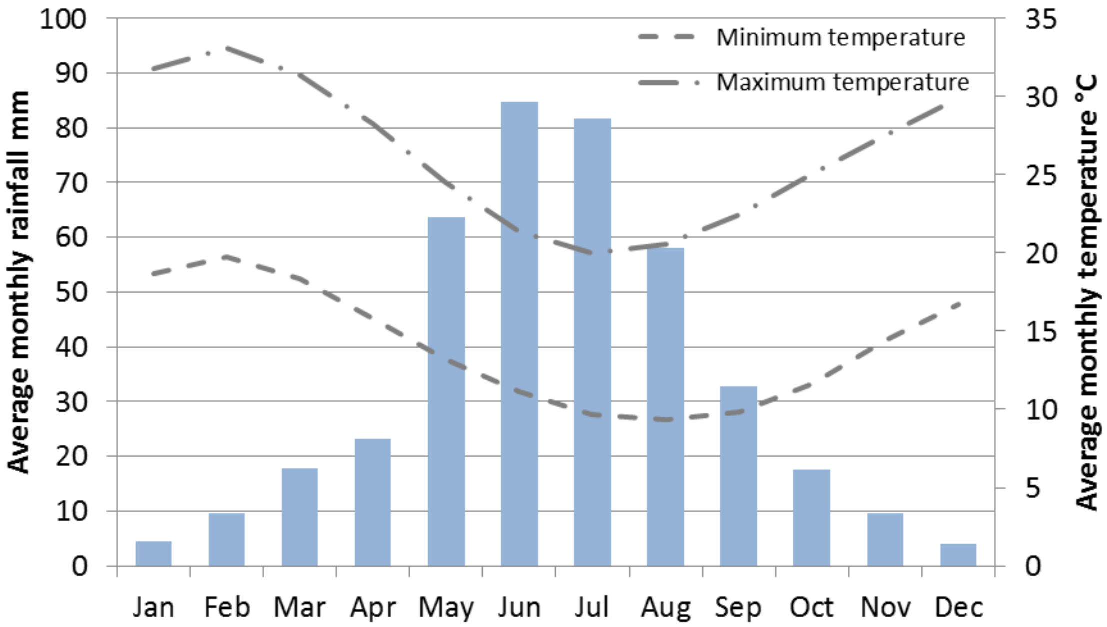
More information on climate change can be found at:

