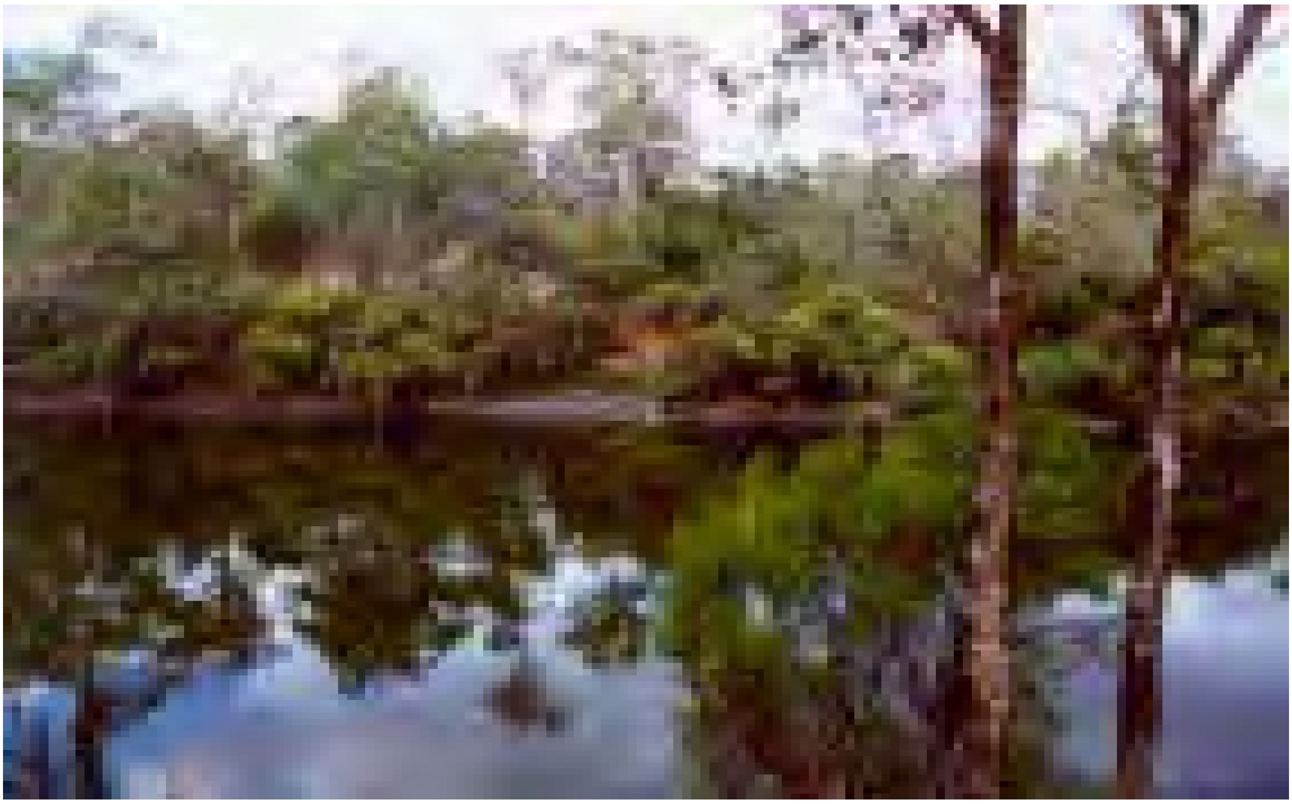
Hydrogeology of the Blackwood River Catchment, Western Australia



Hydrogeological Record Series

Water and Rivers Commission Report HG 6

2000

Water and Rivers Commission

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Cover Photograph: The middle Blackwood River near Asplin Siding just upstream of Boyup Brook.

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Water and Rivers Commission
Science and Evaluation Division

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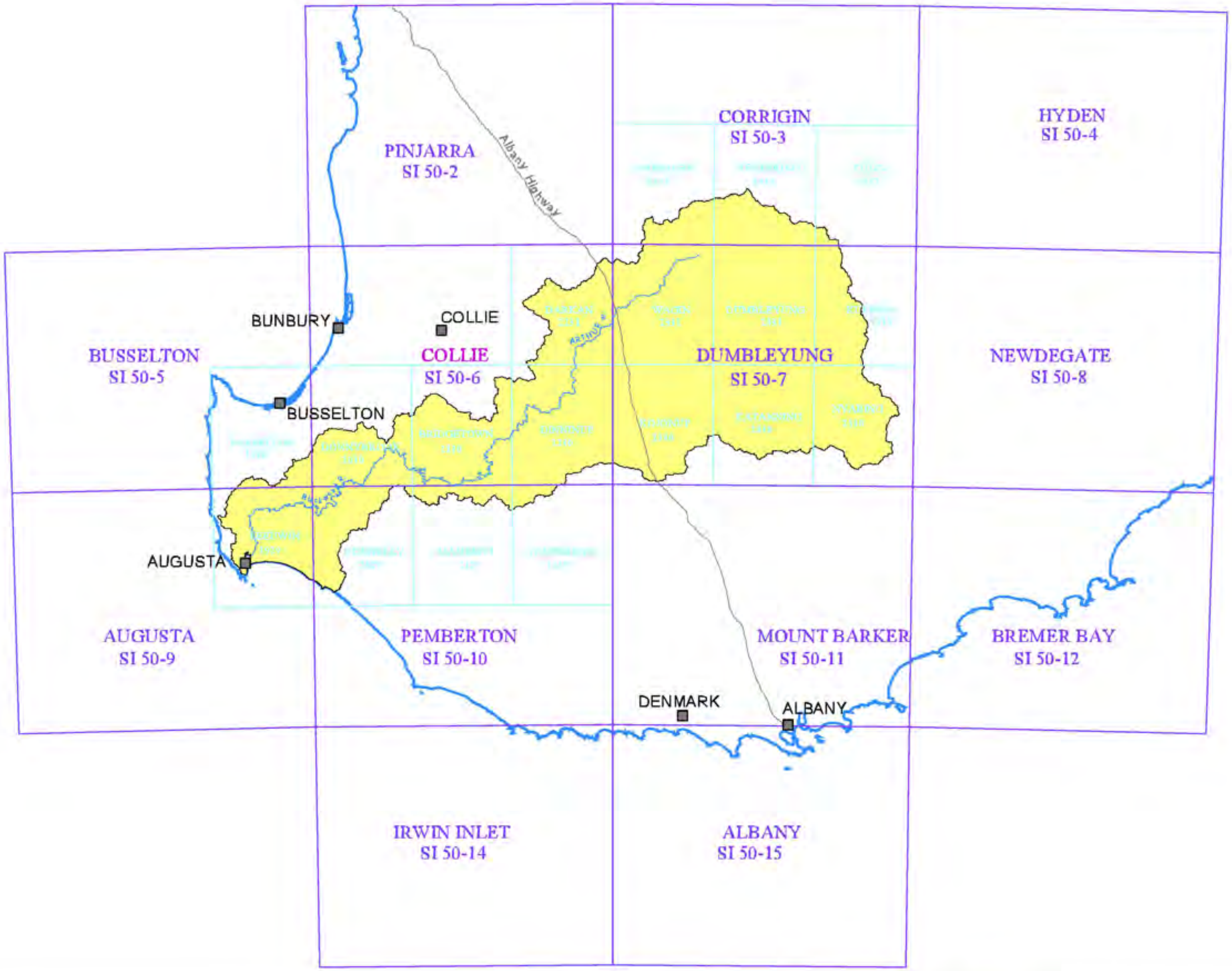

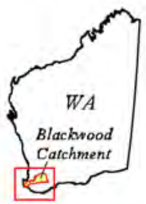

River
Blackwood Catchment
Coast line
Albany Highway

1:250 000 map sheet
1:100 000 map sheet
Town

N

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WATER AND RIVERS COMMISSION

SCIENCE AND EVALUATION DIVISION

Blackwood Hydrogeological Resource Base

The Blackwood Catchment

FIGURE 1

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Hydrogeology of the Blackwood River Catchment, Western Australia

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Summary

Land salinisation is a serious environmental and ecological problem facing the Blackwood Catchment, resulting in the loss of large areas of productive land and the degradation of water and ecological resources. In 1994, with support from Agriculture Western Australia, the Blackwood Basin Group approached the Geological Survey of Western Australia to undertake a groundwater study within the Blackwood Catchment. The aim of the study was to assemble the existing groundwater and salinity data, analyse for trends across the catchment, and package for use by land managers in the management zones determined by the Blackwood Basin Group (Figure 2).

This Report concludes the project and consists of six sections. Sections 1 and 2 provide an overview of the geological setting of the Blackwood Catchment and discuss the development of the database. This includes the acquisition of primary data layers and their subsequent integration to model groundwater levels, groundwater salinity and the distribution of salinity at the watertable. Section 3 provides a comprehensive description of the hydrogeology of the catchment and explains the variation in bore yields and groundwater quality of the different aquifer systems. Section 4 details how increases in recharge to these aquifers impact on watertable rises and land salinisation. The distribution of salinity at the watertable for the catchment area east of the Darling Scarp (Management Zones 3 through to 9) is then discussed in Section 5, and Section 6 reports on the findings.

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The study was successful in identifying and quantifying the major patterns in the development of salinisation and rises in watertables across the Blackwood Catchment. As expected, the most severe land salinisation is in the Upper Catchment, with a declining trend towards the coast. Within all of the management zones, groundwater level and salinity data in both lower and upper landscape positions show wide variation. Before planning investigations to identify local controls on groundwater movement and salinisation, the relationship between salinity and water level with respect to landscape position, aquifer type, landuse and vegetation should be further examined.

Usable water availability is a major issue for land managers in the Blackwood Catchment. The study concluded that fresh groundwater may be at risk in sections of the Beaufort, Qualeup, Toolibin, Darkan and other as yet unidentified palaeochannel aquifers. Continued monitoring of boreholes is recommended, together with the establishment of additional monitoring boreholes.

The acquisition and interpretation of geophysical data may be useful to build a more comprehensive 'picture' of the regional and local controls on salt distribution and groundwater movement. Geophysical methods should target specific issues in each management zone and aim to build on the existing sets of data.

The major visible outputs of the project are this report, three posters and a CD-ROM. This report includes a detailed hydrogeological map of the Blackwood Catchment showing the distribution of aquifers, water point data, groundwater levels and groundwater salinity; a regional model of salinity at the watertable, and a series of case studies on local aquifer behaviour and influence on salinity. These case studies can be extrapolated to similar areas within the management zones. The three posters show the key data layers and potential groundwater resources. The CD-ROM contains the groundwater data in ArcView format. The data was extracted from the GIS database in which it was assembled and analysed.

The outputs of the project will be valuable for landuse planning to address salinity and will complement datasets from other sources such as Land Monitor, SS2020 and geophysical surveys.

Keywords: hydrogeology, catchment, salinity, aquifers, groundwater resources, Blackwood River

1 Introduction

1.1 Purpose and scope

The main aim of this project is to define the relationship between groundwater and the extent and severity of land and water degradation in the Blackwood River Catchment where, without regional planning and implementation of works to counter salinisation, as much as 30% of the landscape could become affected (State Salinity Council, 2000a,b,c). To achieve this, a hydrogeological resource base consisting of maps and digital and graphical databases has been developed. This resource base can provide essential baseline data to assist in the formulation of groundwater and land-management strategies to address dryland salinity within both the catchment and subsidiary catchments.

This Report describes the hydrogeology of the Blackwood Catchment and provides a series of interpreted maps including the watertable contours, depth to watertable, groundwater salinity contours, geology and hydrogeology. These data, together with a model of the distribution of salinity at the watertable, form the basis of the principal maps required for follow-up 'paddock-scale' investigations. The information has been prepared for the Blackwood Basin Group and its management zone committees and can also be used by researchers and other government agencies.

1.2 Location and landuse

The Blackwood Catchment, the largest river catchment in the southwest of Western Australia, covers an area of approximately 2.253 x 10^4 km^2. The catchment is elongated, and trends southwesterly and commences 300 km inland of the Blackwood River mouth, at the town of Augusta (Fig. 1). The catchment is bounded by latitudes 32° 35' and 34° 25' S and longitudes 115° and 118° 25' E, and encompasses several 1:250 000 Series Maps including DUMBLEYUNG[1] and sections of the COLLIE, PEMBERTON-IRWIN INLET AND BUSSELTON-AUGUSTA sheets.

Landuse in the area is predominantly agricultural. Broadacre cereal cropping and sheep grazing methods of the 'wheatbelt' predominate in the east, whereas in the western areas agriculture is more intensive, including horticultural cropping, viticulture, dairy and beef farming. In the large areas of forest in the Southern Forest Region, between Boyup Brook and Augusta, there is both milling for timber and preservation for tourism and ecological purposes.

Major towns within the Blackwood River Catchment include Narrogin, Wagin, Katanning and Dumbleyung in the northeast; Kojonup and Boyup Brook in the central region; and Bridgetown, Nannup and Augusta in the southwest (Fig. 2). Bitumen roads link these towns, and an extensive network of predominantly gravel roads provides access to most of the catchment. In the eastern area of the catchment, part of a once more-extensive rail system freights grain to the ports of Fremantle and Albany.

1.3 Physiography

The greater part of the Blackwood Catchment lies to the east of the Darling Scarp on the Darling Plateau. The remainder of the catchment, located west of the scarp, drains the Blackwood Plateau, Scott Coastal Plain and the Leeuwin-Naturaliste Ridge (Fig. 3). Within the Darling Plateau the catchment is divided into three main zones according to the landforms and soil types (Tille and Percy, 1995). These are the Zone of Ancient Drainage (Upper Catchment), the Zone of Rejuvenated Drainage (Upper-middle Catchment) and the Darling Range (Lower-middle Catchment). A fourth zone termed the Donnybrook Sunklands (Lower Catchment) is located west of the Darling Scarp (Grein, 1995).

The Darling Plateau is underlain by Archaean basement, which has been deeply weathered and lateritized during the Late Cretaceous and Tertiary. The contemporary land surface is undulating and shows variation in relief both within and between the zones of the Blackwood Catchment (Fig. 3). Elevations, expressed in metres above Australian Height Datum (m AHD), range from 150 m AHD in the Lower-middle Catchment, where the topography is dissected, to 360 m AHD, near the Upper Catchment boundary, where the relief becomes subdued (Fig. 3).

[1] *Capitalised names refer to the standard map sheets*

The Upper Catchment, Zone of Ancient Drainage, is located east of the 'Meckering Line' and is characterised by low topographic and hydraulic gradients (Fig. 3) (Mulcahy, 1967). Landforms consist of broad flat-floored valleys containing thick sequences of valley-fill, often inclusive of Tertiary palaeochannel sediments and salt lake systems (Thorpe and Baddock, 1994; van de Graaff *et al*., 1977; Waterhouse *et al*., 1995). As a consequence, surface waters tend to drain internally in this zone, and unless Lake Dumbleyung fills and overflows (not observed by local landholders since 1964) the Upper Catchment does not contribute to flow in the Blackwood River.

Topographic gradients are greater in the Middle Catchments, Zone of Rejuvenated Drainage and Darling Range, situated west of the Meckering Line. The depth of incision of the Blackwood River and its tributaries increases westwards from the Meckering Line through to the Darling Scarp. This trend also corresponds to a decrease in the thickness of valley-fill, the increased topographic gradients causing the more effective removal of weathered and transported material.

The Lower Catchment, the Donnybrook Sunklands, is the area of lower surface elevations located west of the Darling Scarp. The principal drainage channels, crossing the lateritized Mesozoic sedimentary rocks of the Blackwood Plateau and surficial sediments of the Scott Coastal Plain, are less incised. To the southwest, across the plains to the coast, elevations decrease to less than 50 m AHD (Fig. 3). On the plains Quaternary sediments, consisting of sands and clays and thicker sequences of coastal dunes and limestones, overlie eroded Mesozoic sedimentary rocks. On the coast, from Cape Naturaliste to Cape Leeuwin, the Leeuwin-Naturaliste Ridge forms the western margin of the Blackwood Catchment (Fig. 3). Here, high coastal dunes and limestone ridges, with elevations reaching 220 m AHD, overlie Proterozoic crystalline rocks of the Leeuwin Complex (Thorpe and Baddock, 1994).

1.4 Climate

The Blackwood Catchment has a climate characterised by cool, wet winters and warm to hot, dry summers. Average monthly minimum and maximum temperatures for the coastal town of Augusta range between 16.8° and 23.3°C in summer and 11.1° and 16.3°C in winter. The equivalent temperatures for the inland town of Katanning range between 13.7° and 30.3°C in summer and 5.5° and 14.5°C in winter (Fig. 4). Average annual rainfall decreases inland; average summer temperatures average and annual evaporation (class A) both increase (Fig. 4). Most of the rainfall is received in the winter months.

1.5 Vegetation

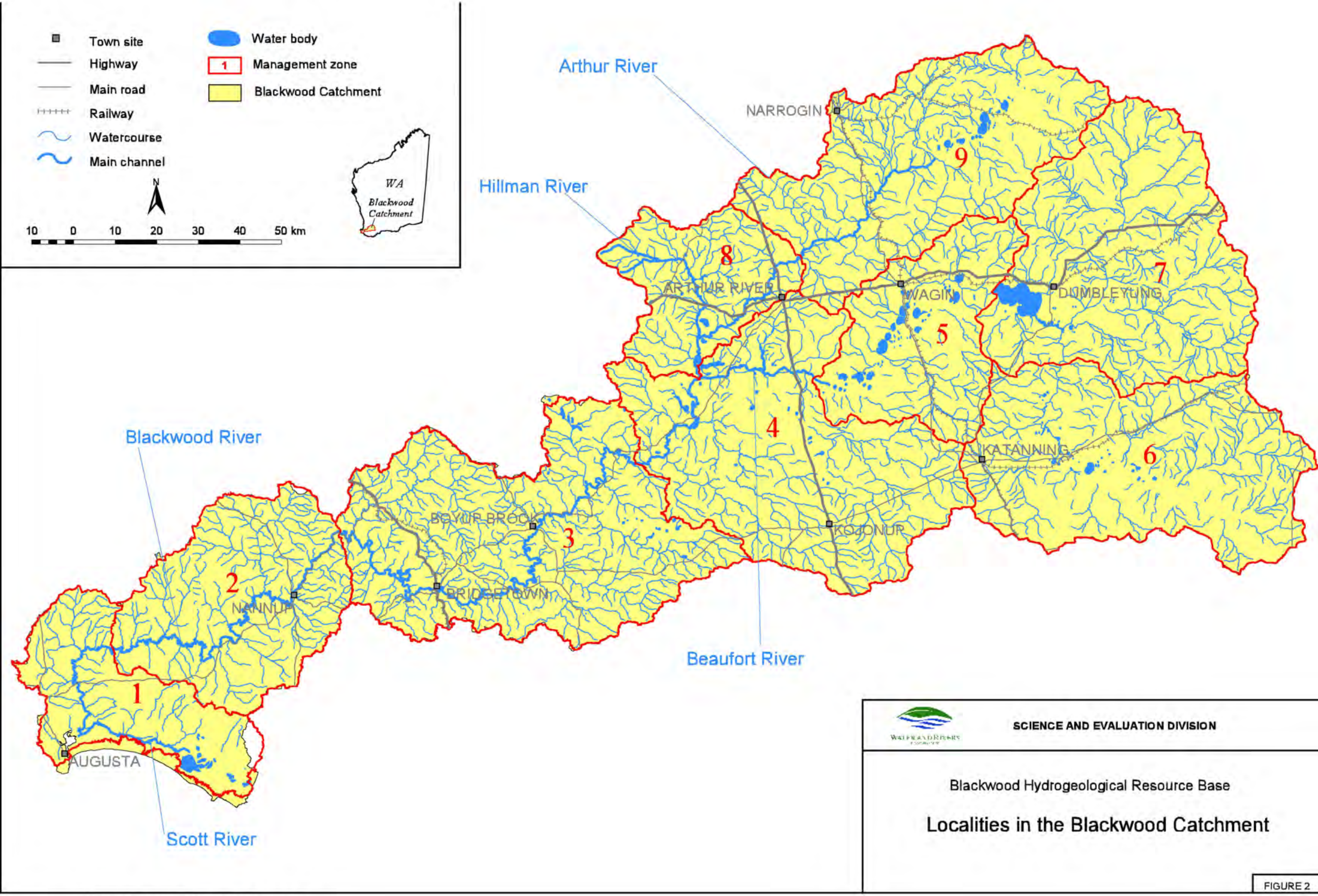
Variation in the native vegetation across the Blackwood River Catchment corresponds with changes in soils, climate and physiography. Vegetation ranges from the low scrub near the coast (Lower Catchment), through karri and jarrah forests (Lower-middle Catchment) to mallee and shrubs in areas to the east where rainfall is low (Upper Catchment). There are three botanical districts, two sub-districts and 16 vegetation systems defined by Grein, (1995) and discussed in detail in Beard (1976a,b, 1980, 1981) in the Blackwood Catchment (Fig. 5, Table 1).

Table 1. Botanical subdivisions of the Blackwood Catchment

Botanical district	*Botanical sub-district*	*Vegetation system*
Avon		Wagin Dumbleyung Broomehill Tambellup Narrogin Pingelly Corrigin
Darling	Menzies	Beaufort Williams Jingalup Bridgetown Boranup Scott River
	Warren	Nornalup
Roe		Hyden Ongerup

1.6 Geological setting

Geological Series Map coverage of the Blackwood Catchment at 1:250 000 scale comprises sections of the CORRIGIN (Chin, 1986), DUMBLEYUNG (Chin and Brakel, 1986), COLLIE (Wilde and Walker, 1982), PEMBERTON-IRWIN INLET (Wilde and Walker, 1984) and BUSSELTON-AUGUSTA (Lowry *et al*., 1964; Lowry, 1967) maps (Fig. 1). Over 85% of the Blackwood Catchment (Upper and Middle Catchments) drains the Archaean (and minor) Proterozoic basement rocks of the Yilgarn



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Blackwood Hydrogeological Resource Base

Localities in the Blackwood Catchment

FIGURE 2

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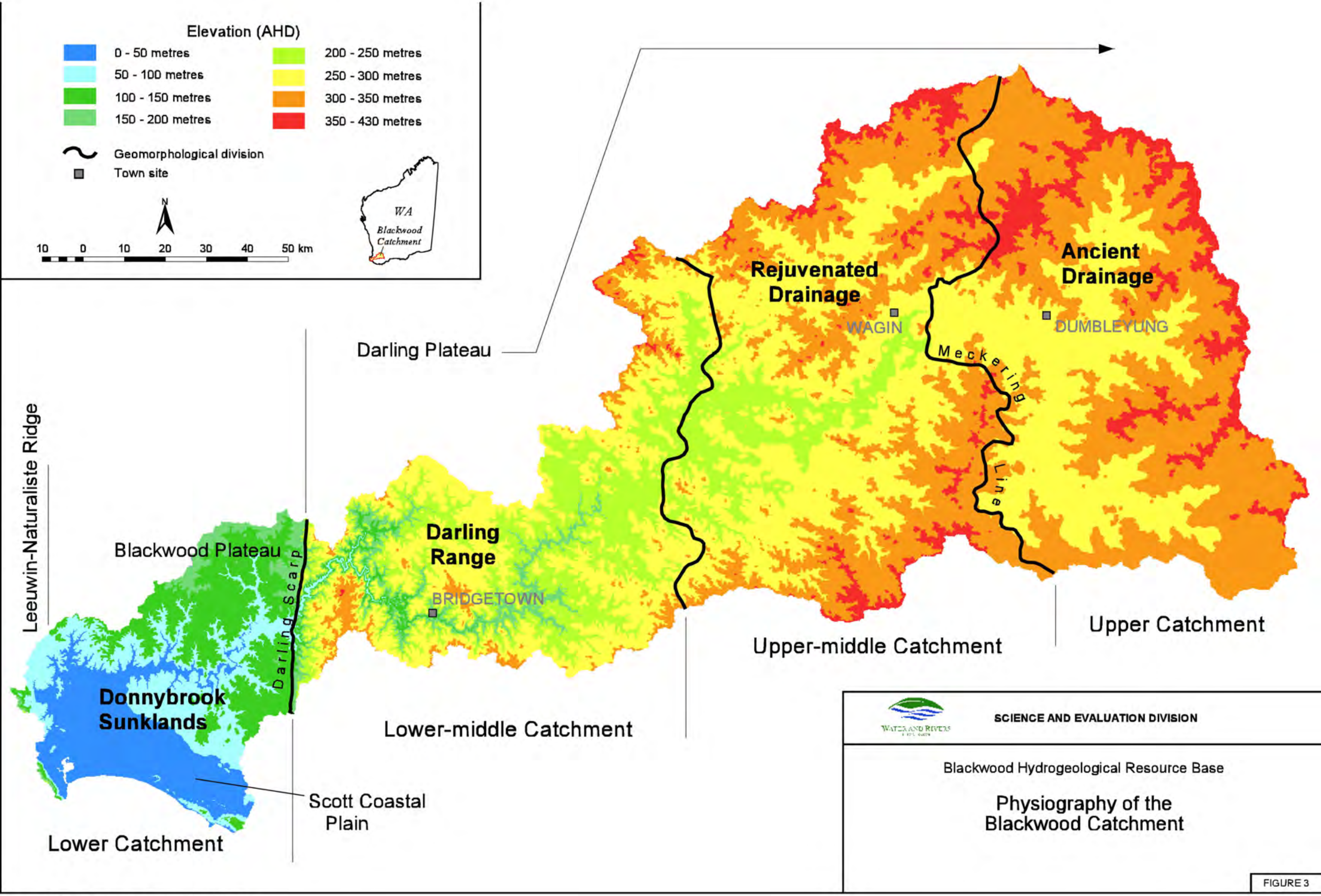

