Government of Western Australia

Hydrogeology of the Pemberton–Irwin Inlet 1:250 000 Sheet

Department of Environment
Hydrogeological Map Explanatory Notes Series
HM 8
2004

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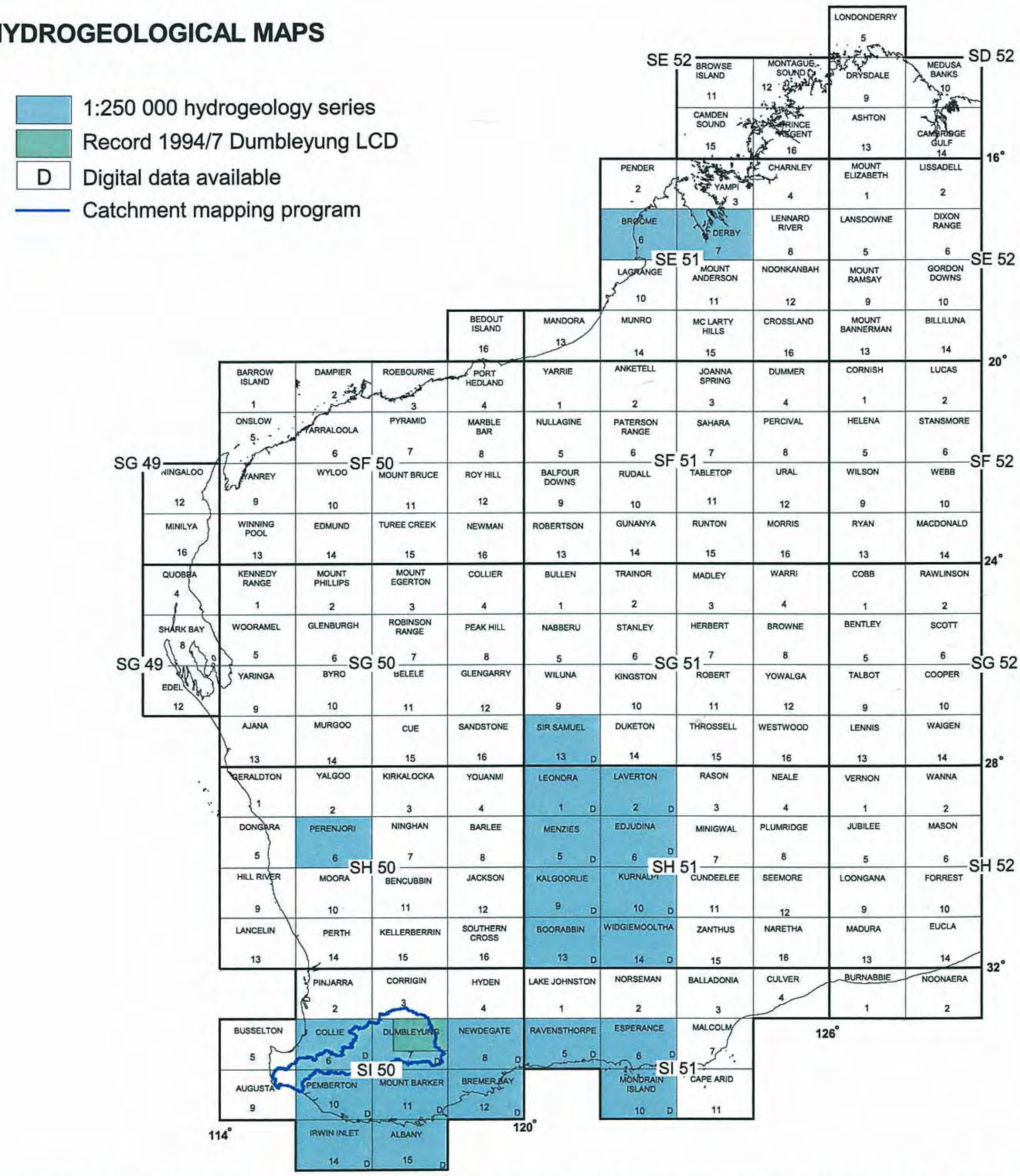
HYDROGEOLOGICAL MAPS



Cover photograph: Western side of Lake Muir looking north from the south-west corner of the lake [taken by Roger Hear

HYDROGEOLOGY OF THE PEMBERTON–IRWIN INLET 1:250 000 SHEET

by

J. DE SILVA

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DEPARTMENT OF ENVIRONMENT
HYDROGEOLOGICAL MAP EXPLANATORY NOTES SERIES
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HYDROGEOLOGY OF THE PEMBERTON–IRWIN INLET 1:250 000 SHEET

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Abstract

The PEMBERTON–IRWIN INLET explanatory notes form a base line for regional groundwater management. The accompanying PEMBERTON–IRWIN INLET hydrogeological sheet covers parts of the Southern Perth Basin, Albany–Fraser Groundwater Province, the Yilgarn–Southwest Groundwater Province and the Bremer Basin. This area contains surficial, sedimentary, weathered and fractured rock aquifers.

Fresh groundwater resources occur mainly in the sedimentary aquifers of the Southern Perth Basin, particularly in the Yarragadee aquifer and the Warnbro Group aquifer. Significant fresh groundwater supplies can also be obtained from surficial aquifers and weathered and fractured aquifers, mainly in high rainfall areas. These aquifers contain saline groundwater in low rainfall areas and beneath broad flat internally draining landscapes.

Although there is a good potential for fresh groundwater development, towns and holiday locations within the PEMBERTON–IRWIN INLET area rely mainly on surface water supply schemes. Windy Harbour gets its water supply from groundwater. Low rainfall areas (< 1100 mm/yr) within the hardrock provinces are at risk from salinisation if native vegetation is replaced with annual crops (Section 5).

Keywords: hydrogeological maps, hydrogeology, aquifers, groundwater resources, salinity, Pemberton, Irwin Inlet

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Figure 1. Location map

1 Introduction

1.1 Location and land use

The PEMBERTON–IRWIN INLET[1] hydrogeological sheet (SI 50-10 PEMBERTON and part of SI 50-14 IRWIN INLET of the International Series) is bounded by latitudes 34°00' and 35°15'S and longitudes 115°30' and 117°00'E (Fig. 1). The map provides baseline information for groundwater resource development and management of land salinisation.

The sheet is named after the town of Pemberton, which lies approximately 300 km from Perth via the South Western Highway, and Irwin Inlet on the South Coast. The main town and service centre on the sheet is Manjimup, and other towns in the region are Pemberton, Northcliffe and Walpole. The rural population is located largely around the Frankland River in the east and adjacent to the major roads and highways. The Peaceful Bay and Windy Harbour caravan parks are popular holiday locations.

Good road access is provided across the region by the South Western Highway, Brockman Highway, Vasse Highway and the Muirs Highway as well as other sealed roads. A narrow-gauge railway that runs from Diamond Mill to Bunbury, passing through Manjimup, also serves the region. There are numerous unsealed roads in the farming areas and timber tracks within the State Forest.

Most of the area is still under the natural vegetation of karri, jarrah and marri forest, with much of the region being classified as State Forest. Logging since 1981 has led to an increase in groundwater salinity. Some areas of outstanding natural beauty have been designated as National Parks and these include D'Entrecasteaux National Park, which stretches along the coast from Black Point to Black Head, Warren National Park and Pemberton National Park, both close to Pemberton, and the Walpole–Nornalup National Park near Walpole.

1.2 Climate

The area has a Mediterranean-type climate with cool, wet winters and warm to hot, dry summers. The average monthly minimum and maximum temperatures range between 14° and 26°C in summer and from 7° to 16°C in winter (Wilde and Walker, 1984). Areas near the coast often receive a cooling southwesterly breeze by early afternoon through the summer months.

Rainfall occurs predominantly during the winter months. The average annual rainfall decreases from over 1400 mm along the south coast to 600 mm in the northeast. An elongate zone of high rainfall (1200–1400 mm/yr) approximately 20 km inland from the coast is centred on Northcliffe, the wettest part of the State, with an average annual rainfall of 1324 mm (1930 to 1990).

1.3 Physiography

The broad physiographic features of PEMBERTON–IRWIN INLET are the Darling Plateau, Ravensthorpe Ramp, Blackwood Plateau, Scott Coastal Plain and coastal dunes (Fig. 2). The Darling Plateau has a broadly undulating lateritic surface that declines southward from 260 m AHD (Australian Height Datum) to much less than 100 m AHD. The southward sloping part of the Darling Plateau is commonly referred to as the Ravensthorpe Ramp (Cope, 1975). Cope proposed that an epeirogenic axis called the Jarrahwood Axis marked the northern limits of the Ravensthorpe Ramp (Fig. 2). From the plains, there are numerous isolated hillocks and knolls with granite tors such as Mount Frankland (at 411 m, the highest peak in the area) Mount Roe (389 m) and Granite Peak (385 m).

The Darling Plateau is drained mainly by the Donnelly, Warren, Shannon, Deep and Frankland rivers, which flow through deep valleys in a south-southwesterly direction before reaching the broad, flat coastal plain. Broad Tertiary alluvial flats occupy the north eastern part of PEMBERTON–IRWIN INLET. These broad flats have very low gradients and weakly developed, mainly internal, drainage. Within the flats a large number of lakes and swamps form two wetland systems: the Lake Muir system at the head of the Deep River catchment and the Unicup system of the upper Tone River.

The Lake Muir wetland is large flat area with internal drainage. It consists of small to very large permanent and intermittent lakes, permanent and intermittent

[1] *Sheet names are printed in capitals to distinguish them from identical place names*

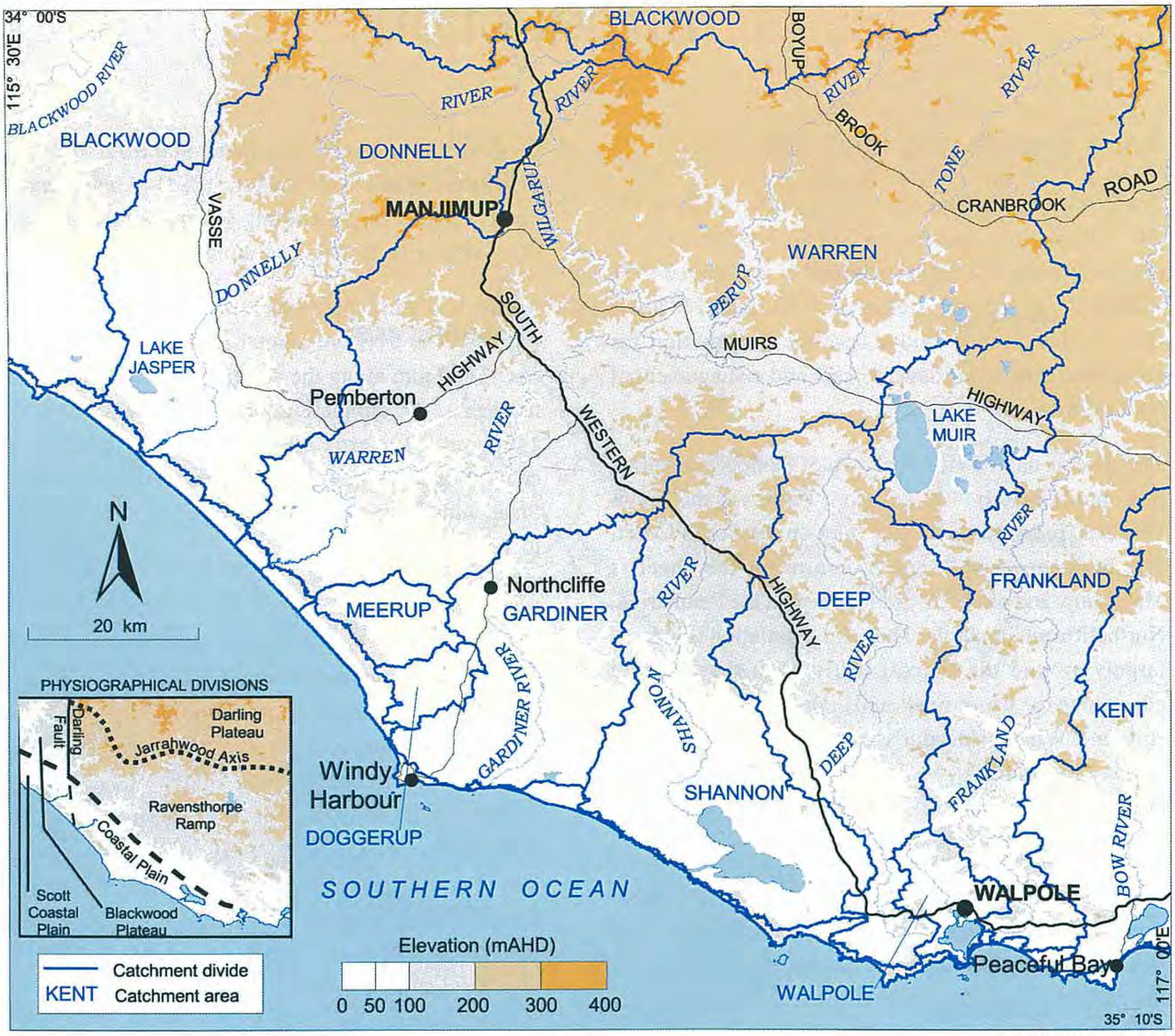

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Figure 2. Physiography

swamps and floodplains. Lake Muir, the largest body of surface water, is an intermittent saline lake about 4600 ha in area. This lake does not have well-developed surface drainage outlets and may, in flood, overflow into the Deep River. Some of the other lakes/swamps in this wetland include Byenup Lagoon, Tordit-Gurrup Lagoon, Pindicup Lake, Red Lake and Neeranup Swamp. This wetland system covers approximately 37 000 ha.