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



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

Figure 7 Long-term rainfall and temperature trends at Geraldton



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

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

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

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

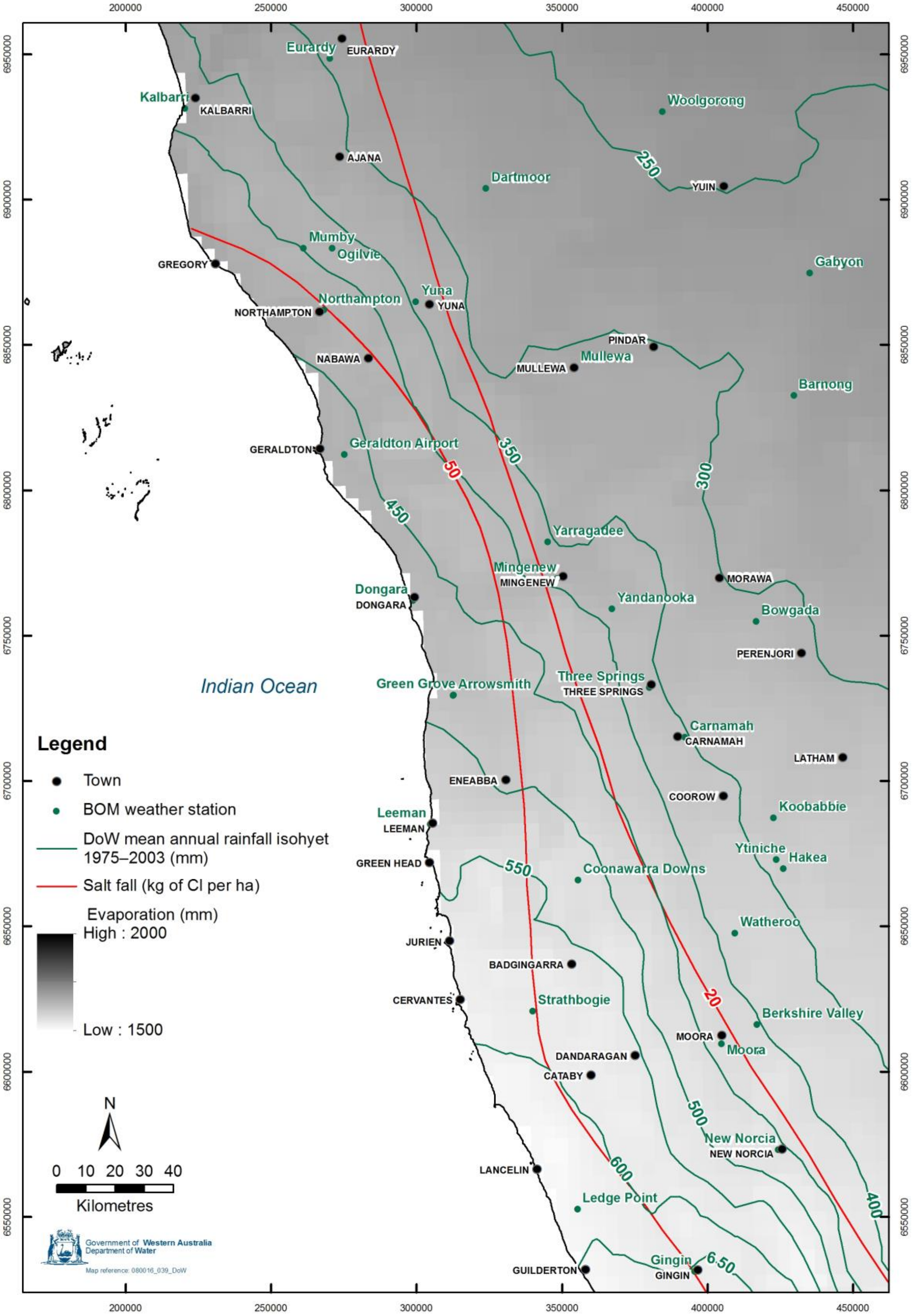


Figure 9 Climate of the northern Perth Basin

3.4 Catchment hydrology

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

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

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

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

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

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

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

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

Murchison River catchment

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

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

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

