GROUNDWATER INFORMATION AND MANAGEMENT OPTIONS FOR THE BROCKMAN RIVER CATCHMENT

WATER AND RIVERS COMMISSION REPORT
SLUI 2
2002
SALINITY AND LAND USE IMPACTS

Water and Rivers Commission

GROUNDWATER INFORMATION AND MANAGEMENT OPTIONS FOR THE BROCKMAN RIVER CATCHMENT

by

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Water and Rivers Commission

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SALINITY AND LAND USE IMPACTS SERIES

REPORT NO. SLUI 2

SEPTEMBER 2002

Acknowledgments

The authors acknowledge help and advice from;
The Advisory Committee (below) to the Swan Hydrogeological Resource Base and Catchment Interpretation Project

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Local Government Authority	Mick McCarthy, Veronica Oma
Ministry for Planning	David Nunn, Marie Ward, Alan Carman-Brown
Swan Catchment Centre	Peter Nash
Swan River Trust	Dr Tom Rose, Declan Morgan, Adrian Tomlinson

Mr Ken Angel (Agriculture Western Australia),
Mr Robert Panasiewicz (formerly Water and Rivers Commission), and
Mr Syl Kubicki (formerly Water and Rivers Commission).

Recommended Reference

The recommended reference for this report is: SMITH, M. G., 2002, Groundwater information and management options for the Brockman River catchment, Western Australia Water and Rivers Commission, Salinity and Land Use Impacts Report SLUI 2, 53p.

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ISBN 1-920687-76-9
ISSN 1447-7394

October 2002

Cover photograph:
Brockman River valley by
Margaret Smith

Foreword

The Swan Hydrogeological Resource Base and Catchment Interpretation project was a Natural Heritage Trust (NHT) and Water and Rivers Commission (WRC) funded project (NHT 973705). The study areas were three priority catchments of the Swan-Canning rivers—the Ellen Brook, Brockman River and the combined Upper Canning Southern Wungong catchments.

The following were the main objectives of the study:

- To liaise with the Swan Working Group and catchment groups to determine issues, needs and appropriate products.
- To provide baseline groundwater information essential for the catchment groups to implement management plans.
- To compile maps of hydrogeological information at a scale appropriate to the decision-making processes of catchment managers.
- To transfer expertise into the priority sub-catchments by training, publications and advice in interpretation.

This report comprises a brief overview of the Brockman River catchment and management guidelines from the perspective of the groundwater issues. More detailed information can be found in the following project reports, posters and CD-ROM.

Reports
Hydrogeological information for management planning in the Ellen Brook catchment SLUI 11
Groundwater information for management of the Ellen Brook, Brockman River and Upper Canning Southern Wungong catchments SLUI 12
Groundwater information for management in the Upper Canning Southern Wungong catchment SLUI 14

Posters
Managing Nutrient Movement into Ellen Brook
Geology of Ellen Brook
Hydrogeology of Ellen Brook
Salt affected land? Yes! It's a groundwater problem! Brockman River catchment

*CD-ROM**
Groundwater information and Management Zones for the Ellen Brook, Brockman River and combined Upper Canning and Southern Rivers and Wungong Brook catchments.

> *The data package on the CD-ROM contains the following themes in GIS format: surface water catchments and their subcatchments; hydrogeological zones; water monitoring sites for groundwater and surface water; management boundaries; regional soil surveys; topographic contours; roads; Local Government boundaries; and general climatic data.

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Summary

The limited good quality groundwater and the development of land salinisation are the main groundwater-related issues in the Brockman River catchment.

Groundwater management will best be achieved through a cooperative approach between landholders, local government, land use planners and catchment coordinators, as groundwater crosses man-made boundaries.

The management options in this report are intended for informed decision making by these community groups.

There is widespread landholder concern over emerging land salinisation from rising groundwater in the Brockman River catchment. Rising groundwater and dryland salinisation are reducing agricultural productivity and lowering economic returns. The businesses that rely on attractions (such as tourism) or the physical infrastructure (roads or buildings) in the catchment are potentially impacted. Rising groundwater needs to be tackled at a catchment level and will require significant community cooperation.

Four groundwater zones are recognised. The regional aquifer in the **Dandaragan Plateau** is managed as part of the Gingin Groundwater Management Area. The **surficial aquifers** and the **western fractured-rock aquifer** zone are both important for private groundwater abstraction in the Brockman Valley. While additional localised groundwater resources are probably available in these two zones, it is unlikely that they will yield large supplies of good quality groundwater. Rising groundwater however, has the potential to contaminate these already limited low salinity resources. Groundwater from the **eastern fractured-rock aquifer** zone is generally suitable for limited irrigation and livestock.

Sixty percent of salt discharged by the Brockman River into the Avon River originates north of Tanamerah monitoring station. This north-to-south variation is due to the difference in land use history, geology and rainfall.

Groundwater resources are limited and localised. Developmental and economic demands of the catchment will in places conflict with optimal groundwater management. Managers need to balance the environmental needs and development demands within the catchment.

Keywords: Yilgarn Southwest Province, Perth Basin, hydrogeology, resources, quality, management, Brockman River catchment, Bindoon, SH5014.

1 Background

Lack of good quality groundwater and salinisation are issues in the Brockman River subcatchment, an area known for its viticulture and citrus orchards. These issues are now threatening expansion of the viticulture and innovative agricultural developments such as olive plantations. Deteriorating groundwater quality and salinisation, although now recognised in the Brockman River catchment, are not issues new to Western Australia. However, in the past, such vulnerability of the groundwater environment to man-made changes was not widely appreciated. Changes in groundwater quality following European settlement represent a complex interaction over time between groundwater movement, the types of sediment and host rocks through which the groundwater flows, recharge and discharge of the groundwater, and land use practices. In many cases 20 to 30 years may elapse from changes in land use practices before any deterioration in the groundwater quality is evident.

The local and regional impacts of deteriorating groundwater quality are being increasingly understood. Consequently, land use managers are asking for interpreted groundwater data and management options that can be incorporated into holistic catchment management plans.

At present, only raw groundwater data are stored on government databases. To develop a groundwater management framework these data must be extracted, collated and reviewed. This need led to the Water and Rivers Commission (WRC) Swan Hydrogeological Resource Base and Catchment Interpretation Project being established and partly funded by Natural Heritage Trust (NHT).

The scope of this Project was the hydrogeological assessment of three subcatchments of the Swan and Canning Rivers catchment — the Ellen Brook subcatchment, the combined upper Canning and Southern Rivers and Wungong Brook subcatchments, and the Brockman River subcatchment.

The Project objectives are listed in the Foreword. Findings and products were presented progressively to the relevant community groups through meetings and feedback collected. The final reports and other products are listed in the Foreword.

This report on the Brockman River subcatchment, referred to here as the **Brockman River catchment,** is prepared principally for catchment managers. Additional background information and definitions are included throughout the text in grey boxes for readers unfamiliar with hydrogeology.

This report is divided into five main sections.

- Section 1 introduces the catchment issues and gives a brief overview of the geological environment of the groundwater in the catchment, surface drainage, previous work and relevant data sources.
- Section 2 identifies the characteristics of the groundwater zones, including potential groundwater quality.
- Section 3 reviews data on rising groundwater levels and salt stores within the catchment with the aim of understanding salinisation within the catchment. This section is not a salinity-risk assessment.
- Section 4 outlines options for the management of groundwater and salinity.
- Section 5 makes recommendations for future work.

1.1 Issues

1.1.1 Water resources

Landholders within the Brockman River catchment have been voicing their concerns over the lack of good quality water needed for new and expanding agricultural developments. To deal with this issue, potential and existing groundwater resources within the catchment need to be identified. Previous groundwater investigations, rather than identifying the catchment's groundwater resources, have concentrated on locating specific groundwater supplies for various clients. One such investigation included locating the town water supply for Bindoon (Boyd, 1979; BSD Consultants Pty Ltd, 1985). These investigations have highlighted the variability of groundwater supply and quality within the Brockman River catchment, but they have not identified the distinctive groundwater zones found in the catchment.

This investigation recognised four groundwater zones and identified which are important to the catchment for groundwater sources. Some understanding of these zones will assist land use managers in making decisions that benefit the catchment in the long term.

1.1.2 Rising groundwater levels and salinisation

Reduced agricultural productivity, decreased biological diversity in wetlands and rivers, land degradation and reduced water resources suitable for irrigation are all manifestations of salinity. Secondary salinisation has both regional and local impacts. At a regional scale, the Action Plan for the Swan–Canning Cleanup Program (Swan River Trust and Water and Rivers Commission, 1999) has identified the Brockman River as contributing brackish to saline water to the Swan River. Local effects of rising groundwater and salt mobilisation are seen within the catchment as salt seeps and salt scalds, with the result that economic returns on salt-affected agricultural land are reduced. The rising saline groundwater is discharged as base flow into the Brockman River, the health of which will deteriorate as the natural ecology of the river is altered. Management of salinisation should be tackled at a catchment level as salinisation will affect every member of the community, either directly or indirectly.

Salinisation refers to increase in salt content of land and water.

Primary salinisation refers to soils and landscapes that are saline in their natural state; classic examples are the numerous salt lakes within Western Australia.

Secondary salinisation refers to land and water becoming saline due to rising groundwater levels and mobilisation of salt stored in the weathered-rock profile above the watertable. Clearing deep-rooted native vegetation allows increased recharge and leads to a rising watertable.

1.2 Water quality terminology related to salinity

Salinity is one aspect of water quality which affects all water users. Terms such as fresh water, brackish water and saline water are very useful descriptive terms. These terms convey information about water quality quickly, but can also lead to misunderstanding. Salinity is expressed as total dissolved solids

(TDS) measured in milligrams per litre (mg/L). In this project the terms of fresh, brackish and saline relate to specific TDS range values listed in Table 1.

Table 1. Groundwater salinity classification (adapted from Australian Water Resources Council, 1988)

Salinity (mg/L TDS)	*Electrical Conductivity (EC) (µS/cm at 25°C)**	*Description*	*Potential use*
<500	<769	fresh	all purposes, domestic and irrigation
500–1000	769–1538	Fresh+	most purposes
1000–1500	1538–2308	fresh+	most purposes, upper limit for drinking
1500–3000	2308–4615	brackish	limited irrigation, all livestock
3000–7000	4615–10 769	saline	most livestock (not pigs or horses)
7000–14 000	10 769–21 538	saline	some livestock (beef cattle, sheep)
>14 000	>21 538	saline to hypersaline	limited industrial use up to 100 000 mg/L

* EC = salinity / 0.65   + these ranges termed 'marginal' in W.A.