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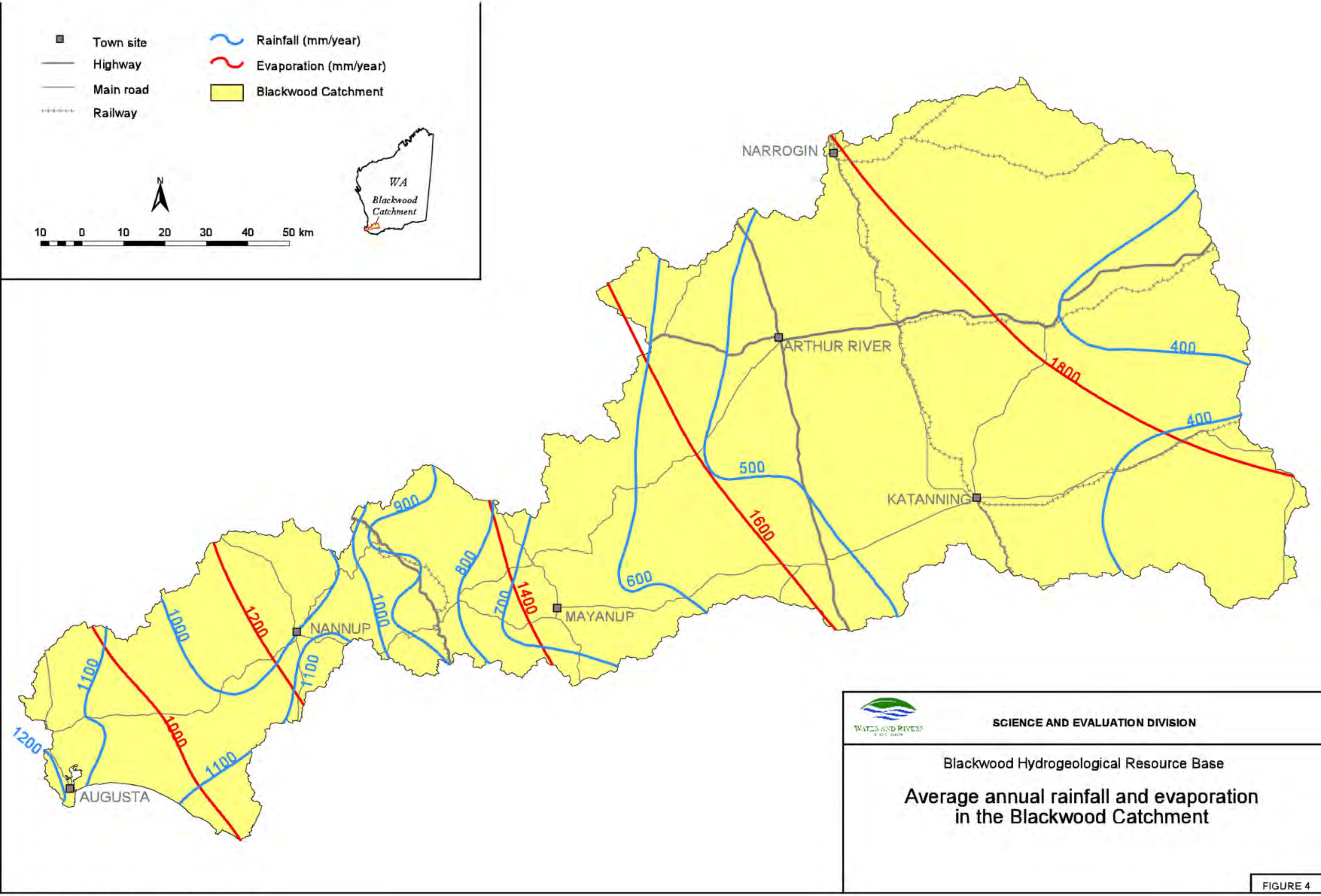

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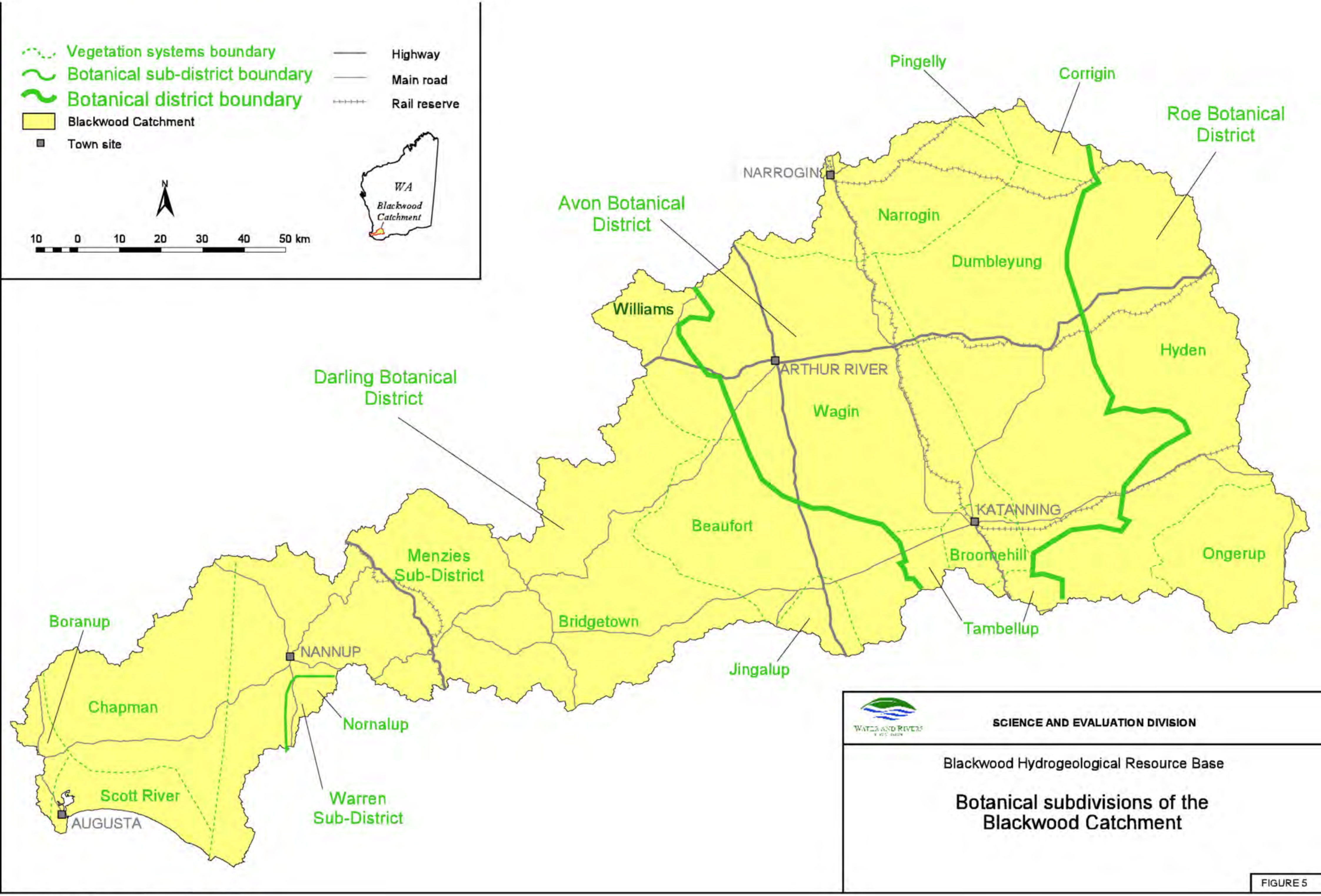

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Blackwood Hydrogeological Resource Base

Botanical subdivisions of the Blackwood Catchment

FIGURE 5

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Craton (Fig. 6). The remaining 15% of the catchment (Lower Catchment) drains the predominantly sedimentary Mesozoic rocks of the southern Perth Basin and the Proterozoic crystalline rocks of the Leeuwin Complex. Within the Yilgarn Craton, Permian sedimentary rocks are preserved in the Boyup Basin. Surficial sediments, primarily Tertiary-Quaternary in age, occur in all three geological provinces.

Basement rocks of the Yilgarn Craton comprise mainly heterogeneous Archaean gneiss complexes and younger, less intensely deformed Archaean granitoid rocks (Wilde and Walker, 1982, 1984; Chin, 1986; Chin and Brakel, 1986). Granitoids are dominant in the central and northern section of the catchment. A number of suites of Proterozoic dykes and veins of predominantly northwest orientation have intruded the basement rocks. Faults dissecting the craton display similar trends (Fig. 6; Myers and Hocking, 1998). Proterozoic metamorphosed plutonic igneous rocks of the Leeuwin Complex form the western margin of the catchment (Myers, 1990).

The southern Perth Basin, located west of the Darling Fault and east of the Leeuwin Complex, is divided into two major structural units, the Bunbury Trough and the Vasse Shelf. The Bunbury Trough, a deep graben bounded by the Darling and Busselton Faults, contains up to 8000 m of Palaeozoic sedimentary rocks which range in age from Permian to Early Cretaceous. The Vasse Shelf lies between the Bunbury Trough and the Leeuwin Complex and contains up to 3000 m of sediments. Jurassic and Cretaceous sedimentary rocks commonly subcrop on these structural units and are overlain by Early Tertiary (middle Eocene) and Quaternary age sediments (Table 2) (Playford *et al*., 1976; Commander, 1984; Hirschberg, 1989; Appleyard, 1991; Iasky, 1993; Baddock, 1994; Thorpe and Baddock, 1994).

1.7 Previous hydrogeological investigations

Hydrogeological Series Map coverage of the Blackwood Catchment at 1:250 000 scale comprises sections of the DUMBLEYUNG (McCombe and Ye, 1999; Leonhard, 2000), COLLIE (McCombe, 1999; Rutherford, 2000) and PEMBERTON-IRWIN INLET (De Silva, 2000) maps (Fig. 1). Detailed hydrogeological investigations in the Middle and Upper Catchments, include work by Cody (1994) and a major drilling program as part of the 1969-1970 drought relief program, both within the Lake Dumbleyung area (Lord, 1971). The Geological Survey of Western Australia (GSWA) carried out minor hydrogeological investigations to locate potable groundwater between 1963 and 1990 (GSWA, unpublished Hydrogeology Reports). Further exploration for groundwater was conducted by Otter Exploration and Rockwater to locate water supplies for a mineral exploration company (Rockwater, 1981).

In the southern Perth Basin the assessment of groundwater resources focused on drilling programs conducted by the GSWA (Appleyard, 1991; Baddock, 1992, 1994).

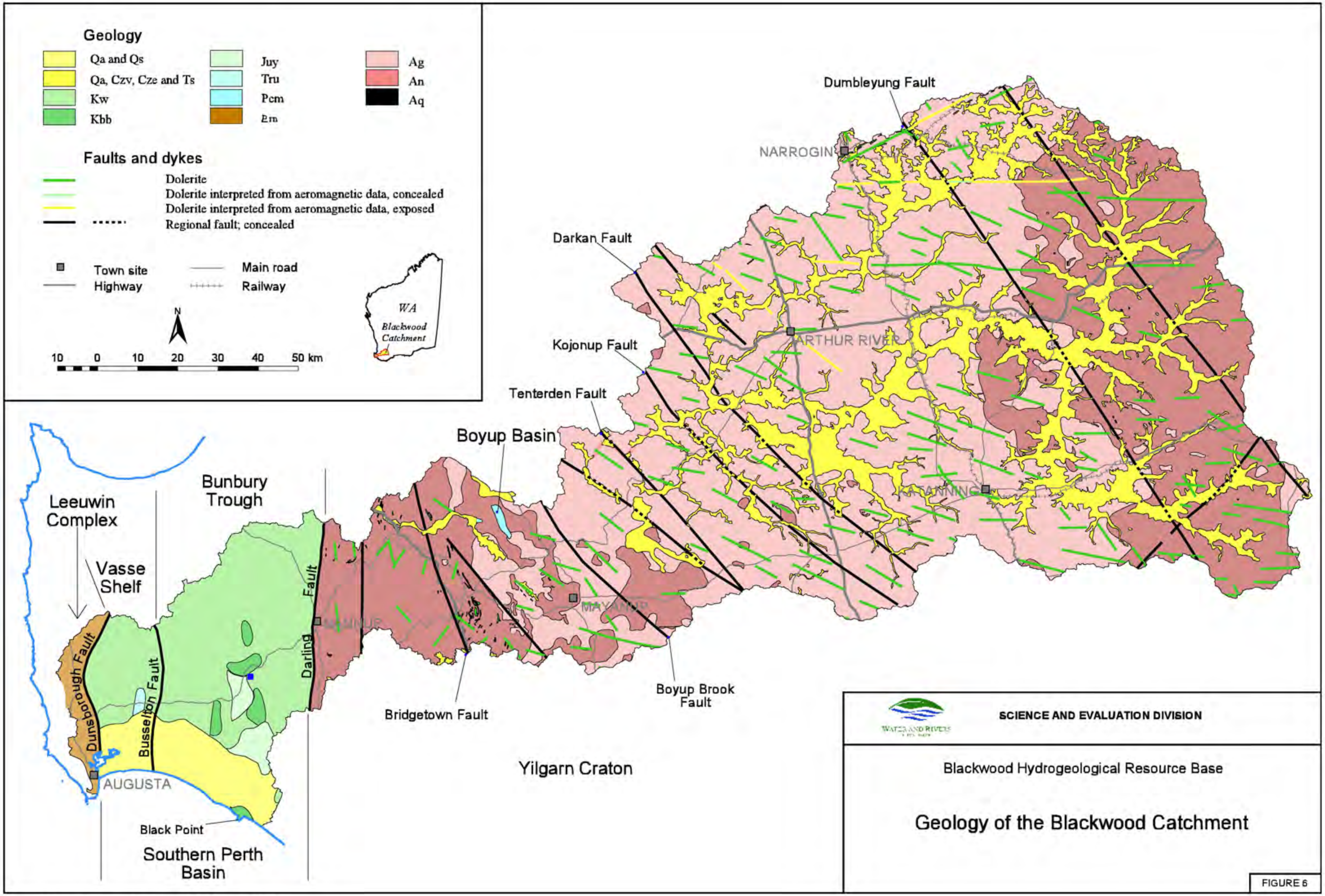

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Table 2. Stratigraphy and aquifer potential of the Blackwood Catchment (adapted from Rutherford, 2000)

Age	*Formation*	*Lithology*	*Aquifer type and potential*
Cainozoic Tertiary–Quaternary	Alluvium (*Qa*)	Sand, silt and clays	Surficial-minor local (fresh to saline)
	Safety Bay Sand/Tamala Limestone (*Qs*)	Eolian and beach sand/ eolian calcarenite	Surficial-minor/major (generally fresh)
	Guildford Formation (sand/clay member)(*Qs*)	Sand, clay and gravel	Surficial-minor local (fresh to brackish)/ very minor (brackish to saline)
	Alluvial and colluvial sediments (*Czv*)	Sand, silt, clay, gravel and minor laterite	Surficial-minor local (brackish to hypersaline)
	Alluvium (*Cze*)	Sand, clay, silt and gravel	Surficial-minor (fresh to brackish)
	Fluvial and lacustrine deposits (palaeochannels) and Greenbushes Formation (*Ts*)	Sand, silt, clay, lignite and gravel	Sedimentary-minor (fresh to brackish) (lacustrine sediments may form an aquitard)
Mesozoic Jurassic– Cretaceous	**Warnbro Group** (*Kw*); (including the Leederville Formation)	Sandstone, siltstone and shale	Sedimentary-major (fresh to brackish)
	Bunbury Basalt (*Kbb*)	Basalt	Weathered rock aquiclude
	Yarragadee Formation (*Juy*)	Sandstone, siltstone and shale	Sedimentary-major (mainly fresh)
	Cockleshell Gully Formation (*Jlo*)	Shale and sandstone	Sedimentary-major (mainly fresh)
	Lesueur Sandstone (*Tru*)	Sandstone	Sedimentary-minor (mainly fresh)
	Sabina Sandstone (*Trs*)	Sandstone and clay	Sedimentary-minor (brackish to saline)
Palaeozoic Permian	Sue Coal Measures (*Ps*)	Siltstone, shale, sandstone and coal	Sedimentary-minor (brackish to saline)
	Boyup Coal Measures and Barron Sandstone (*Pcm*)	Coal, sandstone and shale	Sedimentary-minor/major local (fresh to brackish)
Proterozoic	Mafic dyke and sill (*Prd*)	Dolerite and gabbro	Weathered rock aquiclude
	Quartz dyke (*Prq*)	Quartz	Fractured rock-minor local (fresh to saline)
	Leeuwin Complex (*Prn*)	Gneissic rocks and granulites	Weathered and fractured rock-minor local (fresh to saline)
Archaean	Granitoid basement rocks (*Ag*)	Granitic rocks	Weathered and fractured rock-minor local (fresh to saline)
	Gneissic complexes (*An*)	Granitoid gneiss, migmatite and schist	Weathered and fractured rock-very minor local (fresh to saline)
	Quartzite (*Aq*)	Quartzite	Fractured rock-minor local (fresh to brackish)

2 Blackwood hydrogeological resource base

The major aim of the Blackwood Hydrogeological Resource Base Project was the creation of a groundwater information database to assist land managers in the Blackwood River Catchment.

2.1 Database development

2.1.1 Primary data layers

The development of the database initially involved the examination of water point data from AQWABase[2], where information relating to bore depth, depth to the watertable, geological logs and water quality were compiled. Where there were major deficiencies in the data coverage, additional data were acquired through conducting a bore census, together with a limited drilling program involving the drilling of 21 bores (Panasiewicz *et al*., 1997).

Water point data were divided into three categories based on water usage; namely bores, wells and soaks (Table 3). Bores are subdivided into categories of; existing, abandoned, serviceable and monitoring followed by yield; large (⩾50 m^3/d) and small (<50 m^3 d). Wells are classified as either existing or abandoned.

Table 3. Classification of water points

Type of water point	*Total Number*
Bores	2679
Wells	1172
Soaks	937
Total	**4788**
Date of water point	*Total Number*
Pre-1940	439
1940-1949	127
1950-1959	209
1960-1969	304
1970-1979	361
1980-1989	697
1990-1997	554
No date	2146
Total	**4837**

[2] *AQWABase: Water and Rivers Commission PC relational database*

The following additional datasets were acquired from various government organisations (Appendix 1).

- Roads, railways
- Townsites, local government and cadastral boundaries
- Catchment boundaries and management zones
- Topographic contours
- Drainage lines, other surface water bodies and coastline
- Climatic data such as rainfall and evaporation
- Geological and structural maps

2.1.2 Derived datasets

The Aquifer Type dataset is derived from the interpretation of classified water point information, geology, aerial photographs, topography and structure. The procedure involved plotting aquifer lithology information on topography and geology/structure maps at 1:100 000 scale, using GIS software, ArcView. Aquifer type boundaries, as detailed in Table 2, were then interpreted, drawn manually, digitised and labelled.

2.1.3 Modelled datasets

Groundwater Levels and Groundwater Salinity are modelled through the integration of water point information with topography and geology. The modelling procedure involves using GIS software, ArcView and ArcInfo.

A digital elevation model of the topography is generated using topographic contours. The subtraction of the depth to water level information from the digital elevation model provides a depth to the water level measurement with respect to the land surface. This is calculated for each water point, from which the catchment groundwater contours and groundwater salinity (at or near the watertable) contours are then interpreted, drawn manually, digitised and labelled (Appendix 1).

2.1.4 Spatial analysis

Two of the modelled datasets, Groundwater Levels and Groundwater Salinity, were used to develop the Distribution of Salinity at the Watertable dataset. Categories were produced through interrogating the previously modelled datasets with respect to logical statements/criteria. In this case the criteria are increasing depth to water level in association with decreasing salinity. The resultant modelled data were colour coded according to their prescribed categories.

2.1.5 Data quality

The quality and quantity of recorded information for the water point data are variable and this impacts on the interpretation of the aquifer boundaries and the modelling of the contoured datasets. Not all water point data are surveyed with the same degree of accuracy, in x, y and z directions. To standardise the z direction measurements the digital elevation model was produced and applied to the variably located water point data. However, water point data coverage is not even, so often a high degree of extrapolation between sparse data points was needed. Groundwater Levels and Groundwater Salinity are dynamic parameters which experience seasonal and long-term variations. Therefore, the frequency of measurement and the length of time since the water point was last sampled affect the quality of the recorded information.

These variations are passed on to the derived and modelled datasets, and whilst they are unlikely to have a significant impact at catchment scales, should be taken into account when conducting ‘paddock scale’ investigations.

3 Hydrogeology

3.1 Groundwater occurrence

In the Blackwood River Catchment the major hydrogeological provinces (Smith *et al*., 1999) are the Yilgarn South West Province and the Perth Basin, with the Leeuwin Province and Boyup Basin forming the minor provinces (Fig. 7). In these provinces, groundwater is contained in more than twelve aquifer systems that are classified according to their constituent materials (Table 2). Aquifers exist in the weathered profile and fractures and joints of crystalline rocks (prevalent in the Yilgarn South West Province and Leeuwin Province) and unconsolidated and lithified sediments. Faults, fractures and joints are commonly localised and therefore have limited groundwater potential. Similarly, the weathered profile of crystalline rocks contains only localised groundwater as these materials exhibit variable, but predominantly low, porosity and hydraulic conductivity (George, 1992a; George *et al*., 1994; Clarke *et al*., 2000). As a result, substantial supplies of groundwater are commonly restricted to the sedimentary rocks within the Perth Basin. The relationship of groundwater occurrence, yield and salinity to the aquifer materials of the hydrogeological provinces shown in Figure 7, together with case studies, is described in the rest of section 3.

3.2 Yilgarn South West Province

3.2.1 Surficial (and Tertiary sediments) aquifers (*Qa, Czv, Cze, Ts*)

3.2.1.1 Aquifer materials and location

Surficial aquifers in the Yilgarn South West Province are generally unconfined and comprise mainly heterogeneous fluvial sediments of late Tertiary to Quaternary age (Table 2). Quaternary fluvial sediments are deposited along modern drainage lines of the Blackwood River and consist of clay with sand lenses (*Qa*). Cainozoic alluvial and colluvial deposits (*Czv*) comprising sand, silt, clay, gravel and minor laterite are widespread in the Upper-middle and Upper Catchments, occupying broad river valleys and relict fluvial systems of the Hillman, Arthur and Beaufort Rivers (Fig. 7). These sediments either overlie weathered granitoid basement rocks or early Tertiary sediments, the latter occupying palaeochannels (Fig. 8).

Extensive, 'sheet-like' Cainozoic alluvial deposits (*Cze*) are widespread in the Lower-middle Catchment, preserved in lower landscape areas such as those 30 km east of Boyup Brook (near Kulikup), along with locales higher in the landscape (Laws, 1992; Tille and Percy, 1995).

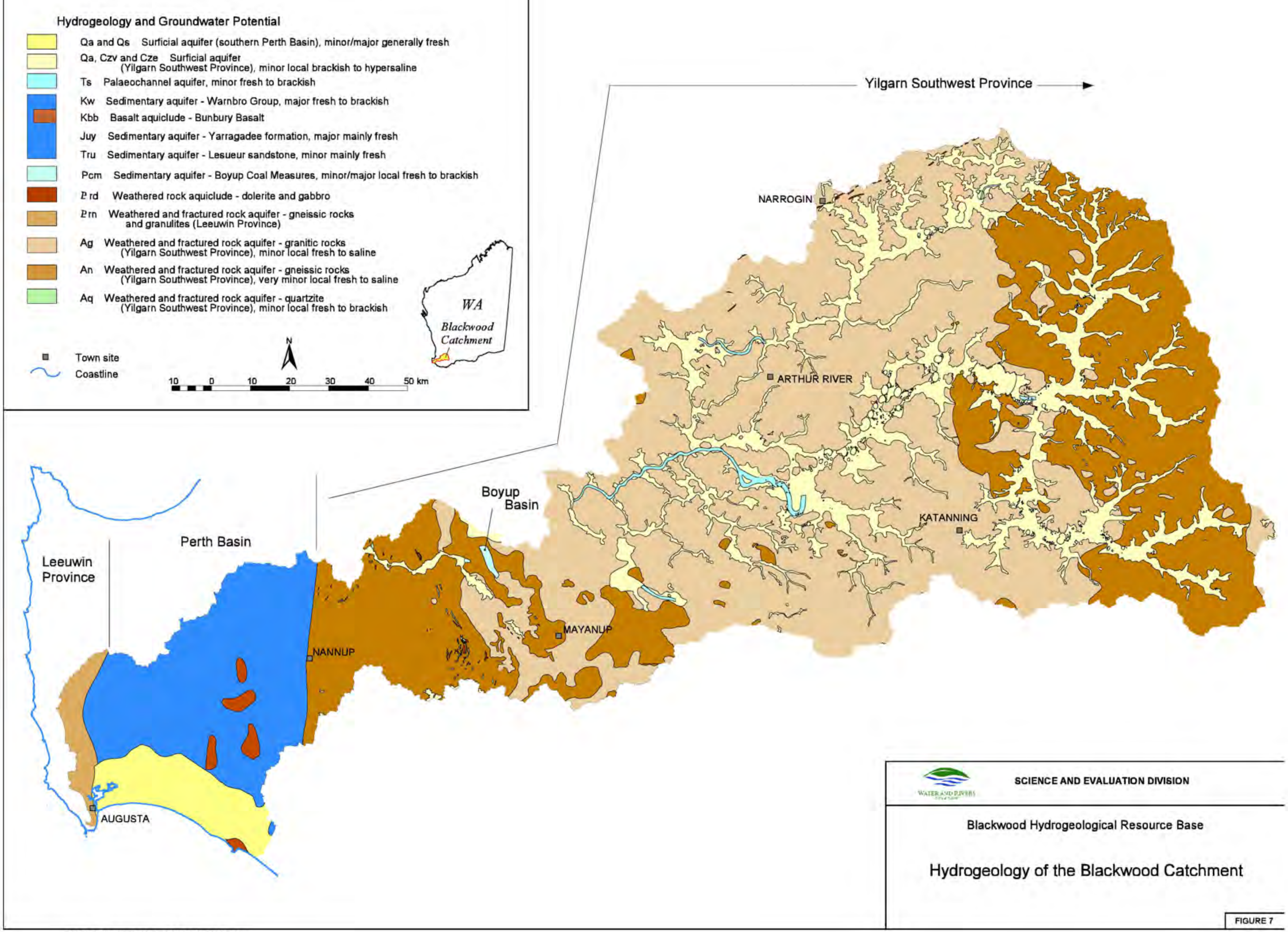
In the Upper-middle and Upper Catchments, Tertiary sediments (*Ts*) occupy major palaeochannels in broad valleys, commonly beneath variable thicknesses of Cainozoic sediments (*Czv*) (Hawkes, 1993; George *et al*., 1994; Perry, 1994; Prangley, 1994a,b, 1995a,b; Waterhouse *et al*., 1995; Commander *et al*., 1996). These sediments form minor to major unconfined to semi-confined aquifers and comprise Eocene to Miocene/Pliocene alluvial sands and clays, commonly overlain by lacustrine clays and silts (Fig. 8). The thickness and lateral extent of the Tertiary sediments preserved in the palaeochannels are reliant on the depth of incision within the palaeovalleys. The average width of these channels is approximately one kilometre, and mapped lengths range from about 8 to over 50 kilometres.

The sediments are estimated by George *et al*. (1994) to attain a maximum thickness in the Beaufort Palaeochannel of over 70 m and to be around 50 m by Waterhouse *et al*. (1995). Sediments within the channels are not always in continual hydraulic connection, thereby restricting major groundwater resources to areas where such connection occurs.

3.2.1.2 Bore yields and groundwater quality

Bore yields and groundwater quality within the surficial and palaeochannel aquifers are dependent on a number of variables influenced by landscape position. These are the thickness and lateral extent of high hydraulic conductivity zones (commonly sands and gravels with intergranular porosities), the degree of hydraulic connection between these zones and the source (quality), and quantity of groundwater throughflow and recharge.