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

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

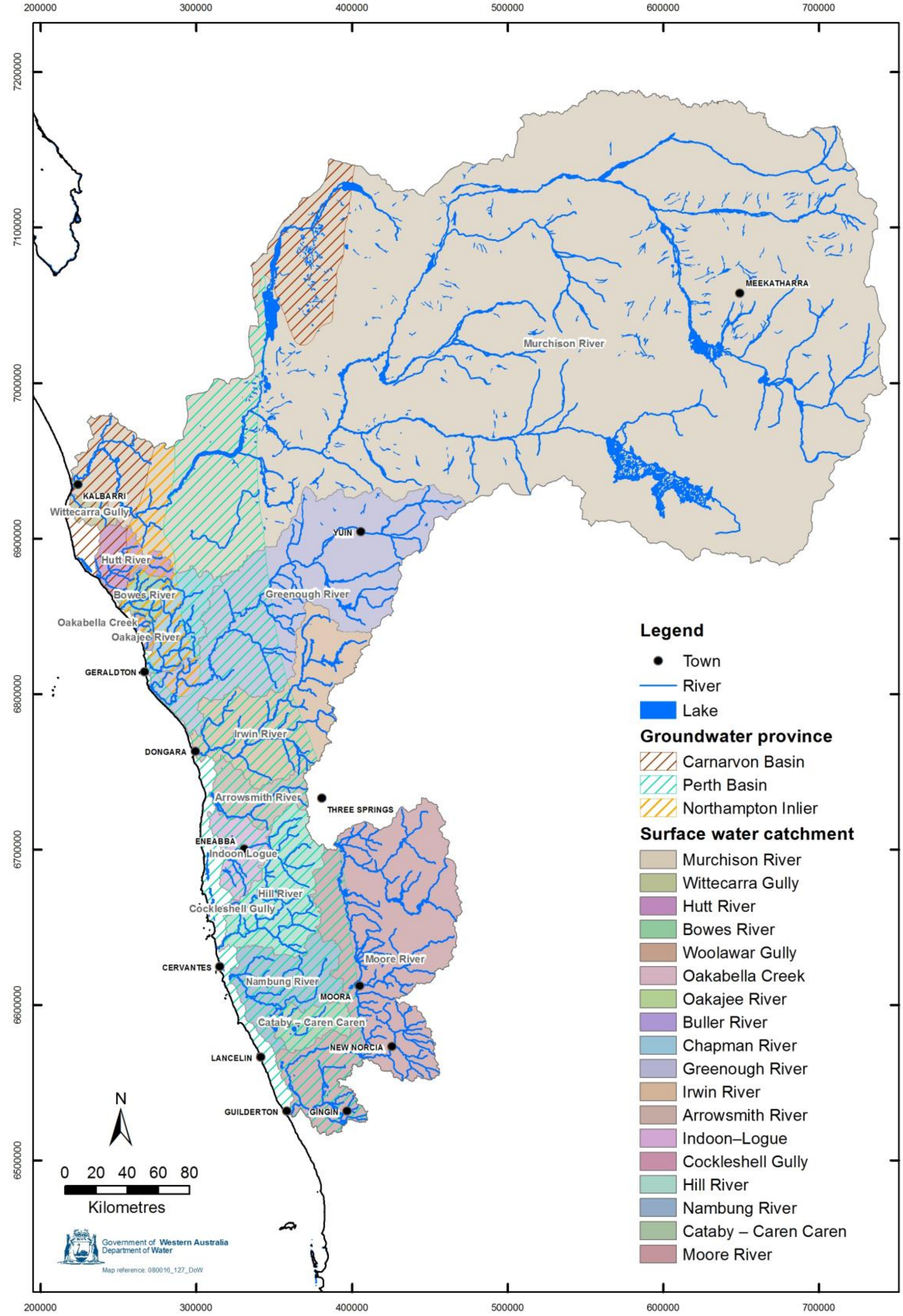


Figure 10 Surface water catchments

Table 3 Surface water catchment, flow and salinity characteristics

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

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

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

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

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

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

Hutt River catchment

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

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

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

Bowes River catchment

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

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

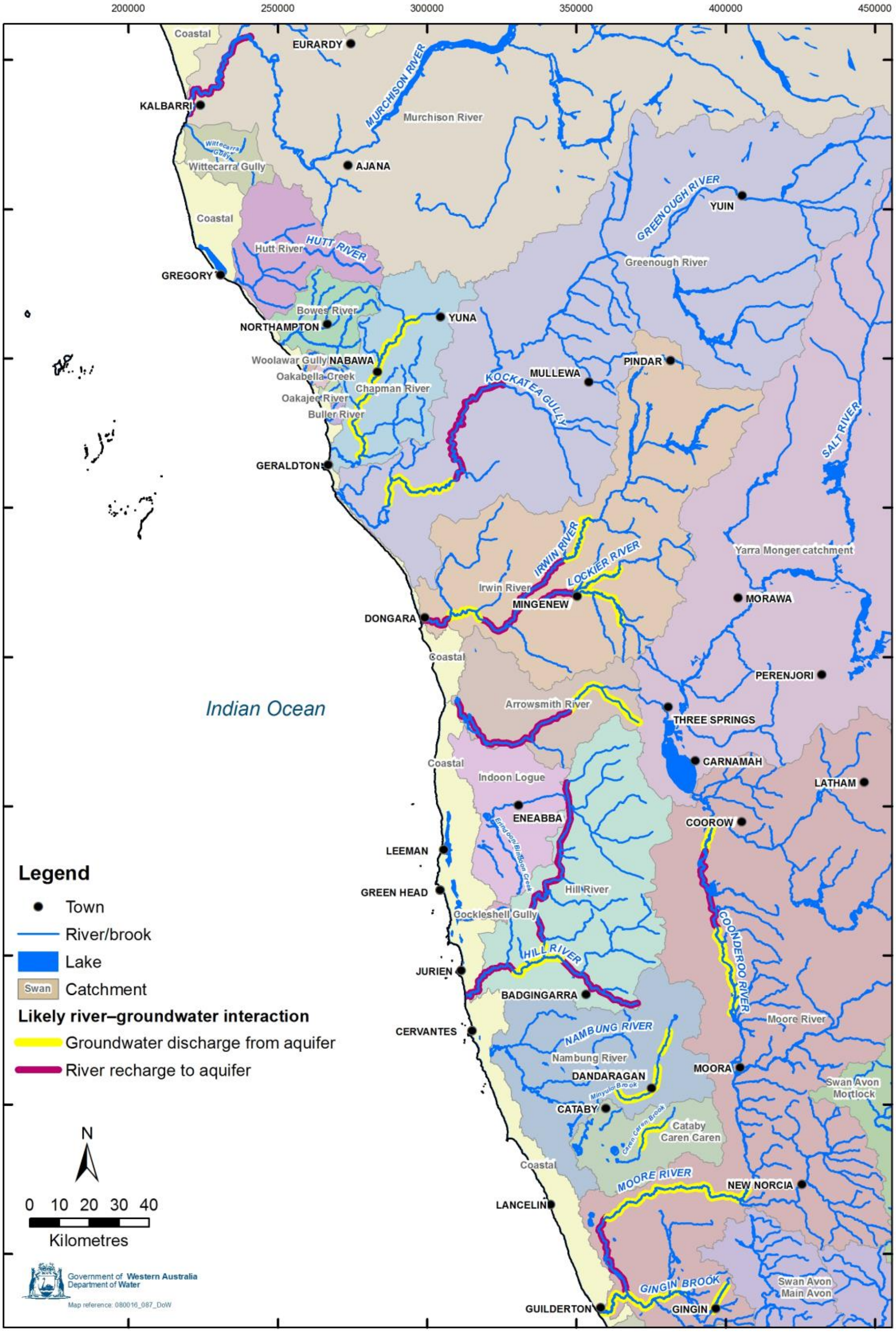


Figure 11 Surface water catchments and likely river–groundwater interaction

Chapman River catchment

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