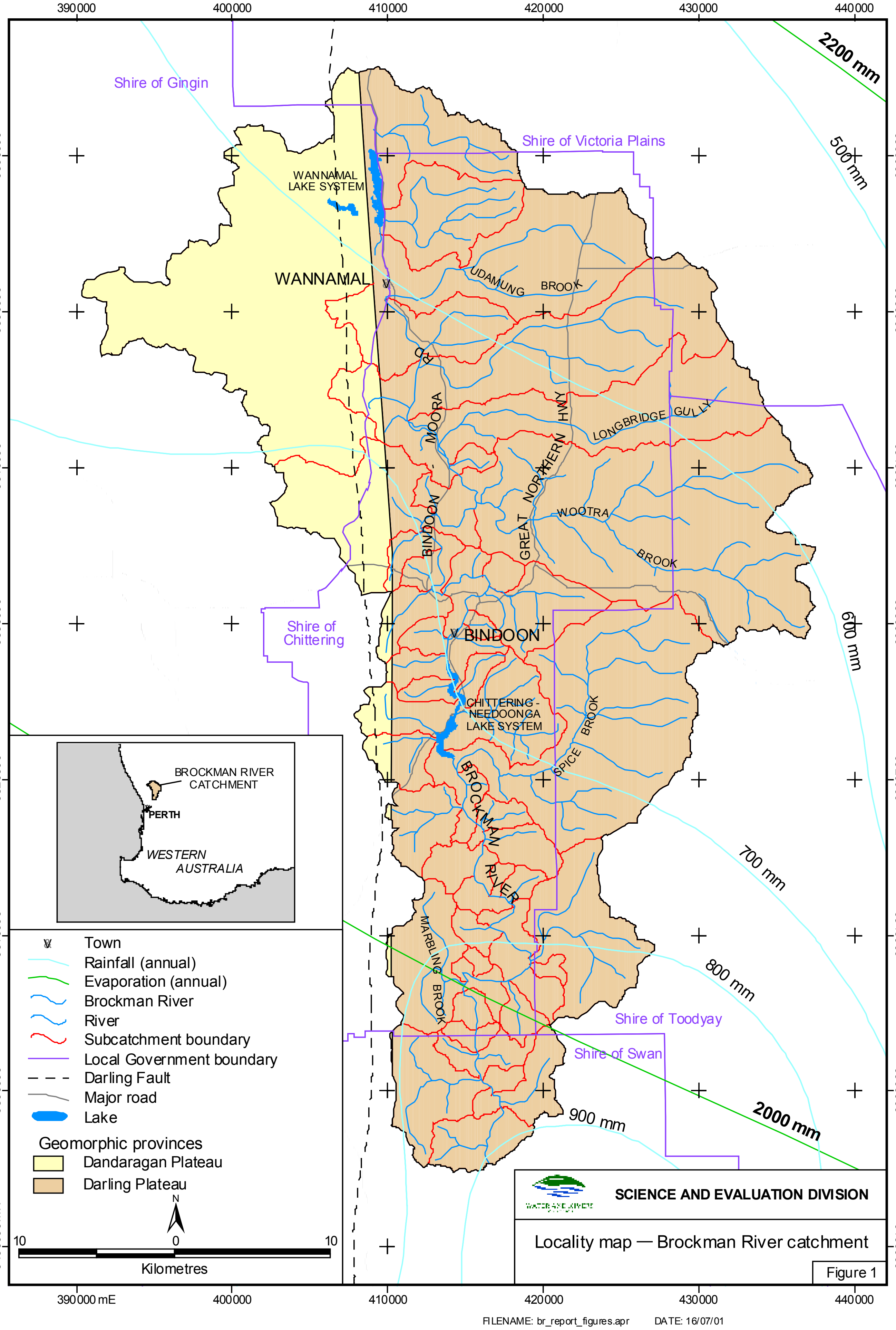
1.3 Environment

1.3.1 Location and Local Government areas

The Brockman River catchment, covering an area of about 1500 km^2, is a subcatchment of the Avon River catchment. Access is via the Great Northern Highway, north of Perth (Fig. 1). Bindoon and Wannamal are towns within the catchment. The catchment falls within the area of five local government authorities with 53% of the catchment being within the Shire of Chittering. The rest of the catchment falls within the Shires of Toodyay (19%), Gingin (18%), Victoria Plains (5%) and Swan (5%).

1.3.2 Geological evolution

Geology and geomorphology influence groundwater. The Brockman River catchment has two distinct geomorphic areas: the Darling and Dandaragan Plateaus. Understanding the geological evolution of these plateaus enables the manager to appreciate why there are limited good quality groundwater resources within the Brockman River catchment. The Darling Plateau covers most of the catchment and rises from 125 to 350 m Australian Height Datum (AHD). The Darling Plateau is separated from the Dandaragan Plateau by the Darling Scarp, with the Dandaragan Plateau rising from 175 to 250 m (AHD) (Figs 1 and 2).



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Shire of Victoria Plains
Shire of Chittering
Shire of Toodyay
Shire of Swan
WANNAMAL LAKE SYSTEM
WANNAMAL
UDAMUNG BROOK
MOORA RD
GREAT NORTHERN HWY
LONGBRIDGE GULLY
WOOTRA BROOK
BINDOON
CHITTERING - NEEDOONGA LAKE SYSTEM
SPICE BROOK
BROCKMAN RIVER
MARBLING BROOK
BROCKMAN RIVER CATCHMENT
PERTH
WESTERN AUSTRALIA
Town
Rainfall (annual)
Evaporation (annual)
Brockman River
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Subcatchment boundary
Local Government boundary
Darling Fault
Major road
Lake
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Locality map — Brockman River catchment
Figure 1
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Darling Plateau

The Darling Plateau within the catchment comprises two major rock sequences (Fig. 3a). The first sequence is a 10 km-wide belt of crystalline rocks consisting of various gneisses and interbedded schists referred to as the Chittering Metamorphic Belt (Wilde and Low, 1978). To the east of the Chittering Metamorphic belt the crystalline rocks are granitic, extensively covered with a lateritic cap (Wilde and Low, 1978) and referred to as the lateritic uplands (Churchward and McArthur, 1980). These crystalline rock sequences were formed during the Archaean between 2500 and 3000 million years ago. The Darling Fault is the western boundary of the Darling Plateau. The Darling Scarp is the surface expression of this fault. Doleritic dykes intruded the crystalline rocks between 750 and 550 million years ago (Myers, 1990a, b). Near the Darling Scarp, some dykes are sheared at the margins whereas others are completely sheared (Wilde and Low, 1978).

The Darling Plateau as seen today is the product of uplift, weathering and erosion that happened after Australia separated from the ancient proto-continent of Gondwana (Cope, 1975). This plateau has been geologically stable allowing *in situ* weathering to produce a deep weathered-rock profile with significant clay content.

Erosion of this deep weathered-rock profile has not been uniform (Fig. 3a). In the east of the catchment, on the lateritic uplands, the weathered-rock profile is up to 30 m thick (GSWA, 1978) but erosion has exposed crystalline bedrock and saprolite clays along tributary streams.

Dandaragan Plateau

As Australia separated from Gondwana, the Perth Basin formed (Cockbain and Hocking, 1990). The Perth Basin contains an extensive thickness of sediments deposited both before and after continental breakup (Davidson, 1995). The Dandaragan Plateau is a wedge-shaped erosional remnant of the Perth Basin (Cope, 1975) where the sediments are now covered by laterite and recent deposits of sand (Wilde and Low, 1978).

*The **lateritic profile** or **weathered-rock profile** covers extensive areas of the Brockman River catchment. According to Nahon and Tardy (1992), a typical laterite profile has five horizons (Fig. 3b) and develops in tropical climates characterised by alternating humid and dry seasons.*

At the base, the parent rock is essentially fresh and unweathered (Horizon 1).

Above the parent rock is the coarse-grained saprolite horizon, and within this horizon unweathered remnants of the parent rock may be present (Horizon 2).

The coarse-grained saprolite becomes a fine-grained saprolite horizon (Horizon 3) in which most of the primary minerals have been altered to clays and iron-based minerals. Only resistant primary minerals such as quartz remain. At the base of the fine-grained saprolite horizon, the saprolite is porous. The porosity reduces up the lateritic profile as clays minerals are precipitated in the pore spaces.

The mottled horizon (Horizon 4) lies between the fine-grained saprolite horizon and the iron-crust horizon (Horizon 5). In the past, the mottled horizon was above the watertable, and water moving through this zone has created a network of channels and voids. The iron-crust horizon that overlies the mottled zone can consist of various layers, ranging from soft nodular iron crust, pisolitic iron crust to indurated or hard iron crust.

Hydraulic conductivity indicates the ease with which water moves through a medium; the higher the hydraulic conductivity, the easier it is for water to move through that medium.

The saprolite aquifer referred to by George (1992) is equivalent to the geological coarse-grained saprolite (Fig. 3b). The saprolite aquifer has typical hydraulic conductivity values of 0.6 m/day and 0.75 m/day (Clarke et al., 2000; George, 1992).

The fine-grained saprolite horizon is also called the pallid zone (Clarke et al., 2000; George, 1992). Typical hydraulic conductivity values of 0.06 m/day and 0.09 m/day have been found for the fine-grained saprolite and mottled zones (Clarke et al., 2000; George, 1992). The hydraulic conductivity value for the lateritic crust is more difficult to determine, but a value of 1 m/day is used for near-surface soil (George, 1992).