The Unicup system is a major wetland system of small to large permanent lakes, permanent and intermittent swamps, and floodplains. This system, which covers approximately 17 300 ha, rarely discharges to the upper Tone River (Pen, 1997).

Broad Tertiary alluvial flats that extend north onto the Ravensthorpe Ramp mark the palaeodrainage system of the Darling Plateau. The present south flowing drainages of the Darling Plateau are short and only the Donnelly, Warren and Frankland Rivers extend back onto the palaeodrainage deposits of the Darling Plateau (Wilde and Walker, 1984).

The Darling Scarp is the surface expression of the Darling Fault and marks the western edge of the Darling Plateau. The relief of the Darling Scarp is about 100 m in the northern part of the area, but this declines southward until the scarp loses expression south of the Donnelly River (Wilde and Walker, 1984).

The Darling Scarp running south from Nannup also delineates the Blackwood Plateau, which lies to the west of the Darling Plateau. Although dissected by the Blackwood River flowing southwest, the Blackwood

Plateau is otherwise gently undulating with a surface composed of laterite, lateritic gravel and sand, above Mesozoic sediments and Bunbury Basalt (Wilde and Walker, 1984). The elevation decreases southwards from 100–150 m AHD to 40–60 m AHD where the plateau meets the Scott Coastal Plain.

The Scott Coastal Plain (Playford *et al.*, 1976) is an extensive swampy plain that has developed from the infilling of coastal lagoons and estuaries south of the Blackwood Plateau (Wilde and Walker, 1984). This plain has permanent freshwater lakes including Lake Jasper and Lake Quitjup, and permanent freshwater swamps including Gingilup. Lake Jasper is considered to be the deepest and largest permanent freshwater lake in the Southwest (Pen, 1997). Barlee Brook, Donnelly and Scott Rivers drain this plain. This swampy plain is traversed by the remnants of siliceous dunes trending west-northwest and drained by Barlee Brook, the Donnelly River and Scott River.

Within the Scott Coastal Plain and east along the coastline is an extensive belt of eolian dunes with east-southeast and east-northeast orientations (Churchward, 1992). They have been partially lithified to calcarenite (Wilde and Walker 1984) and rise to over 200 m AHD. Most of these dunes have been stabilised by vegetation, but there are still some areas of exposed sand between Point D'Entrecasteaux and the mouth of the Donnelly River (Smith, 1972).

1.4 Vegetation

Much of the PEMBERTON–IRWIN INLET area is still under natural vegetation, with large areas of State Forest and several National Parks. Smith (1972) defined and named six vegetation systems aligned approximately parallel to the coast on PEMBERTON–IRWIN INLET: Nornalup, Darling, Chapman, Jingalup, Scott River and Boranup. The alignment of these systems reflects the influence of climate and geology on the topography and soil type. The major vegetation associations (Fig. 3) are based on natural vegetation mapping by Beard (1981). Karri, marri and jarrah forests cover about 70% of the area.

Soils are strongly controlled by the geology and climate, with podzolic soils developing on acidic gneisses, and red earths predominantly on basic gneisses (Smith, 1972). In the drier areas to the northeast of the map sheet, gravelly lateritic soils are dominant and tend to form a cap over pallid zone clays and deeply weathered horizons in which large amounts of soluble salts have accumulated (Steering Committee for Research on the Woodchip Industry, 1980).

The karri forest zone forms the Nornalup forest system extending southwards from Manjimup to near the coast. Karri (*Eucalyptus diversicolor*) grows on red earths in high rainfall areas (>1000 mm/yr) and forms a high, open forest with large understorey trees and mesophytic undergrowth. Interwoven with the karri are jarrah (*E. marginata*), which favour lateritic gravels on the hills, and marri (*E. calophylla*), which may be associated with either karri or jarrah forest, on the richer sandy soils.

Jarrah forest grows in the drier areas on lateritic podzolic soils and forms two vegetation systems: the Darling system to the west of the Darling escarpment, and the Chapman system in the northeast of the map area. Marri is interwoven with jarrah in both systems although denser jarrah–marri growth is found in the Chapman system such that parts of the forest are dense enough to be classified as closed forest.

Jarrah, in areas of poorly drained lateritic soils, is susceptible to dieback disease caused by a fungus (*Phytophthera cinnamomi*) attacking the root system. Dieback is not a serious problem on PEMBERTON–IRWIN INLET except around the periphery of the vegetation areas. Karri and marri, species not affected by the disease, dominate in the central part of the area.

In the extreme northeast of the area jarrah forest gives way to wandoo woodland (*E. redunca* var. *elata*) in the valleys and lower slopes of the Jingalup system. However, much of this vegetation has been cleared for agriculture.

The Scott River system is characterised by extensive seasonal swampy areas, some of which support low, open woodland of banksia, stunted jarrah and paperbark with an understorey of shrubs and sedges.

The coastal sand dunes of the Boranup system support karri, jarrah and marri open forest on their landward side. Peppermint shrub (*Agonis flexuosa*) grows on most of the sand dunes, with open heath and grassland towards the south.

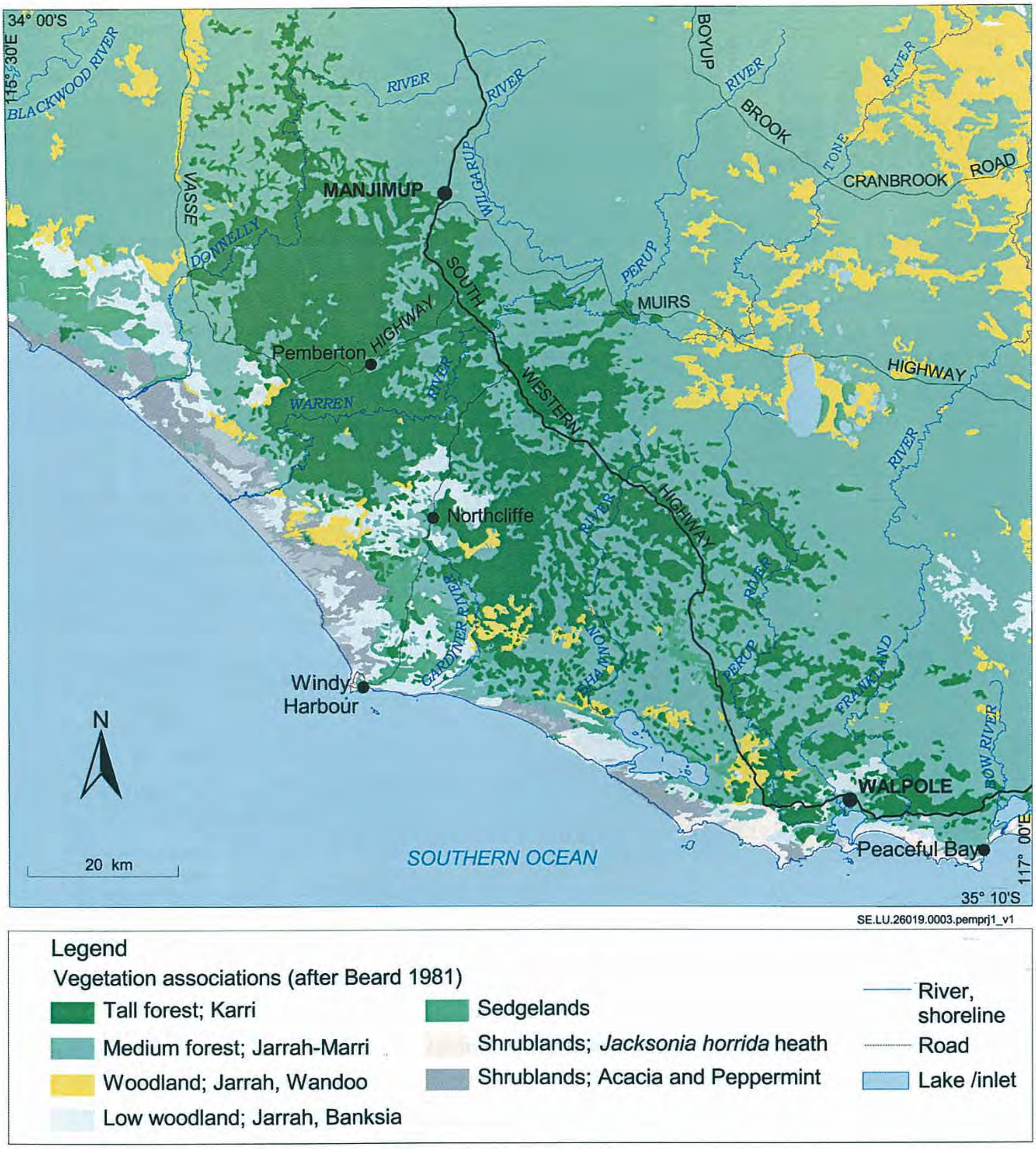

Figure 3. Vegetation associations

1.5 Previous investigations

Early investigations on Pemberton–Irwin Inlet were centred on coal and oil exploration. Gravity investigations in 1935 (Vening Meinesz, 1948) identified the thick sedimentary sequences of the Perth Basin. The Commonwealth Bureau of Mineral Resources (BMR) followed up this work with a regional gravity survey in 1951 (Thyer and Everingham, 1956). Further investigations between 1953 and 1976 clarified the structure and stratigraphy of the Perth Basin (Fairbridge, 1953; Playford and Willmott, 1958; Playford *et al.*, 1976). The Perth Basin on Pemberton–Irwin Inlet was originally mapped by the Geological Survey of Western Australia in 1963 (Lowry, 1965; Low, 1972). Wilde and Walker (1984) compiled the geological map Pemberton–Irwin Inlet. The Commonwealth Bureau of Mineral Resources (now Geoscience Australia) has produced Bouguer anomaly, radiometric and total magnetic intensity maps for the map sheet.

Groundwater resources of the Perth Basin on PEMBERTON–IRWIN INLET have been investigated in a number of projects, with the major ones including the Karridale Line (Baddock, 1994) and Scott Coastal Plain drilling programs (Baddock, 1995). Thorpe and Baddock (1994) assessed the groundwater resources of the map sheet area at reconnaissance level.

The Geological Survey of Western Australia (GSWA) investigated the area within a few kilometres around Peaceful Bay in 1980 for potential groundwater sources to supplement the local town water supply (Hirschberg, 1980). The Walpole (Hirschberg, 1977) and Windy Harbour (Sanders, 1973) areas were also investigated for potential groundwater supplies. Rockwater (1986) assessed supply and quality of groundwater resources near Unicup Lake for potential horticultural development for the Department of Industrial Development. Laws (1992) identified several prospective areas for groundwater exploration within the hard-rock provinces. Thorpe (1994) and Hawkes (1993) carried out detailed hydrogeological investigations to evaluate the groundwater potential of the Manjimup area along the Palgarup, Wilgarup and Chungarup transects. Prangley (1994) conducted a drilling program to assess the groundwater potential of fractured rocks near Manjimup. An exploratory drilling program was carried out in 1997 (Panasiewicz *et al.*, 1997) as a part of the hydrogeological mapping of PEMBERTON–IRWIN INLET.

Dampier Mining Company Limited (1981) conducted coal-exploration drilling programs targeting Eocene sediments in Lake Muir. The Griffin Coal Mining Company (1984) completed a similar drilling program in the Broke Inlet and Shannon Inlet areas.

Extensive research into the hydrological effects of logging in the Manjimup Woodchip Project Licence area, which covers the Donnelly and Warren River catchments, was conducted from 1975 to 1998 (Steering Committee for Research on the Woodchip Industry, 1980; Martin, 1987; Johnston *et al.*, 1980; Borg *et al.*, 1988; Bari and Boyd, 1993).

High-resolution geophysical data, comprising airborne electromagnetics (AEM), radiometrics and magnetics, was acquired by the Water and Rivers Commission for the Mobrup subcatchment of the upper Tone River catchment. These datasets were interpreted to assess the land salinisation risk of the subcatchment (Hundi *et al.*, 2001). The magnetic and radiometric coverage was later extended to cover the upper part of Warren River catchment. Agraria–World Geoscience conducted an aerial geophysical survey covering the Lake Muir–Unicup subcatchments in 1998. This survey collected high-resolution magnetic and radiometric data which were interpreted to clarify the hydrogeological process in catchments that are prone to land salinisation (Chakravartula and Street, 2000). Rogers *et al.* (1999) carried out hydrological modelling of salinity in the Tone and Perup Rivers subcatchments of the Warren Water Resource Recovery Catchment.