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

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

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

Greenough River catchment

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

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

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

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

Irwin River catchment

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

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

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

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

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

Arrowsmith River catchment

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

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

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

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

Hill River catchment

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

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

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

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

Moore River catchment

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

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

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

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

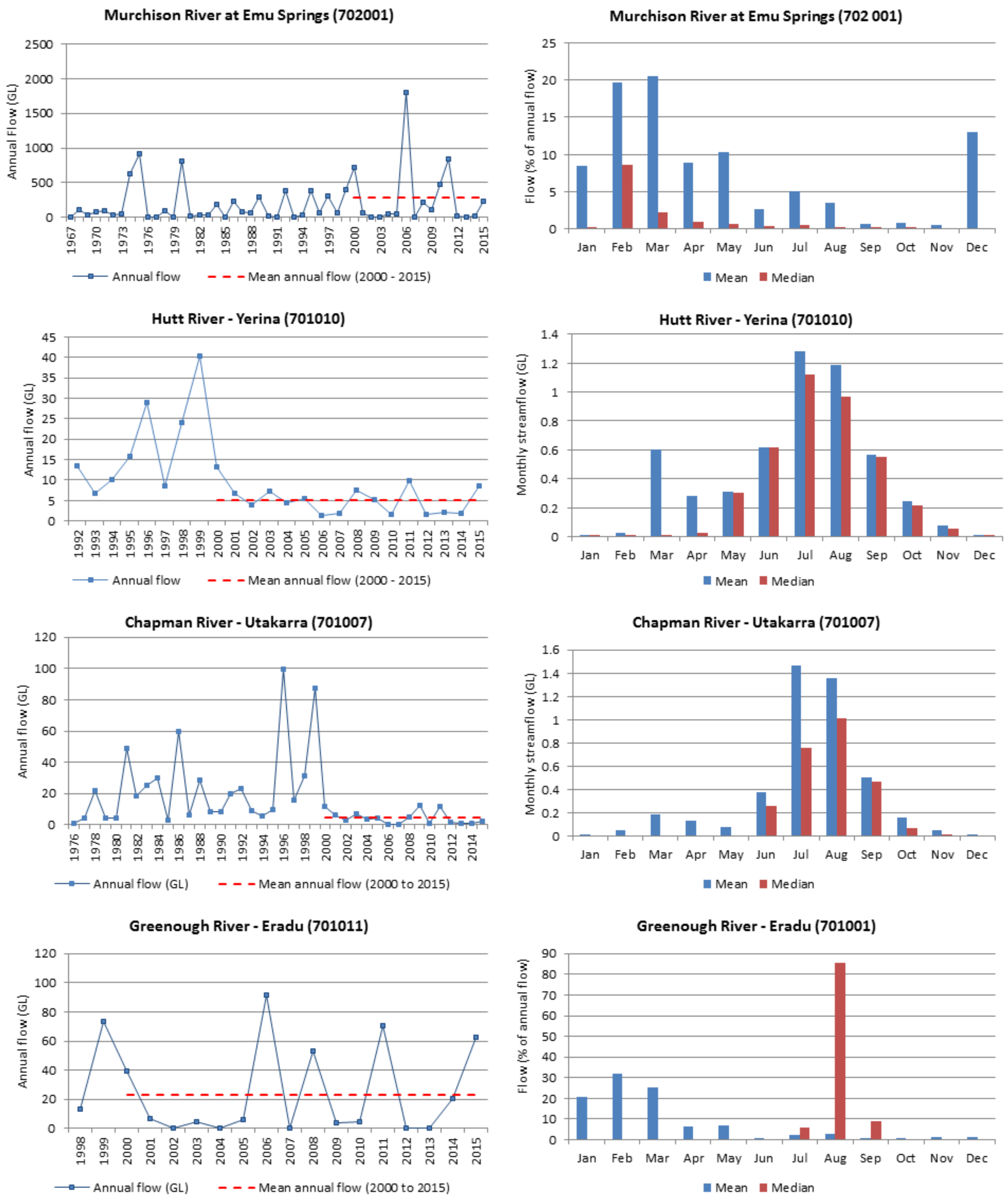


Figure 12 Annual and monthly streamflow distribution – Murchison, Hutt, Chapman and Greenough rivers

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

3.5 Groundwater-dependent ecosystems

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

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

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

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

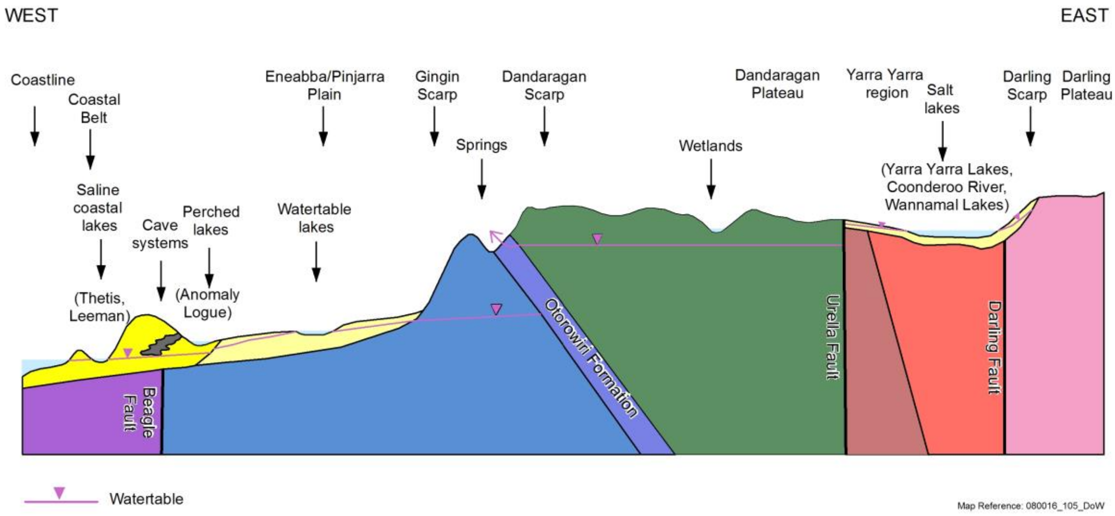
Caves in karstic limestone along the coast support a range of cave-dwelling fauna that depend on groundwater. Aquatic crustaceans live in cave pools in the dark zone, and humid cave entrances form roosting sites for bats and nesting sites for swallows (Susac 2009, 2012). Karstic aquifers support stygofauna,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