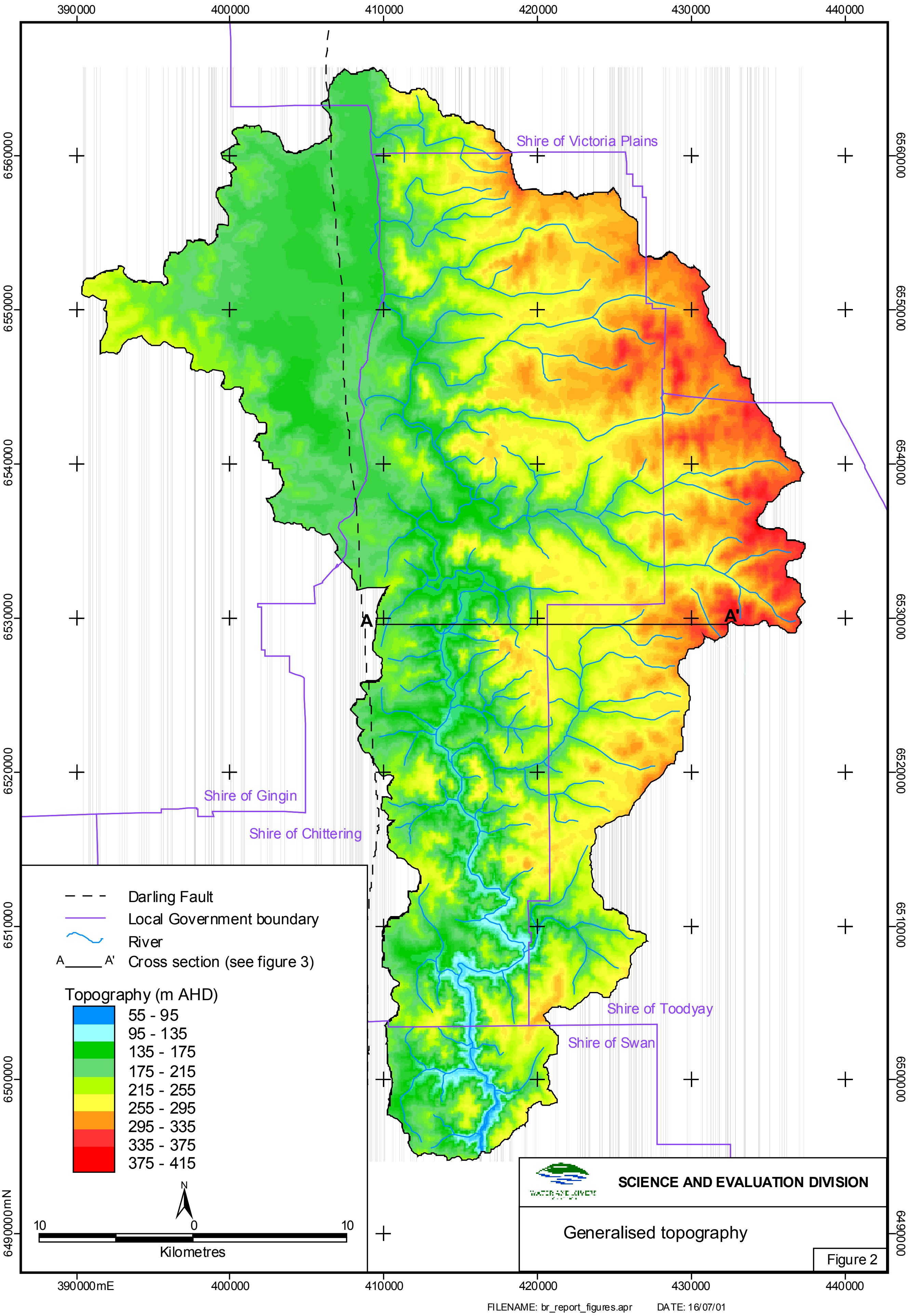
1.3.3 Surface drainage

The Brockman River flows south along the western edge of the Darling Plateau, through a deeply incised valley, to join the Avon River in the Walyunga National Park. The Brockman River receives surface drainage from Wannamal Lake system and ephemeral streams flowing from both the east and the west (Fig. 1).

The Wannamal Lake system is listed in the Directory of Important Wetlands in Australia where it is described as culturally and ecologically significant (Australian Nature Conservation Agency, 1993). Included in the lake system is Wannamal Lake, Mogumber Swamp, Bullingarra Lake and Football Lake. It is located in the north of the catchment near the surface-water divide between the Brockman River catchment and the Moore River catchment.

The surface-water flow direction of the Wannamal Lake system is disputed, with Wannamal Lake and Mogumber Swamp being placed in the Moore River catchment (Evangelisti & Associates, 1998). In June 1999, surface water from Mogumber Swamp was observed flowing south into Wannamal Lake and then into the Brockman River, thus placing this lake system within the Brockman River catchment. Wannamal Lake was already saline when Department of Conservation and Land Management (CALM) commenced water-quality readings in 1978.

Near Bindoon, the Brockman River flows into the Chittering–Needoonga lake system. This lake system is also listed in the Directory of Important Wetlands in Australia and is described as culturally and ecologically significant (Australian Nature Conservation Agency, 1993). Since 1975, CALM has controlled the water flowing through Lake Chittering in order to preserve the local wildlife habitat. During the summer months the weir is closed at the southern end of Lake Chittering, thereby maintaining a maximum water depth of 1.2 m (John Carter, 1999, personal communication). Thus, during the summer months, water flow in the Brockman River is only from the south of the catchment.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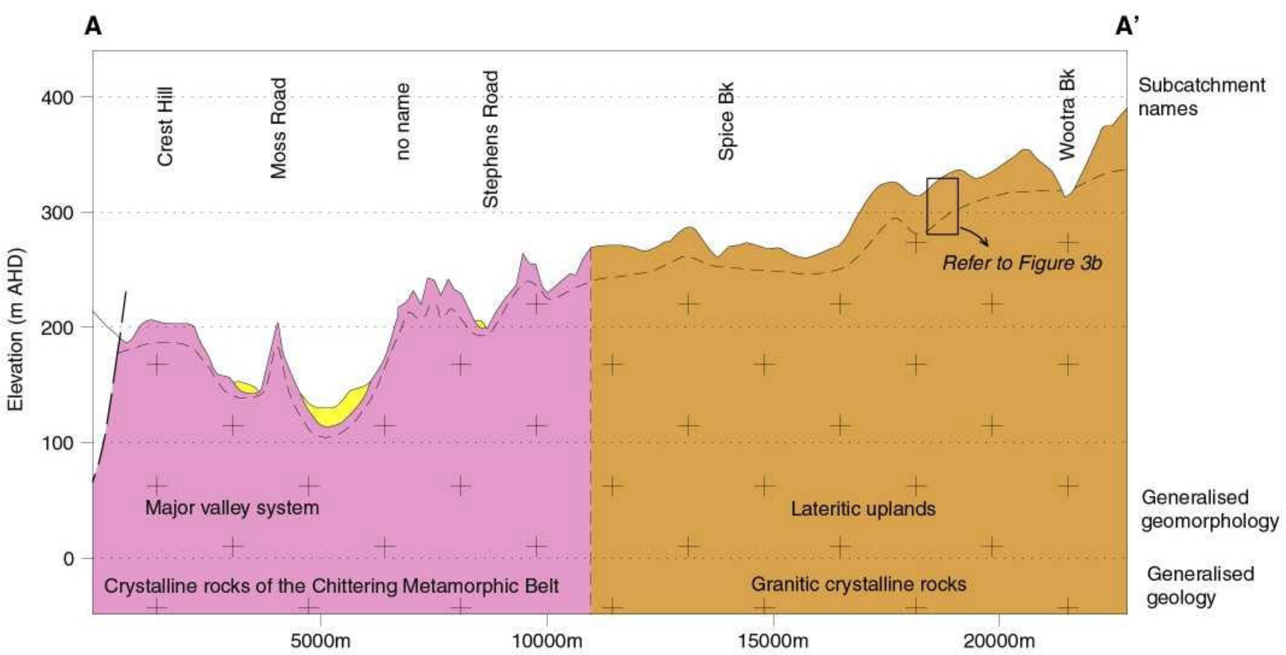

Figure 3a. Schematic section south of Bindoon showing generalised geology and geomorphology, groundwater zones and subcatchments (sources: Churchward and McArthur, 1980: Wilde and Low, 1978)

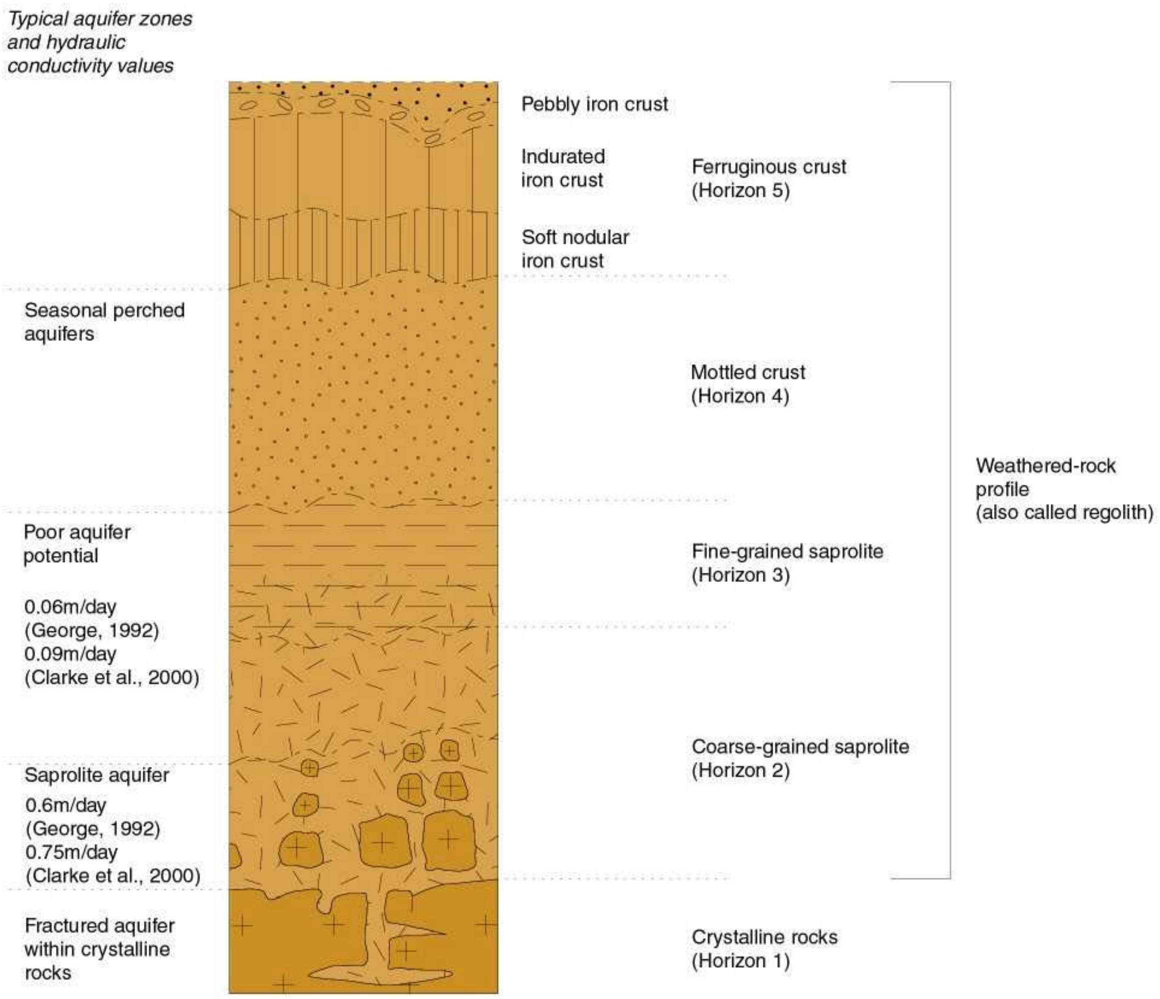

Figure 3b. Schematic weathered-rock profile showing the horizons of the lateritic profile, potential aquifer zones and typical hydraulic conductivity values (sources: Clarke et al., 2000; George, 1992; Nahon and Tardy, 1992)

Symbols for Figure 3a

Groundwater zones

- Surficial aquifer zone
- Fractured-rock aquifer zone A
- Fractured-rock aquifer zone B

— — Darling Fault

A -- A' refer Figure 2

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Generalised geology east of the Darling Fault

FIGURE 3a & 3b

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The Brockman River catchment has been divided into numerous subcatchments identified by the tributary name (Fig. 1). Where tributary is are unnamed the dominant road through the subcatchment is used as the identifier. Many of these subcatchments are unnamed and some have been given other names by local people.