V & C Semeniuk Research Group (1996) mapped and classified major wetlands including the Lake Muir–Unicup area. The landforms and soils of PEMBERTON–IRWIN INLET were mapped and described by Churchward *et al.* (1988) and Churchward (1992).

1.6 Map compilation

Data from more than 1200 groundwater bores, wells and mineral exploration bores were used in the compilation of PEMBERTON–IRWIN INLET. Sources for these point data include the Water and Rivers Commission water point database (WIN), a bore census (Geste, 1998), the Manjimup Office of the Department of Agriculture Western Australia, and the Department of Industry and Resources. Geology and structure data from GSWA and topocadastral data from AUSLIG and DOLA were used in combination with the water point data. Hydrogeological boundaries, groundwater salinity contours and water level contours were derived at the scales of 1:100 000 or 1:50 000 depending on the bore density. These derived data sets were later simplified to produce PEMBERTON–IRWIN INLET at 1:250 000 scale. Derived datasets are approximate and their reliability depends on the bore density. Appendix 1 lists the digital data layers used in the map compilation.

2 Geology

2.1 Regional setting

The PEMBERTON–IRWIN INLET sheet area comprises three geological provinces: the Archaean Yilgarn Craton, the Proterozoic Albany–Fraser Orogen, and the Mesozoic Perth Basin (see Map panel). The north-trending Darling Fault separates the Archaean and Proterozoic metamorphic rocks in the east from the Mesozoic sedimentary rocks of the Perth Basin in the west. The easterly-trending Manjimup Fault marks the boundary between the Archaean Yilgarn Craton and the Proterozoic Albany–Fraser Orogen.

Geological processes associated with the breakup between Australia and Antartica, including sagging of the earth's crust, interrupted the pronounced northward and westward flowing drainage in the Late Neocomian (Smith, 1997). These major drainages were active in the Jurassic–Cretaceous, but had ceased activity by the Eocene. Alluvial and lacustrine sediments, such as the Werillup Formation, were deposited in these palaeodrainage systems prior to this geological event.

As a result of Eocene marine transgression, sediments of the Bremer Basin infilled the hollows in an irregular Precambrian basement. In the Late Tertiary, these sediments were uplifted to a present height of 300 m AHD (Hocking, 1990). Subsequent to these Tertiary sediments, and extending across the main physiographic provinces, are geological units that reflect the development of a lateritic landscape (Wilde and Walker, 1984). Cainozoic sediments overlie Precambrian basement rocks and the Perth Basin sediments, and cover about 75% of the study area. Southward tilting of the Ravensthorpe Ramp, possibly as early as the Oligocene (Smith, 1997), led to partial dissection by new, relatively short, south-flowing drainages.

The geology of the PEMBERTON–IRWIN INLET sheet has been described in detail by Wilde and Walker (1984) and the tectonic history by Myers (1990a, 1990b). The stratigraphic sequence is presented in Table 1.

2.2 Archaean and Proterozoic

Archaean rocks of the southwestern part of the Yilgarn Craton form the basement in the northern part of the area. The Yilgarn Craton consists predominantly of gneiss in the west (Balingup Metamorphic Complex) and granite in the east with the two rock types being separated by a zone of migmatite and quartz monzonite that is associated with the southern continuation of the Hester Lineament (Wilde and Walker, 1984). The major rock types that occur in the Yilgarn Craton on PEMBERTON–IRWIN INLET include fine-to-medium grained layered gneiss (*An*) consisting of various proportions of quartz, microcline, plagioclase and biotite; even-grained granite (*Ag*) consisting of andesine/oligoclase, microcline, quartz and biotite; migmatite; and quartz monzonite. Orthoquartzite (*Aq*) occurs as thin bands that extend south from Bridgetown on COLLIE to latitude 34° 23 S. The other minor rock types include banded iron formation, amphibolite and small lenses of quartz mica schist. The rocks of the Yilgarn Craton include undeformed dolerite dykes (*Pd*) intruded as the Gnowangerup dyke swarm with a pronounced easterly trend (Myers, 1990b; Hawkes, 1993).

The Albany–Fraser Orogen, exposed south of the Yilgarn Craton, is divided into the Biranup Complex and the Nornalup Complex by a series of east-northeast thrust faults. The more northern Biranup Complex is bounded by the Manjimup Fault in the north and the Northcliffe Fault and the Nornalup Complex in the south. The Pemberton Fault separates the two subsections of the Biranup Complex. These major faults are associated with an easterly trending shear zone between the Yilgarn Craton and the Albany–Fraser Orogen (Muhling and Brakel, 1985).

The Biranup Complex is an intensely deformed metamorphic belt, consisting of high-grade quartzo-feldspathic gneiss and minor layers of paragneiss. The BMR aeromagnetic map of ALBANY indicates that the Biranup Complex is characterised by pronounced layering and high total magnetism. Aeromagnetic maps also show that the rocks of this complex occur as steeply dipping tectonic slices, each 5 to 15 km thick (Myers, 1995).

The southerly Nornalup Complex to the south consists of orthogneiss and paragneiss that have been intruded by a large volume of granite (Myers, 1995). Granitic orthogneiss (Pn) and paragneiss (Pn) are strongly, but

Table 1. Stratigraphy

Age	*Formation*	*Maximum thickness (m) intersected (bore)*	*Lithology*
Quaternary	Alluvial and lacustrine sediments (*Qa*)	45 (KL5)	Sand, clay, silt and peat
	Dune limestone (*Qpl*)		Limestone, sand
	Quartz sand dunes (*Qpd*)	29	Sand, silt
	Guildford Formation (*Qpg*)	30 (SC21)	Sand, clay and silt
Cainozoic	Alluvium and colluvium (*Cza*)	24 (PM5)	Sand and clay
	~Unconformity~		
Tertiary	Estuarine, lagoonal and lacustrine deposits (*Tpe*)	75	Clay
	Alluvial, lacustrine and shallow marine deposits (*Tgc*)		Conglomerate, gravel, sand, clay
	Pallinup Siltstone (*Tpp*)	36 (PM 7)	Siltstone
	Werillup Formation (*Tpw*)	65 (LM7)	Sand, clay, gravel and peat
Cretaceous	Warnbro Group (*Kw*)	235 (KL7)	Sandstone, siltstone and shale
	Bunbury Basalt (*Kbb*)	103 (KL6)	Basalt
	~Unconformity~		
Jurassic	Parmelia Formation (*Jkp*)	167 (KL7)	Siltstone, shale and sandstone
	Yarragadee Formation (*Juy*)	1252 (KL7)	Sandstone, siltstone and shale
	Cockleshell Gully Formation (*Jlo*)	775 (KL5)	Sandstone, siltstone and shale
Triassic	Lesueur Sandstone	~ 2000	Sandstone, minor shale
	Sabina Sandstone		Sandstone, conglomerate, siltstone
Permian	Sue Coal Measures	~ 2000	Siltstone, shale, sandstone and coal
	~Unconformity~		
Precambrian (undetermined)	Gnowangerup dyke swarm (*Pd*)		Dolerite intruding *Ag*
	Quartz dykes and veins (*Aq, q*)		Quartz
Proterozoic	Albany–Fraser Orogen		
	Biranup Complex		Gneiss, quartzite, sandy clay
	Nornalup Complex		Gneiss, granite, sandy clay
Archaean	Yilgarn Craton		
	Balingup Complex		Gneiss, migmatite, quartzite, sandy clay
	Yilgarn Craton		Granite, dolerite dykes, sandy clay

less intensely, deformed than the rocks of the Biranup Complex. Even-grained and medium-to coarse-grained porphyritic granites (*Pg*) form a large body called the Burnside Batholith (Wilde and Walker, 1984) in the southern part of Pemberton–Irwin Inlet. The Burnside Batholith extends east onto the adjoining Mount Barker–Albany. Migmatites (*Pm*) also occur in association with these Proterozoic granitic rocks.

There is a general absence of mafic dykes in the Albany–Fraser Orogen that is considered to be a real feature, and not a function of rock exposure (Wilde and Walker, 1984).

2.3 Mesozoic and Palaeozoic

Mesozoic sediments exist in the southern Perth Basin, west of the Darling Fault. This is the southern part of the Perth Basin that extends for almost 1000 km along the western margin of the Australian continent (Playford *et al.*, 1976). A 6 km-thick sequence of continental and fluviatile sandstones, principally from weathering of the bedrock in Antartica and possibly also in the Yilgarn Craton, was deposited in this narrow trough.

In the PEMBERTON–IRWIN INLET area, the oldest of these sediments is the early Permian Sue Coal Measures, which consists of up to 2000 m of interbedded sandstones, siltstones and thin coals. Overlying these rocks are the Triassic Sabina and Lesueur Sandstones which reach 2000 m in thickness. The Sabina Sandstone is of continental origin with some minor shale partings, whereas the Lesueur Sandstone is a thick, fluviatile sandstone which is interbedded with conglomerate and siltstone.

The Cockleshell Gully Formation (*Jlo*), composed of sandstones with interbedded shale and siltstone, conformably overlies the Lesueur Sandstone. This formation is intersected in KL5 and KL6 with the thickest intersection of 775 m in KL5, in which the bottom was not reached (Baddock, 1995). This unit is overlain either conformably by the Yarragadee Formation or, in areas near the south coast, unconformably by the Warnbro Group or Bunbury Basalt.

Middle Jurassic to Early Cretaceous in age, the Yarragadee Formation (*Juy*) conformably overlies the Cockleshell Gully Formation. The formation outcrops at Fly Brook, where there is up to 5 m of feldspathic sandstone, conglomeratic sandstone, siltstone and shale with thin bands of lignite (Wilde and Walker, 1984), and also along the Blackwood River. The maximum thickness intersected was 1252 m in KL7, although the base of the formation was not reached (Baddock, 1995). According to Wilde and Walker (1984), this formation can be up to 1500 m thick. Sandstone generally constitutes over 70% of the formation, with interbedded siltstone and lesser amounts of shale and conglomerate. The base of the Yarragadee Formation lies about 1600 m below sea level adjacent to the Darling Fault and generally shallows to the west and southwest (Baddock, 1995). On PEMBERTON–IRWIN INLET it is overlain either conformably by the Parmelia Formation or unconformably by the Bunbury Basalt, Warnbro Group or surficial formations.

The Parmelia Formation (*Jkp*) was intersected initially in KL7, with a thickness of 167 m. It consists of siltstone and shale, and poorly consolidated clayey sandstone. The siltstone and shale proportion increases upwards and is carbonaceous. It is unconformably overlain by the Bunbury Basalt and the Warnbro Group (Baddock, 1995).

The Bunbury Basalt (*Kbb*) erupted into the Perth Basin during the Cretaceous. This eruption of Bunbury Basalt is considered to be a reflection of tectonic events associated with continental breakup in the Neocomian. The basalt could have been extruded along mainly north-trending faults within the Perth Basin during the continental breakup. Successive flows of basalt spread along valleys (Baddock, 1995). The Bunbury Basalt is a microporphyritic to porphyritic tholeiitic basalt that is locally vesicular and displays columnar jointing (Wilde and Walker, 1984). It is overlain unconformably by the Warnbro Group or Quaternary formations, and extends across the Darling Fault without evidence of later displacement. It crops out along the Blackwood River and its tributaries, at the mouth of the Donnelly River, at Black Point, near Yeagarup Lake, along the Vasse Highway, and at Fly Brook (Wilde and Walker, 1984). The subsurface distribution of Bunbury Basalt, shown on the PEMBERTON–IRWIN INLET map sheet, was mapped by using geophysical and borehole data (Baddock, L. J., 2000, pers. comm.). The Bunbury Basalt was intersected at KL6 and KL7; with the thicker section of 103 m in KL6.

The Warnbro Group (*Kw*) is distributed over both the Blackwood Plateau and the Scott Coastal Plain and is probably represented in this area by the Leederville Formation. The surface of the Warnbro Group is lateritised on the Blackwood Plateau, and on the Scott Coastal Plain it is overlain unconformably by Quaternary formations. The base of the group is irregular and deepens to about 150 m AHD near the Darling Fault (Baddock, 1995). It also extends across the Darling Fault, as does the Bunbury Basalt. It crops out near the confluence of Red Gully with the Blackwood River, and in an old gravel pit near Yeagarup Lake (Wilde and Walker, 1984). The Warnbro Group consists of sandstone, siltstone and shale, and has a maximum recorded thickness of 235 m in KL7.

2.4 Cainozoic

2.4.1 Tertiary sediments

Tertiary sediments, ranging in age from Eocene to Pliocene, lie unconformably on Precambrian basement rocks and Perth Basin sedimentary rocks. Sedimentary sequences are found in Mobrup (Milne, 1999; Hundi, 1999) and in Manjimup (Backhouse, 1994; Thorpe, 1994), and these can be correlated with the Plantagenet

Group of the Bremer Basin, based on palynological evidence and characteristics. The Bremer Basin, overlying the southern Yilgarn Craton and the Albany–Fraser Orogen, consists of numerous small sediment-filled depressions rather than a single continuous basin (Hocking, 1990).