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

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

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

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



(see figures 19 and 51 for legend)

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

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

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

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

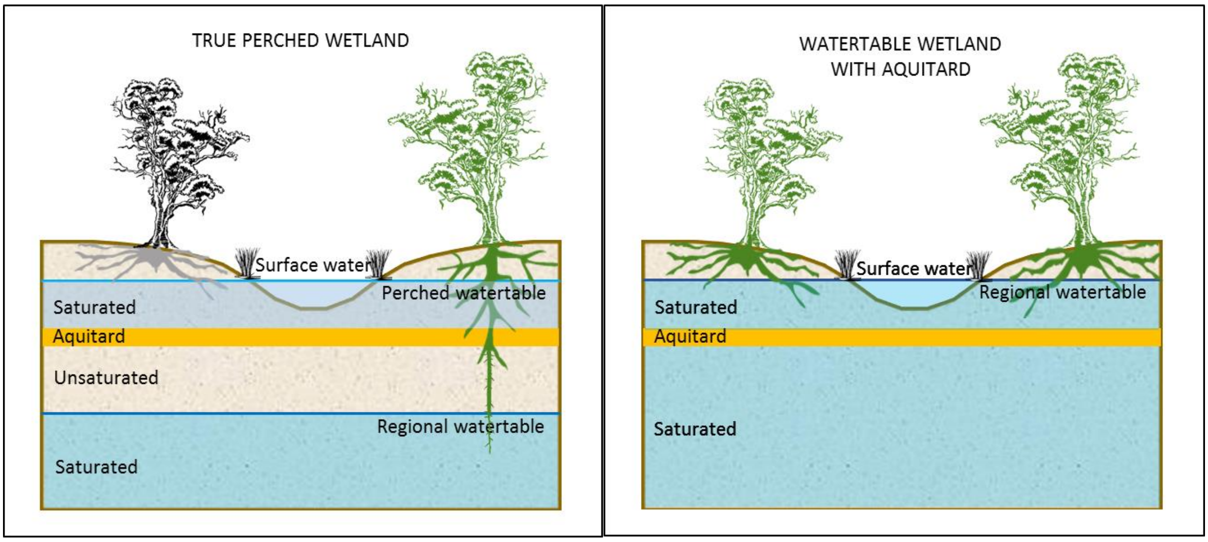
Banksia woodland might also support groundwater-dependent flooded gums (Beard 1979b). At the eastern extent of the Swan Coastal Plain, near the base of the Gingin Scarp, groundwater supports baseflow in rivers, as well as extensive chains of lakes, wetlands, waterlogged flats and groundwater-dependent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

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

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

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

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



(after Richardson et al. 2011)