1.4 Existing land management framework

Part of the Brockman River catchment is included in the Shire of Chittering Land Capability and Management Plan (Evangelisti & Associates, 1998). This is one of three studies commissioned by the Western Australian Planning Commission to provide 'environmental input into the structure, land capability and catchment plans within the Ellen Brook catchment and surrounds'. The study has established Environmental Planning Precincts based on the following criteria:

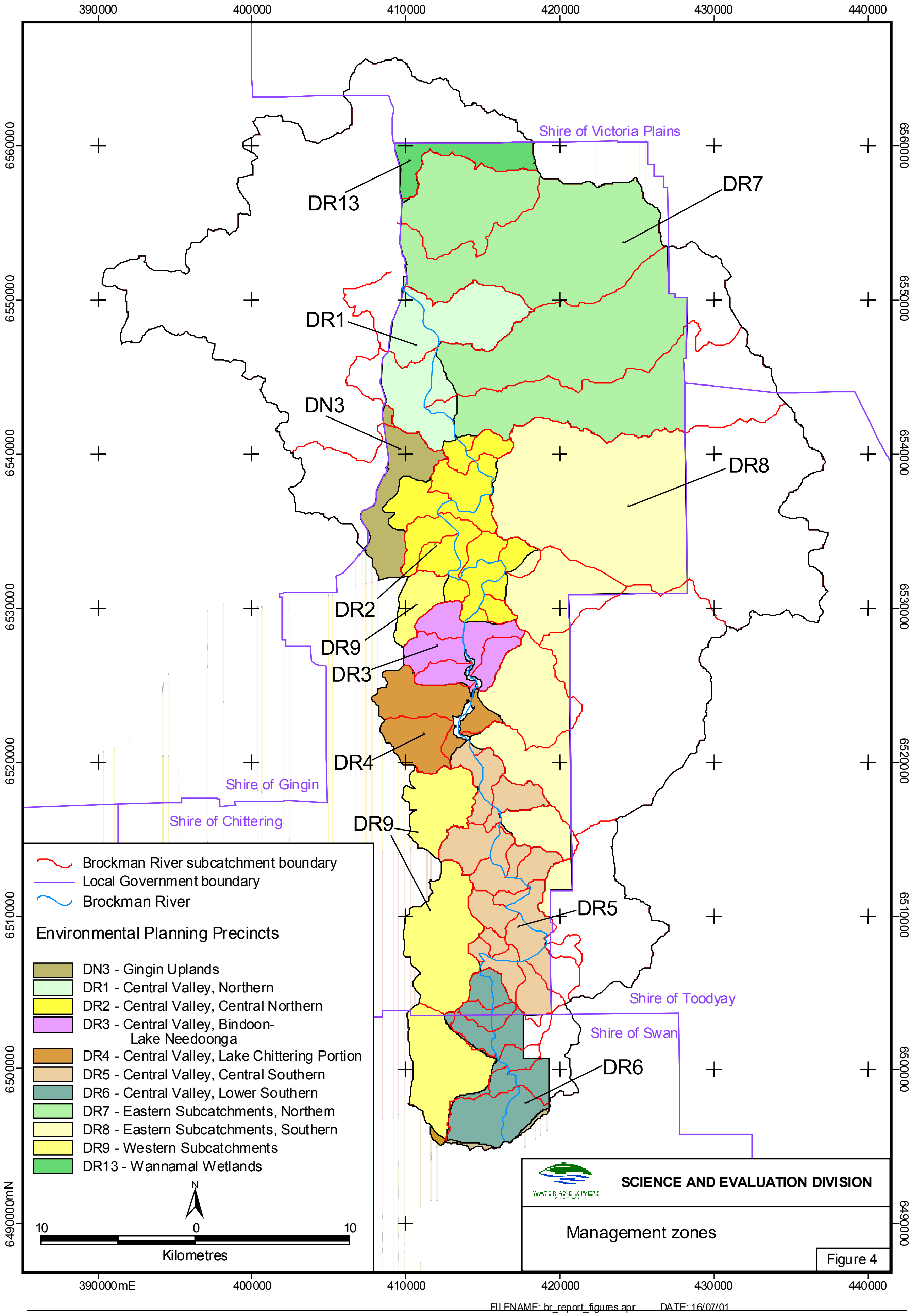
- geomorphic province
- major catchment
- Agriculture WA soil landscape systems
- subcatchments and groupings of subcatchments as defined by Swan River Trust
- consanguineous wetland suites classification.

These criteria are based on natural boundaries. However, the land capability study boundaries are the Shire of Chittering local government boundaries, and thus many of the environmental planning precincts within the Brockman River catchment have artificial boundaries (Fig. 4).

The environmental planning precincts are aimed at providing a framework for land use planning and management decisions. Therefore, the environmental planning precincts are referred to in this study when dealing with the management strategies. Both Environmental Planning Precincts DR13 and DN3 have been included in the Moore River catchment by Evangelisti & Associates (1998). In this Report the Environmental Planning Precinct DR13, incorporating Murphy Gully Creek and the Wannamal Wetlands, has been included in the Brockman River catchment.

Environmental Planning Precinct DN3, the Gingin uplands, has been included in the Brockman River catchment. The surface-water catchment boundaries are difficult to define in this area. However, the groundwater boundaries are unlikely to follow the surface-water boundaries as the aquifers of the Dandaragan Plateau are part of the regional aquifers of the Perth Basin.

A framework for management decision making has been developed for the Shire of Chittering Land Capability and Management Plan (Evangelisti & Associates, 1998). The groundwater management recommendations presented later in the Report relate to the Environmental Planning Precincts where possible (see Section 4).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DR4
DR9
DR5
DR6
Brockman River subcatchment boundary
Local Government boundary
Brockman River
Environmental Planning Precincts
DN3 - Gingin Uplands
DR1 - Central Valley, Northern
DR2 - Central Valley, Central Northern
DR3 - Central Valley, Bindoon-Lake Needoonga
DR4 - Central Valley, Lake Chittering Portion
DR5 - Central Valley, Central Southern
DR6 - Central Valley, Lower Southern
DR7 - Eastern Subcatchments, Northern
DR8 - Eastern Subcatchments, Southern
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DR13 - Wannamal Wetlands
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Management zones
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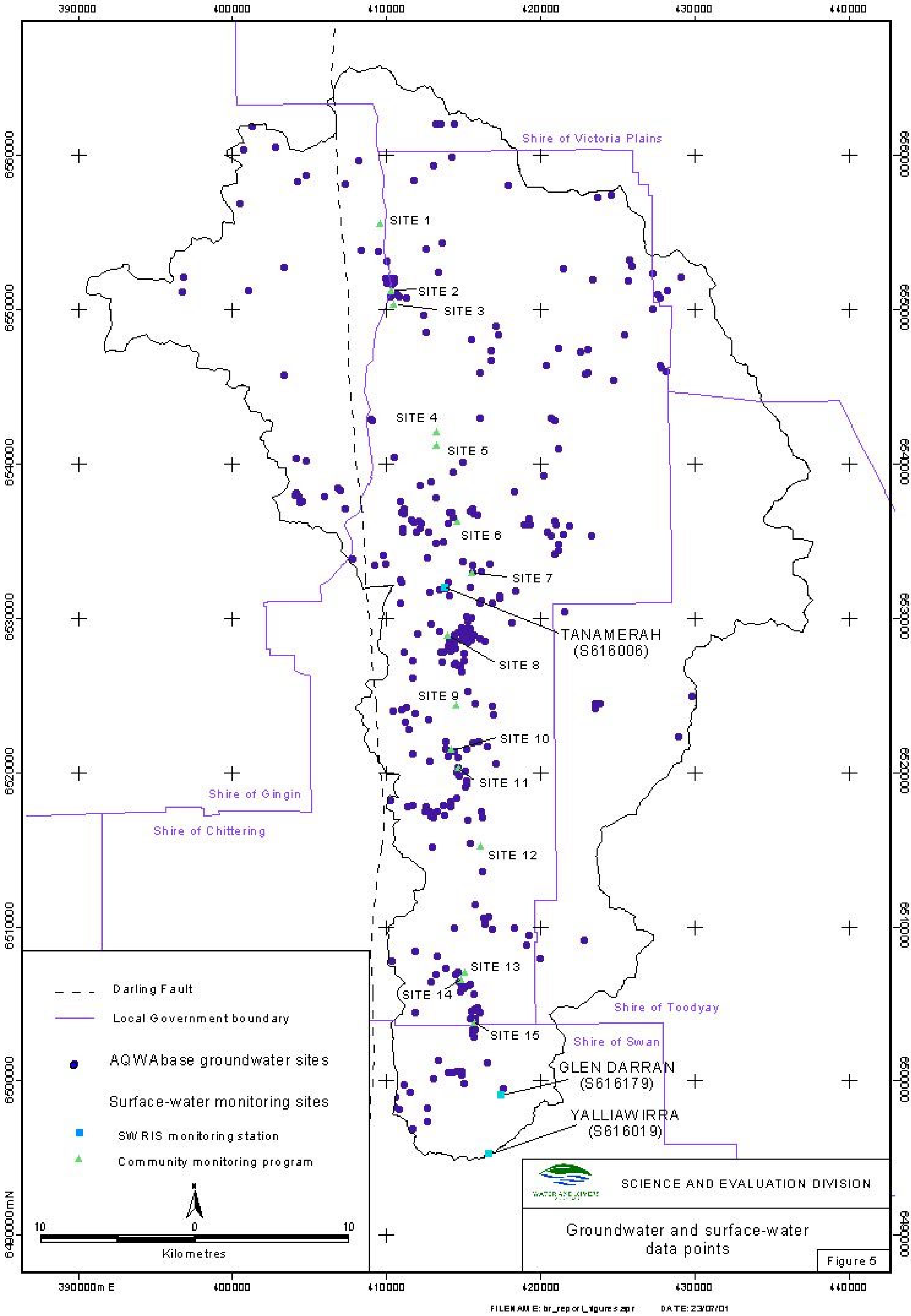
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Shire of Swan
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YALLIAWIRRA
(S616019)
Darling Fault
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Groundwater and surface-water
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1.5 Data sources

1.5.1 Surface hydrology

Surface-water data used in this report are from the WRC State Water Resources Information System (SWRIS) and a community-based monitoring program. SWRIS surface-water monitoring stations (Fig. 5) classified as S type stations collect continuous surface-water flow rates and various physical and chemical water quality parameters. Streamflow records between 1980 and 1998 are available for monitoring station Tanamerah (S616006), and between 1975 and 1998 for monitoring station Yalliawirra (S616019); these are listed in Appendix 1.

From 1991 and 1998 continuous electrical conductivity values have been recorded at both monitoring stations. Mean daily TDS values have been calculated from the electrical conductivity measurements and combined with the mean daily streamflow records to calculate annual salt loads between 1991 and 1998. This has permitted a comparison of water qualities and salt loads between the two localities.