In Tertiary sedimentary aquifers within palaeochannels, generally high salinities are associated with poorly drained lower landscape areas that may contain localised aquifers and receive poor quality recharge


Hydrogeology and Groundwater Potential
Qa and Qs Surficial aquifer (southern Perth Basin), minor/major generally fresh
Qa, Czv and Cze Surficial aquifer (Yilgarn Southwest Province), minor local brackish to hypersaline
Ts Palaeochannel aquifer, minor fresh to brackish
Kw Sedimentary aquifer - Warnbro Group, major fresh to brackish
Kbb Basalt aquiclude - Bunbury Basalt
Juy Sedimentary aquifer - Yarragadee formation, major mainly fresh
Tru Sedimentary aquifer - Lesueur sandstone, minor mainly fresh
Pcm Sedimentary aquifer - Boyup Coal Measures, minor/major local fresh to brackish
P rd Weathered rock aquiclude - dolerite and gabbro
P rn Weathered and fractured rock aquifer - gneissic rocks and granulites (Leeuwin Province)
Ag Weathered and fractured rock aquifer - granitic rocks (Yilgarn Southwest Province), minor local fresh to saline
An Weathered and fractured rock aquifer - gneissic rocks (Yilgarn Southwest Province), very minor local fresh to saline
Aq Weathered and fractured rock aquifer - quartzite (Yilgarn Southwest Province), minor local fresh to brackish
Town site
Coastline
N
10 0 10 20 30 40 50 km
WA
Blackwood Catchment
Yilgarn Southwest Province
NARROGIN
ARTHUR RIVER
KATANNING
Boyup Basin
MAYANUP
Perth Basin
Leeuwin Province
NANNUP
AUGUSTA
SCIENCE AND EVALUATION DIVISION
Blackwood Hydrogeological Resource Base
Hydrogeology of the Blackwood Catchment
FIGURE 7
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from either or both the overlying surficial aquifers (Czv and *Qa*), and the weathered profile of adjacent granitoid basement rocks. Fresh to brackish groundwater is more commonly located in the central sections of the palaeochannels where sandy sediments predominate. This occurs where the major source of groundwater recharge is fresh, derived from the process of throughflow from up-gradient sections of the palaeochannels containing fresh groundwater, or from the direct infiltration of rainfall. Groundwater at the edges of the palaeochannel is commonly saline as the recharge is obtained mainly from the neighbouring weathered granitic rocks. The intermixing of fresh groundwater in the central channel and saline groundwater at the channel margins produces an intermediate zone of brackish groundwater.

High bore yields are therefore restricted to zones containing minimal clay, whereas clay-dominated sediments are characterised by lower yields and generally higher salinities. The groundwater potential of the palaeochannel aquifers has been investigated in several localities within the Upper and Upper-middle Catchments of the Blackwood River. Quantitative data are discussed in the following case studies and the spatial distribution of prospective fresh groundwater resources is shown in Figure 9.

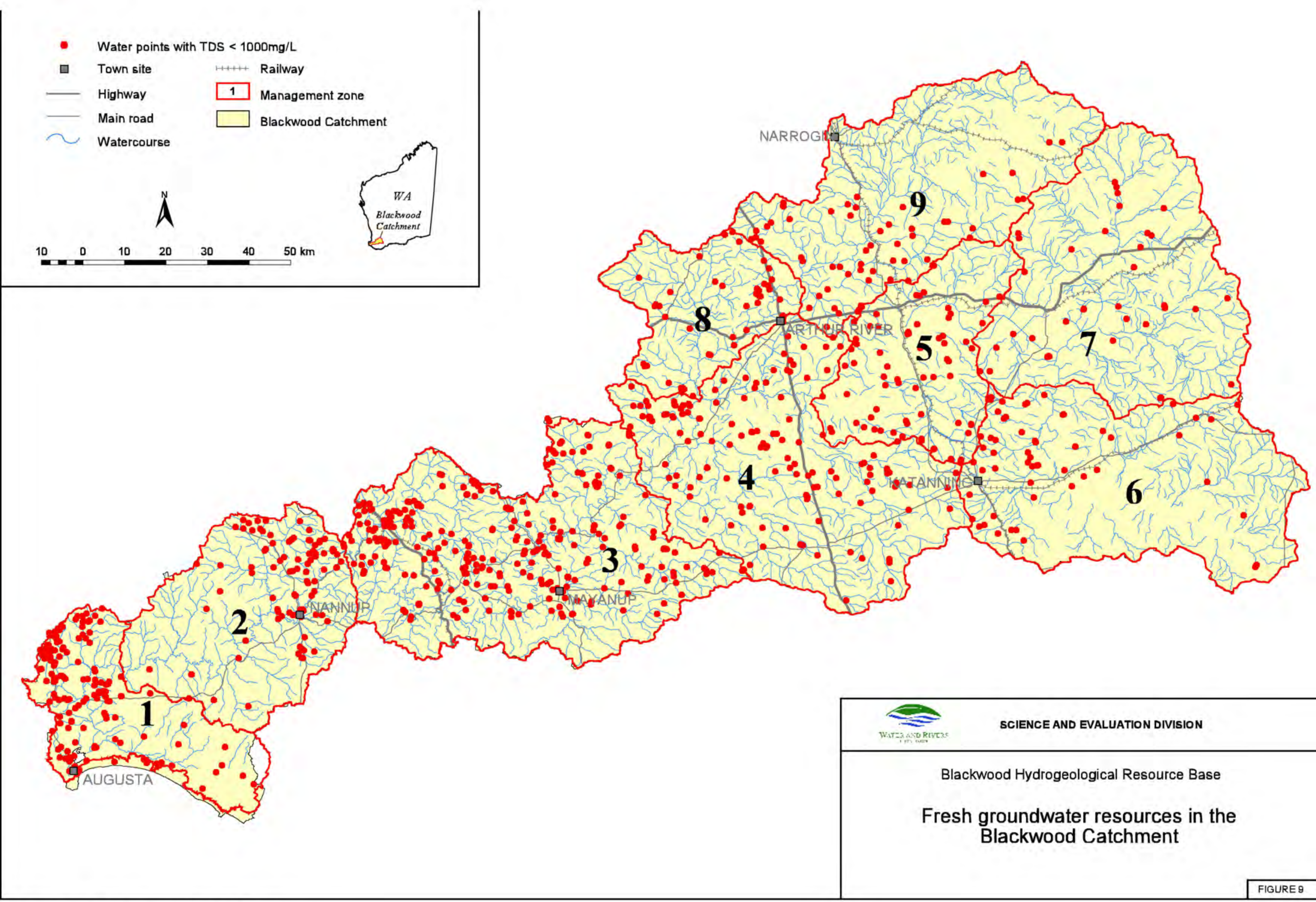
3.2.1.3 Case Studies

Case studies for surficial (and Tertiary sediments) aquifers in the Yilgarn Southwest Province are given below for 6 areas:

- Toolibin Palaeochannel (Fig. 10)
- Qualeup Palaeochannel (Fig. 11)
- Beaufort Palaeochannel, near Boscabel (Fig. 12)
- Beaufort Palaeochannel, near Towerrinning (Fig. 12)
- Darkan Palaeochannel, Hillman River Section, (Fig. 13)
- Darkan Palaeochannel, Dardadine Tannery Section, (Fig. 13)

3.2.1.3.1 Toolibin Palaeochannel

The Toolibin subcatchment is in the northeast of the Blackwood Catchment (Fig. 10). The 'ancient drainage system containing fluviatile deposits of sands and clays' (Martin, 1982) forms an important aquifer (Bore TM1A, Martin, 1987) but its composition is hard to distinguish from material 'derived from weathering in situ of the basement complex' (GSWA, 1985). Experience gained from extensive drilling of Tertiary sediments in the Yilgarn Goldfields Province



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Blackwood Hydrogeological Resource Base

Fresh groundwater resources in the Blackwood Catchment

FIGURE 9

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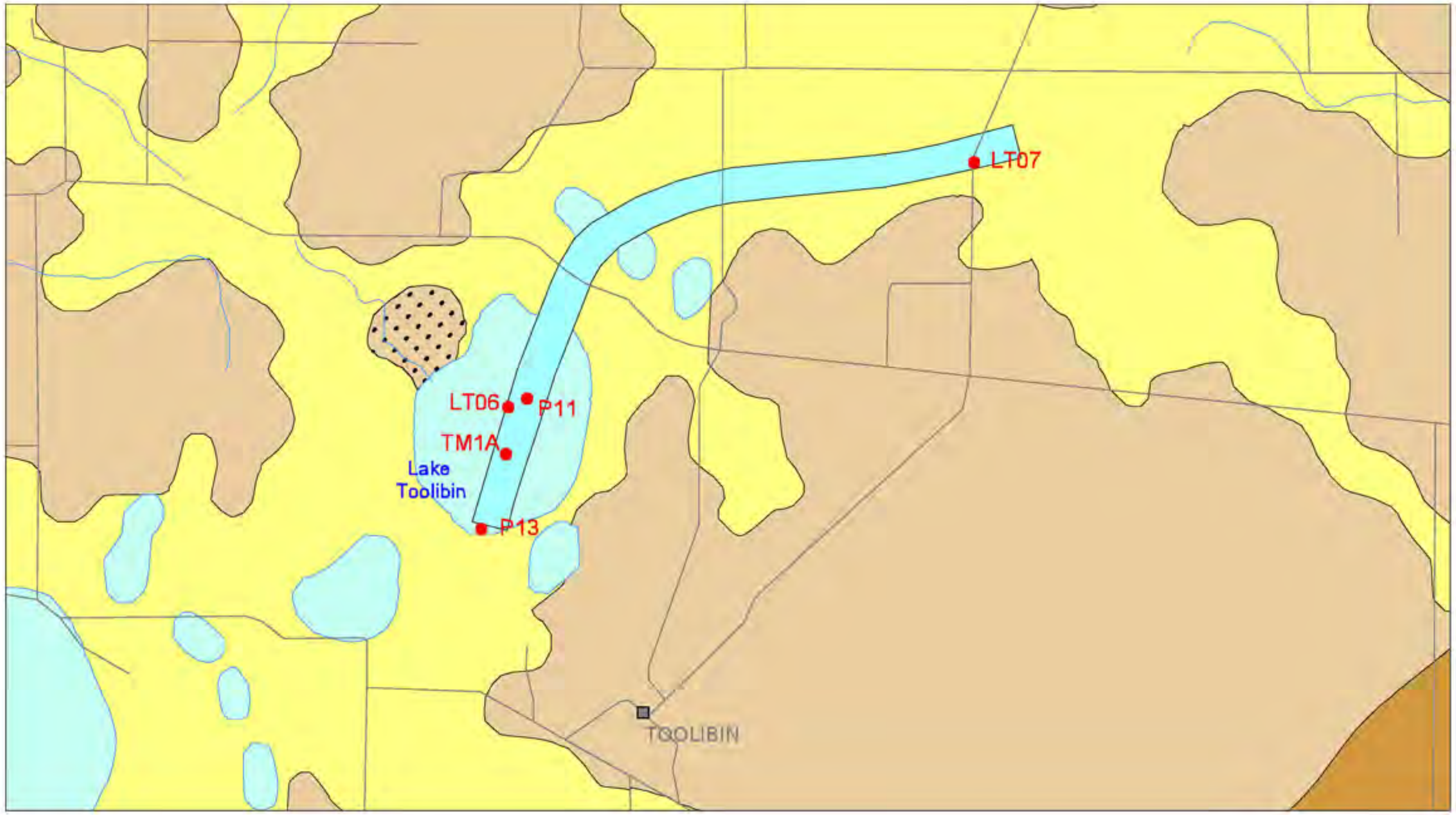

Aquifer types

- Surficial aquifer
- Palaeochannel aquifer
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks
- Outcrop

- Bore
- Drainage
- Road
- Town site
- Lake

N

1 0 1 2 km

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Blackwood Hydrogeological Resource Base

Toolibin groundwater investigation sites

FIGURE 10

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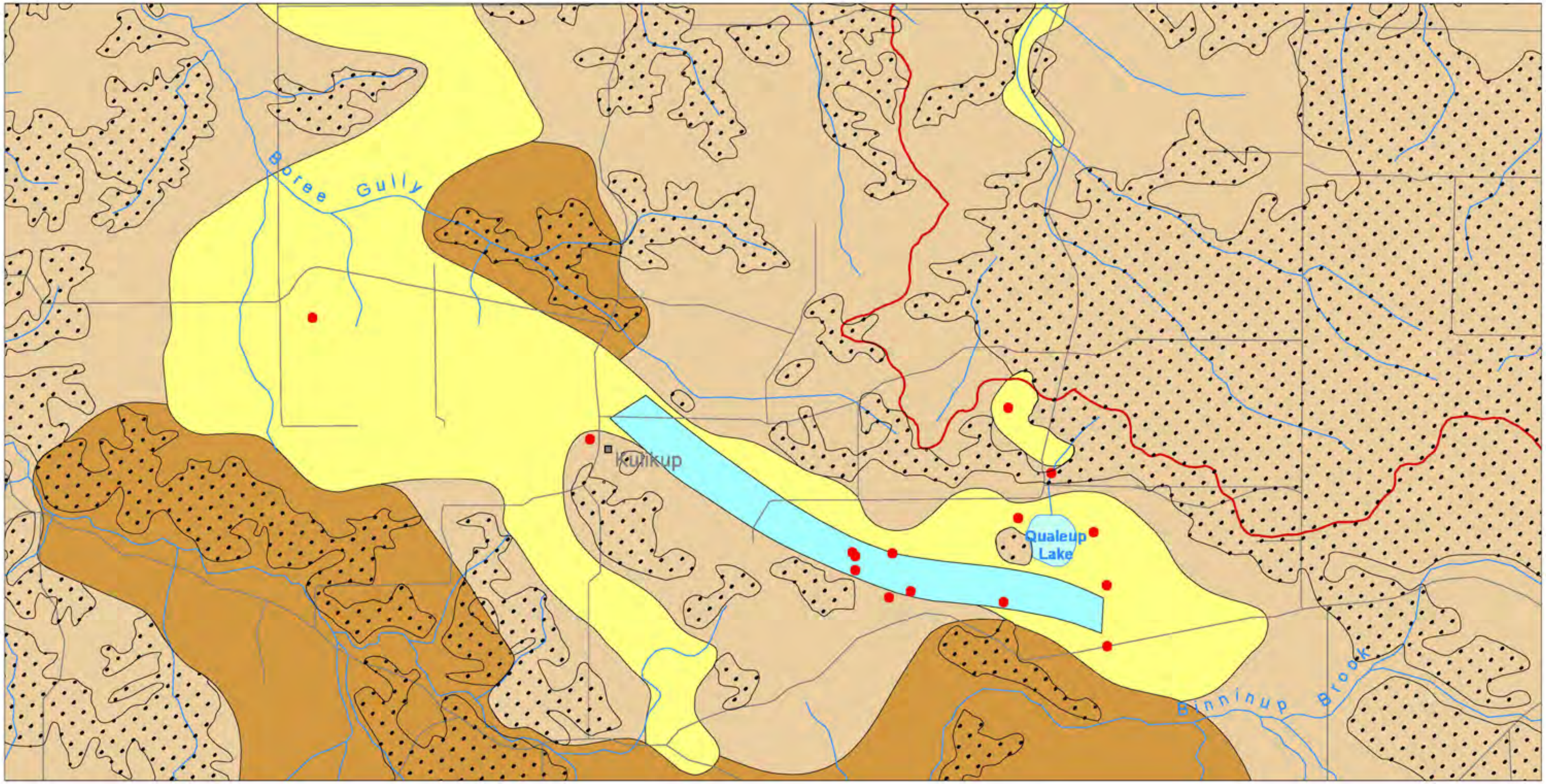

Aquifer types

- Surficial aquifer
- Palaeochannel aquifer
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks
- Outcrop

- Bore
- Town site
- Drainage
- Road
- Management zone boundary
- Lake

N

1 0 1 2 3 4 5 km

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Blackwood Hydrogeological Resource Base

Qualeup groundwater investigation sites

FIGURE 11

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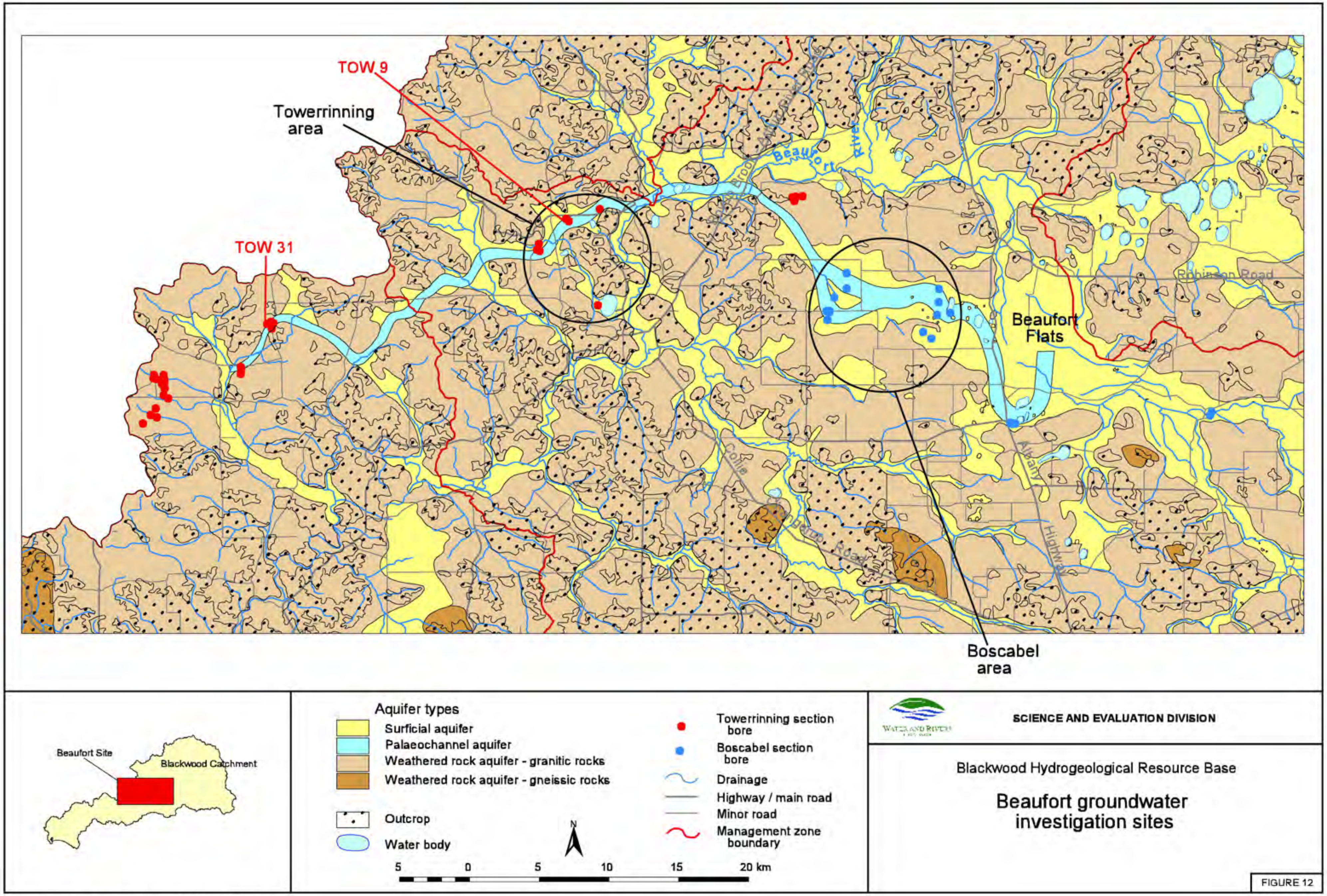

Beaufort groundwater investigation sites

FIGURE 12

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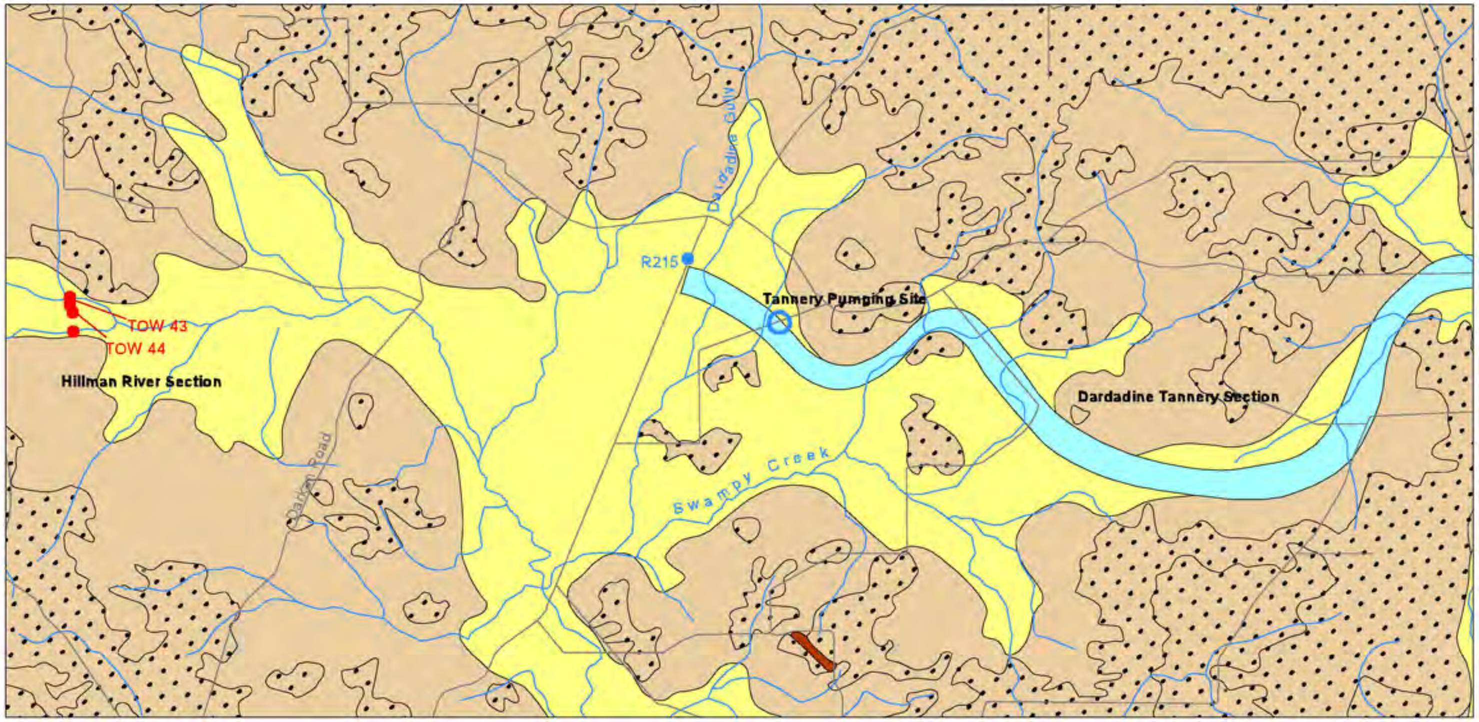

Aquifer types

- Surficial aquifer
- Palaeochannel aquifer
- Weathered rock aquifer - granitic rocks
- Weathered rock aquiclude - dolerite dyke
- Outcrop

- Darkan section bore
- R215
- Pumping site
- Drainage
- Road
- Management zone boundary

1 0 1 2 3 4 km

N

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Blackwood Hydrogeological Resource Base

Darkan groundwater investigation sites

FIGURE 13

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(Commander *et al*., 1992), the Albany-Fraser Province and Bremer Basin (Smith, 1997) led to the recognition of the palaeochannel at Toolibin. Bores LT 06 and LT 07 (Fig. 10) yielded 34 and 31 m of core, respectively, from the palaeochannel (De Silva, 1999). Subsequent drilling, of bores P11 and P13 (Dogramaci, 1999), also intersected these sediments.

The sediments that are considered to be part of the palaeochannel system are typically some 35 m thick and comprise multiple layers of clays, sands and carbonaceous clays of late Miocene to early Pliocene age. The palaeochannel aquifer is confined to semi-confined by a clay layer up to 10 m thick. Extractable groundwater mainly occurs in the multiple layers of sand, estimated yields ranging from 12 to 300 m^3/d (Dogramaci, 1999). Groundwater salinity ranges from 34 000 to 36 000 mg/L (De Silva, 1999).

3.2.1.3.2 Qualeup Palaeochannel

At the locality of Qualeup (Fig. 11) extensive Tertiary sediments, identified as Greenbushes Formation by Wilde and Walker (1982), were investigated by George and Bennett (1995) and the Water and Rivers Commission in the Blackwood drilling program (Panasiewicz *et al*., 1997). Tertiary sediments up to 25 m thick, inclusive of a 9 m sand unit, were identified during drilling. Low permeability sediments at the top of the sequence, combined with the standing water level data, indicate the groundwater system could be unconfined to semi-confined. Bore yields of up to 200 m^3/d have been recorded in the Qualeup Palaeochannel, between Qualeup and Kulikup. Groundwater quality ranges from 3500 to 4500 mg/L (Panasiewicz *et al*., 1997).

3.2.1.3.3 Beaufort Palaeochannel

In the Beaufort Palaeochannel (Fig. 12), the main palaeodrainage of the Blackwood Catchment, a network of over 60 km of Tertiary sediments has been identified (Hawkes, 1993; Prangley, 1994a,b, 1995a,b).

At Boscabel, the Tertiary sediment sequence comprises alluvial and lacustrine sands, clays and silts and ranges in thickness from 13 to 55 m, generally increasing from upper landscape areas to valley floors. The sand units in these sequences vary from very poorly defined to well defined multiple units and comprise very fine to coarse or pebble-size clasts, generally coarsening downwards. The total thickness of sands range from 5 to 26 m, with individual units varying from 5 to 17 m. A clay layer, up to 20 m thick overlies these sands. A surface water divide produces an ‘upstream’ and ‘downstream’ flow system resulting in groundwater discharging east of the divide in the Beaufort Flats and to the west into the Beaufort River. Groundwater systems in these sediments are unconfined to confined, with the water level or potentiometric surface being between 1 and 8 m below ground level. Airlift yields from these sand units are in the range of 40 to 280 m^3/d. However, there is no apparent correlation between the thickness of sand units and the groundwater yields. Groundwater salinity ranges from 1000 to 7500 mg/L and generally increases with depth, as observed in bore BOS 4 (Prangley, 1994b).

In the Towerrinning area Tertiary sediments consist predominantly of sands and clays and range in thickness from 8 to 39 m. Unlike Boscabel, the thickness of sediments shows no obvious correlation with topography. Sand units are 4 to 28 m thick, coarsening downward. Bore yields from sands range from 12 to 187 m^3/d and show no relationship to the thickness of the water-bearing sand unit (Prangley, 1995a). A surface-water divide between TOW 9 and 31 produces an ‘upstream’ and ‘downstream’ groundwater flow system resulting in discharge east of the divide at Darlingup Springs (McCombe, 1999) and about 15 km to the west at Dingo Swamp and Haddleton Springs. Groundwater systems vary from unconfined to confined conditions, with all high-yielding bores (>100 m^3/d) sourced from confined systems.

Groundwater salinity in the Towerrinning section drillholes ranges from 340 to 8700 mg/L, with fresh groundwater observed in two localities (Fig. 12). Bore TOW 31, drilled in a confined groundwater system in the recharge area of a small subcatchment, has groundwater salinity of 340 mg/L. However, two bores in this transect, in close proximity to TOW 31, recorded groundwater salinity in the range of 1400 to 2400 mg/L, indicating fresh groundwater is likely to occur within localised pockets or lenses. Bores in this transect show that groundwater salinity increases with depth. Bore TOW 9, located in another subcatchment, also records fresh groundwater resources with salinities of about 560 mg/L (Prangley, 1994a). However, the extent of this fresh groundwater resource also appears to be limited as other bores, drilled within the same flow path, record much higher groundwater salinities ranging between 4800 and 8700 mg/L. The groundwater flow path within the TOW 9 transect indicates a decrease in salinity from up-gradient to down-gradient areas that could be attributed to a variety of factors such as dilution effect, increased recharge, or increasing thicknesses of the sand unit or units.