The Werillup Formation (*Tpw*) is the lower unit of the late Eocene Plantagenet Group of the Bremer Basin. It was deposited in palaeovalleys and topographic depressions in the weathered basement and consists predominantly of fluvial and lacustrine sediments. This formation is overlain conformably by the Pallinup Siltstone (*Tpp*), or unconformably by Quaternary sediments where the Pallinup Siltstone has been eroded. The Pallinup Siltstone is a transgressive marine sequence and consists typically of white to grey-brown siltstone and spongolite that either overlies the Werillup Formation or lies directly on Precambrian basement. On Pemberton–Irwin Inlet, Tertiary sediments that can be correlated with the Plantagenet Group can be found both in palaeodrainages including Lake Muir and Unicup and in higher landscape positions of rejuvenated or modern-day drainage.

The thickest profile of Late Eocene sediments is 70 m in LM7, located about 8 km north-east of Lake Muir. The sediments sequence in LM7 consists of multiple layers of carbonaceous clay, lignite and carbonaceous sand (Dampier Mining Co Ltd, 1981).

The Werillup formation (*Tpw*) on Pemberton–Irwin Inlet, has been intersected at a wide range of elevations, from 30 m near Broke Inlet to 240 m AHD at Mobrup. The maximum thickness of 65 m was recorded at LM7.

A sediment sequence that can be correlated with the Pallinup Siltstone (*Tpp*) was found in PM6, PM7 and PM10. In PM10, sponge spicules were observed in khaki brown, weakly consolidated silt (Panasiewicz *et al.*, 1997). The maximum thickness of 36 m was recorded in PM7, where Pallinup Siltstone directly overlies the weathered basement.

Deposits of conglomerate, quartz grit, sand and clay (*Tgc*) are developed over the Precambrian shield. They are mainly of alluvial or lacustrine origin, but some are possibly shallow-marine sediments (Wilde and Walker, 1984). They can also be the remnants of the Werillup Formation, which was eroded following uplift during the Late Tertiary (Probably Oligocene).

Estuarine, lagoonal and lacustrine sediments (*Tpe*) are present along much of the south coast. They lie between sea level and 70 m AHD and commonly enclose 'islands' of Precambrian rocks. The thicknesses of these sediments are generally unknown although they exceed 75 m in a bore near Windy Harbour. Palynological evidence indicates they are Late Pliocene in age (Wilde and Walker, 1984). These sediments lie unconformably on both Plantagenet Group sediments and Precambrian weathered basement.

2.4.2 Surficial sediments

Various Cainozoic and Quaternary surficial deposits form a veneer over Archaean, Proterozoic and Mesozoic rocks on Pemberton–Irwin Inlet. The surficial sediments discussed here include Cainozoic alluvial and colluvial sediments (Cza) and four Quaternary units (*Qpg, Qpd, Qpl* and *Qa*). Only the units that contain groundwater are mapped on Pemberton–Irwin Inlet.

Cainozoic alluvial and colluvial sediments (*Cza*), an unassigned Tertiary unit, occur mainly on the Yilgarn Craton and on the Albany–Fraser Orogen. They mark the former course of a pre-Tertiary drainage system and are variously dissected by the present drainage (Wilde and Walker, 1984). These sediments, consisting of sand and clay, overlie either Plantagenet Group sediments or weathered basement and are up to 20 m thick.

The Guildford Formation (*Qpg*) occurs as a shoreline deposit on the Scott Coastal Plain. Numerous small linear dunes, possibly formed by mobilisation of surface sand (*Qpd*) are present on the formation (Baddock, 1995). The Guildford Formation is considered to be of Middle Pleistocene age (Playford *et al.*, 1976).

The Guildford Formation was intersected in three bores (SC16, 19 and 21) on the Scott Coastal Plain. The formation, which ranges from 16 to 30 m thick in these bores, consists of grey to pale brown, fine-to coarse-grained, poorly to well-sorted, subrounded to rounded, unconsolidated quartz sand with some heavy minerals such as ilmenite. Narrow layers of estuarine and wetland plant detritus and clay are also present in this formation (Baddock, 1995). The Guildford Formation lies unconformably on mainly the Yarragadee Formation and Warnbro Group.

Quartz sand of fixed dunes (*Qpd*) occurs inland from the dune limestone (*Qpl*). These dunes consist mainly of quartz sand and are only rarely calcareous (Wilde and Walker, 1984). The unit unconformably overlies Mesozoic sediments in the Perth Basin and weathered bedrock elsewhere. This formation may be equivalent to Bassendean Sand on the Swan Coastal Plain. A bore drilled at Peaceful Bay intersected 29 m of this formation overlying weathered granite.

Eolian calcarenite (*Qpl*) forms a complex system of ridges along the south coast of PEMBERTON–IRWIN INLET. It is variously lithified, calcretised and leached to quartz sand (Wilde and Walker, 1984). Thick sand deposits overlie limestone, especially on the inland slope side of the limestone ridges. Limestone overlies mainly the weathered basement, except on the Scott Coastal Plain where it unconformably overlies Mesozoic sediments of the Perth Basin. This formation probably reaches a thickness of 50 m near the coast and thins inland (Baddock, 1995).

Alluvial and lacustrine deposits (*Qa*) are developed over the major stretches of the rivers and swamps. The maximum thickness of this formation was observed in KL5, where 45 m of channel sediments were intersected. The sediments intersected in KL5 consisted of fine to coarse sand with some feldspar and basalt pebbles at the base (Baddock, 1995). However, the thickness of similar deposits on the Yilgarn Craton or Albany–Fraser Orogen may not exceed 20 m.

3 Hydrogeology

3.1 Groundwater occurrence

Groundwater occurs in four hydrogeological provinces (Smith *et al.*, 1999) on Pemberton–Irwin Inlet:

- the Archaean hard-rock areas forming the Albany–Fraser and Yilgarn Southwest Provinces; and
- the sediments of the Perth Basin (Permian–Quaternary) and Bremer Basin (Tertiary).

Across these provinces, groundwater is contained in 23 aquifers that are classified according to the respective geological formation (Table 1), and described in sections 3.2 and 3.3.

The Warnbro Group, Yarragadee Formation and Cockleshell Gully Formation form major regional aquifers in the Perth Basin on Pemberton–Irwin Inlet. In the Perth Basin, the groundwater system has significant resource potential as the aquifers there have large groundwater storage capacities and good quality water. Quaternary sediments of alluvial, lacustrine and eolian origin form the surficial aquifer system within the Perth Basin. The surficial aquifer contains substantial fresh groundwater resources, mainly within the Scott Coastal Plain (Fig. 2). Bunbury Basalt, comprising porphyritic and vesicular basalt, acts as an aquiclude for some parts of the Perth Basin groundwater system. The Parmelia Formation, consisting of sandstone, siltstone and shale, forms an aquitard. The hydrostratigraphy of the Perth Basin is illustrated in the Map Section AB.

In the Albany–Fraser and the Yilgarn Southwest Provinces, groundwater exists mainly in the weathered profile and in the fractures and joints of the granitic and gneissic basement rocks. These form aquifers commonly referred to as the weathered-rock aquifers. Tertiary sediments of the Plantagenet Group form the Tertiary sediments aquifer within the hard-rock provinces. Groundwater also occurs in the unconsolidated sediments of Cainozoic age (surficial aquifers), which overlie the weathered bedrock profile. The weathered-rock aquifers can be considered as having local to intermediate groundwater flow patterns and have limited potential as a groundwater resource. Moderate to high groundwater salinities further limits the groundwater resource potential of these aquifers. The Tertiary sediments aquifer within the hard-rock provinces has significant potential to be developed as a water resource in high rainfall zones. Surficial aquifers in the coastal areas also have good potential as a groundwater resource. However, further inland, the potential of this aquifer decreases due to both the limited storage capacity and the increasing groundwater salinity.

3.2 Perth Basin

3.2.1 Surficial aquifer (*Qa, Qpl, Qpd, Qpg* and *Cza*)

The surficial aquifer is found mainly in the Scott Coastal Plain and the coastal dunes. It consists predominantly of sand (*Qpd*), with calcarenite (*Qpl*) near the coast and common thin layers of plant detritus and clay within the Guildford Formation (*Qpg*). The alluvial sediments (*Qa* and *Cza*) are restricted mainly to the flood plains of the Donnelly River and Warren River, with minor occurrences in the Blackwood River. The average saturated thickness of the surficial aquifer is about 10 m (Baddock, 1995).

The surficial aquifer is generally unconfined. However, in some areas ferruginous cemented sand developed extensively within the Guildford Formation (*Qpg*) acts as a confining layer to this aquifer.

The watertable is generally shallow except in the elevated coastal dunes, where there is a significant thickness of unsaturated sediment. Groundwater within the surficial aquifer moves southward toward the coast.

Groundwater recharge to the surficial aquifer is by direct infiltration of rainfall. The water level fluctuates by 1 to 3 m mostly in response to seasonal variations in rainfall. The water level peaks about September and reaches its lowest level around March–April (Baddock, 1995). Groundwater discharge is mainly through evapotranspiration from the shallow watertable. Groundwater can also discharge into wetlands and watercourses. It is generally fresh, with total dissolved solids (TDS) ranging between 200 and 530 mg/L (Baddock, 1995).

3.2.2 Warnbro Group aquifer (*Kw*)

The Warnbro Group aquifer is located mainly within the Blackwood Plateau, with only limited occurrence in the Scott Coastal Plain and in the Albany–Fraser Province. This aquifer is confined and multi-layered comprising interbedded shale, silt and sand. The thickness of the Warnbro Group aquifer increases northward (Baddock, 1995) and exceeds 200 m. On the Blackwood Plateau, the watertable is a subdued reflection of the topography and is about 10 to 30 m below ground level (Baddock, 1995). Groundwater generally flows toward the Blackwood River.

Recharge to the Warnbro Group aquifer on the Blackwood Plateau is mainly through rainfall infiltration. On the Scott Coastal Plain, recharge to the aquifer is by downward leakage from the surficial formations. Thorpe and Baddock (1994) estimated groundwater recharge to this aquifer on the Blackwood Plateau to be 8.4% of average annual rainfall. Groundwater discharges into underlying formations by downward leakage (Thorpe and Baddock, 1994). It also discharges into valleys and the Blackwood River by upward leakage where upward potentiometric heads dominate. The groundwater salinity ranges between 200 and 500 mg/L TDS. The hydraulic conductivity of the Warnbro Formation in the Southern Perth Basin ranges between 2 and 6 m/day (Hirschberg, 1989).

3.2.3 Yarragadee aquifer (*Juy*)

The Yarragadee aquifer is a major regional aquifer that extends for about 150 km north from the south coast and is some 40 km wide. It is composed predominantly of sandstone, with interbeded siltstone and shale, and has a maximum thickness that exceeds 1200 m on PEMBERTON–IRWIN INLET (Baddock, 1995). Groundwater flows north and south from the southern end of the Blackwood Plateau (see the side panel of PEMBERTON–IRWIN INLET), where the Yarragadee Formation is exposed.

The Yarragadee aquifer is recharged by direct infiltration of rainfall where it is exposed over approximately 120 km^2 in PEMBERTON–IRWIN INLET, and by downward leakage from overlying formations including the surficial sediments and the Warnbro Group (Baddock, 1995). Thorpe and Baddock (1994) estimated a recharge rate of 20% of annual average rainfall in areas where the Yarragadee Formation is exposed, and a recharge rate of 10% of annual average rainfall in areas where the Yarragadee Formation is overlain by the surficial formations.

Groundwater discharges from the Yarragadee Formation directly into the Southern Ocean near Black Point. It also discharges into the Blackwood River, north of drill hole KL 5. Groundwater probably also discharges directly into the lower Donnelly River. Groundwater salinity ranges between 130 and 590 mg/L TDS (Baddock, 1995). The hydraulic conductivity of the Yarragadee Formation in the Southern Perth Basin ranges from 6 to 20 m/day (Commander, 1984; Thorpe, 1992).

3.2.4 Cockleshell Gully aquifer (*Jlo*)

The Cockleshell Gully aquifer extends throughout the Perth Basin portion of PEMBERTON–IRWIN INLET. It consists of sandstone with interbeded shale and siltstone and reaches about 1000 m in thickness. The Cockleshell Gully aquifer is confined by the overlying Yarragadee aquifer and is recharged mainly from that aquifer through faulted contacts. Groundwater discharges from the aquifer offshore via overlying formations (Baddock, 1995). Groundwater within the upper part of the Cockleshell Gully aquifer generally contains less than 300 mg/L TDS owing to groundwater flowing across faults from the Yarragadee aquifer, but is likely to be brackish or saline elsewhere (Baddock, 1995).

3.3 Hard Rock Provinces

3.3.1 Surficial aquifer (*Qpl* and *Qpd*)

Dune limestone (*Qpl*) and quartz sand in fixed dunes (*Qpd*) form the coastal belt. The surficial aquifer (*Qpl* and *Qpd*) directly overlies the basement rocks. This aquifer produced 300 m^3/day in a Public Works Department (1983) pumping test at Peaceful Bay. Here the aquifer is 29 m thick and consists mainly of sand overlying weathered basement rock. The surficial aquifer is sandy and unconfined and thus may receive recharge of more than 20% of rainfall. The groundwater salinity is about 400 mg/L TDS.