The community-based monitoring program initiated by the Chittering Landcare Coordinator produced a measure of water quality within the Brockman River (Fig. 5). Monthly field measurements of surface-water quality were recorded between May 1997 and May 1998 at 15 sites along the river. Gaps in this dataset have not been coded to indicate why the measurement was not recorded. The data between May 1997 and December 1997 are nearly complete. Few data were collected for the north of the catchment between January 1998 and May 1998, and it is likely that the river was not flowing. The TDS values are given in Appendix 2.

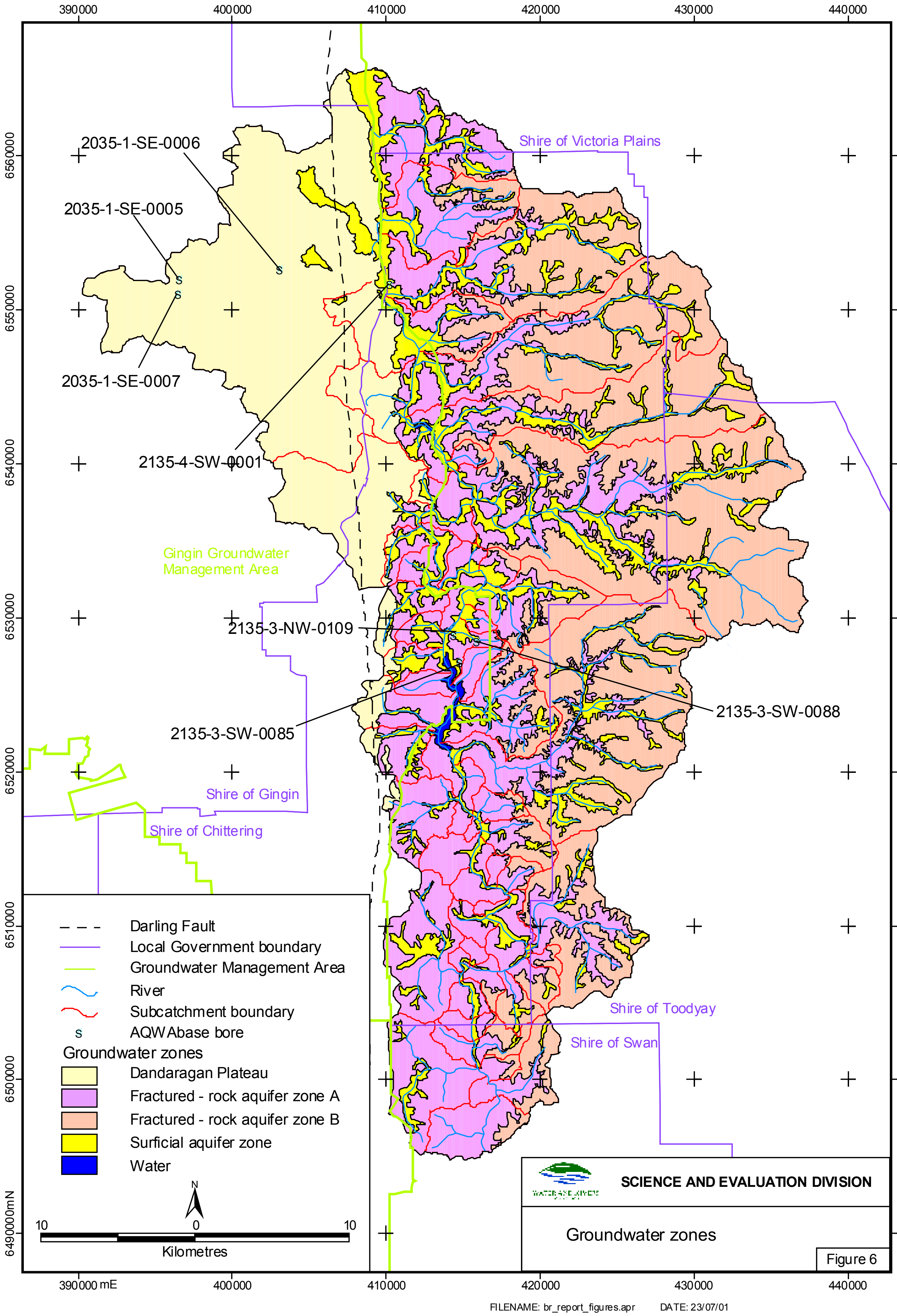
1.5.2 Groundwater hydrology

Many Western Australian groundwater sites are recorded in AQWABase, a database maintained by WRC. This database includes groundwater data from private drilling companies, local landholders, industry and state government agencies. Interrogation of AQWABase produced 427 recorded groundwater sites within the Brockman River catchment (Fig. 5). Examination of these data revealed a variation in the quality of data available which ranged from site location only, to extensive data on borehole construction, water quality, water yields and geological logging of boreholes. Of the 427 groundwater sites:

- 64 boreholes included geological logs of various quality
- 300 boreholes included TDS field measurements
- 200 boreholes included depth to water level
- no hydrograph is available to show the inferred rising groundwater levels.

1.5.3 Landsat imagery

Landsat imagery has been interpreted by the Land Monitor Project to establish baseline data for continued monitoring of salt-affected land (Caccetta *et al.*, 1999). The Land Monitor Project has assumed that land with consistently low productivity is salt-affected land and, based on this assumption, the Landsat imagery has been used to determine salt-affected land before 1987 and any change in the affected area between 1987 and 1996.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2135-3-NW-0109
2135-3-SW-0088
2135-3-SW-0085
Shire of Gingin
Shire of Chittering
Shire of Toodyay
Shire of Swan
Darling Fault
Local Government boundary
Groundwater Management Area
River
Subcatchment boundary
AQWAbase bore
Groundwater zones
Dandaragan Plateau
Fractured - rock aquifer zone A
Fractured - rock aquifer zone B
Surficial aquifer zone
Water
N
10
0
10
Kilometres
SCIENCE AND EVALUATION DIVISION
Groundwater zones
Figure 6
FILENAME: br_report_figures.apr
DATE: 23/07/01

2 Aquifers

2.1 What types of aquifers are in the catchment?

Based on the geology and geomorphology, the Brockman River catchment can be divided into four distinct groundwater zones (Fig. 6; Table 2). West of the Darling Fault, the sediments of the Dandaragan Plateau are part of a regional aquifer system (Kay and Diamond, 2001), whereas east of the Darling Fault the crystalline rocks of the Darling Plateau can be subdivided into two fractured-rock groundwater zones. Fractured-rock aquifer zone A is roughly coincidental with the Chittering Metamorphic Belt and the minor valley systems. East of this zone is fractured-rock aquifer zone B, on the lateritic uplands. Traversing both the Dandaragan Plateau and Darling Plateau are alluvial and colluvial deposits that contain the surficial aquifers.

Aquifer and groundwater are terms often used interchangeably, which can lead to confusion, especially within the Brockman River catchment where aquifers are localised, rather than extensive, and hard to locate.

***Groundwater** is water that exists beneath the watertable in soil and geological units or formations that are fully saturated.*

*The **watertable** is the surface between the saturated zone and the unsaturated zone of the geological unit or formation.*

*The term **aquifer** is best defined as a geological unit or formation saturated with water that can be **abstracted,** or removed, in economic quantities.*

Confusion arises because geological units or formations that are not aquifers may also contain groundwater. However, if the groundwater cannot be abstracted in sufficient quantities to be economically significant to the landholder, then although groundwater is present, it is not part of an aquifer.

2.2 Where are the aquifers?

2.2.1 Shallow regional aquifer zone

The Dandaragan Plateau contains unconsolidated sediments that were deposited before and after continental breakup, and recently deposited overlying sands and gravels. The groundwater within these sediments forms part of a regional aquifer system of the Perth Basin (Fig. 6). Interbedded sequences of sands and clays have been intersected to depths of 49 and 52 m in boreholes 2035-1-SE-0006 and 2035-1-SE-0005 respectively, and to 112 m in 2035-1-SE-0007 (Fig. 6). Below the interbedded sand and clays lie interbedded sandstone and clays. From this limited geological data the division between the older sediments and overlying recent sands and gravels cannot be identified. Regional work (Kay and Diamond, 2001) has defined this semi-confined aquifer as the Mirrabooka aquifer.

The Mirrabooka aquifer is separated from the underlying confined Leederville–Parmelia aquifer by the Kardinya Shale, except where the Leederville–Parmelia aquifer is in direct contact with the Wannamal Lake system (Kay and Diamond, 2001). Where the Mirrabooka aquifer is unconfined, recharge will be by direct precipitation and thus the water quality is generally good.

Table 2. Groundwater zones within the Brockman River catchment

Groundwater zones	*Geomorphic provinces*	*Geology*	*Landforms*	*Landform characteristics*	*Aquifer characteristics*
Regional aquifer	Dandaragan Plateau	lateritic sands and gravels overlying sand and clay sediments	sandy uplands	1) subdued elevation 2) deep sands and clays	part of a regional aquifer
Surficial aquifers	Dandaragan and Darling Plateaus	alluvial and colluvium deposits including valley-fill deposits	major valley floors and some minor valley floors	1) generally located along valley floors 2) variable depth and extent of deposits	localised with very variable supply
Fractured-rock aquifers (zone A)	Darling Plateau	crystalline rocks of the Chittering Metamorphic Belt and overlying lateritic profile	major valleys and some minor valleys	1) moderate to steep valley slopes 2) depth of weathered material above crystalline rock very variable, in many places crystalline rock exposed at surface	localised with very variable supply
Fractured-rock aquifers (zone B)	Darling Plateau	crystalline rock and overlying lateritic profile	lateritic uplands	1) subdued elevation 2) lateritic surface tends to be 3–5 m thick, and up to 30 m of weathered material above crystalline rocks	localised with very variable supply

Limited groundwater data indicate that the depth to the watertable in this area is variable and ranges from 6 to 30 m below ground surface. The thickness of the shallow aquifer within the catchment has not been defined, although regional work indicates that the saturated thickness is about 40 m (Kay and Diamond, 2001). Within the Brockman River catchment local groundwater discharge from this aquifer is into the Wannamal Lake system (Kay and Diamond, 2001).

The watertable is the upper boundary of an ***unconfined aquifer.***

The upper and lower boundaries of a ***confined aquifer*** *are formations of low permeability.*

In a ***semi-confined*** *aquifer, the upper boundary is the watertable in some places, and a formation of low permeability in others.*

2.2.2 Surficial aquifer zone

Erosion has transported sand, gravels, clays and rock fragments within the valleys of the Brockman River catchment. These rock materials have been deposited on the lower slopes and valley floors, especially along sections of the stream lines. Where extensive enough, these materials have been mapped as alluvial and colluvial deposits (Wilde and Low, 1978) and form surficial aquifers. The surficial aquifers traverse the Dandaragan and Darling Plateaus (Figs 3a and 6) and include:

- Tertiary age palaeochannel deposits under the Wannamal Lake system (Kay and Diamond, 2001)
- Early Quaternary river gravels under the Brockman River and, to a lesser extent, the tributaries
- Recent valley-fill deposits located on the floor and lower slopes of the valley (Wilde and Low, 1978).