3.2.1.3.4 Darkan Palaeochannel (Hillman River section)

Up to 23 m of Tertiary sediments, primarily sands and clays, overlain by up to 5 m of Quaternary sediments (*Qa*) were identified whilst drilling a transect of four bores across a valley in the Hillman River (Fig. 13), 9 kms north of Darkan. Two bores, TOW 43 and TOW 44, intersect Tertiary sands and produce yields ranging from 230 to 302 m^3/day. Yields decrease from the centre to the edges of the valley, where the Tertiary sequence thins (Prangley, 1995b). The aquifer is unconfined to semi-confined. Semi-confined conditions are produced by a discontinuous 2 m thick weathered clay layer; depth to the water level at the centre of the valley is 0.5 m below the land surface. The salinity of the groundwater ranges from 5600 mg/L in the centre of the valley to 26 000 mg/L near the margins of the palaeochannel.

3.2.1.3.5 Darkan Palaeochannel (Dardadine Tannery section)

Exploratory bores drilled 12 km northeast of Darkan, in an area known to produce high yielding fresh water bores and permanent fresh water soaks, identified at least 30 m of Tertiary sands containing fresh water (Rockwater Pty Ltd, 1990). Drilling delineated a tract of sediments, approximately 20 km in length (Fig. 13), from Albany Highway to the east to the Dardadine sub-basin (a small Tertiary basin delineated by gravity surveying and limited drilling by Western Collieries Limited). The salinity in this section of palaeochannel is low, around 450 mg/L, influenced by fresh recharge from overlying sandy soils. Up to 30 million cubic metres of freshwater are estimated to be stored in this 20 km-long section of palaeochannel, if the channel sands are approximately 500 m wide and the depth of the channel is at least 45 m (Rockwater Pty Ltd, 1990). Lower bore yields and increased groundwater salinity are expected at the palaeochannel margins where the thickness of the sands decreases, grading to interbedded sands and clays, and saline groundwater from adjacent weathered granitoid rocks recharges the Tertiary sediments (Bore R215; Fig. 13).

Yields from test pumping one of the high-yielding bores at the Tannery Pumping Site indicate that the bore can be continuously and safely pumped at 320 m^3/d with the drawdown effect extending 950 m down-gradient and 500 m up-gradient (Fig. 13) (Rockwater Pty Ltd, 1992). This test confirmed that the palaeochannel aquifer is only partially confined by the overlying Cainozoic and Quaternary sediments (*Czv* and *Qa*), as water levels in these materials were affected through the extraction of groundwater from the palaeochannel.

3.2.2 Weathered rock aquifers and aquicludes (*An, Ag, Prd*)

The gneissic (*An*) and granitoid rocks (*Ag*) of the Yilgarn Craton cover over 85% of the Blackwood River Catchment. Where these rocks outcrop they represent areas of high surface runoff and retain little to no groundwater in joints and fractures. However, with the incidence of outcrop in the craton approximately 20%, the remaining area is deeply weathered, containing groundwater in pore spaces within the weathered profile and in fractures/joints below the weathering front.

3.2.2.1 Aquifer materials and location

The weathering profile, where fully developed, is typified by a complex vertical zonation (Fig. 14). The fragmental disintegration of granitic bedrock at the weathering front produces a friable zone with high intergranular porosities, often referred to as 'grus' (Nahon and Tardy, 1992). In rocks containing low quartz, saprock develops which is generally compact and has lower hydraulic conductivities. Grus is described by many authors (e.g. Johnston *et al*., 1983; Johnston, 1987a,b; George, 1992a; George *et al*., 1997; Clarke *et al*., 2000) as saprolite 'grit' or saprolite and is ascribed saturated hydraulic conductivities approximating 0.5 m per day. Saprolite develops as primary minerals weather to the secondary clays, which occur above the grus in granitic rocks and commonly above the saprock in gneissic rocks (Nahon and Tardy, 1992; Dobereiner and Porto. 1993; Cody, 1994).

Saprolite contains variable quantities of groundwater. This is due to the mineralogical variation of granitoid and gneissic basement rocks giving rise to weathered material with a range of porosity, but generally low permeability and hydraulic conductivity (Fig. 14) (Anand and Gilkes, 1984, 1987; Anand *et al*., 1985; McCrea *et al*., 1990). Low hydraulic conductivities recorded at less than 0.05 m per day correlate with clay-rich sections within the saprolite, which frequently develop at the top of the profile forming an aquitard (George *et al*., 1997). Saprolite commonly grades upwards into mottled and ferruginised zones that tend to correlate with clay dominant sections (Bettenay *et al*., 1980). However, in granitoid rocks containing major quartz, an arenose horizon (sandy, quartz-rich zone) may develop at the top of the profile (Nahon and Tardy, 1992). Weathered rock aquifers in granitoid and gneissic rocks are therefore different.

3.2.2.2 Bore yields and groundwater quality

Higher bores yields are obtained from the grus, which develops specifically through the weathering of granitoid rocks (Fig. 14). Saprolite, developed from the weathering of either granitoid and gneissic rocks, has low transmissivity and forms an aquitard where clay-rich zones develop.

Groundwater conditions within the weathered rock aquifer are unconfined, but semi-confined conditions develop where a clay-rich saprolite forms within the weathered profile, or where overlying surficial sediments contain major clays. Perched aquifers may form in surficial sediments where the weathered rock aquifer is semi-confined and low hydraulic gradients delay groundwater from discharging into drainage lines.

The groundwater in weathered rock aquifers of granitoid and gneissic rocks is typically brackish to highly saline. In the Blackwood Catchment, groundwater salinity typically increases from west to east, with fresh to brackish groundwater generally restricted to the western margin of the Yilgarn Craton, in the Lower-middle Catchment (Fig. 3). Here, higher rainfall and undulating topography increase recharge and effectively flush salts from the catchments. Low rainfall in the Upper-middle and Upper Catchments, combined with a poorly drained landscape of low relief, has resulted in the storage of salts and poor groundwater quality. Within catchments and subcatchments there is a general topographic control on salinity; lower landscape areas contain groundwater with higher salinities than groundwater higher in the landscape.

Mafic dykes and sills (*Ꝑrd*) have been mapped throughout the Yilgarn Craton. As these Proterozoic crystalline rocks contain only minor quartz, and produce high volumes of clay minerals during weathering, they form aquicludes. Recent work by Clarke *et al*. (2000) suggests that the hydraulic conductivity of material in the weathered profile of mafic dykes is similar to, or greater than, that of granitic rocks. However, these results contradict Johnston *et al*. (1983), McCrea *et al*. (1990) and Engel *et al*. (1987), who found that these dykes possess low hydraulic conductivities and were likely to form barriers to groundwater travelling down gradient through weathered granitoid and gneissic basement.

The salinity of the groundwater in aquifers located behind dykes is dependent on the quality of the water received up gradient via throughflow. These groundwater resources are localised and yields vary according to the position of the dyke in relation to the local groundwater flow regime.

The spatial distribution of prospective fresh groundwater resources in these aquifers is shown in Figure 9, and quantitative data are discussed in the following case studies conducted by De Silva (1999) and Leonhard (1999) (Fig. 15). These studies were carried out as follow up work to that of Panasiewicz *et al*. (1997).

3.2.2.3 Case studies

Case studies for weathered rock aquifers in the Yilgarn Southwest Province are given below for 2 areas.

3.2.2.3.1 Toolibin subcatchment

The Toolibin subcatchment is located in the Upper Catchment, near the northeastern boundary of the Blackwood Catchment (Fig. 15). Here, weathered rock aquifers develop in both granitoid and granitic gneiss basement rocks and mafic dykes form aquicludes. The generalised weathered profile of the granitoid rocks comprises coarse-grained quartz-rich grit (grus) near the unweathered basement rocks, clay-rich saprolite containing dominant pale kaolinitic clays, and sandy, quartz-rich horizons (arenose horizons). The weathered profile of mafic rocks drilled at bore LT 34 (De Silva, 1999) consists mainly of clays and silt-sized material; grus or coarse-grained grit is absent. Depth to fresh bedrock ranges from 6 to 60 m.

Permeable horizons (grus grading into saprolite) range in thickness from 1 to 10 m, thicker sequences correlating with deeper weathered profiles. The thickness of these horizons does not show a good correlation with groundwater yield. Yields range from less than 1 to 40 m^3/d, the highest being obtained from bore BW12 (Panasiewicz *et al*., 1997) where 10 m of permeable material was drilled above granitoid basement rock that was intersected at a depth of 28 m. The variation in yield reflects the localised nature of these aquifers. Bores drilled in shallow weathered profiles up to 10 m thick are either dry or have minor seepage, indicating that depending on the hydraulic gradients, these areas may form zones of either high recharge or discharge.

Depth to water level ranges from 2 to 52 m, and salinities range from 300 mg/L in the upper landscape, to 30 000 mg/L in lower landscape areas. In the upper 10 m of palaeochannel aquifer, salt storage varies from 12 to 21 kg/m^3 (De Silva, 1999). Salt storage in the upper 10 m of the weathered profile ranges from 0.09 to 17.95 kg/m^3, whilst for the regolith (the full weathered profile and overlying sediments) the range is 0.14 to 28 kg/m^3. In this case study De Silva (1999) reported a relationship between groundwater salinity and salt storage in the full regolith profile for 14 bores (Fig. 16).

3.2.2.3.2 Carlecatup subcatchment

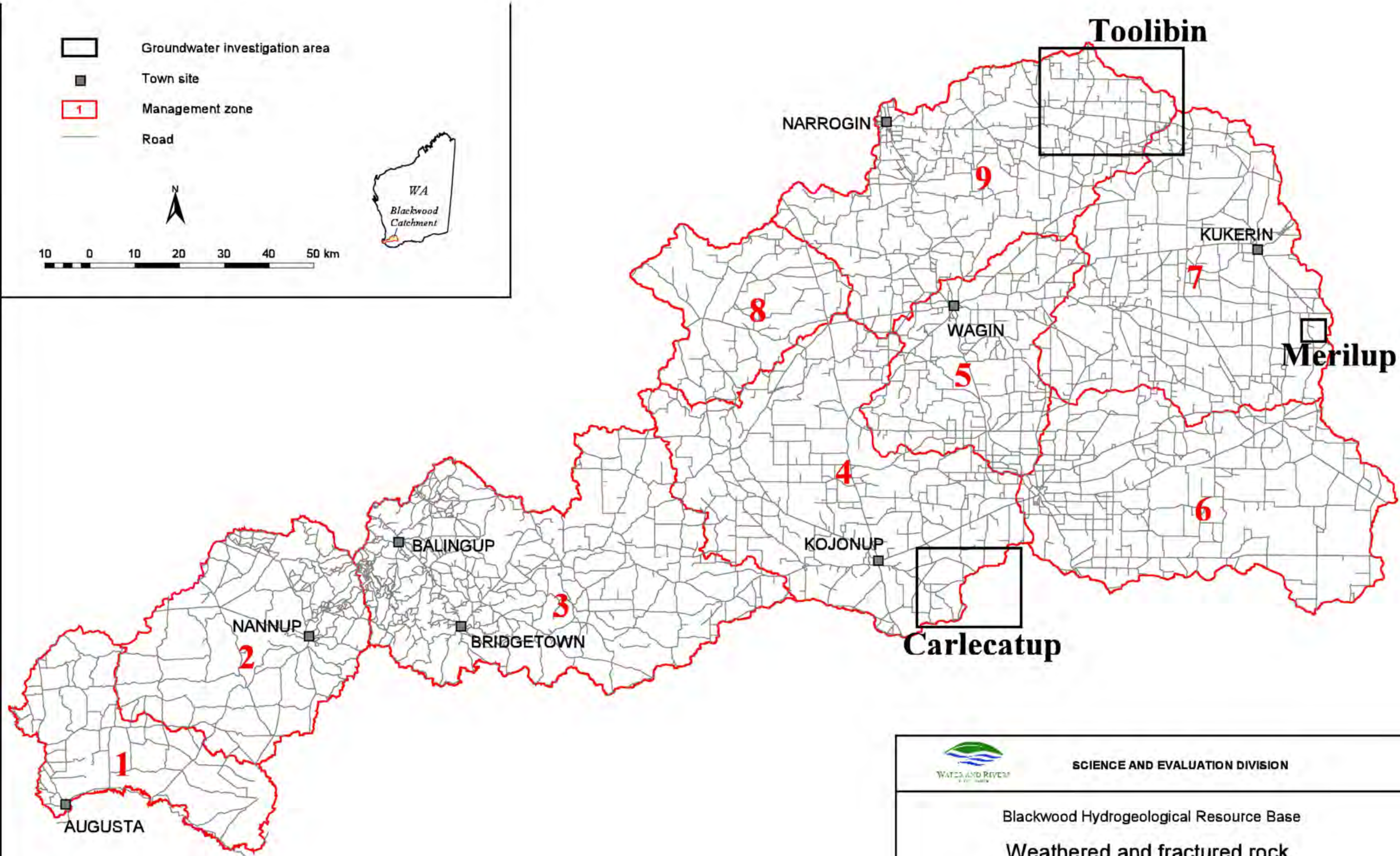
The Carlecatup subcatchment (Fig. 15) is located on the southwestern margin of the Upper-middle Catchment. In this catchment, the weathered profile for the granitoid basement rocks consists of a saprolite gritty layer (grus) at the weathering front, grading into saprolite comprising sandy clay with abundant quartz- to clay-rich zones with pallid clays (kaolinitic) and mottling (iron-rich segregations) towards the top of the profile (Leonhard, 1999). Depth to bedrock ranges from 7 to 50 m, with the thickness of the weathered profile generally decreasing from upper to the lower landscape areas. Permeable horizons (grus grading into saprolite) are up to 6 m thick. Groundwater yields from bores are low, less than 1 to 36 m^3/d, with the highest having being obtained from bore BH08 (Panasiewicz *et al*., 1997), where 19 m of permeable material was drilled.

Depth to water level ranges from 5 to 16 m; shallow depths are generally constrained to lower landscape areas. Groundwater salinity ranges from 500 to 11 000 mg/L and shows no clear correlation with landscape position. Salt storage in the top 10 m of the granitoid rock weathered profile ranges from 0.55 to 7.58 kg/m^3 (Leonhard, 1999).

3.2.3. Fractured rock aquifers (*Ag, An, Aq, Prq*)

3.2.3.1 Aquifer materials and locations

Major and minor faulting, which has produced extensive fracturing of the crystalline basement rocks (*Ag, An*) of the Yilgarn Craton, exerts control on the movement of groundwater. Faults align with preferential weaknesses in the basement, a number of which coincide with the margins of previously injected intrusives such as Proterozoic mafic ($\overline{P}rd$), and quartz dykes ($\overline{P}rq$, too small to show on Fig. 7) and sills. These fractures may contain groundwater depending on groundwater processes, basement topography, and the ability of the faults, dykes or sills and low hydraulic conductivity zones within the weathered profile to form effective barriers to groundwater flow (Fig. 14) (George *et. al*., 1997). These zones form a potential groundwater resource as their hydraulic conductivities are commonly high (Clarke, 1998).



SCIENCE AND EVALUATION DIVISION

Blackwood Hydrogeological Resource Base

Weathered and fractured rock groundwater investigation areas

FIGURE 15

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3.2.3.2 Bore yields and groundwater quality

Drilling records show that groundwater yields up to and greater than 500 m^3/day have been obtained where zones fractured from faulting are intercepted. However, areas with high yields are limited in their extent and bore yields from the granitoid (*Ag*) and gneissic (*An*) basement rocks are typically small (<10-50 m^3/d). The highest yields are obtained from the fractured-zone aquifers where they occur at the base of the weathering profile, commonly at depths of 5-20 m below the weathering front. Bore yields from weathered rock aquifers may be enhanced where the basement rocks are fractured, if the bores are extended up to 10 m into the fractured basement.

High-yielding fractured-rock aquifers are more likely to be detected in the more brittle rocks in the craton, such as Archaean quartzites (*Aq*) and Proterozoic quartz dykes and veins (*Prq*, too small to show on Fig. 7). Quartzite outcrops as irregular boudins or continuous bands in the Bridgetown area. Proterozoic quartz dykes and veins are more widely distributed over the Blackwood Catchment, with higher concentrations in the area adjacent the Darling Scarp, near Nannup. These rocks consist almost entirely of quartz and may hold substantial groundwater in joint and fracture systems. The quality of the groundwater is likely to be fresh to brackish, depending on the quality of the recharge. However, due to their limited dimensions and sporadic occurrence, these rocks represent only a minor groundwater resource, and bore yields are dependent on the amount of recharge and the size and hydraulic conductivity of the aquifer. Yields of up to 498 m^3/d have been recorded from the quartzites near Manjimup on PEMBERTON (Prangley, 1994c).

Locating fractures that are prospective for groundwater is complex and may be assisted through techniques such as interpretation of aerial photographs. In the Blackwood Catchment, the groundwater potential of fractured-rock aquifers has not been investigated in detail apart from a few localities, one of which is the Merilup subcatchment case study (Panasiewicz *et al*., 1997).

3.2.3.3 Case study

One case study for a fractured rock aquifer in the Yilgarn Southwest Province is given below.

3.2.3.3.1 Merilup subcatchment

The Merilup subcatchment is located in the Upper Catchment near the town of Kukerin (Fig. 15). Bore hole BW 15 (Panasiewicz *et al*., 1997), drilled during the Blackwood drilling program, is near a northwest-trending fracture zone parallelling the Pingarning Fault (Myers and Hocking, 1998). Dry granitoid saprolite, grading to grus with depth, was intersected at 7 m and fine-grained granitoid bedrock at 9 m. Drilling continued into the granite bedrock for an additional 9 m to a depth of 18 m, where water-bearing fractures were intercepted. This fractured-rock aquifer is semi-confined to confined; the water level stands at 7.5 m below ground level. The groundwater yield is low, with a short-term pumping test from a pump installed at 17 m depth producing groundwater at only 10 m^3/d, with salinity around 14 500 mg/L.

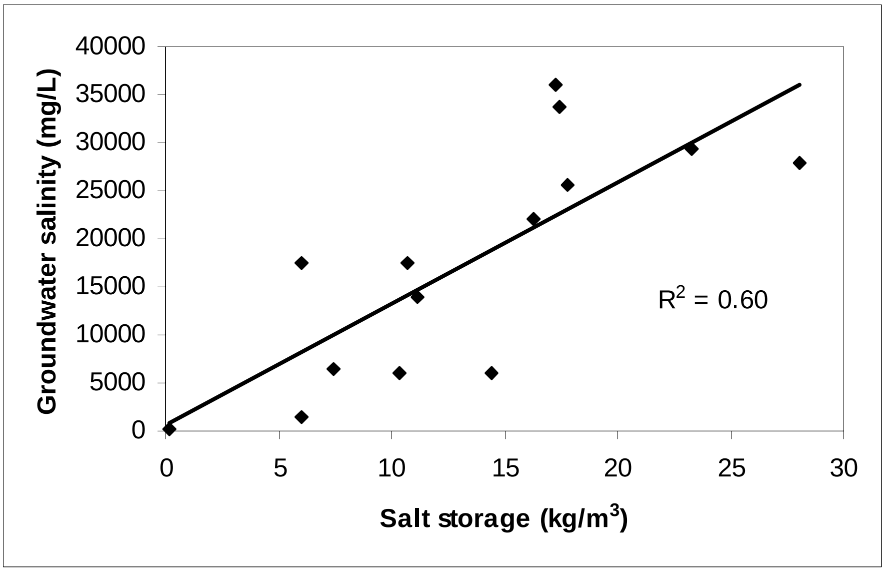


Figure 16. The relationship of regolith salt storage to groundwater salinity in Toolibin bores (De Silva, 1999).

3.3 Boyup Basin

3.3.1 Sedimentary aquifers (*Pcm*)

3.3.1.1 Aquifer materials and location

The Boyup Basin is located on the Yilgarn Craton, approximately 5 km south of the Wilga rail siding (Fig. 17). The basin is fault-bounded to the west and forms an elongate feature with a general north-northwesterly trend. The basin is around 9 km in length and between 2 and 0.5 km wide, with an approximate surface area of 15 km^2 (Yesertener, 1997). The basin comprises remnants of a formerly extensive sedimentary sequence comprising Permian units at the base, partially overlain by Cretaceous and Tertiary sediments (Le Blanc Smith, 1993).

The Permian Boyup Coal Measures (Pcm) and Barrons Sandstone are the main aquifers in the Boyup Basin, forming upper and lower aquifer systems respectively. There is limited hydraulic connection of the two aquifers through faults and fractures (Yesertener, 1997). Recharge through the direct infiltration of rainfall occurs in the northwest of the basin where the aquifers outcrop. Additional recharge takes place where the overlying Cretaceous Boonarie Claystone thins to approximately 8-20 m along the eastern and southeastern section of the basin, and along a fault zone in the western part of the basin (Yesertener, 1997). The basin receives only limited recharge, with the average annual recharge of the upper and lower aquifers having been calculated as 16 950 and 21 500 m^3 respectively (Yesertener, 1997). Insufficient information is available to establish groundwater flow patterns throughout the basin; however, in the northern half of the basin groundwater appears to flow in a northwesterly direction with discharge at Wilgee Spring (Yesertener, 1997).

3.3.1.2 Bore yields and groundwater quality

Groundwater yields and salinities (from limited borehole data) are 39 m^3/day and 3830 mg/L for the upper aquifer and 20 m^3/day and 5280 mg/L for the lower aquifer. Yesertener (1997) calculated total groundwater storage for the basin to be in the order of 350 x 10^6 m^3.

3.4 Perth Basin

Sediments in the southern Perth Basin contain major groundwater resources. They include the Sue Coal Measures (Permian), Sabina Sandstone (Late Permain to Early Triassic), Lesueur Sandstone (Triassic), Cockleshell Gully Formation (Early Jurassic), Yarragadee Formation (Middle to Late Jurassic), and the Cretaceous Warnbro Group (Table 2). The sediments within these formations form multi-layered aquifer systems ranging in thickness from hundreds of metres to several kilometres. These aquifers contain fresh to saline groundwater located at various depths and sites throughout the basin (Commander, 1984; Appleyard, 1991; Baddock, 1994; Thorpe and Baddock, 1994).

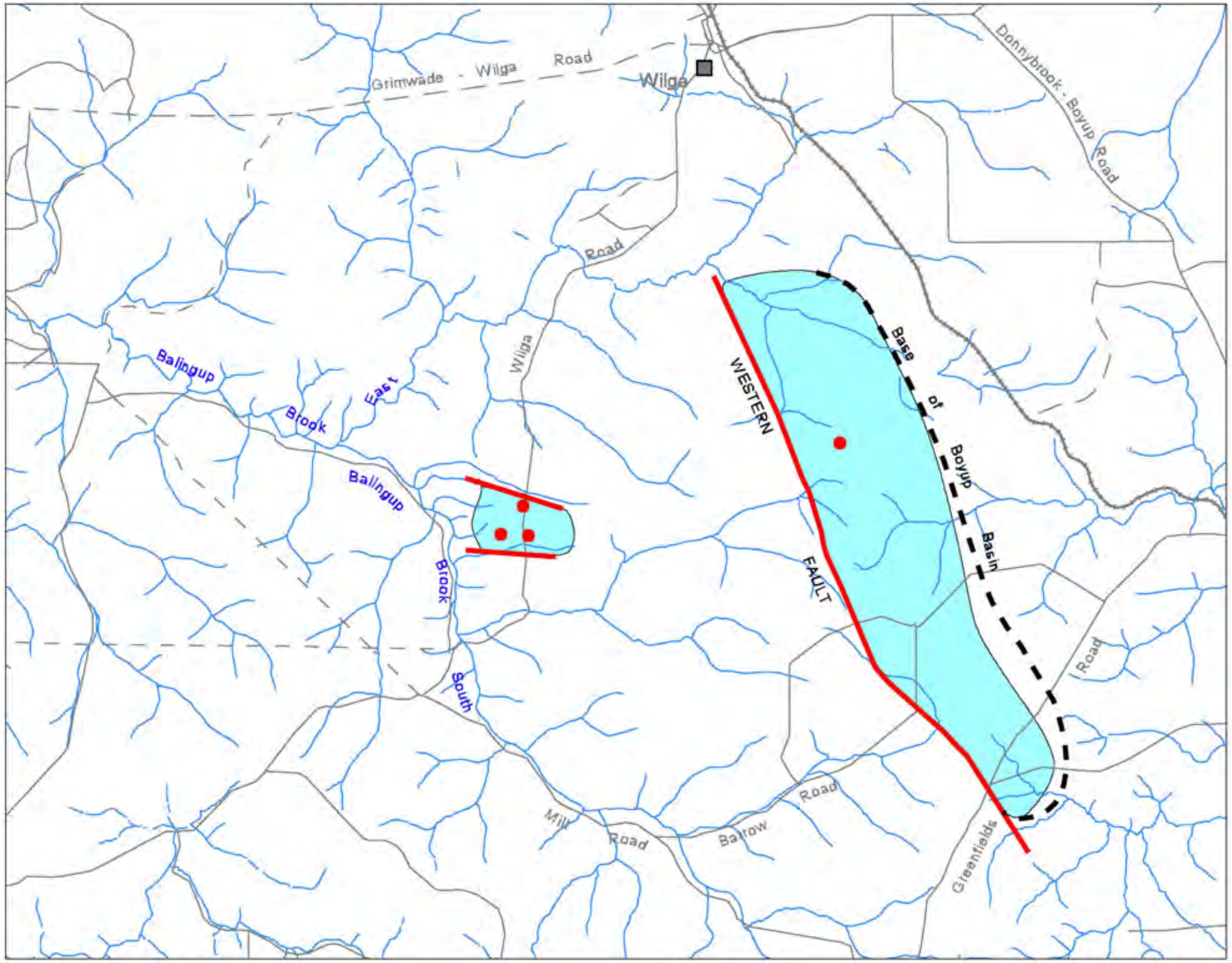
Sedimentary aquifers of significance for the Blackwood Catchment are the Yarragadee Formation and the Warnbro Group (inclusive of the Leederville Formation). The overlying surficial aquifer may also contain substantial groundwater (Table 2). Figure 9 shows the fresh groundwater resources in the southern Perth Basin.

3.4.1 Surficial aquifer (*Qa, Qs*)

Hydraulically connected Quaternary sediments form a relatively thin unconfined aquifer in the southern Perth Basin, with a saturated thickness of less than 10 m (Hirschberg, 1989; Thorpe and Baddock, 1994; Baddock, 1995).

These sediments consist predominantly of sand and limestone in the south and clay and sand in the north. The Safety Bay Sand (eolian and beach calcareous/ quartz sand) and Tamala Limestone (eolian calcarenite) formations constitute the surficial aquifer (*Qs*) in the coastal dune belt on the southwestern margin of the catchment (Fig. 7). To the east, minor groundwater resources occur within the Guildford Formation (Sand and Clay members) (*Qs*). Across the Perth Basin, Quaternary alluvium (sand, silt and clay) (*Qa*) deposited by contemporary landscape processes contains minor groundwater resources (not shown in Fig. 7). Significant groundwater resources in the surficial formations correlate with minimal amounts of clayey sediments.