3.3.2 Surficial aquifer (*Cza* and *Qa*)

The surficial aquifer comprises widespread alluvial, colluvial and lacustrine deposits (*Cza* and *Qa*) occupying valleys, broad flats and wetlands. The aquifer, consisting of sands, clays and gravels, overlies either the basement rocks or Tertiary sediments and is between 5 and 20 m thick. The aquifer is generally unconfined and depth to water level is 1 to 2 m. Yields from this aquifer depend on the lithology; sandier profiles can produce higher yields, whereas clayey or peaty profiles produce little or no water (Panasiewicz *et al.*, 1997). Aquifer yields up to 86 m^3/day have been recorded at Palgarup, north of Manjimup (Thorpe, 1994). Groundwater salinity, which varies significantly across Pemberton–Irwin Inlet, is between 250 and 800 mg/L (Thorpe, 1994) in the upper parts of the Donnelly River catchment, where average annual rainfall ranges from 800 to 900 mm. However, in the upper parts of Warren River catchment groundwater salinity exceeds 4000 mg/L (Hundi *et al.*, 2001). Apart from direct infiltration of rainfall, this aquifer can receive throughflow from the adjoining weathered bedrock aquifer. Groundwater discharge is mainly through evapotranspiration. This aquifer can be considered as a good water supply source in high rainfall areas of Pemberton–Irwin Inlet.

3.3.3 Tertiary sediments aquifer *(Tpe, Tgc* and *Tpp)*

Estuarine, lagoonal and lacustrine deposits (*Tpe*), alluvial, lacustrine and shallow marine deposits (*Tgc*), and Pallinup Siltstone (*Tpp*) form aquitards to minor local aquifers. These deposits overlie the Werillup Formation (*Tpw*), or weathered or fresh basement rocks. The sediments (*Tpe*) are 75 m thick at Windy Harbour (Wilde and Walker, 1984), although the average thickness for these sediments is between 20 and 30 m. Owing to their clayey nature, they rarely form an aquifer and in most situations act as an aquitard to the aquifers beneath. Groundwater is fresh to brackish, containing up to 1500 mg/L TDS.

3.3.4 Tertiary sediments aquifer *(Tpw)*

The Werillup Formation (*Tpw*) forms a semi-confined to confined aquifer in several situations. The aquifer occupies in the lower parts of palaeovalleys, and specifically some palaeochannels including Mobrup, Tonebridge, Unicup, Noobijup, Lake Muir and Wilgarup (Map Sections BC and DEFGH). Apart from palaeochannels, the aquifer is present at Walpole and near Lake Surprise, at Nornalup. In some localities, the aquifer is confined by the Pallinup Siltstone (*Tpp*).

Mobrup palaeochannel

At Mobrup, the Werillup Formation aquifer can be traced 15 km along a broad valley flat comprising Cainozoic sediments. The palaeochannel is 1000 m wide and the sediments (inclusive of Quaternary) range from 30 to 48 m in thickness (Hundi, 1999). Tertiary sediments consist of sand, silt and carbonaceous clay. The maximum thickness of sand is about 25 m in MOB3 (Hundi, 1999). The total thickness of sediments and sands tends to decrease eastwards. Groundwater occurs mainly in two sand layers separated by about 5 m of carbonaceous clay. The upper and lower sand layers are about 8 and 15 m thick respectively. The lower sand layer is coarse grained to gravel size in contrast to the upper sand layer, which is fine to medium grained. The upper sand layer can be considered as an unconfined aquifer system whereas the lower sand layer is a confined aquifer system. Groundwater yields vary from 80 to 150 m^3/day. Depth to water level is shallow and varies from 1 to 2 m below ground level (Hundi, 1999). The groundwater flow in the western part of the palaeochannel is northwest towards the Tone River. This aquifer probably extends eastwards onto Mount Barker–Albany, along the valleys containing Cainozoic sediments and across the surface water divide of the Warren River catchment. Groundwater salinity ranges from 2400 to 3100 mg/L.

Tonebridge palaeochannel

At Tonebridge, the Werillup Formation aquifer (*Tpw*) is about 3 km long and 500 m wide. The aquifer probably continues to the east along the flats of Cainozoic sediments. In PM11, the aquifer exceeds 46 m in thickness and comprises mainly medium-to coarse-grained, sub-angular to sub-rounded, moderately sorted sand with abundant gravel (Panasiewicz *et al.*, 1997). This sand layer is overlain to a depth of 9 m by up to 6 m of clay and thus the aquifer is confined. The potentiometric head stands at about the ground surface. Groundwater salinity is about 4000 mg/L, and yield is expected to be around 150 to 200 m^3/day.

Unicup palaeochannel

The Unicup palaeochannel is mapped as 750 m wide and about 10 km long. The Werillup Formation aquifer (*Tpw*) probably extends westwards and eastwards along the flats and terraces of Cainozoic sediments. This palaeochannel was intersected at PM4 and PM12 (Panasiewicz *et al.*, 1997) with sediment thickness exceeding 42 m at PM4. The sediments and sands tend to thin eastwards. The palaeochannel sediments consist of plastic clay, carbonaceous clay, silt and sand.

Groundwater occurs mainly in a sand layer that extends to a depth of 16 to 38 m, between carbonaceous clay layers, thus forming a confined groundwater system. The potentiometric head is from 4.5 to 0.2 m below ground level. However, during winter recharge, the potentiometric head may rise to 0.4 m above ground level. Groundwater salinity varies from 3400 mg/L in PM4 to 12 800 mg/L in PM12.

Noobijup palaeochannel

The Noobijup palaeochannel runs northwest and may be traced about 12 km from Pindicup Road to north of Noobijup Lake. A tributary channel joins the main channel from the southeast. The Werillup Formation (*Tpw*) is between 37 and 73 m thick and increases westward. The sediments consist of carbonaceous clay and sand, sand, clay and silt. Two production bores drilled in the tributary yielded 800 to 1400 m^3/day from coarse-grained quartz river sand below 16 m depth. Groundwater salinity ranges from 250 to 5600 mg/L.

Lake Muir palaeochannel

The Lake Muir palaeochannel, about 1250 m wide and 7.5 km long, has been identified from coal and groundwater exploration drilling. The Werillup Formation (*Tpw*) is between 37 and 46 m thick and comprises sand, clay and carbonaceous clay. A sand layer extending from 17 to 41 m in PM1A (Panasiewicz *et al.*, 1997) forms a confined aquifer. The potentiometric head during summer varies from 0.2 to 1 m below ground level. In response to winter recharge, it rises to 0.4 m above the natural surface. Groundwater yields are between 50 and 100 m^3/day, and salinity is about 23 500 mg/L.

Wilgarup palaeochannel

The Wilgarup palaeochannel was identified during the Manjimup Shallow Basins Drilling Project Phase 3 (Thorpe, 1994). On PEMBERTON–IRWIN INLET, it is mapped some 12 km north of Manjimup at about 11 km long, 500 m wide, and running west. The Werillup Formation comprises light grey plastic clay, coarse-to medium-grained, well-sorted quartz sand, and carbonaceous clayey sand. The drilled depth to weathered bedrock ranges from 13 to 20 m and the thickness of the sand layers ranges from 5 to 17 m. Groundwater occurs mainly in these sand layers and is confined by a plastic clay layer. The potentiometric head stands about 1 m below ground level. Yields of up to 430 m^3/day are recorded from this palaeochannel aquifer, but a screened production bore is likely to yield about 1500–2000 m^3/day (Thorpe, 1994). Groundwater, which varies

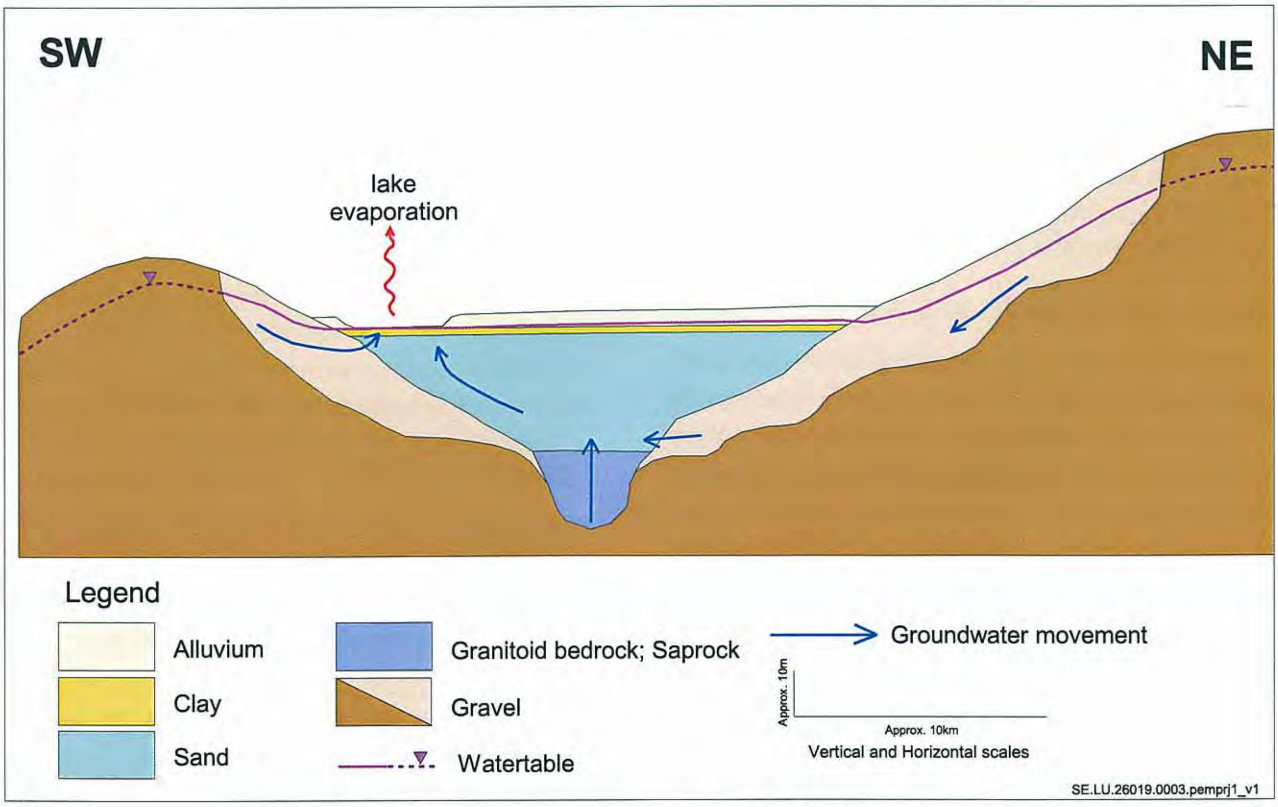

Figure 4. Diagrammatic section across Lake Muir

salinity, both vertically and laterally (Thorpe, 1994) ranges from 810 to 4190 mg/L. The highest groundwater salinities are at the channel margins because of groundwater inflow from weathered bedrock.

Walpole

The Werillup Formation aquifer (*Tpw*), intersected in PM9 about 20 km north of Walpole (Panasiewicz *et al.*, 1997), contains groundwater in two sand layers at depths of 15 to 19 m and 21 to 25 m. The aquifer here is confined beneath a 15 m-thick clay layer. The potentiometric head stands around 2 m above ground level. Groundwater salinity is about 240 mg/L.

Bore PM6, located some 22 km south from Muirs Highway on Nornalup Road, also intersected Werillup Formation aquifer (*Tpw*) (Panasiewicz *et al.*, 1997). PM6 was drilled up to a depth of 42 m without fully penetrating the Tertiary sediments. Groundwater occurs mainly in a sand layer below 33 m. This sand layer is confined by 33 m of clay, possibly Pallinup Siltstone (*Tpp*), and the potentiometric head stands about 8 m below ground level. Groundwater salinity is 2000 mg/L.

3.3.5 Weathered-rock aquifer (*Pg, Pn, Ag* and *An*)

The weathered rock aquifer is developed in moderately to highly weathered granitic (*Ag* and *Pg*) and gneissic rocks (*An* and *Pn*), and is extensive on PEMBERTON–IRWIN INLET in various river catchments including the Warren, Blackwood, Donnelly and Frankland. The weathered profile overlies fresh or fractured bedrock and ranges from about 5 to 30 m thick. Groundwater occurs mainly in the permeable zones of the weathered profile comprising a high content of coarse-grained quartz sand or grit, in a clay matrix. This permeable zone in the weathered profile is commonly referred as the saprolite grits. This aquifer is usually semi-confined or confined by the pallid clay developed within the weathered profile.

Groundwater yields of up to 86 m^3/day can be obtained from the weathered-rock aquifer. They are dependent on the intensity of jointing and fracturing in the bedrock, the lithology of the rock, the amount of recharge and the topographic position. Granitic rocks tend to weather to a sandier profile, whereas gneissic rocks produce a more clayey weathered profile. Thus the weathered profile of granitic rocks can produce higher yields than the weathered profile of gneissic rocks.