The palaeochannel deposits extend beneath the Moore River from Moora to Mogumber and down to the Wannamal Lake (Kay and Diamond, 2001). This palaeochannel then possibly extends to the Barnes Road aquifer (but additional work would be needed to confirm this). The depth of the palaeochannel under the Wannamal Lake is not known, although the Barnes Road aquifer is assumed to be some 20 m thick (WRC, 1999).

The extent and thickness of the sand, gravel, clay deposits in the valleys are variable, but borehole 2135-3-NW-0109 intersected 5 m of sand and river gravels from 14.5 to 19.5 m depth. The surficial aquifer tends to be thickest in the Brockman River valley and very thin if present along the tributaries of the Brockman River (Fig. 3a). Groundwater yields are dependent on both the thickness of these deposits and the proportion of sand and gravel between the clay, thus ensuring that aquifers within this zone are localised.

Palaeochannel *— A remnant of an ancient stream channel cut into the bedrock, infilled by distinctly older deposits than the covering sediments.*

2.2.3 Fractured-rock aquifer zones

Two distinct fractured-rock aquifer zones exist within the Brockman River catchment (Figs 3a and 6). Zone A, adjacent to the Darling Fault, trends north–south with some eastward extensions, and incorporates the valley of the Brockman River and minor east–west valley systems. Zone B incorporates the lateritic uplands extending to the eastern edge of the catchment.

Uplift and subsequent erosion formed the major and minor valley systems of Zone A (Figs 3a and 6). Erosion has stripped weathered rock material from the valley slopes of the Brockman River and, to a lesser extent, the east–west tributaries. Throughout these valleys the thickness of weathered rock material above the crystalline rock is varied, with the crystalline rock being exposed in many areas. The depth of weathered rock material reaches 39 m, with measured thicknesses of 6.1 m in borehole 2135-4-SW-0001, 9.5 m in borehole 2135-3-SW-0085 and 39 m in borehole 2135-3-SW-0088.

Due to its proximity to the Darling Fault, faulting is more intense in fractured-rock aquifer zone A than in fractured-rock aquifer zone B. Groundwater abstraction is dependent on the size of the fractures. Aquifers within Zone A are localised, with variable water quality and supply. Borehole 2135-3-SW-0088 intersected one of these fault zones from 18 to 39 m, which is logged as ‘schist and sand’. The water supply was good, but the borehole was abandoned owing to water quality (GSWA, 1981).

In the east of the catchment is fractured-rock aquifer zone B. This groundwater zone covers the lateritic upland, which has a subdued topographic relief and is less intensely fractured than aquifer Zone A (Figs 3a and 6). Mineral exploration boreholes within this area have intersected some 30 m of weathered material (GSWA, 1978).

Groundwater in these fractured-rock zones resides in fractures that can be difficult to locate, and in the overlying weathered-rock profile. From the weathered-rock profile, water abstraction is most successful from the coarse-grained saprolite horizon (Fig. 3b), with an average hydraulic conductivity of about 0.6 m/day (George, 1992). Generally, the fine-grained saprolite horizon, with an average hydraulic conductivity of 0.06 m/day (George, 1992), is not suitable for groundwater abstraction because of the increased clay minerals. However, this weathered-rock profile is variable and areas suitable for groundwater abstraction are localised both laterally and vertically.

2.3 Which aquifers are likely to contain the freshest groundwater?

2.3.1 Groundwater quality by groundwater zones

Groundwater in the Brockman River catchment is needed for domestic supplies, irrigation and livestock. Fresh groundwater is not readily found in the catchment but brackish groundwater can be used for livestock and for some irrigation (Australian Water Resources Council, 1988). Of the 427 recorded boreholes within the Brockman River catchment, 300 have known groundwater TDS values. These water-quality measurements have been classified according to the groundwater zone (Fig. 7).

The groundwater abstracted from the shallow regional aquifer beneath the Dandaragan Plateau and surficial aquifer zone beneath both the Dandaragan and Darling Plateaus can be used for most purposes. However, some of the groundwater abstracted from the surficial aquifer zone is saline. In the fractured-rock aquifer zone A the groundwater tends to be suitable for drinking, irrigation and livestock, whereas in fracture-rock aquifer zone B the groundwater is generally suitable for limited irrigation and livestock.

These water-quality data need to be used with care. Boreholes intersecting saline groundwater are often abandoned without the details having been sent to WRC for inclusion in the groundwater database. This may create a bias and the groundwater quality may be lower overall than that presented in Figure 7.

2.3.2 Groundwater quality by depth

The variation of groundwater quality with depth beneath the Darling Plateau has been analysed using scatter plots (Fig. 8). Available TDS values show a distinct cluster of boreholes with fresh to brackish groundwater at depths less than 20 m in the surficial aquifers zone and fractured-rock aquifer zone A. Saline groundwater also exists within this depth range. Within fractured-rock aquifer zone B, this fresh to brackish groundwater quality cluster is not so prominent but still present to a depth 40 m. In both fractured-rock aquifer zone A and the surficial aquifer zone the water quality at depth is generally fresh to brackish, but saline groundwater exists.

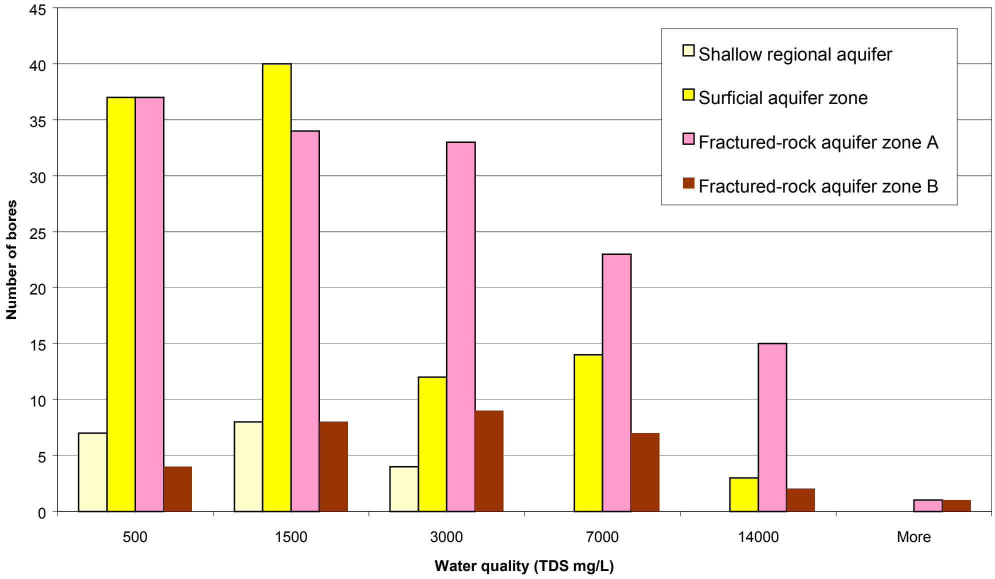


Figure 7. Summary of groundwater-quality measurements based on groundwater zones

2.4 Which are the important zones for groundwater supply?

Groundwater supply within the Brockman River catchment is very variable.

- Regional work suggests that the shallow regional aquifer beneath the Dandaragan Plateau has a saturated thickness of 40 m (Kay and Diamond, 2001). From the limited information available the supply cannot be determined, due to the variable interbedded nature of the sediments.
- The surficial aquifer zone is an important source of groundwater in the catchment. Groundwater supply is dependent on local thickness of the aquifer. Anecdotal evidence suggests that some boreholes into this zone do not supply water in late summer.
- As fractured-rock aquifer zone A is adjacent to the Darling Fault, this zone is more intensely fractured than fractured-rock aquifer zone B. The decreased incidence of rock fractures and the deep weathered-rock profile in fractured-rock aquifer zone B means that groundwater supplies are both smaller more difficult to locate in this zone than in fracture-rock aquifer zone A.