The thickness of these sediments generally ranges from 3 to 10 m, except in the coastal dune belt where thicknesses reach 200 m. The depth to the watertable varies seasonally between about 0.5 and 3 m (Thorpe and Baddock, 1994). The aquifer is mostly unconfined, but may be confined to semi-confined where the Guildford Formation (Sand member) is indurated through ferruginous cementation. Groundwater recharge is from rainfall infiltration, whilst discharge



Fault
Base of basin
Permian sedimentary aquifer - coal basins
Bore
Town site
Watercourse
Road
Track
Forest track
Railway

N

1 0 1 2 km

WATER AND RIVERS COMMISSION

SCIENCE AND EVALUATION DIVISION

Blackwood Hydrogeological Resource Base

Location of Boyup Basin

FIGURE 17

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occurs in watercourses and wetlands and through evapotranspiration and downward leakage into the underlying aquifers.

3.4.2 Warnbro Group aquifer (*Kw*)

The Warnbro Group sediments form a multi-layered confined aquifer (*Kw*) comprising interbedded shale, silt, clay and, commonly, basal sands. Apart from areas where the sequence has been eroded, the aquifer outcrops or is overlain by surficial sediments of the southern Perth Basin. The thickness of this aquifer varies, but is typically 150 m (Baddock, 1995).

Groundwater recharge to the aquifer is through the direct infiltration of rainfall or downward leakage from the overlying surficial aquifer. Recharge rates of 8.4% of rainfall (approximately 80 mm/a) were estimated by Thorpe and Baddock (1994) for the Blackwood Plateau, where the argillaceous sequences of the aquifer outcrop or subcrop. The water level in this part of the sequence is usually 10 to 30 m below the land surface, commonly reflecting the topography (Baddock,1995).

Groundwater flow patterns within the aquifer are locally complex. Most of the recharge eventually discharges through downward leakage into the Yarragadee Formation. However, discharge into the Blackwood River and valleys of the Blackwood Plateau takes place where local flow systems produce upward hydraulic gradients, generally within the argillaceous sequences of the aquifer.

3.4.3 Yarragadee Formation (*Juy*)

The Yarragadee Formation is the major aquifer in the southern Perth Basin, together with the upper section of the Cockleshell Gully Formation in the Bunbury Trough, and the Lesueur Sandstone and Sue Coal Measures on the Vasse Shelf (Fig. 6) (Thorpe and Baddock, 1994). In the Bunbury Trough, the aquifer thickness is 600 to 1600 m, whereas on the Vasse Shelf it is up to 800 m thick. Sediments within the aquifer generally consist of weakly to well consolidated, fine- to coarse-grained, sandstone. Shale and siltstone interbeds are characteristic of the Cockleshell Gully and Yarragadee Formations, as are sub-bituminous coal seams in the Sue Coal Measures.

The Yarragadee Formation is confined, except where the formation outcrops in the southeastern area of Blackwood Plateau. Recharge is through the direct infiltration of rainfall at outcrop, or downward leakage from the Warnbro Group and surficial sediments on the Scott Coastal Plain (Fig. 3). Thorpe and Baddock (1994) estimated recharge rates of 20% of rainfall (approximately 200 mm/a) in outcrop areas, reducing to 10% of rainfall (approximately 100 mm/a) where surficial sediments overlie the Yarragadee Formation (Thorpe and Baddock, 1994).

Groundwater discharges from the Yarragadee Formation directly into the Southern Ocean near Black Point, but probably discharges into the ocean via overlying formations in the other areas. A substantial volume of groundwater discharges into the Blackwood River, approximately 10 x 10^6 m^3/a between the Darradup gauging station and Leyman Flat (Thorpe and Baddock, 1994).

No testing to determine the hydrogeological properties of the Yarragadee Formation has taken place within the Blackwood Catchment. However, hydraulic conductivity values for the aquifer, estimated in other areas, range from 6 to 20 m/day (Thorpe, 1992; Commander, 1984; Baddock, 1995).

3.5 Leeuwin Province

3.5.1 Surficial aquifer (*Qa, Qs*)

Surficial aquifers overlying the crystalline basement of this province are predominantly Quaternary calcarenites (*Qs*) with minor Quaternary alluvium (*Qa*, not shown on Fig, 7). The calcarenite formation is up to 50 m thick and highly permeable, resulting in a thin saturated thickness commonly less than 1 m, with watertables occurring at depth (Thorpe and Baddock, 1994). Moderate to high groundwater yields may be obtained from saturated thicknesses exceeding 5 m (Thorpe and Baddock, 1994). However, near the coast, where the base of the formation is below sea level, salt water may contaminate fresh groundwater.

3.5.2 Weathered and fractured rock aquifer (*Prn*)

The Proterozoic gneissic and granulitic rocks of the Leeuwin Province develop weathered and fractured rock aquifers similar to those of the gneissic rocks of the Yilgarn Southwest Province.

4 Rising watertables and land salinisation

The identification of areas threatened by rising watertables and land salinisation requires not only an understanding of the location and extent of different aquifer systems, but a knowledge of salt distribution and the processes by which groundwater may mobilise salt (Coram, 1998).

Processes on regional, intermediate and local scales influence the distribution of salt and groundwater flow. Climate, hydrogeology, landform, landuse and vegetation form major regional controls. At smaller scales the relief of the contemporary land surface, the topography of the basement, the thickness of the regolith (weathered profile and overlying surficial sediments), and the presence of geological barriers such as faults, quartz and mafic dykes and aquitards are important (Johnston *et al*., 1983; Martin, 1984; Johnston 1987a,b; Salama *et al*., 1994; George *et al*., 1997; Clarke *et al*., 2000).

All of these controls vary significantly across the Blackwood Catchment, particularly over the Yilgarn Southwest Province. The mapping of the aquifer systems along with contouring depth to water level and salinity provides a regional framework from which smaller scale investigations can be planned to identify local controls on groundwater movement and salt distribution.

4.1 Groundwater recharge and discharge

Rainfall, geology, landform, landuse and vegetation control the amount of rainfall that recharges the regolith (Salama *et al*., 1994). Locally, higher recharge rates occur through preferential pathways such as grus, faults, fractures and joints, zones of higher hydraulic conductivity within the regolith such as quartz 'rich' bands or veins, and vegetation root structures and channels (Johnston, 1987a; Lerner *et al*., 1990).

Recharge rates calculated for the Toolibin subcatchment, in the Upper Catchment, using the groundwater chloride mass balance, are 0.3 and 0.45% of average annual rainfall (De Silva, 1999). This method generally underestimates the recharge as it does not take into account the presence of preferential pathways in the regolith. Other groundwater recharge studies have been conducted in wheatbelt catchments to the northeast of the Blackwood Catchment, which receive less rainfall than the Toolibin subcatchment (<400 mm/a). Here, recharge was found to occur at higher rates, ranging from 6 to 10 mm/a, about 2 to 3% of average annual rainfall, with the highest recharge rates in the deep sandplain and the lowest in the heavy textured mid-slope and valley soils (George, 1992b).

Similar to recharge, groundwater also discharges from regional, intermediate or local-scale flow paths. Regional scale discharge in the Yilgarn Southwest Province takes place in large-scale fractured rock and palaeochannel aquifers. Groundwater discharge from weathered rock aquifers into the palaeochannel and surficial aquifers in the lower landscape is considered intermediate between regional and local scales. Locally, landform and geological barriers affect groundwater flow, influencing the development of hillslope seepage in mid- to upper landscape areas and evapotranspiration from shallow watertables. Likewise, in the southern Perth and Boyup Basins, regional to intermediate- scale processes are represented by the groundwater flow patterns and associated discharge from the sedimentary aquifers.

4.2 Depth to water level maps

The watertable represents a surface below which the pore spaces and fractures within rocks are saturated. It is a dynamic surface which commonly experiences seasonal fluctuations and long-term changes, the latter in response to alterations in the balance of recharge and discharge.

Groundwater-level contours represent the water level of the aquifer closest to the land surface. In the case of the Yilgarn Southwest Province, they represent the water level of the weathered rock aquifer, palaeochannel aquifer or surficial aquifer, assuming unconfined groundwater conditions exist. In the figures and maps in this report the water level is depicted as either point values or contours and is expressed in metres above Australian Height Datum.

Based on historical data and more-recent drilling programs in the Blackwood Catchment, groundwater levels have been determined as ranging from ~20 m beneath the land surface in the upper landscape to less than 2 m below the valley floors. On this basis, depth to water level classes were mapped for <2 m, 2 to 5 m, 5 to 10 m, 10 to 20 m, and >20 m. Of these classes, the <2 m class has the highest environmental significance as it represents a critical depth range in terms of catchment management. In this range, water from the groundwater table is lost through evapotranspiration or capillary evaporation, in the process accumulating salt at the land surface. The water level class, 2 to 5 m, can be also considered as a critical depth range if coupled with a rising watertable trend. Figure 18 shows the distribution of each water level class for the catchment management zones.

4.3 Water level trends-case studies

In the Yilgarn Southwest Province low relief encourages recharge to groundwater. This problem is compounded where low hydraulic gradients fail to cope with the influx of groundwater from increased recharge, resulting in watertable rises and discharge into the lower landscape. Nulsen (1998) reported the following trends of watertable rises in the Blackwood Catchment (for the few bores with groundwater monitoring data):

A bore monitored since 1993 at Dinninup, in the Kitchanning Brook subcatchment, indicates that the groundwater level rose at a rate of 2 m/a, from 24 m bns (metres below natural surface) in 1993 to 18 m bns in 1996. This bore was drilled into granite basement to a depth of 27 m. The locality had been cleared for 15 years (since 1978).

At Duranillin, a bore located in a mid-slope position in the Date Creek catchment (a subcatchment of the Arthur-Blackwood river system), revealed that the water level is rising at an average rate of 0.5 m/a. The water level of the bore was around 14 m bns in 1996. The bore is located in a fracture zone that crosses three surface subcatchments and was drilled into fractured granite basement to a depth of 17 m.

A monitoring bore located in the broad valley flats of the Arthur-Blackwood River system at Capercup has recorded a potentiometric level at 1.5 m above ground level over a four-year period between 1992 and 1996. This steady water level is attributed to groundwater discharging at saline springs nearby combined with below average rainfall in 1993/94. This bore is 14 m deep and was drilled into the margin of a palaeochannel aquifer.

Groundwater levels of the Toolibin Lake subcatchment were monitored in remnant bush and cleared farmland. Groundwater monitoring bores were drilled in 1977 into the surficial and weathered rock aquifers located beneath the broad valley flats. The water level beneath both cleared farmland and remnant bush reserves has risen over the past 17 years. The water level beneath the bush reserve, now 1 m bns, has risen at 0.05 m/a.

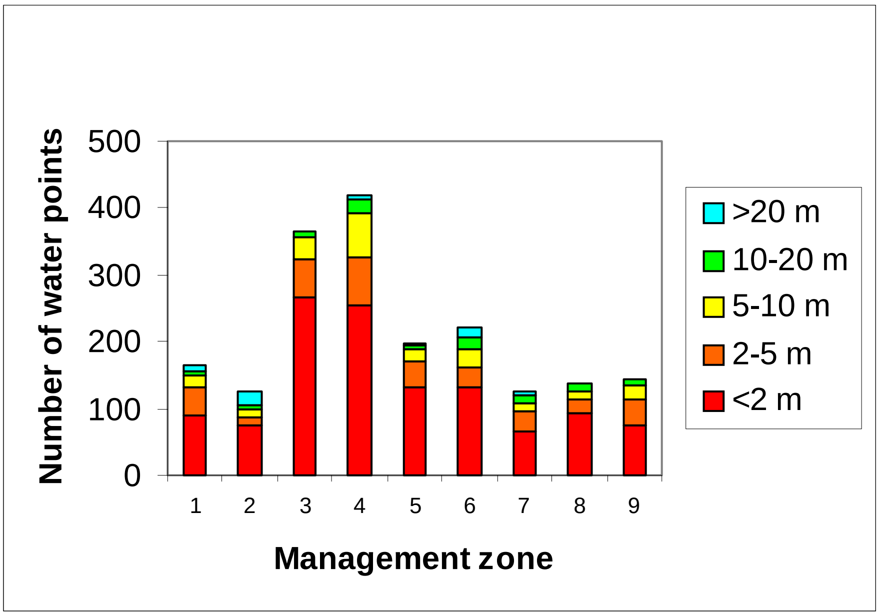


Figure 18. Depth to water level classificaiton

In the Geegalup Brook subcatchment, near the town of Bridgetown, a monitoring bore drilled 14 m into the weathered profile of gneissic rocks has recorded a decrease in groundwater level at a rate of 0.8 m/a since 1992. This decrease in water level was attributed to the area being revegetated with Tasmanian and Sydney Bluegums. Adjacent to the subcatchment, in an area that remains cleared, the water level in another bore continued to rise, and is now between 2 and 3 m bns.

These case studies suggest groundwater levels are rising in both weathered and fractured rock aquifers at Duranillin and Dinninup. The bore with the deepest water level recorded the maximum water level rise, indicating that the groundwater system is not in equilibrium and that reaching a steady state condition may take a long time.

Bores, in Early Tertiary and surficial sediments, that exhibit shallow water levels or above-surface potentiometric heads generally indicate steady water levels. This suggests that the groundwater system associated with these sediments may have reached steady-state conditions. The attainment of these conditions is aided by groundwater discharge from saline springs, water loss from the shallow water levels due to evapotranspiration, and recent below average rainfalls.

4.4 Salinisation

In the Blackwood Catchment, coastal areas receive higher rainfall and, as a consequence, more salt. However, they are generally well drained, with the unsaturated zone regularly flushed by rainfall, which limits the quantity of salt retained within the regolith. Conversely, areas farther inland receive less rainfall and hence less salt fall (Hingston and Gailitis, 1976). More salt is retained in these areas in response to the subdued topography and increased evaporation rates (Fig. 4). Therefore, salt storage within the catchment generally increases from west to east, being greatest in the Upper and Upper-middle Catchments, located in the Yilgarn Southwest Province (Fig. 7). The mobilisation of salt, as the water balance adjusts to changes produced by land clearing, may produce land salinisation. The Yilgarn Southwest Province, by virtue of receiving more salt, possessing heterogeneous aquifers and exhibiting generally subdued relief, is at greater risk of salinisation.

Salama *et al*. (1994) suggested that, at regional scales, the concentration of salt correlates with topographic position, salt stores generally increasing with regolith thickness which tends to increase from upper to lower landscape areas. This association is exacerbated by the movement of groundwater, which follows the bedrock topography, and as a consequence transfers salt into the lower landscape (Martin, 1984). At smaller, or local scales, there is a more complex pattern of salt storage across the landscape. The movement and concentration of salt by groundwater is influenced by local variations in bedrock topography and changes in hydraulic conductivity, the latter determined primarily by the fabric, texture and mineralogy of the basement rocks (Johnston, 1987a,b).

Increased recharge as a consequence of land clearing increases groundwater movement in zones of higher hydraulic conductivity. This often results in the saturation of the saprolite in lower landscape areas and the mobilisation of salt from previously unsaturated zones. Leaching of salt may also take place in mid- to upper landscape positions as the watertable continues to rise. As the watertable rises to depths of less than 2 m, capillary discharge and evaporation of groundwater concentrates salt in the shallow soil layer.

Watertable rises and salinisation also affect water quality within the palaeochannel aquifers in the Yilgarn Southwest Province. Where these sediments occupy poorly drained broad valleys, groundwater salinities are typically high (>7000 mg/L). Increased recharge to these sediments from the adjacent weathered profile of granitoid and gneissic basement rocks may result in the deterioration of localised fresh water within these channels (Clarke *et al*., 2000). Depending on hydraulic gradients, the thickness of the sediments and the hydraulic conductivity of overlying sediments (where they are present), the watertable may rise and groundwater discharge at the land surface (George *et al*., 1994; Clarke, 1998). Palaeochannel sediments situated upslope and across surface water divides are less likely to suffer a decline in water quality. These aquifers are only partially confined and tend to contain brackish to fresh groundwater as a consequence of receiving increased recharge from rainfall.

Salinity in the surficial aquifers in the Yilgarn Southwest Province generally increases from west to east, following much the same trend as weathered and fractured basement aquifers. In the western part of the Province, adjacent to the Darling Scarp, groundwater is fresh to brackish. This reflects both the high rainfall and runoff, the latter due to a high proportion of outcrop. Most supplies in these areas are from shallow bores and springs and are therefore not an indication of groundwater salinity deeper in the regolith. Farther east, groundwater salinity increases significantly with decreasing rainfall, larger areas of weathered bedrock aquifers, and poorer drainage. In particular, groundwater in swamps and playa lakes, formed in depressions in the landscape and drainage lines, has become particularly saline through evaporation and the leaching of salts from higher areas to areas downslope. In most eastern areas, groundwater salinity around drainage lines exceeds 7000 mg/L and in some areas exceeds 14 000 mg/L.

In the southern Perth Basin the areas vulnerable to salinisation are generally restricted to specific lithologic and geomorphic zones. Groundwater salinities in the major confined sedimentary aquifers, the Leederville Formation (lower sequence of the Warnbro Group aquifer) and Yarragadee Formation aquifers, are fresh and mostly below 500 mg/L (Baddock, 1995). Groundwater salinity within the unconfined surficial aquifer varies. For example in coastal areas, with high rainfall and generally well drained sediments, the salinity is between 200 and 530 mg/L. Areas vulnerable to salinisation are mainly restricted to poorly drained areas inland from the coastline where salts are stored in shallow watertables in the surficial sediments. At times of high rainfall lakes form, with ensuing evaporation concentrating the salt within the groundwater and increasing the salinity at the watertable.

4.5 Groundwater salinity maps

Groundwater salinity within the Blackwood Catchment ranges from 300 to 35 000 mg/L. These values represent the salinity of the groundwater at or close to the watertable, in the sense that they are indications of salinities that would be expected from a shallow pumping bore. Groundwater salinity is categorised in Table 4 according to the possible usage of groundwater, and Figure 19 shows the distribution of these salinity categories for each of the catchment management zones.

Table 4. Groundwater salinity ranges and potential use

Groundwater salinity (mg/L)	*Possible usage*
<500	Good potable.
500 - 1000	Marginal potable, most plants, direct adverse biological affects in river, stream and wetland ecosystems around 1000 mg/L, and good quality for stock.
1000 - 3000	Some plants depending on crop, soils and drainage, and good quality for stock.
3000 - 7000	Acceptable for most stock requirements, and some irrigation.
7000 - 14 000	For some stock but careful animal health monitoring required.
>14 000	No agricultural use, potential for careful industrial and mining use.

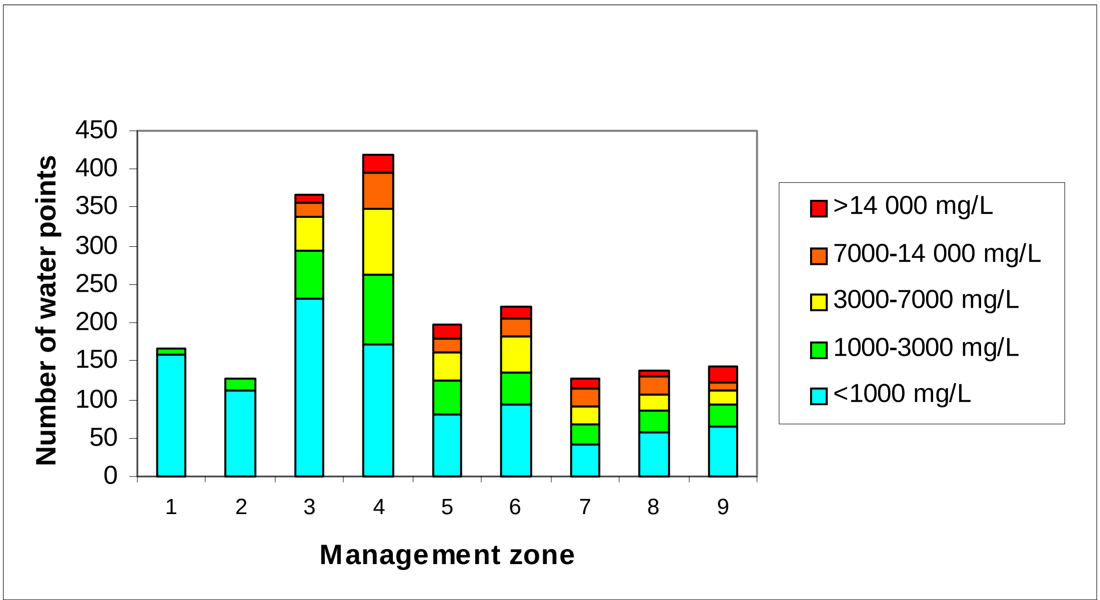


Figure 19. Groundwater salinity classificaiton

5 Distribution of salinity at the watertable

The distribution of salinity at the watertable for the Blackwood Catchment was modelled using groundwater salinity and groundwater level datasets (Fig. 20). Only water points drilled to depths exceeding 2 m were used in the modelling. This was to ensure water level observations correspond to the regional watertable, as opposed to surface water and shallow perched aquifer systems that commonly supply water to dams, soaks and springs. Management Zones 3 through to 9, where the rising watertable and salinisation pose the most serious threat, are discussed in detail in this section.

In each of Figures 21 to 27, for Management Zones 3 through to 9, two histograms display statistics of salinity variation in relation to depth to water level classes (<2 m, 2-5 m, 5-10 m, 10-20 m, and >20 m). One of the graphs displays water point information from both shallow (<=2 m depth) and deep (>2 m depth) water points, and the other displays data for the water points used in the modelling (>2 m depth). This information is presented in separate graphs to show how shallow water point information may bias statistics that relate to the regional watertable.

5.1 Summary: Management Zone 3

5.1.1 Landform/physiography

Management Zone 3 is the largest zone, covering an area of 3640 km^2 which extends through the shires of Bridgetown-Green Bushes, Boyup Brook, West Arthur and Donnybrook-Balingup (Fig. 21). This zone is located in the Lower-middle Catchment, within the western and eastern Darling Range landscapes (Fig. 3). The western Darling Range landscape is characterised by broad undulating lateritic plateau with deep incised valleys of the Blackwood River. The well-developed dendritic drainage system, with high frequency of drainage lines per unit area, that drains this zone is in contrast to the less efficient drainage of other management zones. The eastern Darling Range is typified by undulating to rolling, dissected terrain with many large remnants of the lateritic plateau. Lake systems developed in the eastern areas, near Kulikup and Qualeup, are marked by extensive flats and sluggish drainage. Broad, flat areas of Tertiary sediments have been mapped in higher landscape positions, such as surface-water divides (Grein, 1995).

5.1.2 Relief

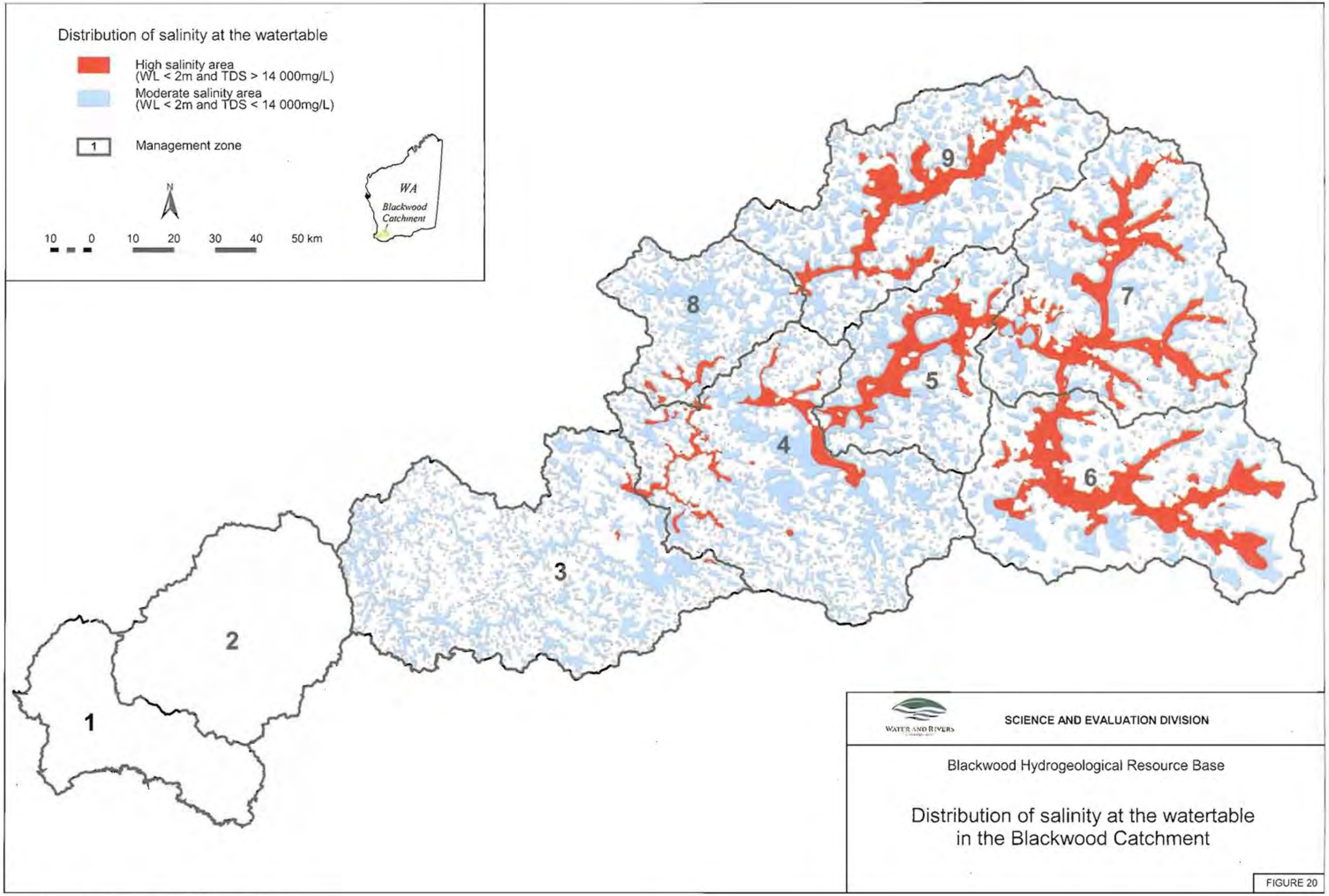
The western margin of this zone is coincident with the transitional boundary of the Lower-middle Catchment and Donnybrook Sunklands and is characterised by low relief (Fig. 3). Immediately inland from this area relief increases, as do the slopes. Farther east, the steepness of slopes decreases and there is a reduction in relief. Here, lower topographic gradients have lessened the effectiveness of the river systems to remove weathered and transported material from the craton, resulting in the accumulation of Tertiary, Cainozoic and Quaternary sediments, generally in the lower landscape.

5.1.3 Climate

There is a forty percent reduction in annual average rainfall across the management zone, decreasing from 1000 mm on the western margin to 600 mm near the eastern boundary. Measured pan evaporation (class A) generally increases eastwards from the western boundary, ranging from approximately 1250 to 1500 mm/a. However, there are localised variations within all of the management zones, for example the town of Bridgetown, in the middle of this zone, records an evaporation of approximately 1400 mm/a (Fig. 4).