Figure 15 Perched and non-perched wetlands

3.6 Regional geological setting

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

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

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

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

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

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

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

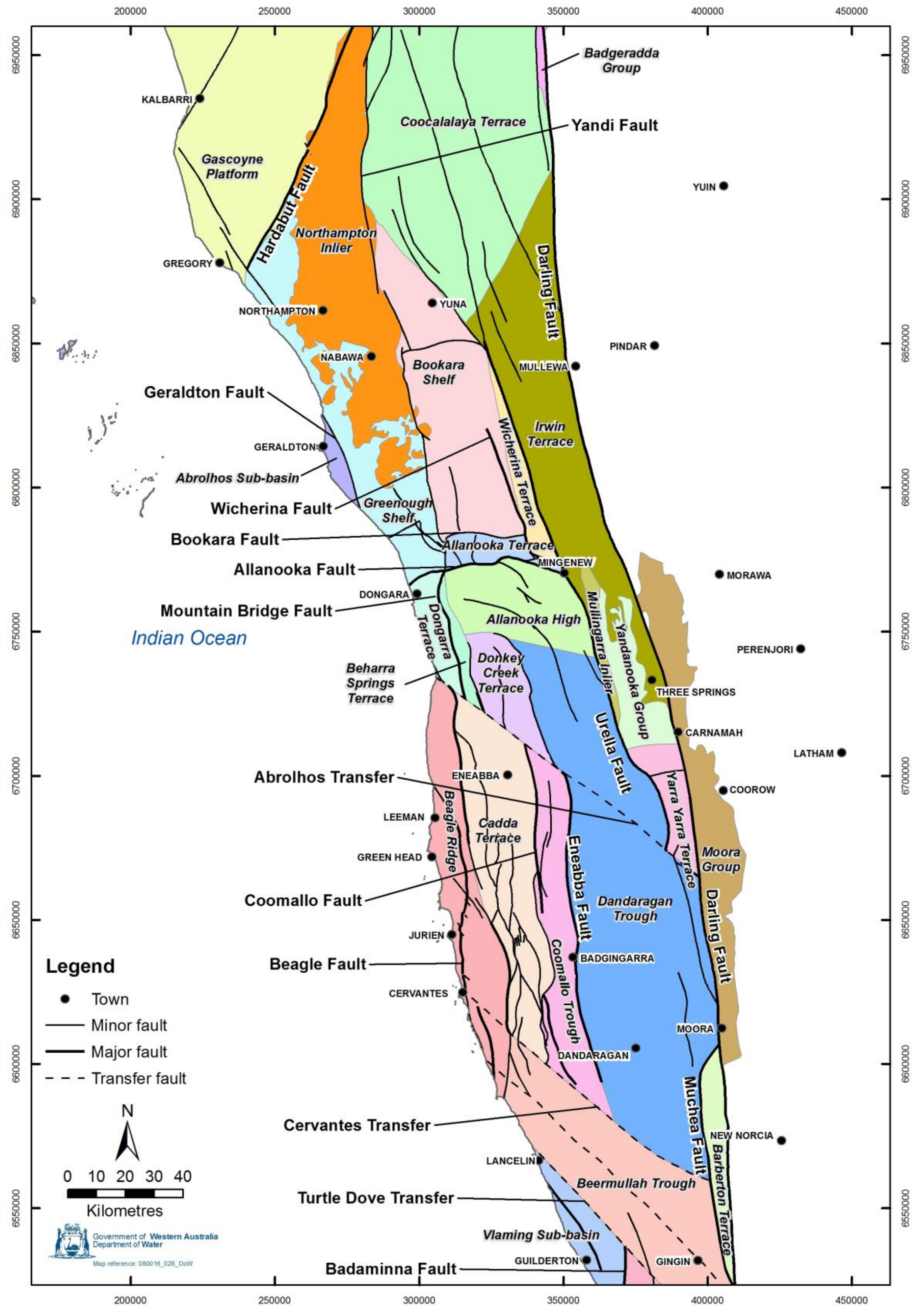
The thickest sediments of the northern Perth Basin are found in the Dandaragan Trough, a large syncline between the Darling Fault (or Urella Fault at its northern maximum) and the Eneabba Fault (Crostella 1995), where the depth to basement is up to 15 000 m (Figure 17). The Dandaragan Trough becomes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