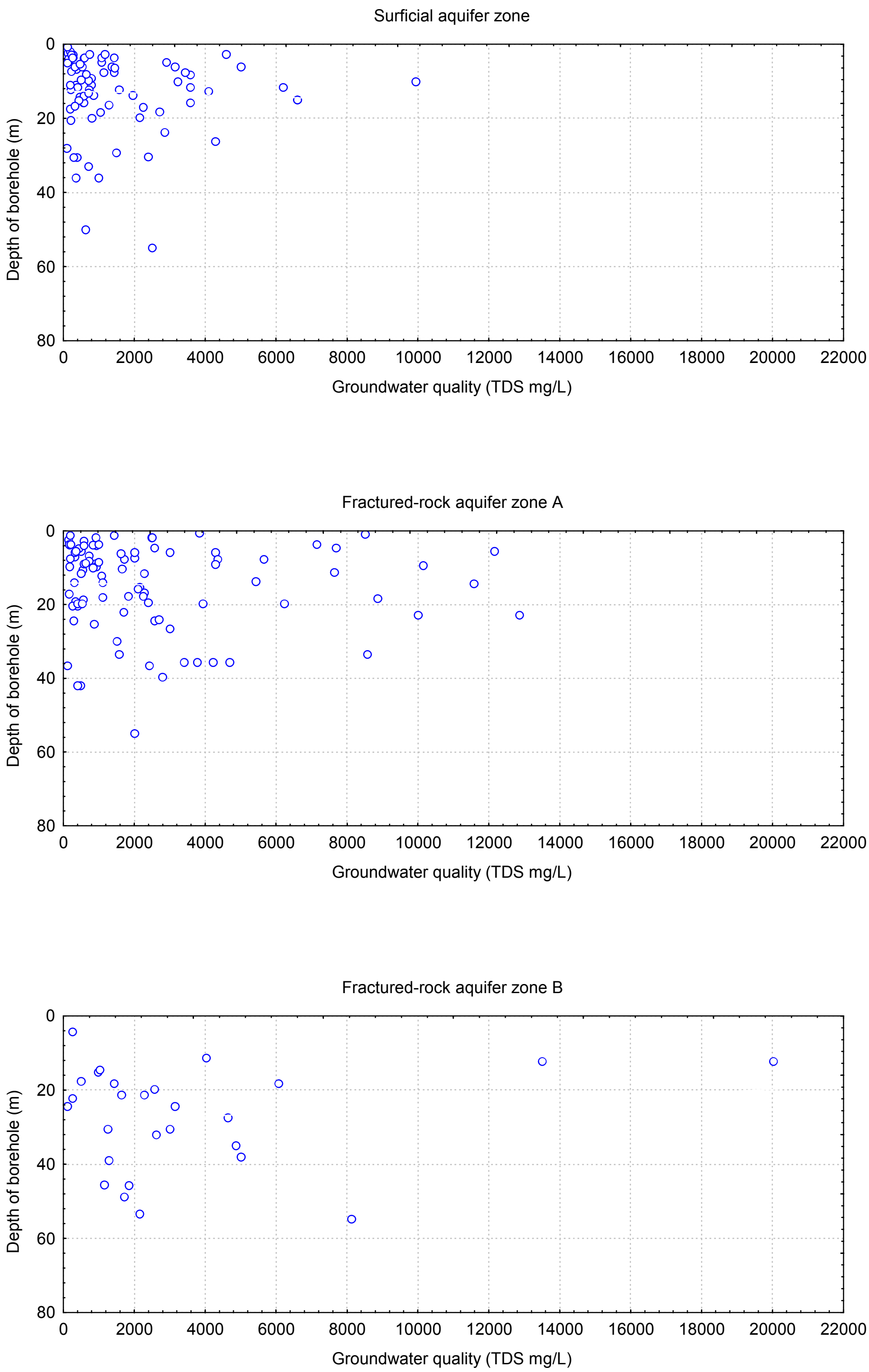


Figure 8a–c. Groundwater quality with depth

2.5 Legal requirements for groundwater abstraction

The Gingin Groundwater Management Area incorporates sections along the western boundary of the Brockman River catchment (Fig. 6). The Gingin Groundwater Area was proclaimed in 1975 and modified in 1988 (Water Authority of Western Australia, 1993). At present, the allocations limits are being reviewed (WRC, 2000). A hydrogeological assessment of the major aquifer systems underlying the Victoria Plains, Red Gully, Gingin and Eclipse Hill Sub-areas of the Gingin Groundwater Area has been completed as part of this review (Kay and Diamond, 2001). Within the Brockman River catchment, the hydrogeological assessment has redefined the Leederville–Parmelia aquifer and identified the shallow Mirrabooka aquifer and the palaeochannel deposits under the Wannamal Lake system (Kay and Diamond, 2001).

The sub-areas of Eclipse Hill, Bindoon, Gingin Townsite and Red Gully include sections of the Brockman River catchment. Licences are not needed for unconfined aquifers if groundwater abstraction is less than 1 500 kL/yr. All groundwater abstraction from the confined aquifers needs to be licensed. This includes the Leederville–Parmelia and the Yarragadee aquifers, which are confined aquifers, and the Mirrabooka aquifer, even though it is semi-confined (WRC, 2000).

3 Salinisation east of the Darling Fault

3.1 History and causes

Clearing of native vegetation and the utilisation of the land for residential use, agriculture, horticulture and light industry has changed the water balance within the Brockman River catchment. The catchment lies between average annual isohyets of 500 mm in the north and 900 mm in the south. The history of land clearing in the Brockman River catchment is difficult to quantify. Landsat imagery, interpreted by the Land Monitor Project for vegetation history, shows that most of the catchment was cleared of native perennial vegetation by 1988. Exceptions include the Julimar State Forest and land owned by the Commonwealth Government in the east of the catchment. The native vegetation has been replaced by pastures, annual cereal crops and horticultural crops (Evangelisti & Associates, 1998).

Groundwater recharge in the Brockman River catchment has increased and groundwater accumulates faster than it can be drained from the catchment. As groundwater rises, salt that has been accumulating in the weathered-rock profile over many thousands of years is mobilised and is discharged at the surface as seeps or base flow directly into creeks, streams or rivers.

For more information on water balance see:

The water cycle, Water Facts 7, Water and Rivers Commission 1998

What is groundwater?, Water Facts 8, Water and Rivers Commission 1998

Moore G., 1998. Soil Guide — a handbook for understanding and managing agricultural soils: Agriculture Western Australia, Bulletin 4343

3.2 Rising groundwater levels

3.2.1 Factors affecting groundwater recharge

The local geology and geomorphology will affect recharge rates. Potential recharge areas are sand plains, lateritic duricrust and the outcrops of basement (crystalline bedrock) in the watershed zones of the catchment (Salama *et al.*, 1994). Using these observations, potentially high recharge areas throughout the Brockman River catchment can be identified. Examples include the cleared topographic high area that is bounded by the Great Northern Highway, Maddern Road, Blue Plains Road and Chittering Road within fractured-rock aquifer zone A; the extensively cleared lateritic uplands, especially towards the watershed boundaries of the subcatchments found in fractured-rock aquifer zone B; and the sand plains of the Dandaragan Plateau.

The Dandaragan Plateau is a potentially active recharge area for groundwater, but is west of the Darling Fault and does not have the crystalline bedrock or associated weathered profile required for the salinisation processes associated with the Darling Plateau.

3.2.2 Are the groundwater levels rising?

That groundwater levels are rising is indicated by the changing flow patterns of the Brockman River and its tributaries. The Brockman River is classified as a non-perennial river, but the southern section now flows through summer. Summer flow has been recorded at monitoring station Yalliawirra (S616019) since 1982. No summer flows have been measured for the northern section of the Brockman River at gauging station Tanamerah (S616006). However, oral history recalls that 30 years ago the Udamung Brook flowed only after heavy rains; Udamung Brook now flows till early summer.

The differences between the north and south of the catchment can be explained by variation in groundwater storage capacity and rainfall. Owing to the thickness of the weathered-rock profile, the groundwater storage capacity is greater for fractured-rock aquifer zone B than for fractured-rock aquifer zone A. Fractured-rock aquifer zone B characteristically has a subdued topographic relief, deep weathered-rock profile and is more common in the north compared with the steep topographic relief and shallow but irregular weathered-rock profile of the valley systems found in fractured-rock aquifer zone A (Fig. 3a). Together with the lower average annual rainfall in the north of the catchment (Fig. 1), this increases the delay between the clearing of native vegetation and the rising groundwater reaching the surface.

The rate of groundwater rise within the catchment has not been monitored, but as the factors that affect groundwater recharge and movement within the weathered-rock profile are not uniform, neither will be the rate of groundwater rise over the catchment.

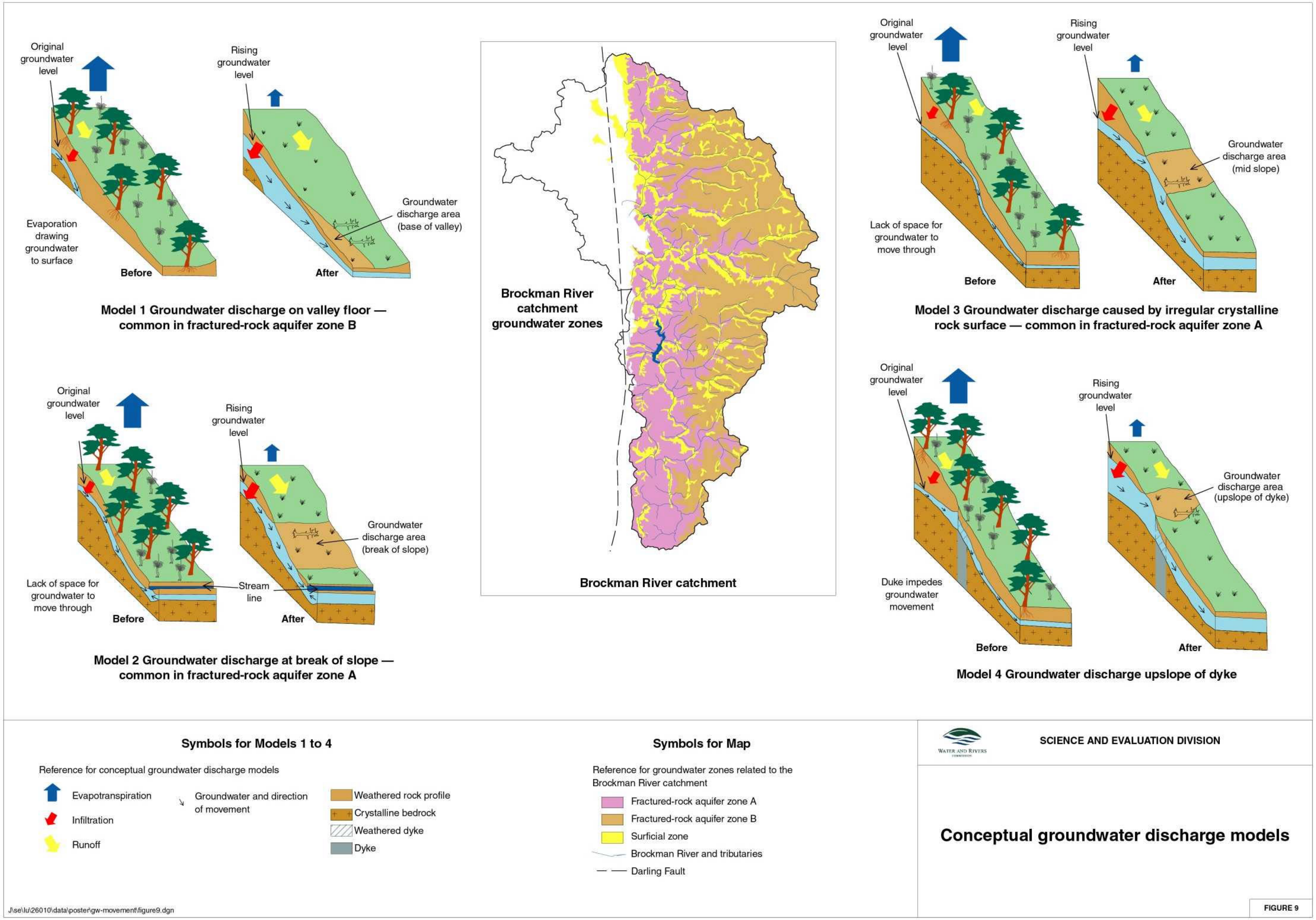
3.2.3 Where will groundwater discharge?

Four conceptual groundwater models (Coram, 1998) have been adapted for the Brockman River catchment to explain how local geology and geomorphology affect groundwater movement and contribute to the formation of groundwater discharge sites. Groundwater moves both vertically and laterally. The lateral movement is from high areas in the landscape to low areas. These conceptual groundwater discharge models are by no means exhaustive and discharge may also be due to a combination of local geologic and geomorphic factors.

Groundwater discharge sites form upslope of any geological or geomorphic structures that restrict the movement of groundwater. Geomorphic changes are seen in groundwater discharge models 1 and 2, and local geological changes in groundwater discharge models 3 and 4 (Fig. 9).

Low-lying areas of shallow basins and broad, open valleys seen in fractured-rock aquifer zone B are often sites of groundwater discharge, especially if the saprolite horizon is exposed or is near the ground surface. These sites are often associated with surface drainage lines. Groundwater moves slowly down the gentle valley slopes and groundwater discharge appears where the groundwater flows converge at the base of the depression. In summer, groundwater within 1 to 2 m of the ground surface evaporates, leaving the salts to concentrate in the soil, thus exacerbating the problem and creating salt scalds as seen in the northern subcatchments such as the subcatchment for Udamung Brook.