5.1.4 Hydrogeology

Weathered and fractured granitoid, gneissic and quartzite basement rock aquifers occupy the greater part of this zone. Other aquifers include the Permian sedimentary aquifers within the Boyup Basin, the Tertiary sedimentary aquifer in the Qualeup Palaeochannel, and the surficial aquifers which generally relate to either palaeo- or modern drainage systems. Sedimentary and surficial aquifers tend to be located in lower landscape areas (<210 m AHD) where groundwater levels range from 0.1 to 5.0 m below ground level, with corresponding salinities of 100 to 11 000 mg/L. At higher elevations (>300 m AHD) groundwater levels range from 0.7 to 11.5 m bns, with salinities ranging from 90 to 16 000 mg/L. A number of bores drilled in upper landscape areas show potentiometric heads up to 0.2 m above the land surface.



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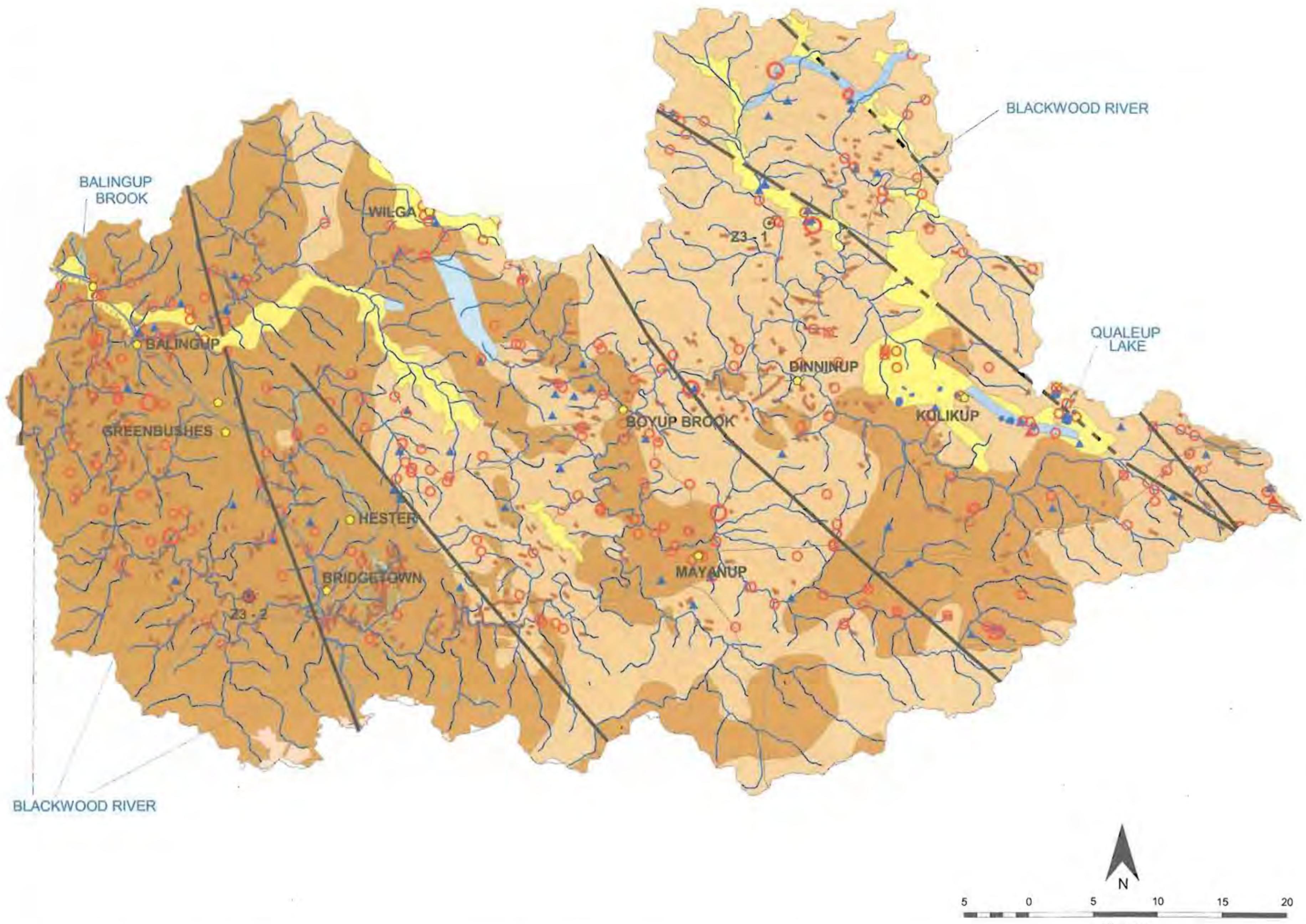

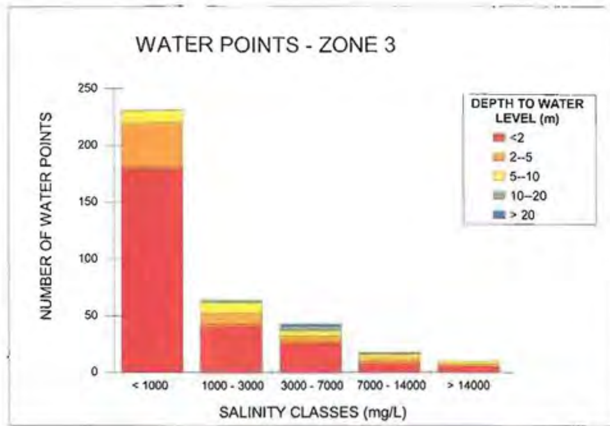

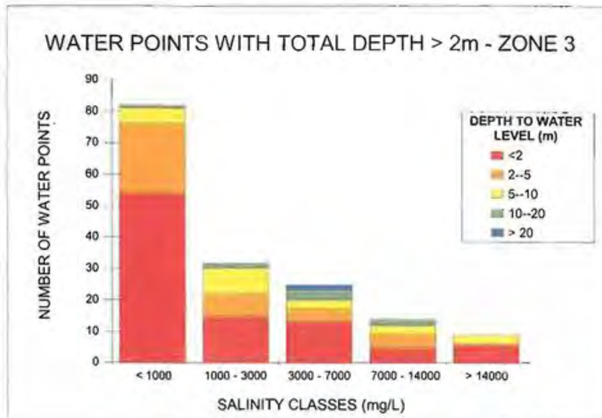

Water points with salinity risk

- TDS ≥ 14 000 mg/L WL < 2m: grouped points; single points
- TDS ≥ 14 000 mg/L: grouped points; single points
- WL < 2m: grouped points; single points
- Points with potentiometric surface above ground level

Low salinity risk points

- Water points that have total depth > 2m and TDS < 1000 mg/L: grouped points; single points

NOTE: grouped points refer to more than 2 points within a 1km radius.

Symbols

- Highway
- Main road
- Railway
- Topographic contour - 50m
- Town centre
- Fault; concealed
- Watercourse
- Water body
- Z3-1 Monitoring bore

Aquifer types

- Surficial aquifer
- Surficial aquitard
- Palaeochannel aquifer
- Permian sedimentary aquifer - coal basins
- Weathered rock aquiclude - dolerite dykes
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks
- Fractured rock aquifer - quartzites

WATER AND RIVERS

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Distribution of salinity at the watertable in Management Zone 3

FIGURE 21

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5.1.5 Water level trends

Nulsen (1998) discussed water level trends at several sites in this management zone. Site Z3-1, cleared in 1978, displays groundwater level rises of 2 m/a. In contrast groundwater levels at site Z3-2 have been falling since the affected area has been revegetated, demonstrating the effect of revegetation (Fig. 21). Groundwater monitoring results are available for the Qualeup Palaeochannel in the Kulikup area (Fig. 21). Water levels are rising at all sites in both the weathered rock aquifer and palaeochannel aquifer at an average rate of 0.27 m/a, except for bore QK1 where there is small decline in water level, and QK5 with a steady water level (Fig. 11) (George and Bennett, 1995).

5.1.6 Geological barriers

There is a higher proportion of outcrop on the western margin of the Yilgarn Southwest Province, which influences runoff and therefore affects recharge. Outcrop and subcrop overlain by thin regolith may also assist in the development of mid-slope seepage areas. This occurs where the saprolite in the weathered rock aquifer (upslope of outcrop/subcrop) becomes saturated, with groundwater subsequently discharging at the land surface as it moves down gradient. Bands of quartzite near the Bridgetown area may form fractured rock aquifers but may also impede and re-direct groundwater flow. Likewise, dolerite dykes, either coincident with or cutting major drainage lines, can form geological barriers to groundwater flow and may be potential sites for the development of land salinisation (Fig. 21). However, owing to the limited distribution of bores, it is not clear what role the dykes play in regards to groundwater flow and salinisation.

5.1.7 Water point distribution

Management Zone 3 contains the highest number of water point data. The area modelled as being of high environmental significance in this management zone is over 28% (Fig. 20). However, over 57% of water points drilled to depths of over 2 m have shallow water levels (<2 m) and less than 4% of these data have groundwater salinities exceeding 14 000 mg/L (Fig. 21). Fresh, deep groundwater (>2 m) occurs in a range of landscape positions, but generally groundwater supplies, particularly in the western half of this zone, are derived from shallow bores and springs in mid- to upper landscape positions. Many of these water points do not indicate groundwater salinity deeper in the regolith and are currently fresh to brackish. This makes them susceptible to salinisation in the future if the watertable rises in saline deeper weathered rock aquifers. Major water points in the lower landscape target the surficial and palaeochannel aquifers, biasing the sampling of data in these landscape positions (Fig. 21). The surficial and palaeochannel aquifers are continuing to be monitored to assess the impact of the rising watertable in the adjacent weathered rock aquifers.

5.2 Summary: Management Zone 4

5.2.1 Landform/physiography

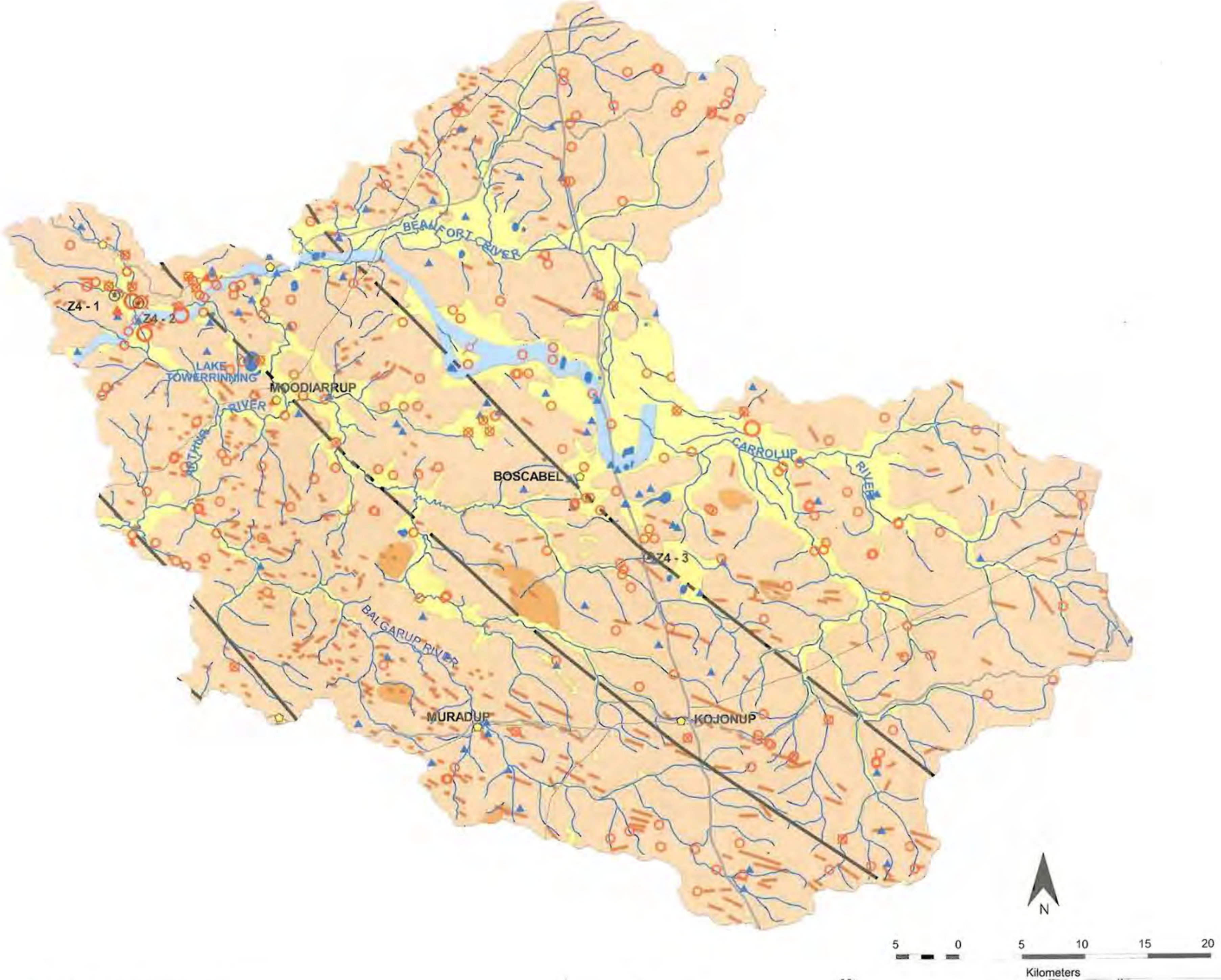
Management Zone 4 covers an area of 3390 km² within the shires of West Arthur, Kojonup and Broomehill (Fig. 22). This zone is mainly in the southern Upper-middle Catchment, the Zone of Rejuvenated Drainage (Fig. 3). The northeastern area extends into the Lower-middle Catchment within the eastern Darling Range sector. The landscape is characterised by gently undulating rises, low hills, narrow incised valleys and broad flats. Carrolup, Balgarup, Beaufort and Arthur Rivers are the major watercourses; the Arthur and Balgarup Rivers combine in this zone to form the Blackwood River. In the north and northeastern areas, lake systems develop within the broad flats in reponse to low topographic gradients. Lake Towerrinning is one of the major lakes within this zone.

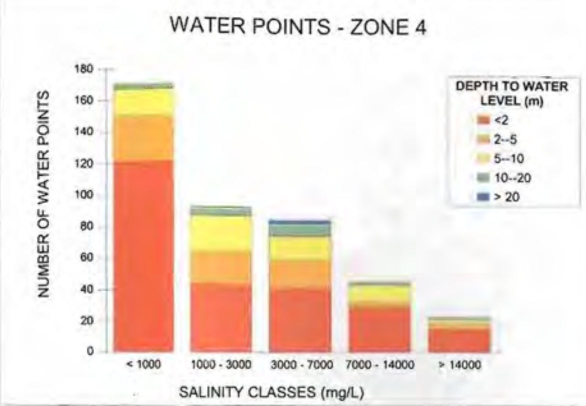
5.2.2 Relief

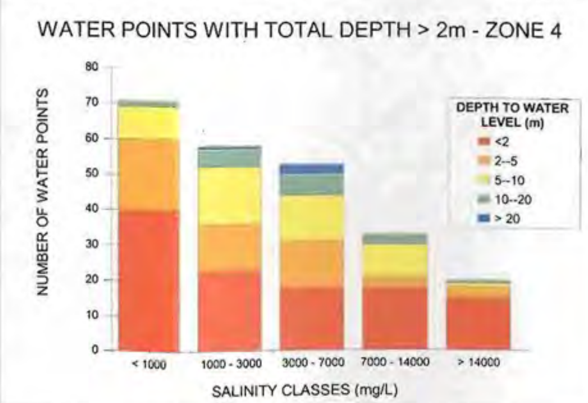
Relief is similar to that of the eastern area of Management Zone 3. Major differences relate to the extensive nature of the broad flats (characterised by slopes of less than 1 in 100) which form some 24% of the zone (826 km²) (Fig. 3). Approximately 20 km² of these areas are subject to seasonal inundation which raises their salinisation potential. This is supported by a soil and landform study by Grein (1995), who reported that about 20% of the land area in the broad flats of the Beaufort River and the downstream parts of the Carrolup River is affected by secondary salinisation.

5.2.3 Climate

There is little variation in rainfall; the average annual rainfall across the zone is approximately 500 mm; higher rainfall (600 mm) is received in the northwestern area. Likewise, measured pan evaporation (class A) is fairly constant at around 1600 mm/a (Fig. 4).







Water points with salinity risk

- TDS ≥ 14 000 mg/L WL < 2m: grouped points; single points
- TDS ≥ 14 000 mg/L: grouped points; single points
- WL < 2m: grouped points; single points
- Points with potentiometric surface above ground level

Low salinity risk points

- Water points that have total depth > 2m and TDS < 1000 mg/L: grouped points; single points

NOTE: grouped points refer to more than 2 points within a 1km radius.

Symbols

- Highway
- Main road
- Railway
- Topographic contour - 50m
- Town centre
- Fault; concealed
- Watercourse
- Water body
- Z4-1 Monitoring bore

Aquifer types

- Surficial aquifer
- Palaeochannel aquifer
- Weathered rock aquiclude - dolerite dykes
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks

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Distribution of salinity at the watertable in Management Zone 4

FIGURE 22

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5.2.4 Hydrogeology

Weathered and fractured granitoid and gneissic basement rock aquifers occupy most of this zone. Palaeochannel aquifers are located in the Beaufort Palaeochannel, whereas surficial aquifers are typically constrained to the broad flats in the lower landscape. At low elevations (<250 m AHD), the depth to water level ranges from 0.3 to 20 m, with salinities of 115 to 21 700 mg/L. Potentiometric heads of up to 0.70 m above ground level are also evident. In the upper landscape (>300 m AHD), depth to water level is between 0.2 and 23 m, with salinities ranging from 70 to 15 300 mg/L TDS.

5.2.5 Water level trends

Groundwater trends are detailed from three sites studied by Nulsen (1998) (Table 5). Groundwater levels are steady in bore Z4-1. Lower rates of groundwater movement at this site are influenced by its location in a potential zone of low hydraulic conductivity, at the margin of the surficial/palaeochannel and weathered rock aquifers. However, if potentiometric heads continue to rise in mid- to upper landscape areas, saline groundwater from the adjacent weathered rock aquifers may recharge fresh to brackish water resources within the surficial aquifer and groundwater levels could rise (Nulsen, 1998). Water level trends for the weathered rock aquifer, under two different landuse conditions (annual pasture and alley farming), were determined from monitoring bores at sites, Z4-2 and Z4-3. Trees in the alley farming area have lowered the watertable in the late summer, autumn and early winter periods (Nulsen, 1998).

5.2.6 Geological barriers

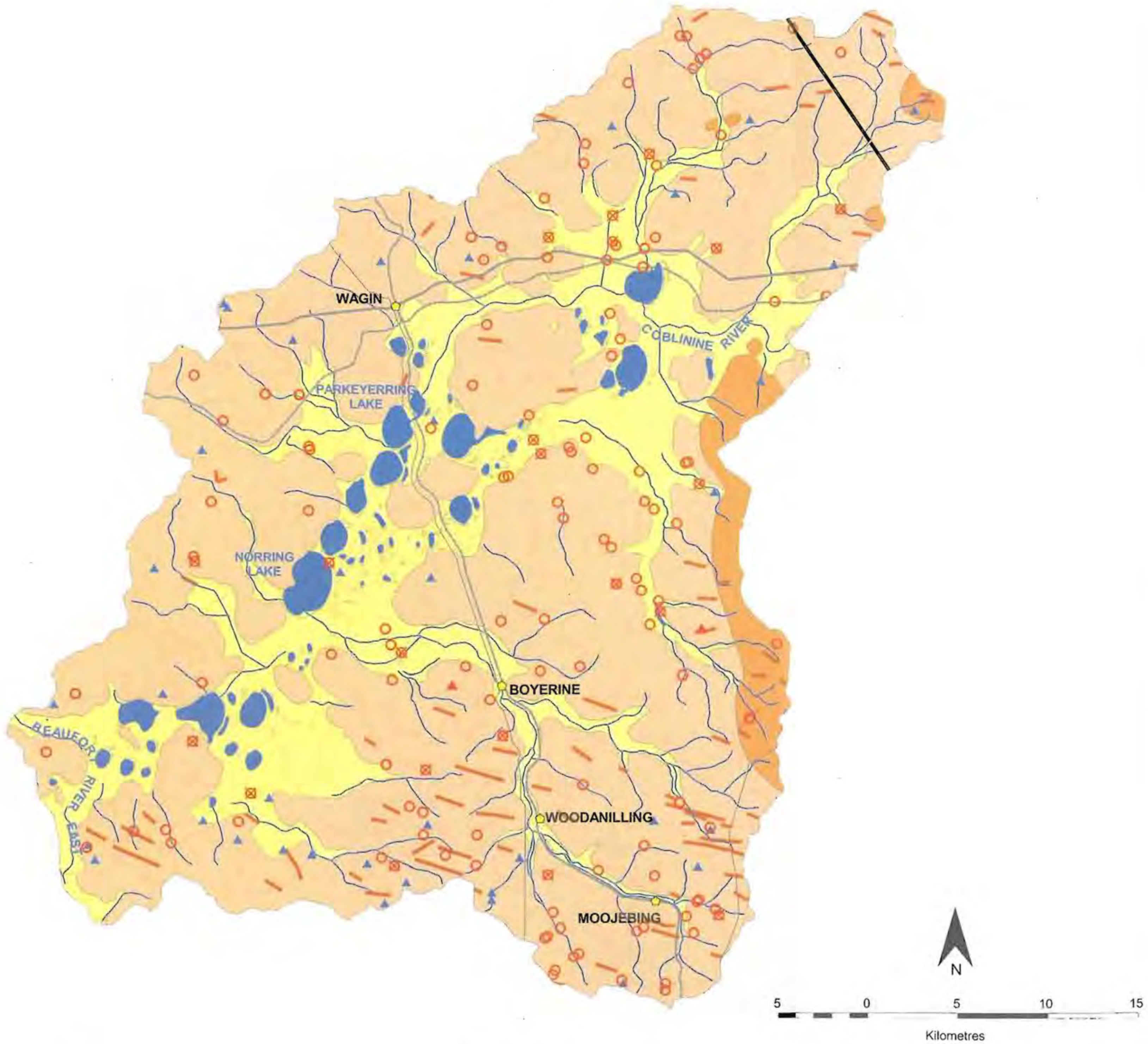
Dolerite dykes, displaying dominant northwesterly orientations, can form geological barriers to groundwater movement and may form sites for the development of land salinisation (Fig. 22). However, owing to the limited distribution of bores, it is not clear what role the dykes play in regard to groundwater movement and salinisation. Similarly, northwest-trending faults that cross this management zone may form fractured rock aquifers but may also impede and redirect groundwater flow and therefore influence salinisation.

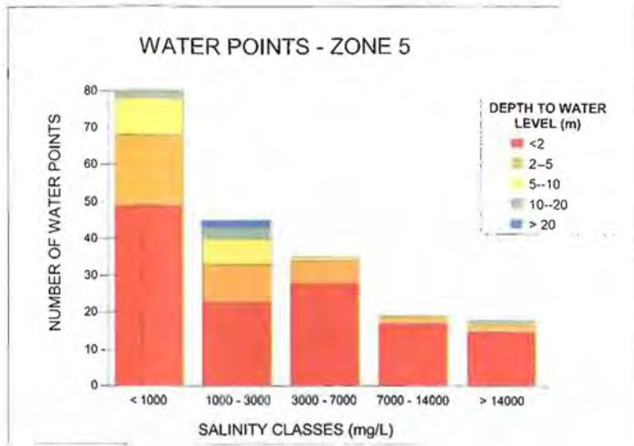
5.2.7 Water point distribution

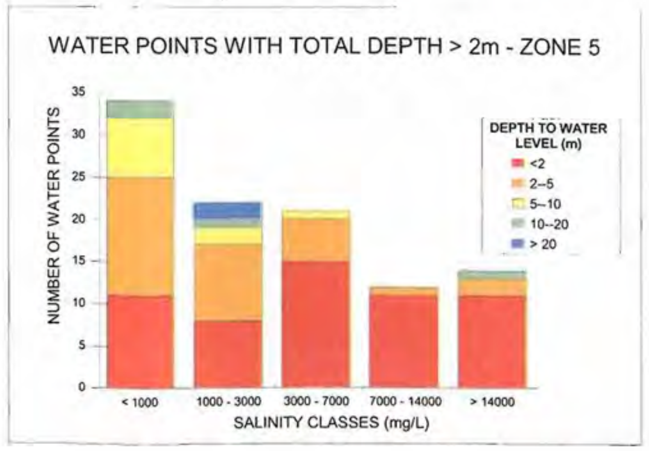
This zone is of a similar size to Management Zone 3 but has approximately 30% fewer water point data. However, the data sample the range of landscape positions as well as the different aquifers. The area modelled as being of high environmental significance is almost 40% (Fig. 20). Over 48% of the water points drilled to depths greater than 2 m have shallow water levels (<2 m) and less than 7% of these data have groundwater salinities exceeding 14 000 mg/L (Fig. 22). Fresh, deep groundwater (>2 m) occurs in a range of landscape positions. Shallow groundwater with high salinities is more common in lower landscape positions, in palaeochannel or surficial aquifers. These aquifers yield groundwater of variable quality, generally reflecting the heterogeneity of the aquifer materials, their degree of interconnection and the source of recharge. Groundwater quality of the fresh to brackish sections of the surficial or palaeochannel aquifers may deteriorate in the future. This could occur where increased recharge to the adjacent saline weathered rock aquifers subsequently recharges (via throughflow) the surficial or palaeochannel aquifers. Groundwater levels could also rise as a consequence (Nulsen, 1998). These areas are continuing to be monitored to assess water level and quality trends.

Table 5. Groundwater trends in monitoring bores in Management Zone 4 (Nulsen, 1998)

Bore location	*Map reference*	*Water level trend*	*Groundwater salinity (mg/L)*	*Depth to water level (m bns)*	*Remarks*
Scott Road, Capercup	Z4-1	Static	5 475	1.5	palaeochannel margin
Scott Road, Capercup	Z4-2	falling	13 000	2.0	alley farming
Scott Road, Capercup	Z4-2	static	10 500	1.0	annual pasture
Bailye Road, Kojonup	Z4-3	falling	1 250	4.0	tree plantation
Bailye Road, Kojonup	Z4-3	static	1 250	2.8	annual pasture







Water points with salinity risk

- TDS ≥ 14 000 mg/L WL < 2m: grouped points; single points
- TDS ≥ 14 000 mg/L: grouped points; single points
- WL < 2m: grouped points; single points
- Points with potentiometric surface above ground level

Low salinity risk points

- Water points that have total depth > 2m and TDS < 1000 mg/L: grouped points; single points

NOTE: grouped points refer to more than 2 points within a 1km radius.