Groundwater flow within the weathered rock aquifer is characterised mainly by local flow systems originating close to the surface water catchment divide and discharging at the nearest drainage line. Recharge to this aquifer is mainly by direct infiltration of rainfall. Groundwater discharges to watercourses, wetlands and through evapotranspiration from a shallow watertable. Groundwater from the weathered-rock aquifer also flows (discharges) into surficial and Tertiary sediments that occupy broad flats and valleys.

Groundwater salinity varies greatly on PEMBERTON–IRWIN INLET. It is less than 1000 mg/L in areas where rainfall exceeds 1000 mm/a and reaches more than 14 000 mg/L in the northeast, where rainfall is between 600 and 800 mm/a. Groundwater salinities are lower in more undulating terrain than in flat or gently sloping areas. This is attributed to undulating terrains having a more dynamic groundwater system and well-developed surface water drainage that can flush salt from the weathered profile. In contrast, flat to gently sloping areas with stagnant groundwater systems and poor surface water drainage accumulate salt in the weathered profile. Consequently, at the catchment scale, groundwater salinity increases from upper middle slope areas to lower slope areas.

Groundwater also occurs in the fractures and joints that extend for possibly 10 m or more beneath the limit of weathering. The extent and intensity of fracturing depends on the tectonic history of the area. The areas criss-crossed by regional fractures and faults, such as the Boyup Brook Fault and the Manjimup Fault, can be expected to have bedrock intensely fractured and jointed. Thus, in such areas groundwater occurrence extends beyond the weathered zone into the fractured horizons that can accommodate significant volumes of groundwater. Chakravartula and Street (2000) consider that the late northwesterly to northeasterly trending faults cutting across easterly trending major faults influence groundwater movement because they tend to be more open and therefore carriers of groundwater.

3.3.6 Fractured-rock aquifer (*q* and *Aq*)

Quartz veins and quartzite form a high-yielding fractured-rock aquifer as they are brittle rocks with a high intensity of joints and fractures that can store a significant amount of groundwater. This aquifer has a limited occurrence within PEMBERTON–IRWIN INLET and is found mainly within the lower part of the Warren River catchment and throughout the Donnelly catchment. Groundwater yields of up to 500 m^3/day have been recorded from this aquifer near Manjimup (Prangley, 1994). At this location, bedrock weathering extends to 30 m, but fracturing continues to 130 m in fresh to slightly weathered quartzite. Groundwater yields increased significantly within the fracture zones of the bedrock. Groundwater salinity is less than 500 mg/L TDS.

3.3.7 Weathered-rock aquifer (*Pd*)

Dolerite dykes intruded into the basement rock weather to form this aquifer. Dolerite dykes are mapped mainly within the Yilgarn Southwest Province with minor occurrence in the Albany–Fraser Province. The weathered profile of dolerite dykes (*Pd*) tends to have higher clay content than the weathered profiles of basement rocks such as granites and gneisses and consequently forms a poorer aquifer. Engel *et al.* (1987) found that weathered dolerite dykes can act as barriers to groundwater flow within the weathered profiles of basement rocks.

4 Groundwater quality

4.1 Regional groundwater salinity

Groundwater quality on Pemberton–Irwin Inlet ranges from fresh to saline (up to half the salinity of seawater). Groundwater in the surficial, Warnbro Group, and Yarragadee aquifers of the Perth Basin is generally fresh. Within the hard-rock provinces (Yilgarn Southwest and Albany–Fraser) groundwater salinity generally increases from the coastal areas towards the northeast. It ranges from less than 1000 to more than 14 000 mg/L TDS within the weathered bedrock aquifer in response to the differences in the rainfall, land use and topography. The groundwater is least saline higher in the landscape and increasingly saline towards the lower slopes and valley floors.

Groundwater in the Werillup Formation (Bremer Basin) aquifer is highly variable in salinity, ranging from 250 to 23 500 mg/L TDS. It is generally fresh in high rainfall zones where the surficial and Cainozoic sediments have higher recharge. Groundwater salinity increases towards the major lakes, such as Lake Muir, due to higher concentrations of salt in groundwater through evaporative discharge. Variation in groundwater salinity is common along a groundwater flow path from the weathered-rock aquifer to the surficial and Werillup Formation aquifers. Salinity is highest at the contact between weathered-rock and sediments.

4.2 Hydrochemistry

Chemical analyses of groundwater samples from selected WRC bores are given in Table 2. Groundwater is mainly sodium chloride type, but sulphate ions are also present in significant amounts in high-salinity groundwater. High sulphate content of saline groundwater is nevertheless depleted relative to ratios in seawater. This may be due to separation by evaporation and wind in salt lakes. High values of calcium (up to 330 mg/L) and bicarbonate (up to 350mg/L) are recorded from the surficial aquifer in coastal dune areas. Baddock (1995) attributed these high levels of calcium and bicarbonate to dissolution, by groundwater, of limestone and other calcareous dune components.

The pH of groundwater on the map sheet ranges from 3.1 to 10.9 on the map sheet. Most of the low pH groundwater is associated with the Tertiary sediments aquifer. Nitrate concentrations are low and generally not more than 2 mg/L. The maximum fluoride concentration recorded is 0.4 mg/L. High soluble iron concentrations (up to 13 mg/L) were recorded in the Warnbro Group and Yarragadee aquifers. The iron concentrations for Perth Basin aquifers generally increase along the flow path, are highest in groundwater with pH from 5.1 to 7.3, and also increase with depth (Baddock, 1995). Iron concentrations range from less than 0.1 to 3.2 mg/L for the weathered-rock aquifer.

Table 2. Selected groundwater chemical analyses

Bore	pH	EC	TDS	Total hardness	Total alkalinity	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	SiO_2	F	Fe
		mS/m	(mg/L)													
Surficial aquifer (*Q*)																
2029-3-SE-0004	10.9	70	330	115	95	46	<1	66	9	<2	78	70	<1	12	<0.1	-
Surficial aquifer (*Cza*)																
2129-2-NE-0019	6.5	14	90	-	-	2	3	10	1	12	30	<5	<1	-	-	<0.1
Tertiary sediments (*Tpw*)																
2229-3-SW-0008	6.2	3 120	21 000	4 600	10	560	780	5 000	46	10	11 000	850	-	8.7	0.2	-
2229-3-NE-0017	6.5	574	3 060	650	22	58	120	900	10	22	1 600	240	-	10.8	<0.2	-
2228-2-NW-0001	5.3	34	250	23	8	1	5	43	4	8	90	10	-	10	<0.2	-
2229-1-NE-0011	7	370	2 400	-	-	34	120	590	4.1	25	1 200	120	<1	ND		<0.05
2129-4-SE-0007	7.6	170	850	257	42	24	48	224	2	51	476	39	<1	11	0.1	-
Warnbro Group (*Kw*)																
2029-3-NE-0008	6	59.1	320	46	15	2	10	89	9	18	157	18	<1	26	0.1	9
Yarragadee aquifer (*Jky*)																
2029-3-SE-0003	6.3	34.8	190	32	29	3	6	53	3	35	88	7	<1	14	<0.1	4.2
Fractured-rock aquifer (*Aq*)																
2129-3-SE-0001	7.8	77.7	460	223	156	35	33	69	23	190	132	42	<1	33	0.4	-
Weathered-rock aquifer (*Ag* and *An*)																
2129-2-SW-0007	6	59	370	-	-	3	11	90	4	28	150	15	<1	-	-	0.6
2128-1-NW-0026	5.9	71	440	-	-	4	15	100	3	36	170	14	<1	-	-	3.2
2229-1-SE-0019	7.6	1 500	9 300	-	-	97	350	2 200	15	110	4 300	360	2	-	-	<0.05
2029-1-SW-0014	5.8	64	400	-	-	5	12	90	3	28	150	16	<1	-	-	<0.1
2029-1-NE-0002	4.9	25	160	-	-	1	4	40	1	22	70	5	1	-	-	2.4

EC = Electrical conductivity (mS/m @ 25°C); TDS = Total dissolved solids; - = Not detected

5 Rising watertable and land salinisation

On Pemberton–Irwin Inlet, land has been cleared for settlement and agricultural purposes. Logging of old growth forest continued until 2002. These land use changes have contributed to the increase in vertical recharge to aquifers and to the development of shallow groundwater levels in the cleared parts of Pemberton–Irwin Inlet. However, the risk of land salinisation due to shallow water levels varies significantly from no risk to high risk, depending mainly on factors such as:

- salt leaching (rainfall distribution, salt store);
- clay content and thickness of weathered profile (geology, soils);
- slope and relief of landscape (topography); and
- groundwater salinity and water level.

5.1 Salinisation processes

The clearing of native vegetation carried out during the last 50 to 100 years for the establishment of agricultural crops and pastures has been the major cause of increasing land and water salinisation in the southwest of Western Australia, including the Tone and Frankland catchments of Pemberton–Irwin Inlet. Removal of deep-rooted vegetation altered the water balance of catchments by reducing the evapotranspiration and interception components and led to increased groundwater recharge and to rising water levels. Rising groundwater increases its salinity by dissolving salt within the unsaturated zone. Once the water is less than 2 m below the ground surface, it can be drawn up by capillary action and evaporated. The resulting increased soil salinity reduces agricultural production and, in severe cases, causes salt scalding at the ground surface, especially in combination with waterlogging. Pasture and vegetation can be destroyed and the land rendered useless. Salt accumulated on the surface and within the shallow layers of the soil profile is mobilised by surface runoff, thus contributing to increased stream salinity levels.

Land and stream salinisation processes that operate in various landscape positions within Pemberton–Irwin Inlet are listed in Table 3. Salinisation processes on hill slopes are controlled by local flow systems, whereas processes that are associated with lakes and valley flats are governed by intermediate flow systems.

Table 3. Salinisation processes

Topographical position	*Salinisation process*	*Hydrogeological characteristics*
Drainage lines	Baseflow, convergence	Weathered bedrock aquifer, Water level (WL), above ground surface
	Evaporative discharge	Weathered bedrock aquifer WL < 2 m below ground level (bgl)
	Saline surface water runoff	
Hill Slopes	Break of slope	Weathered bedrock aquifer WL < 2 m bgl
	Dolerite dyke	Weathered bedrock aquifer WL < 2 m bgl
	Fractures and joints	Weathered bedrock aquifer WL above ground surface
	Contact zone	Weathered bedrock and surficial sediments aquifer WL < 2 m bgl
Lakes	Throughflow	Surficial sediments, Werillup Formation WL above ground surface
	Evaporative discharge	Surficial sediments, Werillup Formation WL < 2 m bgl
	Saline surface water inflow	
Flats	Evaporative discharge	Surficial sediments, Werillup Formation WL < 2 m bgl
	Bedrock highs	Surficial sediments aquifer WL < 2 m bgl

5.2 Salt storage and rainfall

Before clearing, the weathered profile is unsaturated; most infiltrating water is taken and transpired by deep-rooted vegetation leaving the salt to accumulate. However, in areas where annual rainfall exceeds 1200 mm, the weathered profile is saturated and groundwater discharges into the stream system, thus inhibiting large accumulations of salt.

Clayey weathered bedrock profiles with lateritic subsoils have accumulated high salt stores over thousands of years. Soil solute concentrations invariably exceed 2000 mg/L total soluble salts (TSS) and surpass 20 000 mg/L TSS in areas where the average annual rainfall is less than 900 mm (Steering Committee for Research on the Woodchip Industry, 1980). These high salt stores indicate inadequate flushing of the prior to clearing.

5.3 Salinisation risk

The Perth Basin has little risk of land salinisation because of the low salt storage, high rainfall and the relatively high hydraulic conductivity of the sedimentary rocks. By contrast, the hard-rock provinces have a low to high risk of land salinisation.

In the hard-rock provinces, rainfall decreases from 1400 mm/year near the coast to 600 mm/year northeast of Tonebridge. The salt storage in the weathered profile of hard-rock provinces increases from high-rainfall areas in the southwest to low-rainfall areas in the northeast. Thus, the upper Warren River catchment in the low-rainfall zone has a higher risk of land salinisation than the lower and middle Warren River catchment, where rainfall is 900–1400 mm/year. In fact, cleared low-rainfall areas contribute some 80% of the current Warren River salt load.

The broad flats that contain wetlands such as Lake Muir and Unicup Lake have the highest risk of land salinisation due to poor drainage, groundwater aquifers with low hydraulic gradients, shallow water levels and high salinity. Both surface water inflow and groundwater discharge through lake beds provide significant amounts of salt into the lakes. So, rising water levels and groundwater discharge turn intermittent swamps or wetlands into more saline and permanent waterbodies.

5.4 Research on salinisation

Extensive research was conducted from 1975 to 1998 into the hydrological effects of logging in the Manjimup Woodchip Project Licence Area (Martin, 1987; Bari and Boyd, 1993). In addition to streamflow, groundwater levels and salinity were monitored during this period using bores located in Lewin North, Lewin South, March Road East, April Road North, April Road South, Yerraminnup North and Yerraminnup South paired catchments (Fig. 5). Groundwater was also monitored in the bores located in Poole, Crowea, Mooralup and Iffley operational coupes (Project 4) (Steering Committee for Research on the Woodchip Industry, 1980). These paired catchments and operational coupes are within the Warren River and Donnelly River catchments.