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

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

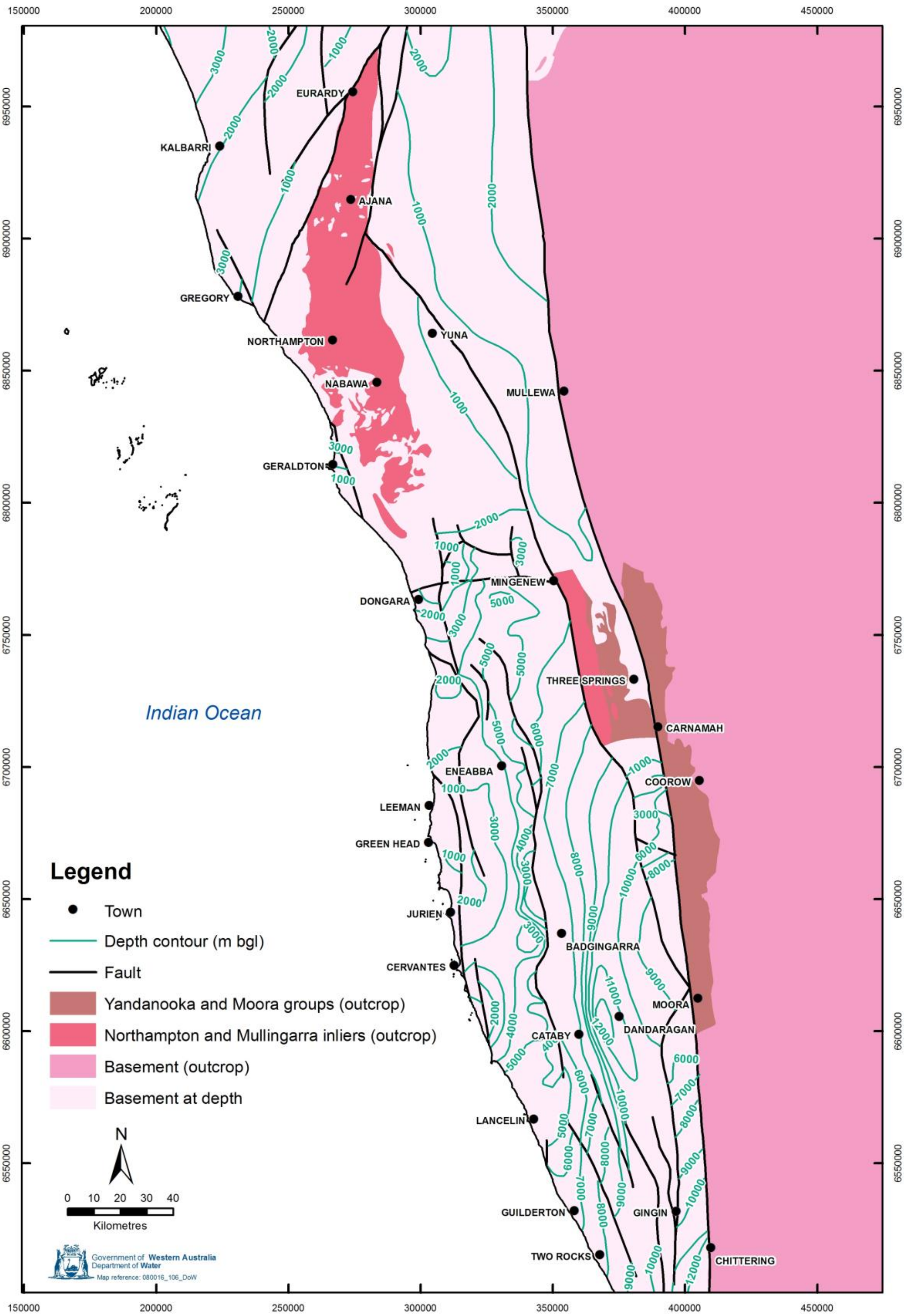
Structural unit	Description
Vlaming Sub-basin	Found mostly offshore, but is onshore south of the Turtle Dove Transfer Fault and west of the Badaminna Fault System. Contains up to 15 km of mostly Lower Cretaceous sediments.
Mandurah Terrace	Situated south of the Turtle Dove Transfer Fault and between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

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



(see Table 5)

Figure 16 Structural subdivisions



(after Mory & Iasky 1996)

Figure 17 Depth to basement