Symbols

- Highway
- Main road
- Railway
- Topographic contour - 50m
- Town centre
- Fault; concealed
- Watercourse
- Water body

Aquifer types

- Surficial aquifer
- Weathered rock aquiclude - dolerite dykes
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks

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Distribution of salinity at the watertable in Management Zone 5

FIGURE 23

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5.3 Summary: Management Zone 5

5.3.1 Landform/physiography

Management Zone 5 covers an area of 1630 km² within the shires of Woodanilling and Wagin (Fig. 23). This zone is mainly in the Upper-middle Catchment, the Zone of Rejuvenated Drainage (Fig. 3). The northwestern area extends into the Zone of Ancient Drainage in the Upper Catchment. The landscape is characterised by gently undulating to undulating rises, low hills and the broad flats of the Coblinine River and Beaufort River East. A northeast-trending salt lake system, including the Norring and Parkeyerring Lakes, occupies the central part of the management zone.

5.3.2 Relief

Relief is similar to that of Management Zone 4. The extent of the broad flats (characterised by slopes of less than 1 in 100) increases to 32% of the zone area (520 km²) (Fig. 3). Approximately 96 km² of these areas are subject to seasonal inundation which raises their salinisation potential. Grein (1995) estimates that at least 60% of the land in the flats of Beaufort River East and the lower reaches of Boyerine Creek is affected by secondary salinisation, with much of the remainder at high risk of salinisation and waterlogging.

5.3.3 Climate

There is little variation in rainfall; the average annual rainfall across the zone is approximately 450 mm. Likewise, measured pan evaporation (class A) is fairly constant at around 1700 mm/a throughout the zone (Fig. 4).

5.3.4 Hydrogeology

Weathered and fractured granitoid and gneissic basement rock aquifers occupy the greater part of this zone. Surficial and palaeochannel aquifers are generally constrained to the broad flats in the lower landscape where they correlate with either palaeo- or modern drainage systems. At low elevations (<280 m AHD), the depth to water level ranges from 0.1 to 20 m with salinities of 100 to 46 000 mg/L. In the upper landscape (>330 m AHD), depth to water level is between 0.6 and 24 m, with salinities ranging from 90 to 10 000 mg/L.

5.3.5 Water level trends

Water level trends have not been reported for this management zone.

5.3.6 Geological barriers

Westerly to northwesterly-trending dolerite dykes can act as geological barriers to groundwater movement and form potential sites for the development of land salinisation (Fig. 23). However, owing to the limited distribution of bores it is not clear what role the dykes play in regard to groundwater movement and salinisation.

5.3.7 Water point distribution

This zone is approximately 45% smaller in area than Management Zone 3 and has some 40% fewer water point data. The water point data sample the range of landscape positions for most of the aquifers. The area in Management Zone 5 modelled as being of high environmental significance is over 46% (Fig. 20). Over 54% of water points drilled to depths greater than 2 m have shallow water levels (<2 m) and less than 11% of these data have groundwater salinities exceeding 14 000 mg/L (Fig. 23). Fresh, deep groundwater (>2 m) is more prevalent in the mid- to upper landscape areas. Shallow groundwater with high salinities is more common in the surficial and palaeochannel aquifers where local to intermediate groundwater flow systems operate (Fig. 23).

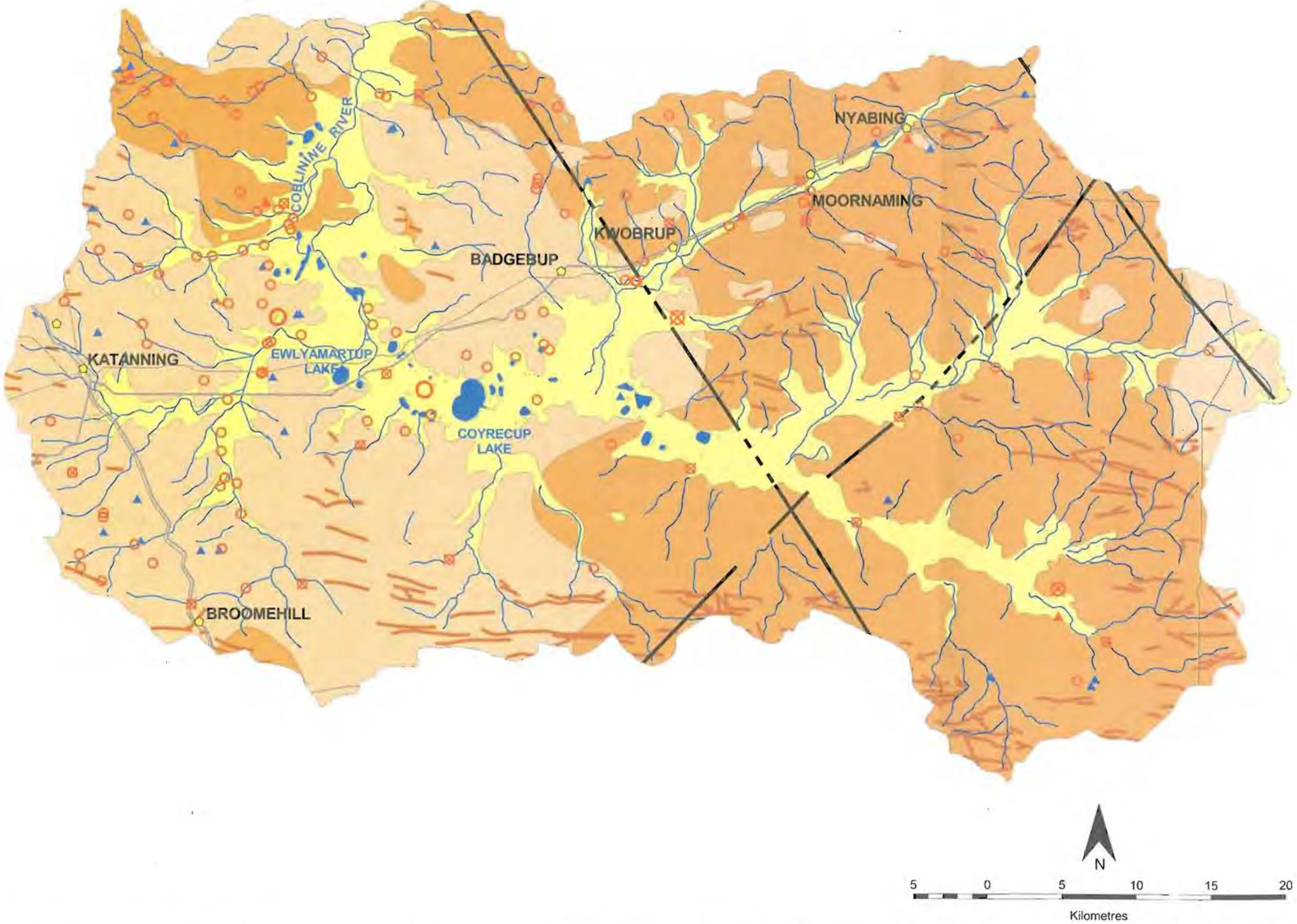
5.4 Summary: Management Zone 6

5.4.1 Landform/physiography

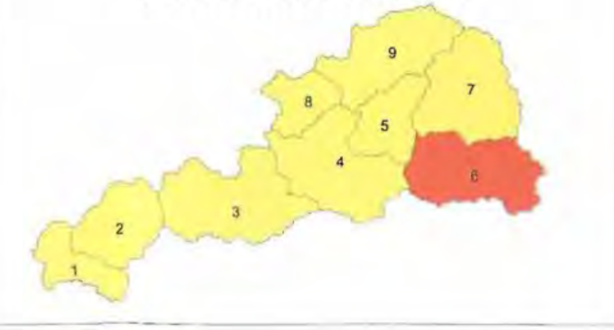
Management Zone 6 covers an area of 3069 km² within the shires of Katanning, Kent, Gnowangerup and Broomehill (Fig. 24). This zone lies mainly in the Zone of Ancient Drainage in the Upper Catchment (Fig. 3). The landscape is gently undulating with subdued relief. The zone is drained by the north- to northeast-trending Coblinine River and its tributaries, which occupy the broad flat-floored valleys. A salt lake system, including lakes Coyrecup and Ewlyamartup, occupies the central part of this management zone.

5.4.2 Relief

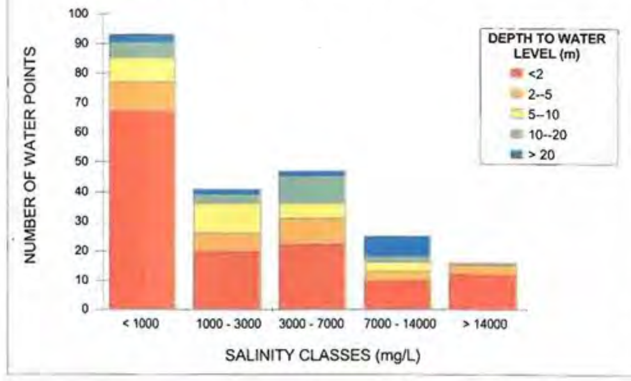
Broad flats and valleys (characterised by slopes of less than 1 in 100) constitute approximately 48% of the zone (1480 km²) (Fig. 3). Some 155 km² of the Coblinine River alluvial plain is subject to seasonal inundation which raises the salinisation potential of this area (Grein, 1995).



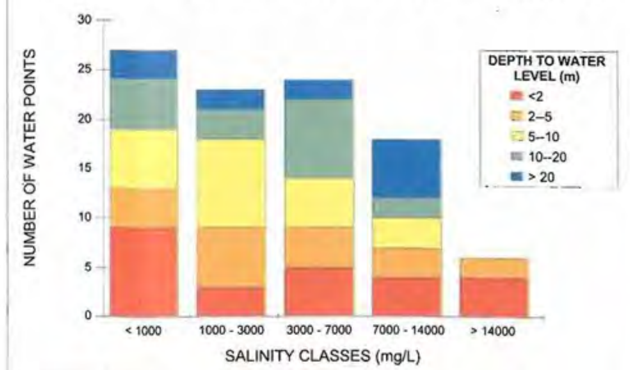
LOCATION OF ZONE 6 WITHIN THE BLACKWOOD CATCHMENT



WATER POINTS - ZONE 6



WATER POINTS WITH TOTAL DEPTH > 2m - ZONE 6



Water points with salinity risk

- TDS ≥ 14 000 mg/L WL < 2m: grouped points; single points
- TDS ≥ 14 000 mg/L: grouped points; single points
- WL < 2m: grouped points; single points
- Points with potentiometric surface above ground level

Low salinity risk points

- Water points that have total depth > 2m and TDS < 1000 mg/L: grouped points; single points

Symbols

- Highway
- Main road
- Railway
- Topographic contour - 50m
- Town centre
- Fault; concealed
- Watercourse
- Water body

Aquifer types

- Surficial aquifer
- Weathered rock aquiclude - dolerite dykes
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks

NOTE: grouped points refer to more than 2 points within a 1km radius.

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Distribution of salinity at the watertable in Management Zone 6

FIGURE 24

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5.4.3 Climate

There is little variation in rainfall; the average annual rainfall across the zone ranges from 500 to 400 mm, with the town of Katanning receiving 483 mm. Likewise, measured pan evaporation (class A) is fairly constant at around 1700 to 1800 mm/a throughout the zone (Fig. 4).

5.4.4 Hydrogeology

Weathered and fractured granitoid and gneissic basement rock aquifers occupy most of Management Zone 6. Surficial and palaeochannel aquifers are largely constrained to the broad flats in the lower landscape where they correlate with either palaeo- or modern drainage systems. At low elevations (<290 m AHD) the depth to water level ranges from 0.2 to 16 m, with salinities of 105 to 33 000 mg/L. In the upper landscape (>330 m AHD), depth to water level is between 0.3 and 41 m, with salinities ranging from 90 to 12 500 mg/L.

5.4.5 Water level trends

Water level trends have not been reported for this management zone.

5.4.6 Geological barriers

Westerly to northwesterly-trending dolerite dykes can form geological barriers to groundwater movement and may be potential sites for the development of land salinisation (Fig. 24). However, owing to the limited distribution of bores, it is not clear what role the dykes play in regard to groundwater movement and salinisation. Similarly, northwest-trending faults that cross this management zone may form fractured rock aquifers but may also impede and redirect groundwater movement and therefore influence salinisation.

5.4.7 Water point distribution

This zone is approximately 15% smaller in area than Management Zone 3, but has 40% fewer water point data. The data, particularly in the eastern half of the zone, are fairly sparse. Most drilling is located in the surficial and palaeochannel aquifers in the lower landscape areas or near drainage lines. The area in Management Zone 6 modelled as being of high environmental significance is about 39% (Fig. 20). Over 26% of water points drilled to depths greater than 2 m have shallow water levels (<2 m) and less than 6% of these data have groundwater salinities exceeding 14 000 mg/L (Fig. 24). Fresh, deep groundwater (>2 m) is more prevalent in the mid- to upper landscape areas in the weathered granitoid rock aquifer. Shallow groundwater with high salinities is more common in the surficial and palaeochannel aquifers (Fig. 24). In these aquifers variable groundwater quality generally reflects hydraulic gradients, the heterogeneity of the aquifer materials, their degree of interconnection and the source of recharge.

5.5 Summary: Management Zone 7

5.5.1 Landform/physiography

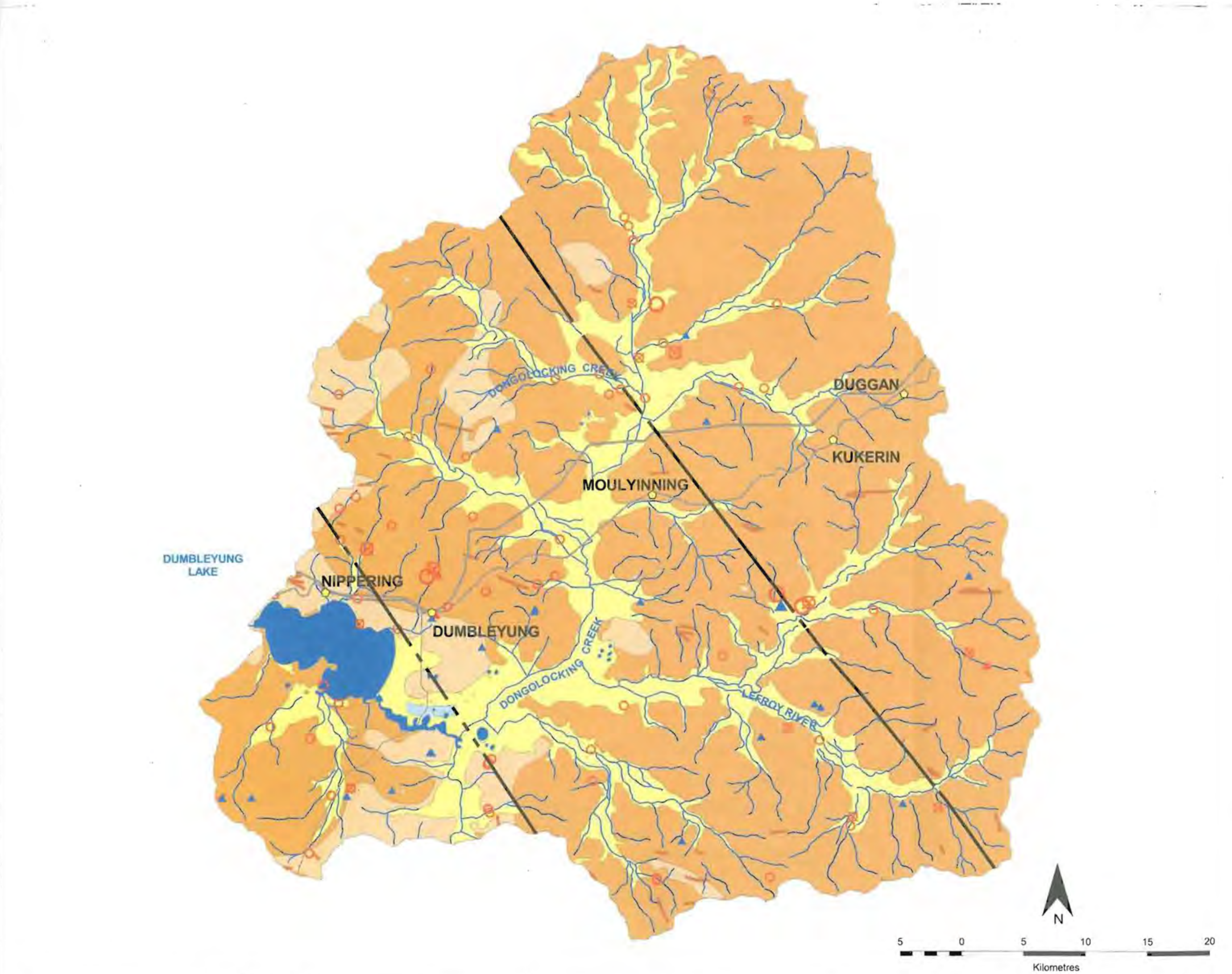
Management Zone 7 covers an area of 3200 km^2 within the shires of Dumbleyung, Kulin, Wickepin and Kent (Fig. 25). This zone is located in the Zone of Ancient Drainage in the Upper Catchment (Fig. 3). The landscape is gently undulating and has low relief. The zone is drained by the Coblinine River and its tributaries, including the Lefroy River and Dongolocking Creek. These water courses drain into Lake Dumbleyung, a large saline lake with a surface area of approximately 56 km^2. At peak flow periods, recorded only three times last century, the lake overflows through a narrow discharge area into the western section of the Coblinine River (Lane *et al.*, 1993; Cody, 1994).

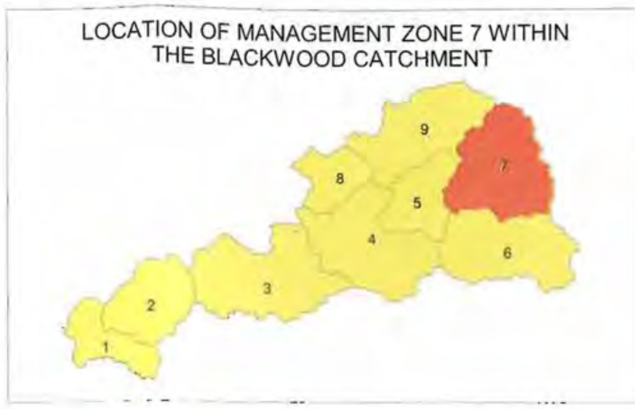
5.5.2 Relief

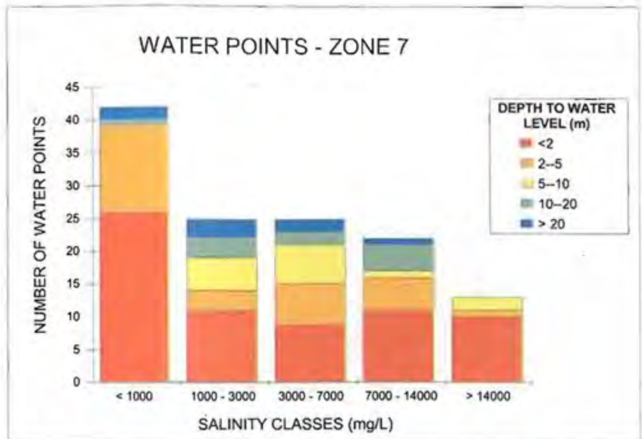
Broad flats and valleys (characterised by slopes of less than 1 in 100) constitute about 32% of the zone (1020 km^2) (Fig. 3). Approximately 91 km^2 of the area within the Coblinine River alluvial plain in this management zone is subject to inundation which raises the salinisation potential of this area. Grein (1995) reported that at least 50% of the Coblinine landscape system (flat to gently sloping alluvial plain of the Coblinine River and its tributaries) are affected by secondary salinisation with much of the remainder at high risk of salinisation and waterlogging.

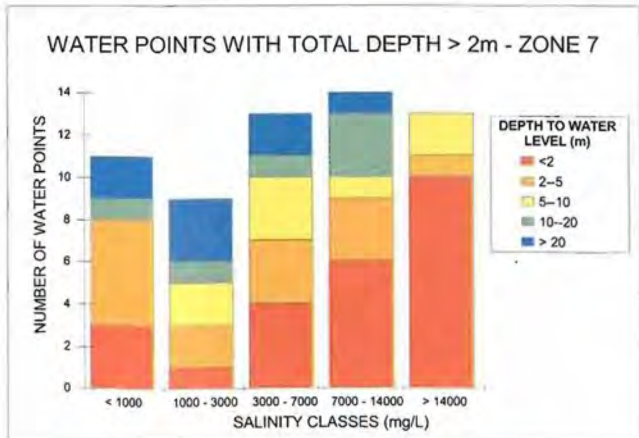
5.5.3 Climate

There is little variation in rainfall; the average annual rainfall is approximately 400 mm while the measured pan evaporation (class A) is fairly constant at around 1800 mm/a throughout the zone (Fig. 4).









Water points with salinity risk

- TDS ≥ 14 000 mg/L WL < 2m: grouped points; single points
- TDS ≥ 14 000 mg/L: grouped points; single points
- WL < 2m: grouped points; single points
- Points with potentiometric surface above ground level

Low salinity risk points

- Water points that have total depth > 2m and TDS < 1000 mg/L: grouped points; single points

NOTE: grouped points refer to more than 2 points within a 1km radius.

Symbols

- Highway
- Main road
- Railway
- Topographic contour - 50m
- Town centre
- Fault; concealed
- Watercourse
- Water body

Aquifer types

- Surficial aquifer
- Palaeochannel aquifer
- Weathered rock aquiclude - dolerite dykes
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks
- Fractured rock aquifer - quartzites

WATER AND RIVERS

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Distribution of salinity at the watertable in Management Zone 7

FIGURE 25

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5.5.4 Hydrogeology

The greater part of Management Zone 7 contains weathered and fractured granitoid, gneissic and quartzite basement rock aquifers. Surficial and palaeochannel aquifers are generally constrained to the broad flats in the lower landscape where they correlate with either palaeo- or modern drainage systems. At low elevations (<300 m AHD) the depth to water level ranges from 0.3 to 27 m with salinities of 100 to 38 000 mg/L. In the upper landscape (>330 m AHD), depth to water level is between 0.3 and 41 m, with salinities ranging from 100 to 15 000 mg/L.

5.5.5 Water level trends

Water level trends have not been reported for this management zone.

5.5.6 Geological barriers

West to northwest-trending dolerite dykes can form geological barriers to groundwater movement and may be potential sites for the development of land salinisation. However, owing to the limited distribution of bores it is not clear what role the dykes play in regard to groundwater movement and salinity outbreaks. Similarly, northwest-trending faults that cross this management zone may form fractured rock aquifers but may also impede and redirect groundwater movement and therefore influence salinisation (Fig. 25).

5.5.7 Water point distribution

This zone is some 10% smaller in area than Management Zone 3 and has approximately 80% fewer water point data. The data are fairly sparse, with the majority located in surficial and palaeochannel aquifers in lower landscape areas or near drainage lines. The area in this management zone modelled as being of high environmental significance is about 41% (Fig. 20). Over 40% of water points drilled to depths greater than 2 m have shallow water levels (<2 m) and almost 17% of these data have groundwater salinities exceeding 14 000 mg/L. Fresh, deep groundwater (>2 m) occurs in a range of landscape positions. Shallow groundwater with high salinities is more common in the surficial and palaeochannel aquifers (Fig. 25). Here, local to intermediate groundwater flow paths control salinisation, with variable groundwater quality within these aquifers generally reflecting hydraulic gradients, the heterogeneity of the aquifer materials, their degree of interconnection, and the source of recharge. A salinity survey conducted by the Dumbleyung shire in 1980, found that salinity problems affected 16.5% of the farms responding to the survey (Cody, 1994). Cody (1994) described the land salinisation associated with the palaeodrainage systems (mainly the palaeochannel aquifer) as severe, having a shallow watertable and saturated soils exhibiting salinities between 7000 and 30 000 mg/L.

5.6 Summary: Management Zone 8

5.6.1 Landform/physiography

Management Zone 8 covers an area of 1216 km^2 within the shires of Williams and West Arthur (Fig. 26). This zone is located in the Upper and Lower-middle Catchments, in the Zone of Rejuvenated Drainage (Fig. 3). The landscape is gently undulating to undulating, with broad flat-floored valleys located in the centre of the management zone. The western section is a subcatchment of the north-south flowing Hillman River; to the east the zone drains into the Arthur River.

5.6.2 Relief

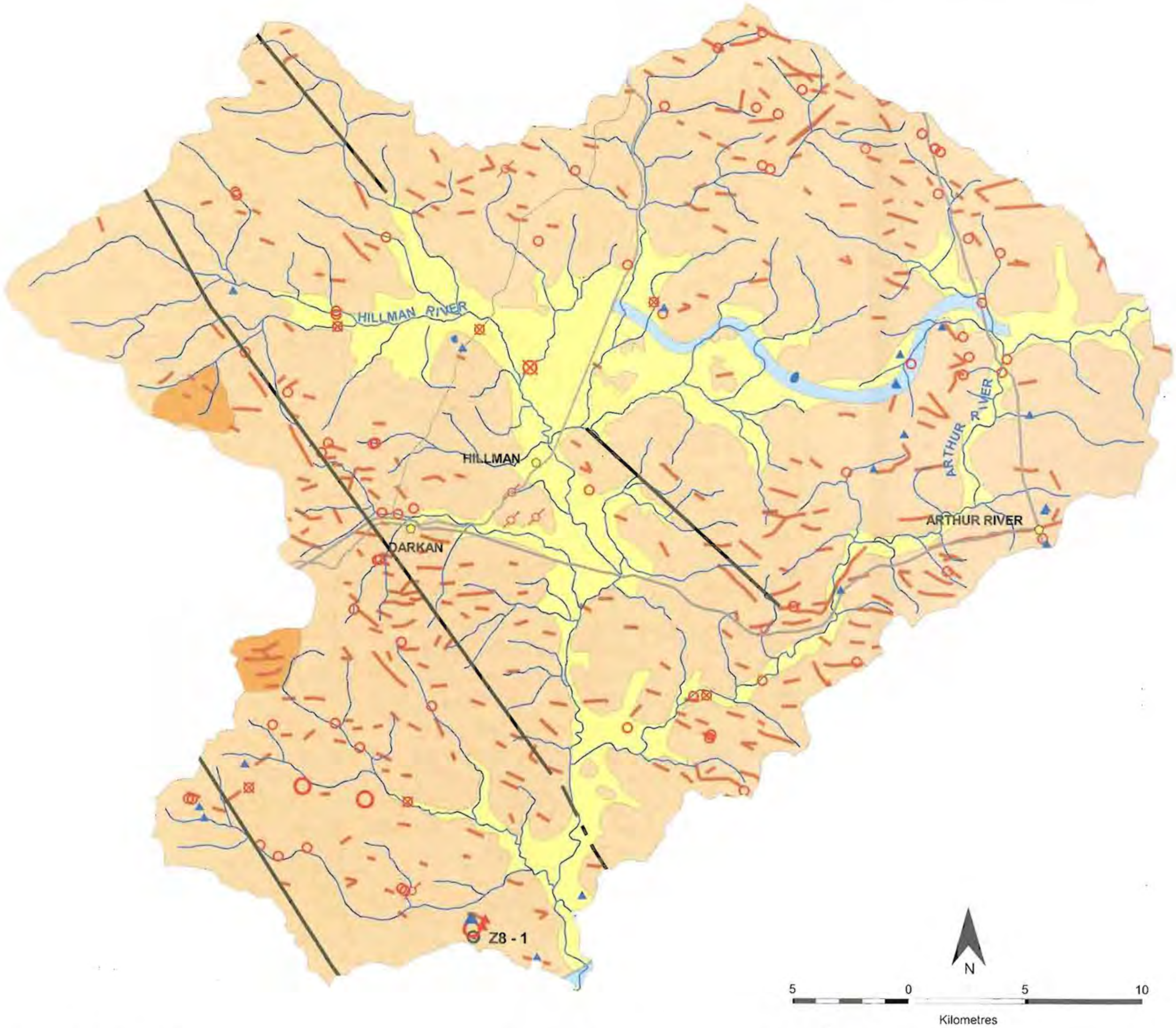
Approximately 42% of the area (described as gently undulating) exhibits slopes ranging from 3 in 100 to 10 in 100. Broad flats and valleys (characterised by slopes of less than 1 in 100) form about 12% of the zone (146 km^2) and correspond primarily to the alluvial plain of the Hillman River (Fig. 3). A soil and landform study by Grein (1995) reported that almost 20% of the land in the Hillman River system (alluvial plain of the Hillman River and its tributaries) is affected by secondary salinisation.