The mean groundwater levels increased in all four coupes following clearing, whereas mean levels in the control catchment bores remained relatively static over the same period (Steering Committee for Research on the Woodchip Industry, 1980). As a broad generalisation, in bores located in the 900 to 1400 mm high-rainfall zone (Crowea, Poole, Iffley coupes) groundwater levels rose within a few months of logging. By contrast, in Mooralup coupe, where rainfall is less than 900 mm (intermediate and low rainfall zones), groundwater levels responded to clearing a year after logging. The water level rises were between a few centimetres in low-rainfall areas and 2 m in the high-rainfall areas.

As part of the Salinity Action Plan the Warren River catchment was identified in 1996 as a one of five Water Resource Recovery Catchments in Western Australia (State Salinity Council, 1998). An objective of the Salinity Action Plan is to prepare integrated catchment plans in partnership with catchment groups, with the target of achieving potable water supply levels by 2030.

The hydrological modelling of the Tone and Perup subcatchments, covering a total area of 2318 km^2, identified saline seepage due to low water use by existing pasture in 1996 (Rogers *et al.*, 1999). Modelling suggested that saline seepage needs to be reduced by 45% to meet the salinity target of 500 mg/L at the Barker Road gauging station.

Chakravartula and Street (2000) examined salinisation processes in Lake Muir–Unicup subcatchments using

Figure 5. Paired catchments, operational coupes and recovery catchments

airborne geophysical data and field investigations and concluded that saline seeps and salt scalds were structurally controlled. They observed salinity occurrences in valleys above 220 m AHD and inferred that, if these salt scalds were due to a regional watertable rise, they should be more widespread in the flats and valleys landscapes. Consequently, they attributed the control of salt scalds at higher elevations to other factors such as the intersection of faults and fractures facilitating the movement of saline groundwater to the surface.

Hundi *et al.* (2001) assessed the salinity risk of the Mobrup subcatchment of the Warren River catchment. This study identified the weathered bedrock aquifer as the major source of salt for the subcatchment. Nearly 30% of the subcatchment has water levels less than 2 m below the ground surface. These shallow water level areas can be considered as the areas at risk of salinisation from evaporative concentration of salts in groundwater and soils. Structures in bedrock areas influence, but are not the major control on groundwater movement and discharge. Convergence of groundwater movement at subcatchment scale can lead to saline seepage. Hydrological modelling identified saline seepage areas for the catchment.

5.5 Salinity management

Rising groundwater levels can be controlled by measures that include revegetation, agro-forestry, high-water-use crops and pastures, shallow and deep drains, and groundwater pumping. Biological options such as revegetation can be considered as a long-term strategy for controlling groundwater recharge. Engineering options are useful in managing groundwater discharge in the short to medium term.

6 Groundwater development

6.1 Existing water supply

Surface water supply dams and headworks supply the major towns of Manjimup, Pemberton, Northcliffe and Walpole. The Windy Harbour scheme is supplied from two groundwater bores drilled in 1978. Apart from the town water supply schemes, excavated dams provide water supply for farms and stock. Some of the farm dams may receive groundwater discharge.

Manjimup is supplied from two dams, Manjimup Dam and Phillips Creek Dam, on tributaries of Lefroy Brook. Manjimup Dam, also known as Scabby Gully Dam, is located about 10 km southwest of Manjimup. The dam, originally built in 1967 and raised in 1995 has a zoned earthfill embankment and storage capacity of 1.6 GL. Phillips Creek Dam on Jarnadup Brook was built in 1936; since the dam wall was raised in 1956 (Water Corporation, 2002), the storage capacity is 0.27 GL.

The major sources for the water supply of Pemberton, Big Brook Dam and Lefroy Brook Pipehead Dam are also on tributaries of Lefroy Brook. Big Brook Dam, built in 1986 to augment the Lefroy Brook Pipehead Dam, is a concrete and earthfill zoned embankment with a storage capacity of 0.63 GL. It is located some 3 km north of Pemberton (Water Corporation, 2002).

The Northcliffe Water Scheme comprises two headwork sources, the Armstrong Spring and the supplementary Armstrong Weir. The Armstrong Spring, located 2 km east of the town, is the main supply source for the two gravity-fed concrete tanks of 54 KL and 16 KL capacity. The weir, used as a supplementary source when the spring is unable to satisfy demand, has negligible storage and relies on run-of-the-river (Water Corporation, 2002).

The Walpole water supply is sourced from a reinforced concrete weir on the Walpole River 2 km west of Walpole. The weir, built in 1985, has negligible storage and is being operated as a run-of-the-river scheme.

6.2 Potential groundwater supply

Significant potential for groundwater development exists on Pemberton–Irwin Inlet. Table 4 summarises the potential for groundwater development from different aquifers for a variety of uses.

Table 4. Groundwater development potential of aquifers

Aquifer	*Maximum recorded yield (m^3/day)*	*Water salinity mg/L (TDS)*	*Comments*
Perth Basin			
Surficial		100–500	Suitable for stock and domestic use High risk of contamination
Warnbro Group		100–500	Irrigation, water supply
Yarragadee		100–500	Irrigation, water supply
Cockleshell Gully		1000–3000	Water supply
Hard-rock provinces			
Surficial (*Qpl* and *Qpd*)	300	100–500	Stock and domestic purposes High risk of contamination
Surficial (*Cza* and *Qa*)	100	500–1000 (medium rainfall) > 3000 (low rainfall)	Stock and domestic purposes Limited usage
Werillup Formation	1400	1000–5000 (Wilgarup)	Stock, minor irrigation where fresh
Weathered-rock aquifer (granitic and gneissic rocks)	100	100–1000 (high rainfall) > 14 000 (low rainfall)	Stock purposes
Fractured-rock aquifer (quartzite)	500	100–500	Stock and domestic purposes

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Appendix 1

Digital data documentation

Design file	Levels	Description
Pembore.*dgn*	6	Bore: yield<50 m³/day
	11	Bore: yield>50 m³/day
	3	Monitoring bore
	1	Bore abandoned
	2	Bore dry
	8	Well
	5	Well abandoned
	4	Excavated soak and seepage areas
	9	Cluster of monitoring bores
	7	Mineral exploration drill hole
	10	Spring
Pembgeo.*dgn*	1	Geological boundaries
	2*	Outcrop boundaries
	3*	Ql boundaries and coastline
	4*	Hidden polygon boundaries
	5	Faults concealed, faults inferred, Darling Fault
	16	Dolerite dykes interpreted from WRC airborne magnetics
	17	Dolerite dykes
	18	Quartz veins
	19	Fractures interpreted
	40	Geological labels
	41	X-section lines and labels
	45	AMG grid
	60	Ticks, text for latitude and longitude grid
	62	Map border
	63*	Level structure

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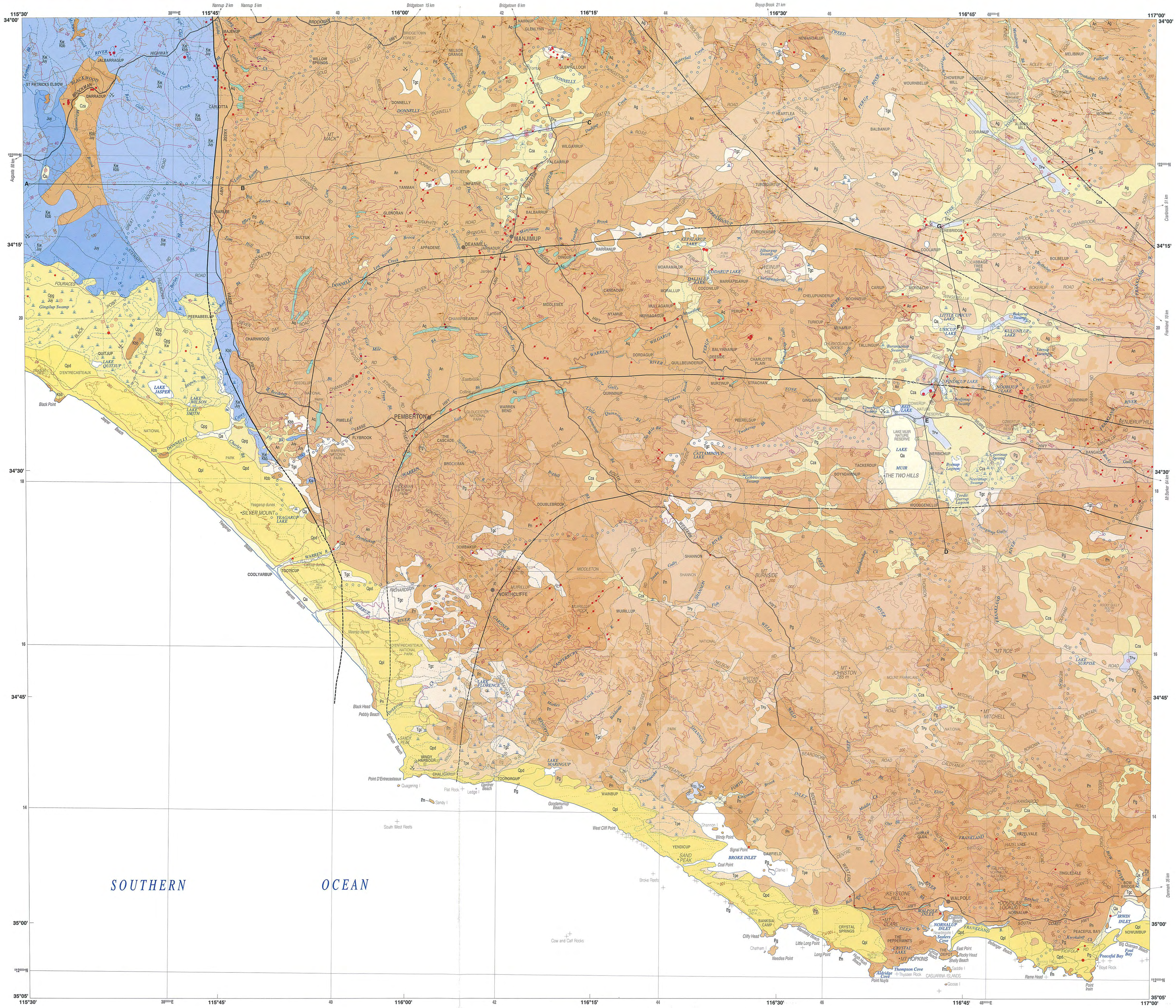
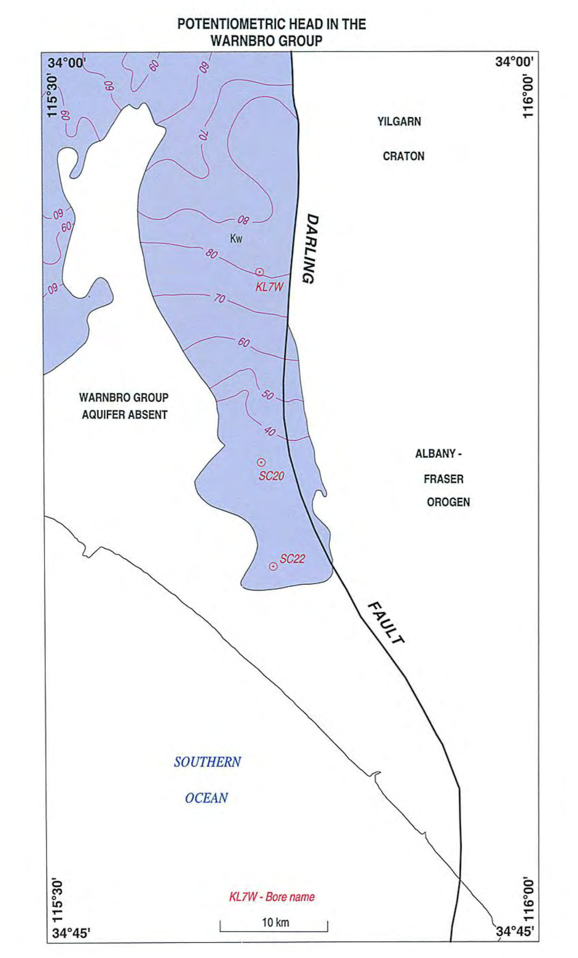
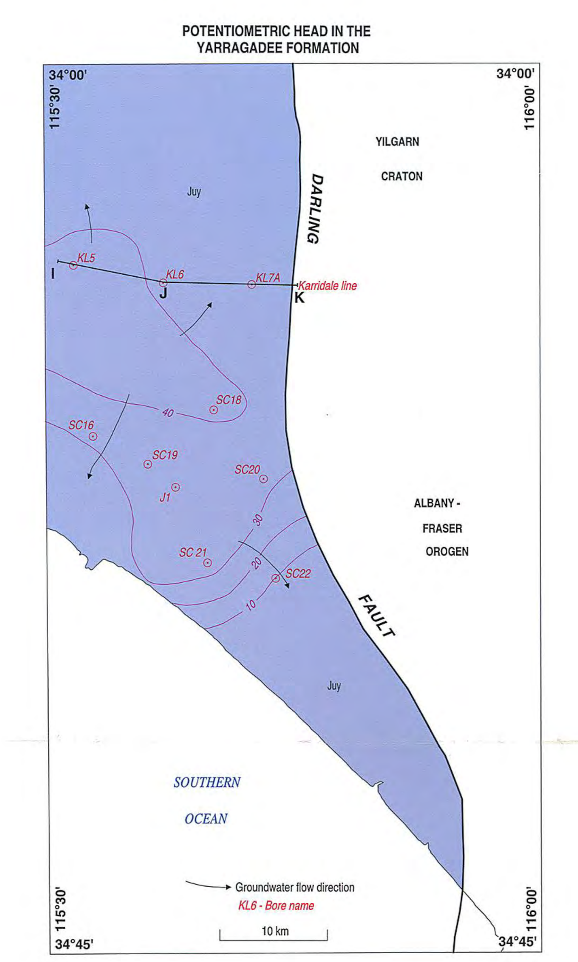
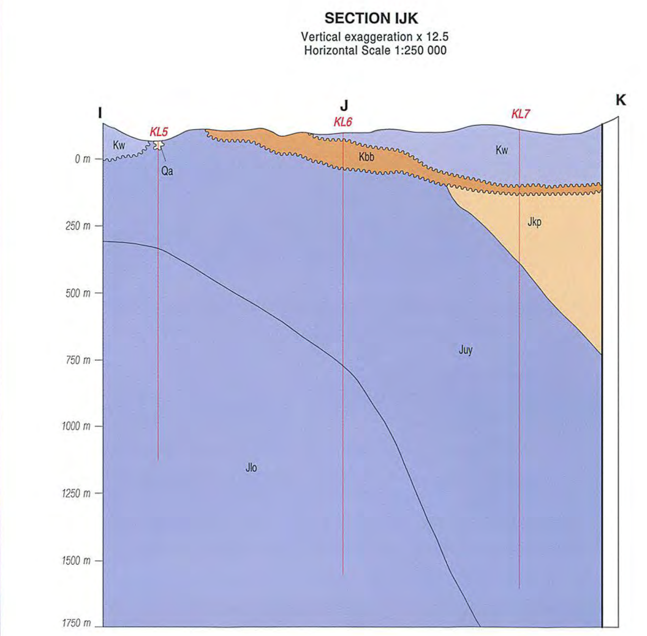
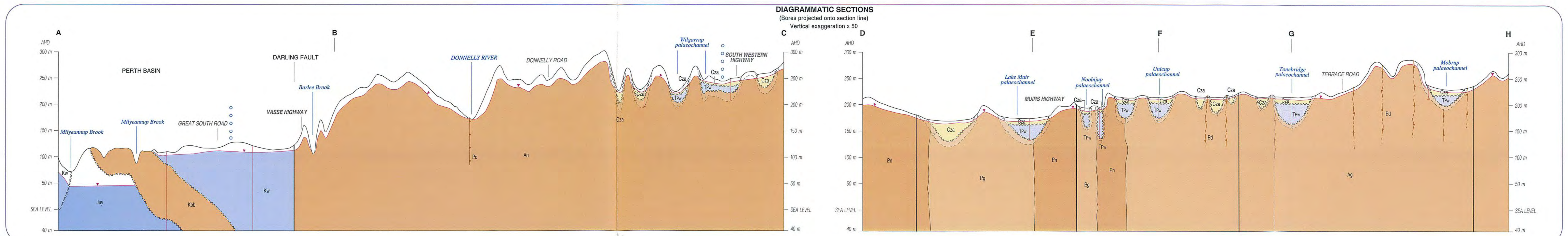
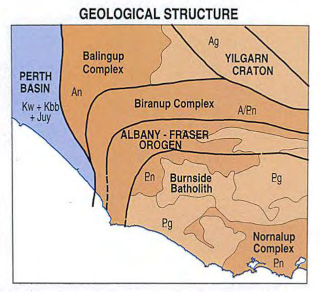


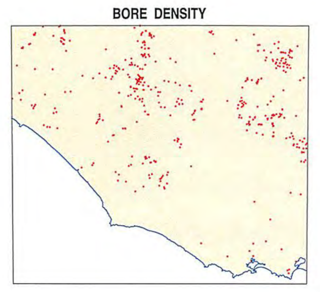


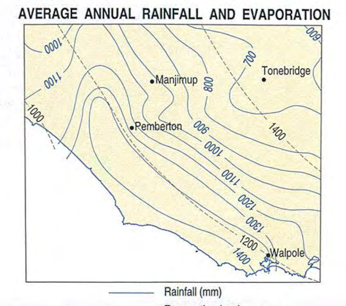


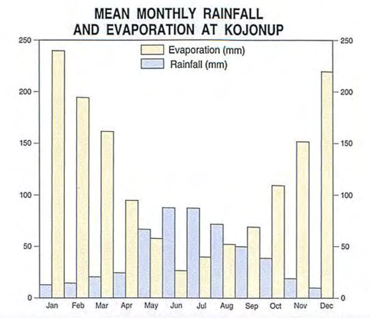


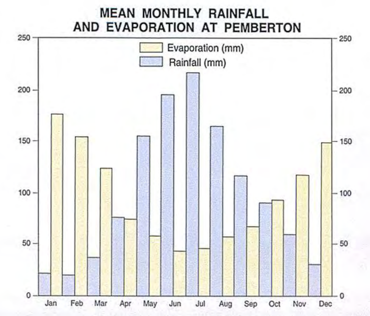


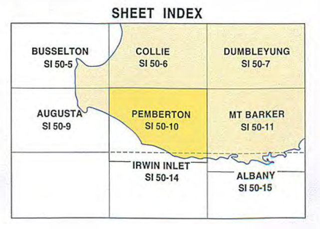












REFERENCE

AQUIFER CHARACTERISTICS

- Surficial aquifer – local aquifer, minor groundwater resources
- Sedimentary aquifer – intermediate to regional aquifer with intergranular porosity, major groundwater resources
- Sedimentary aquitards and local aquifer – minor or no groundwater resources
- Aquiclude– no groundwater resource
- Fissured aquifer, locally fractured and jointed – minor groundwater resources
- Fractured and weathered rocks – local aquifer, minor groundwater resources
- Fractured and weathered rocks – local aquifer, very minor or no groundwater resources

HYDROGEOLOGY

PHANEROZOIC – CAINOZOIC – QUATERNARY	Qa	Alluvial and lacustrine sediments	Minor local aquifer; fresh to saline		
	Qpl	Dune limestone – eolian calcarenite	Minor to major aquifer; fresh		
	Qpd	Quartz sand in fixed dunes; overlies weathered basement or Mesozoic sediments	Minor to major aquifer; fresh		
	Qpg	GUILDFORD FORMATION – alluvial sand and clay with minor estuarine deposits	Minor local aquifer; fresh		
	Cza	Alluvial and colluvial deposits; overlies weathered basement or older sedimentary rocks	Minor local aquifer; fresh to saline		
PHANEROZOIC – CAINOZOIC – TERTIARY	Tpe	Estuarine, lagoonal and lacustrine deposits	Aquitard to minor local aquifer; fresh to brackish		
	Tgc	Alluvial, lacustrine and shallow marine deposits – clay and sand	Aquitard to minor local aquifer; fresh to brackish		
	TPp	PALLINUP SILTSTONE – grey, brown siltstone, overlies WERRILUP FORMATION or weathered basement	Minor local aquifer; fresh to brackish		
	TPw	WERRILUP FORMATION or palaeochannel deposits – sand, clay and carbonaceous sediments	Major local aquifer; fresh to hypersaline		
PHANEROZOIC – MESOZOIC – CRETACEOUS	Kw	WARNBRO GROUP – sandstone, siltstone and shale	Major regional aquifer; fresh	PERTH BASIN	
	Kbb	BUNBURY BASALT – porphyritic and vesicular basalt: outcrop (indicated by darker colour)	Aquiclude		
PHANEROZOIC – MESOZOIC – JURASSIC	Jkp	PARMELIA FORMATION – sandstone, siltstone and shale (section only)	Aquitard		
	Juy	YARRAGADEE FORMATION – sandstone, siltstone and shale	Major regional aquifer; fresh		
	Jlo	COCKLESHELL GULLY FORMATION – sandstone with interbedded shale and siltstone (section only)	Major regional aquifer; fresh		
PROTEROZOIC	Pd	Mafic dyke and sill – fine to coarse-grained, doleritic and gabbroic dykes, interpreted where dashed	Very minor local aquifer; fresh to saline	ALBANY - FRASER OROGEN	
	q	Quartz dyke	Minor local aquifer; fresh to saline		
	Pg	Granitoid rock; porphyritic and even-grained: outcrop (indicated by darker colour); subsurface generally weathered to clayey sand	Minor local aquifer; fresh to saline		
	Pn	Granitoid gneiss, migmatite, quartzo-feldspathic gneisses: outcrop (indicated by darker colour); subsurface generally weathered to clay	Very minor local aquifer; fresh to saline		
ARCHAEAN	Ag	Granitoid rocks and adamellite: even-grained; outcrop (indicated by darker colour); subsurface generally weathered to clayey sand	Minor local aquifer; fresh to saline	YILGARN CRATON	
	An	Granitic gneiss, minor schists and minor quartz-feldspar gneisses: outcrop (indicated by darker colour); subsurface generally weathered to clay	Very minor local aquifer; fresh to saline		
	Aq	Quartzite	Minor local aquifer; fresh to saline		

SYMBOLS

GEOLOGY

- hydrogeological boundary; concealed
- unconformity (section only)
- fault; inferred
- fracture zones
- extent of weathering (section only)

SURFACE WATER FEATURES

- drainage; permanent, intermittent
- lake; permanent, intermittent; swamp
- surface water divide

GROUNDWATER FEATURES

- spring
- watertable contour (m AHD)
- watertable; position uncertain (section only)

MINING FEATURES

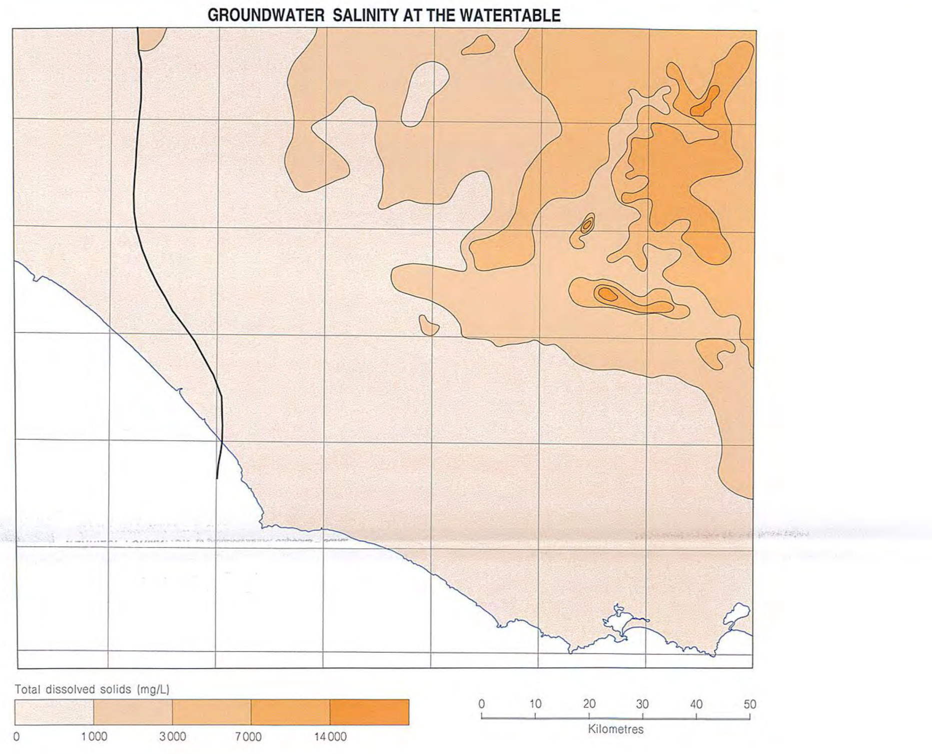
- open cut mine

ARTIFICIAL FEATURES

- water bore: yield < 50m³/day; > 50m³/day; monitoring
- water bore abandoned: yield > 50m³/day; dry
- well; abandoned
- excavated soak and seepage areas
- cluster of monitoring bores
- mineral exploration drillhole

TOPOCADASTRAL INFORMATION

- major road with national route marker
- minor road
- track
- Jardee — railway with siding
- landing ground
- WALPOLE — townsite, population < 1000
- PEMBERTON — townsite, population > 1000
- TONEBRIDGE — locality
- submerged rock
- topographic contour, 50 metre interval (AHD)
- sand dune
- PEM 2 — horizontal control; major, minor (AHD)
- national park boundary



Hydrogeology by J. De Silva, 2000
Geology by S.A. Wilde and I.W. Walker, 1984
J.S. Myers, 1989.
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SCALE 1: 250 000

TRANSVERSE MERCATOR PROJECTION
Grid lines indicate 20 000 metre interval of the Australian Map Grid Zone 50

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