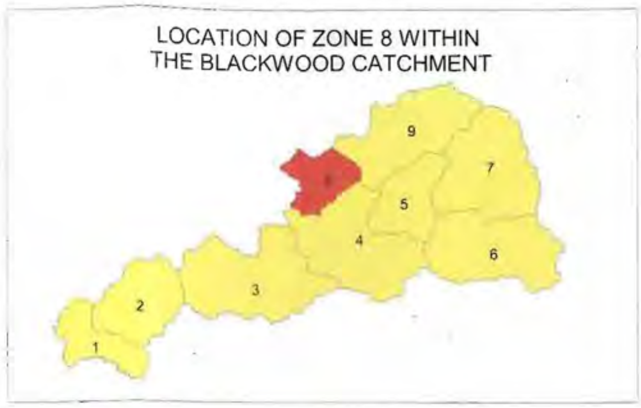
5.6.3 Climate

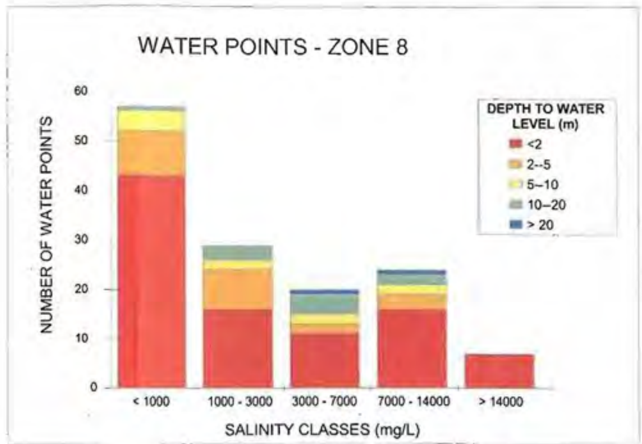
The average annual rainfall ranges from 500 to 600 mm. The measured pan evaporation (class A) is fairly constant at around 1600 to 1700 mm/a throughout the zone (Fig. 4).

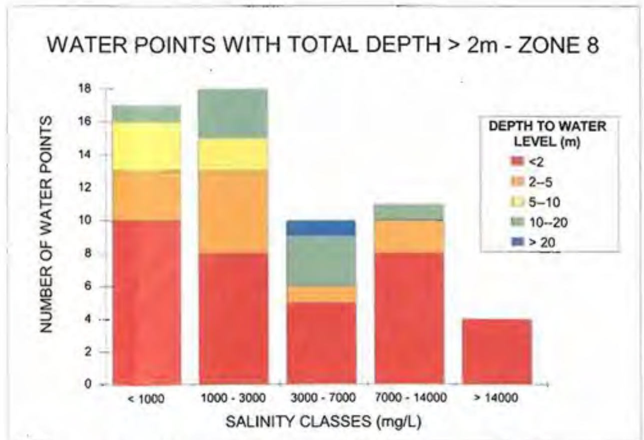
5.6.4 Hydrogeology

Weathered and fractured granitoid and gneissic basement rock aquifers occupy most of this zone. Palaeochannel aquifers are located in the Darkan Palaeochannel, whereas surficial sediment aquifers are generally constrained to the broad flats in the lower landscape. At low elevations (<260 m AHD) the depth to water level ranges from 0.3 to 7.2 m with salinities of 130 to 14 800 mg/L. In the upper landscape (>300 m









Water points with salinity risk

- TDS ≥ 14 000 mg/L WL < 2m: grouped points; single points
- TDS ≥ 14 000 mg/L: grouped points; single points
- WL < 2m: grouped points; single points
- Points with potentiometric surface above ground level

Low salinity risk points

- Water points that have total depth > 2m and TDS < 1000 mg/L: grouped points; single points

NOTE: grouped points refer to more than 2 points within a 1km radius.

Symbols

- Highway
- Main road
- Railway
- Topographic contour - 50m
- Town centre
- Fault; concealed
- Watercourse
- Water body
- Z8-1 Monitoring bore

Aquifer types

- Surficial aquifer
- Palaeochannel aquifer
- Weathered rock aquiclude - dolerite dykes
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks

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Distribution of salinity at the watertable in Management Zone 8

FIGURE 26

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AHD), depth to water level is between 0.6 and 16.9 m, with salinities ranging from 110 to 5050 mg/L.

5.6.5 Water level trends

Groundwater monitoring bore Z8-1, located in the fractured bedrock aquifer near the northern catchment boundary, records water levels rises at a rate of 0.5 m/a (Fig. 26).

5.6.6 Geological barriers

Westerly to northwesterly trending dolerite dykes can form geological barriers to groundwater movement and may be potential sites for the development of land salinisation. However, owing to the limited distribution of bores it is not clear what role the dykes play in regard to groundwater movement and salinisation. Similarly, northwest-trending faults that cross this management zone may form fractured rock aquifers but may also impede and redirect groundwater movement and therefore influence salinisation (Fig. 26).

5.6.7 Water point distribution

This zone is approximately 66% smaller in area than Management Zone 3 and has 75% fewer water point data. The data sample a range of landscape positions. A higher percentage of water point data is located in the surficial and palaeochannel aquifers in the lower landscape areas or near drainage lines. The area in Management Zone 8 modelled as being of high environmental significance is about 37% (Fig. 20). Over 60% of water points drilled to depths greater than 2 m have shallow water levels (<2 m) and about 7% of these data have groundwater salinities exceeding 14 000 mg/L. Fresh, deep groundwater (>2 m) exists in a range of landscape positions. Shallow groundwater with high salinities is more common in palaeochannel aquifers (Fig. 26). Here local to intermediate groundwater flow paths control salinisation, with variable groundwater quality within these aquifers generally reflecting hydraulic gradients, the heterogeneity of the aquifer materials, their degree of interconnection, and the source of recharge. Groundwater quality of the fresh to brackish sections of the palaeochannel aquifers may deteriorate in the future. This could occur where increased recharge to the adjacent saline weathered rock aquifers subsequently recharges (via throughflow) the palaeochannel aquifers. Groundwater levels could also rise as a consequence (Nulsen, 1998).

5.7 Summary: Management Zone 9

5.7.1 Landform/physiography

Management Zone 9 covers an area of 2880 km² within the shires of Narrogin, Wickepin and Wagin (Fig. 27). The eastern section of the zone lies in the Upper Catchment, the Zone of Ancient Drainage, whilst the area to the west is within the Upper-middle Catchment, the Zone of Rejuvenated Drainage (Fig. 3). The area within the Zone of Ancient Drainage (Toolibin to Harrismith) has low relief consisting of gently undulating rises and broad valley floors with characteristically low gradients (generally 1 in 1500, or less). The area in the Zone of Rejuvenated Drainage comprises gently undulating to undulating rises with well defined drainage lines. The main waterways of this management zone include Arthur River, Buchanan River, Lake Dulbining, Lake Toolibin and Lake Taarblin. Lake Toolibin is considered to be one of few remaining fresh water lakes in the agricultural area (Grein, 1995). The other lakes, Lake Dulbining and Lake Taarblin, are brackish and brackish to saline respectively.

5.7.2 Relief

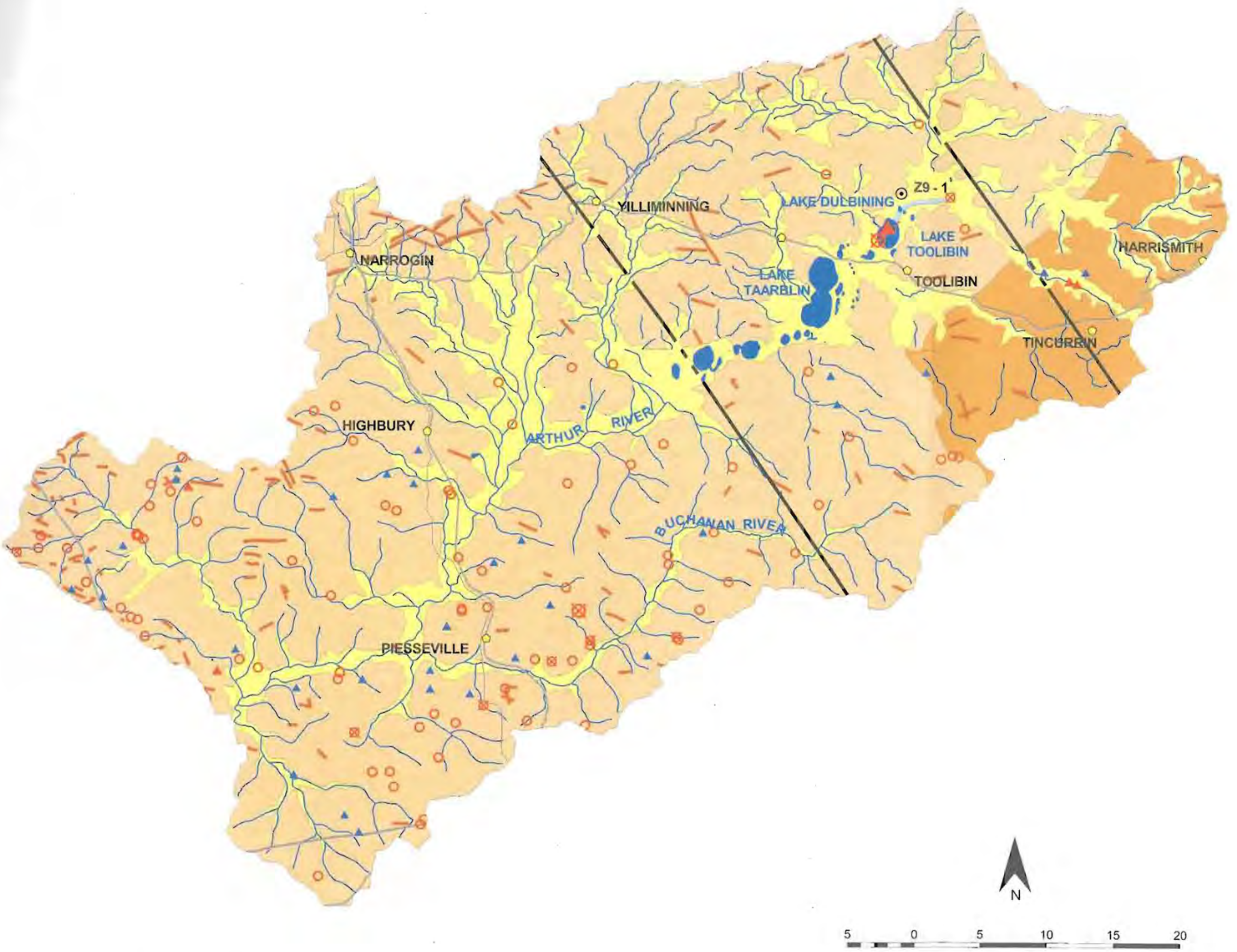
Broad flats and valleys (characterised by slopes of less than 1 in 100) constitute about 31% of the zone (885 km²) (Fig. 3). About 65 km² of the area occupied by the valley floors of the Arthur and Buchanan Rivers are subject to seasonal inundation which raises its salinisation potential. A soil and landform study by Grein (1995) reported that approximately 30% of the land in the Arthur River system (alluvial plain of the Arthur River downstream to its junction with the Buchanan River) are affected by secondary salinisation.

5.7.3 Climate

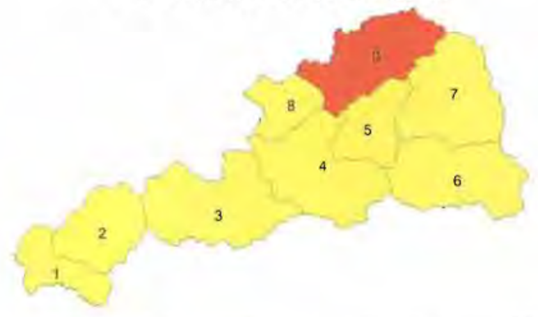
The average annual rainfall ranges from 450 to 500 mm. The measured pan evaporation (class A) is fairly constant at around 1800 mm/a throughout the zone (Fig. 4).

5.7.4 Hydrogeology

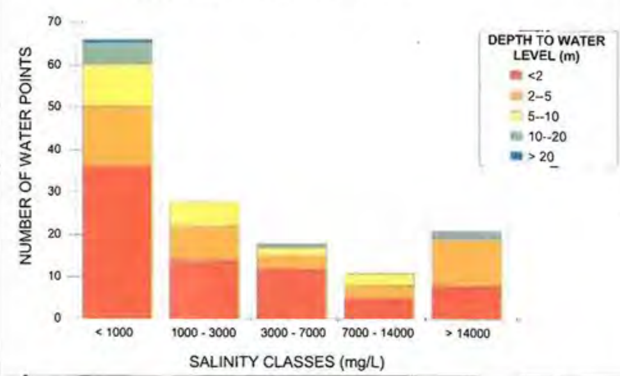
Weathered and fractured granitoid and gneissic basement rock aquifers occupy the greater part of this zone. Palaeochannel aquifers are located in the Toolibin Palaeochannel, whereas surficial sediment aquifers are generally constrained to the broad flats in the lower landscape. At low elevations (<310 m AHD) the depth to water level ranges from 0.2 to 14 m with salinities of 100 to 60 000 mg/L. In the upper landscape



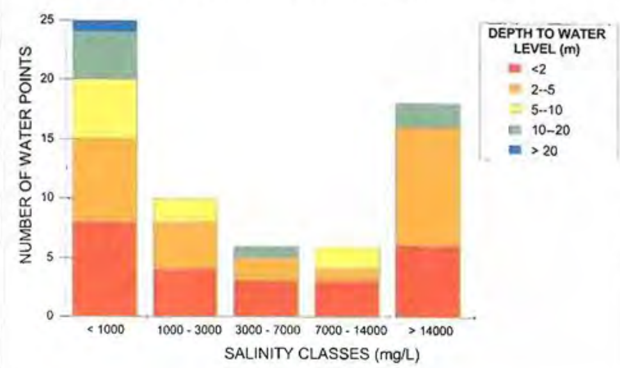
LOCATION OF MANAGEMENT ZONE 9 WITHIN THE BLACKWOOD CATCHMENT



WATER POINTS - ZONE 9



WATER POINTS WITH TOTAL DEPTH > 2m - ZONE 9



Water points with salinity risk

- TDS ≥ 14 000 mg/L WL < 2m: grouped points; single points
- TDS ≥ 14 000 mg/L: grouped points; single points
- WL < 2m: grouped points; single points
- Points with potentiometric surface above ground level

Low salinity risk points

- Water points that have total depth > 2m and TDS < 1000 mg/L: grouped points; single points

NOTE: grouped points refer to more than 2 points within a 1km radius.

Symbols

- Highway
- Main road
- Railway
- Topographic contour - 50m
- Town centre
- Fault; concealed
- Watercourse
- Water body
- Z9-1 Monitoring bore

Aquifer types

- Surficial aquifer
- Palaeochannel aquifer
- Weathered rock aquiclude - dolerite dykes
- Weathered rock aquifer - granitic rocks
- Weathered rock aquifer - gneissic rocks

WATER AND RIVERS

SCIENCE AND EVALUATION DIVISION

Blackwood Hydrogeological Resource Base

Distribution of salinity at the watertable in Management Zone 9

FIGURE 27

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(>340 m AHD), depth to water level is between 0.5 and 52 m, with salinities ranging from 100 to 23 000 mg/L. Groundwater salinity and depth to water levels show significant variation in both upper and lower landscape positions.

5.7.5 Water level trends

Groundwater monitoring bore Z9-1, located in the weathered rock aquifer, records water levels rising at a rate of 0.05 m/a (Fig. 27).

5.7.6 Geological barriers

Westerly to northwesterly trending dolerite dykes can form geological barriers to groundwater movement and may be potential sites for the development of land salinisation. However, owing to the limited distribution of bores it is not clear what role the dykes play in regard to groundwater movement and salinisation. Similarly, northwest-trending faults that cross this management zone may form fractured rock aquifers but may also impede and redirect groundwater movement and therefore influence salinisation (Fig. 27).

5.7.7 Water point distribution

This zone is approximately 20% smaller in area than Management Zone 3 and has 70% fewer water point data. Data sample a range of landscape positions, although drilling density is higher in the southern half of the zone (Fig. 27). The area in Management Zone 9 modelled as being of high environmental significance is about 40% (Fig. 20). Over 37% of water points drilled to depths greater than 2 m have shallow water levels (<2 m) and about 9% of these data have groundwater salinities exceeding 14 000 mg/L. Fresh, deep groundwater (>2 m) is more prevalent in the mid- to upper landscape areas in the weathered granitoid rock aquifer. Shallow groundwater with high salinities is more common in the surficial and palaeochannel aquifers. Water level rises within the palaeochannel and weathered rock aquifers in the lower landscape (broad valley flats) is considered to be the major factor causing land salinisation in this management zone (De Silva, 1999; Dogramaci, 1999).

6 Discussion

Prior to the clearing of native vegetation, natural land salinisation was present in the Blackwood Catchment, particularly in the Upper Catchment, where hydraulic gradients are low and more salt is retained in the landscape (Fig. 3). Groundwater systems control the distribution of salt once it enters the regolith and prior to clearing these systems were in general equilibrium (i.e. the amount of recharge to the groundwater approximated the amount of discharge). Under these conditions naturally saline areas are clearly defined. However, equilibrium conditions ceased with land clearing, and increases in recharge have exerted pressure on the groundwater regime, with water levels rising in response. This has led to larger areas being at risk of land salinisation and the extension of the 'established' risk areas in the Upper Catchment into the Middle, and to a lesser extent, Lower Catchments.

Salinity in the Middle and Lower Catchments, being influenced by higher relief and a well defined drainage system, is not as severe as in the Upper Catchment (Fig. 3). However, higher salinity has developed in the Middle Catchment in response to a dramatic increase in recharge rates which has put pressure on the groundwater systems. Low hydraulic gradients (~1 in 10 000) coupled with the low hydraulic conductivities of weathered rock aquifers (~10^{-4} m/s) produce very slow lateral groundwater movement and long groundwater residence time. The rise of groundwater levels, and to a lesser extent lateral movement from regional and local groundwater systems, has resulted in the development of saline seepage, particularly in low-lying areas. As watertables rise to within 1-2 m from the land surface, groundwater will contribute more salt to water courses.

Increased recharge to the weathered rock aquifer in the Yilgarn Southwest Province not only results in watertable rises, but may also affect fresh water resources in the intermediate (the palaeochannel aquifers) and local groundwater systems (those constrained by geological barriers). For example, fresh groundwater in sections of the Beaufort, Qualeup, Toolibin and Darkan Palaeochannels may be at risk, along with groundwater in palaeochannel aquifers that have not yet been identified. To ensure that fresh water resources in these systems do not deteriorate, their degree of interconnection with the weathered rock aquifer must be assessed, along with the rate at which water levels are rising. However, there is insufficient water level trend information to enable the variation in rates of rise to be assessed, and then used to prioritise areas requiring remediation (Table 6). To make better use of this information, the continued monitoring of existing boreholes is essential, together with the establishment of a network of additional monitoring boreholes where data coverage is inadequate.

The major controls on rising watertables and salinisation across the Blackwood Catchment are summarised in Table 6. Results from this regional-scale study confirm that salinity at the watertable in the lower landscape increases eastward from the Darling Scarp, as does the prevalence of shallow watertables (<2 m). This variation is to be expected as the relief becomes more subdued to the east; the increasingly broad flats and valleys will necessarily lessen the extent of groundwater movement. Salt distribution also increases from west to east, as average annual rainfall decreases and evaporation increases. Groundwater level and salinity data in both lower and upper landscape positions show wide variation within all of the management zones (Table 6). Further interrogation of these data should be conducted to determine if relationships exist between salinity and water level with respect to landscape position, aquifer type, landuse and vegetation. These relationships should be examined for individual management zones before planning investigations to identify local controls on groundwater flow and salinisation.

The number and distribution of water point data vary between the management zones. It is therefore difficult to compare salinity and water level statistics between, and often within, management zones. The unequal distribution of water point data over the Blackwood Catchment can be redressed through further drilling. To build a more comprehensive 'picture' of the regional and local controls on salt distribution and groundwater flow, the acquisition and interpretation of geophysical data may be useful. There are many geophysical methods, ranging from directly sampling material in close proximity to the instrument (such as borehole logging), to remote-sensing methods such as the imaging of multispectral data received from satellites. Geophysical methods selected to provide information on land salinisation should target specific problems in individual management zones and aim at building on existing data in the Blackwood Hydrogeological Resource Base, together with information from the Land Monitor and SS2020 projects.

Table 6. Major regional controls on salt distribution, groundwater movement and water level trends in the Blackwood Catchment

Management zone	*Physiography/landform*	*Relief*	*Climate*		*Groundwater level and salinity*		*Water level trends*
			Average rainfall (mm/a)	*Pan evaporation (class A) (mm/a)*	*Lower landscape*	*Upper landscape*	
Zone 3	*East and West Darling Range*: undulating lateritic plateau with deep incised valleys grading to broad valleys in the east	Greatest relief of the management zones, decreases to the east from the Darling Scarp, lake systems develop in the eastern areas near Kulikup and Qualeup	~1000 on the western margin to ~600 in the east	increases eastwards ~1250 to ~1500	(<210 m AHD) groundwater level 0.1–5.0 m salinity 100–11 000 mg/L	(<300 m AHD) groundwater level 0.7–11.5 m salinity 90–16 000 mg/L	Limited data suggest average rises of ~0.27 m/a (weathered rock and palaeochannel aquifers)
Zone 4	*Zone of Rejuvenated Drainage and east Darling Range*: gently undulating to undulating rises, low hills, narrow incised valleys and broad flats	Broad flats form ~24% of the zone, ~20 km^2 are subject to seasonal inundation, lake systems develop in the north and northeastern areas within the broad flats including Lake Towerrinning	~500, ~600 in the northwest	~1600	(<250 m AHD) groundwater level 0.3–20 m salinity 115–21 700 mg/L	(>300 m AHD) groundwater level 0.2–23 m salinity 70–15 300 mg/L	Insufficient reported data
Zone 5	*Zone of Rejuvenated Drainage and Zone of Ancient Drainage* (northwestern area): gently undulating to undulating rises, low hills and broad flats	Broad flats form ~32% of the zone, ~96 km^2 are subject to seasonal inundation, northeast trending salt lake system in the centre of the zone includes the Norring and Parkeyerring Lakes	~450	~1700	(<280 m AHD) groundwater level 0.1–20 m salinity 100–46 000 mg/L	(>330 m AHD) groundwater level 0.6–24 m salinity 90–10 000 mg/L	Insufficient reported data
Zone 6	*Zone of Ancient Drainage*: gently undulating rises and broad flat-floored valleys	Broad flats and valleys form ~48% of the zone, ~155 km^2 are subject to seasonal inundation, salt lake system in the centre of the zone includes Coyrecup and Ewlyamartup Lakes	~500 to 400	~1700 to 1800	(<290 m AHD) groundwater level 0.2–16 m salinity 105–33 000 mg/L	(>330 m AHD) groundwater level 0.3–41 m salinity 90–12 500 mg/L	Insufficient reported data
Zone 7	*Zone of Ancient Drainage*: gently undulating rises	Broad flats and valleys form ~32% of the zone, ~91 km^2 is subject to seasonal inundation, water courses drain into the saline Dumbleyung Lake	~400	~1800	(<300 m AHD) groundwater level 0.3–27 m salinity 100–38 000 mg/L	(>330 m AHD) groundwater level 0.3–41 m salinity 100–15 000 mg/L	Insufficient reported data
Zone 8	*Zone of Rejuvenated Drainage*: gently undulating to undulating, with broad flat-floored valleys	Broad flats and valleys form ~12% of the zone, ~20% of the land in the Hillman River system is affected by secondary salinisation	~500 to 600	~1600 to 1700	(<260 m AHD) groundwater level 0.3–7.2 m salinity 130–14 800 mg/L	(>300 m AHD) groundwater level 0.6–16.9 m salinity 110–5050 mg/L	Insufficient reported data
Zone 9	*Zone of Ancient Drainage and Zone of Rejuvenated Drainage*: gently undulating rises and broad valley floors, well defined drainage lines restricted to the zone of rejuvenated drainage	Broad flats and valleys form ~31% of the zone, ~65 km^2 of the area occupied by the valley floors of the Arthur and Buchanan Rivers is subject to seasonal inundation	~450 to 500	~1800	(<310 m AHD) groundwater level 0.2–14 m salinity 100– 60 000 mg/L	(>340 m AHD) groundwater level 0.5–52 m salinity 100–23 000 mg/L	Insufficient reported data

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Appendix 1

Arc Info digital data and reference files documentation

Data category	Description	Feature	Source
Primary	Roads	Line	DOLA 100k
	Railways	Line	DOLA 100k
	Local towns and villages	Point	DOLA 100k
	Local government authority	Polygon	DOLA 100k
	18 x 1:100k sheets that cover the Blackwood Catchment	Line, polygon	WRC, this project
	Blackwood Catchment boundary	Line, polygon	WRC, this project
	9 management zones of the Blackwood Catchment	Line, polygon	Blackwood Basin Group
	10m Topographic contours	Line	DOLA 100k
	Drainage	Line	DOLA 100k
	Water body	Line	DOLA 100k
	Coast of Blackwood Catchment	Line, polygon	AUSLIG 250k
	Coast of WA	Line	
	Rainfall (mm) in WA	Line	Bureau of Meteorology
	Evaporation (mm) in WA	Line	Bureau of Meteorology
	Bores and attributes	Point	WRC, this project
	Dykes	Line	DME 1:250k geological maps captured by NGIS Ltd
	Lithology	Polygon	DME 1:250k geological maps captured by NGIS Ltd
Derived or	Hydrogeology	Polygon	WRC, this project
modelled	Groundwater level contour (20 m interval)	Line	WRC, this project
	Groundwater level model (100 m cell size)	Grid	WRC, this project
	Surface elevation model (100 m cell size)	Grid	WRC, this project
	Depth to water model (100 m cell size)	Grid	WRC, this project
	Groundwater salinity, contours and ranges	Line, polygon	WRC, this project

Appendix 2

Project flow chart