A sudden decrease in slope (as shown in model 2) reduces the cross-sectional area between the bedrock surface and ground surface. This reduces the volume of groundwater that can move between the ground surface and the bedrock, so forcing groundwater onto the ground surface. The reduction in cross-sectional


Original groundwater level
Rising groundwater level
Evaporation drawing groundwater to surface
Groundwater discharge area (base of valley)
Before
After
Model 1 Groundwater discharge on valley floor — common in fractured-rock aquifer zone B
Original groundwater level
Rising groundwater level
Lack of space for groundwater to move through
Groundwater discharge area (break of slope)
Stream line
Before
After
Model 2 Groundwater discharge at break of slope — common in fractured-rock aquifer zone A
Brockman River catchment groundwater zones
Brockman River catchment
Original groundwater level
Rising groundwater level
Groundwater discharge area (mid slope)
Lack of space for groundwater to move through
Before
After
Model 3 Groundwater discharge caused by irregular crystalline rock surface — common in fractured-rock aquifer zone A
Original groundwater level
Rising groundwater level
Groundwater discharge area (upslope of dyke)
Duke impedes groundwater movement
Before
After
Model 4 Groundwater discharge upslope of dyke
Symbols for Models 1 to 4
Reference for conceptual groundwater discharge models
Evapotranspiration
Infiltration
Runoff
Groundwater and direction of movement
Weathered rock profile
Crystalline bedrock
Weathered dyke
Dyke
Symbols for Map
Reference for groundwater zones related to the Brockman River catchment
Fractured-rock aquifer zone A
Fractured-rock aquifer zone B
Surficial zone
Brockman River and tributaries
Darling Fault
SCIENCE AND EVALUATION DIVISION
Conceptual groundwater discharge models
FIGURE 9
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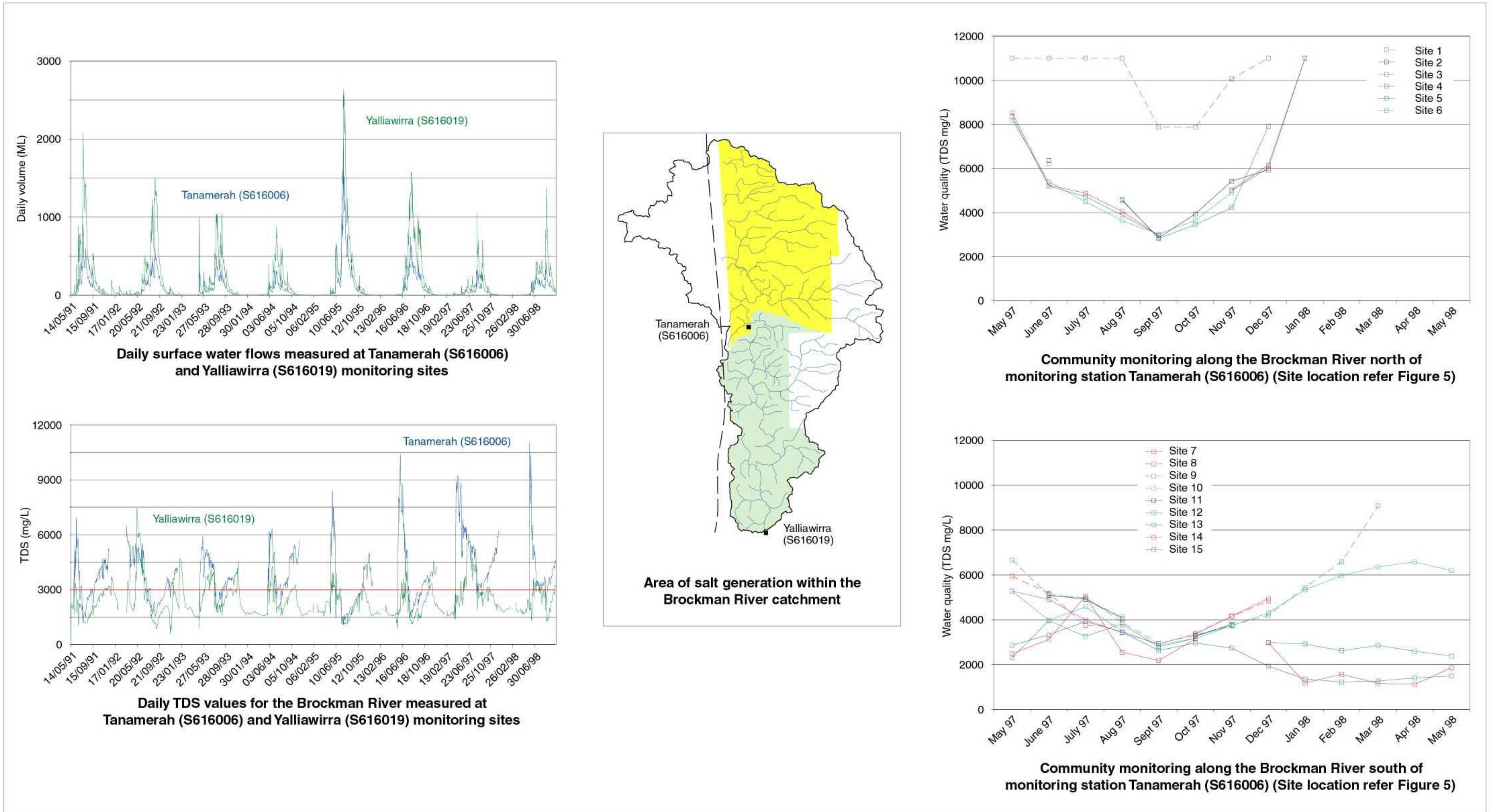

Symbols for Map

~ 60% of salt load
~ 40% of salt load
Brockman River and tributaries
Darling Fault
Monitoring station

WATER AND RIVERS COMMISSION

SCIENCE AND EVALUATION DIVISION

Hydrology of the Brockman River

FIGURE 10

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area may also be due to an irregular bedrock topography as seen in groundwater discharge model 3. Sites resembling groundwater discharge models 2 and 3 will be common in fractured-rock aquifer zone A and help explain some of the groundwater seeps in the area bounded by the Great Northern Highway, Maddern Road, Blue Plains Road and Chittering Road.

Not only does bedrock topography change, the physical characteristics of the geology vary throughout the catchment. One common change in the geology is the intrusion of dykes, and subsequent weathering, as shown in model 4. If groundwater moves more slowly through a weathered dyke than through the surrounding material, and the dyke is perpendicular to the groundwater movement, then groundwater will accumulate upslope of the dyke (Coram, 1998). Groundwater that collects behind the dyke is eventually forced onto the ground surface. In the past, landholders drilled upslope of dykes located perpendicular to groundwater flow to abstract groundwater.

Groundwater discharge sites conforming to the conceptual groundwater discharge models are found throughout the catchment east of the Darling Fault. The subdued topographic relief found on the lateritic uplands of fractured-rock aquifer zone B means that sites resembling model 1 will dominate this zone. The rugged topographic relief and irregularly eroded weathered-rock profile in fractured-rock aquifer zone A will result in sites like models 2 to 3 dominating in this zone. Sites resembling model 4 will be found through out both fractured-rock aquifer zones A and B.

3.3 Salt distribution

3.3.1 General trends

No direct data on salt stores or the distribution of salt stores for the Brockman River catchment are available. However, between 1992 and 1997, annual salt loads exported from the catchment were calculated using the TDS values and surface-water flow rates measured at monitoring stations Tanamerah (S616006) and Yalliawirra (S616019) (Fig.10). About 60% of the salt exported by the Brockman River is generated in the catchment above monitoring station Tanamerah (S616006) and remaining 40% below this monitoring station (Figs 10 and 11).

Monitoring station Tanamerah (S616006) receives surface water from the Brockman River and tributaries between and including Udamung Brook and Wootra Brook, and in high-rainfall years from Wannamal Lake and Mogumber Swamp. Tributaries north of Udamung Brook drain into the Wannamal Lake and Mogumber Swamp. The surface water in Wannamal Lake has been predominantly saline since CALM started monitoring the water quality and lake depth in 1978. The salt load of the lake cannot be determined as the lake bathymetry has not been surveyed. Groundwater flows between the Wannamal Lake system and the Brockman River have not been investigated. Depending on the rate at which groundwater moves between Wannamal Lake and the Brockman River, this may be a significant source of saline groundwater.

All west flowing tributaries north of monitoring station Tanamerah (S616006) drain agricultural land, except the source of the Wootra Brook, which drains land covered by native perennial vegetation. Landsat imagery interpreted by Land Monitor Project shows that salt-affected land increases towards the northeast within the catchment (Fig. 12). Within the Brockman River catchment, prior to 1987, the salt-affected land was largely along the Brockman River and its tributaries. Between 1987 and 1996, the area of salt-affected land increased, predominantly in the north of the catchment.

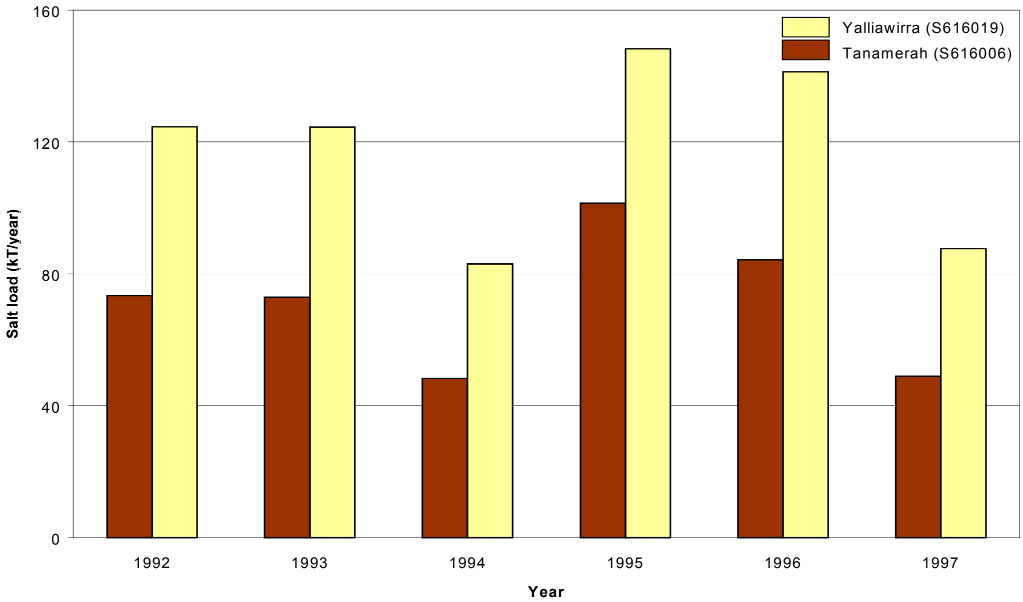
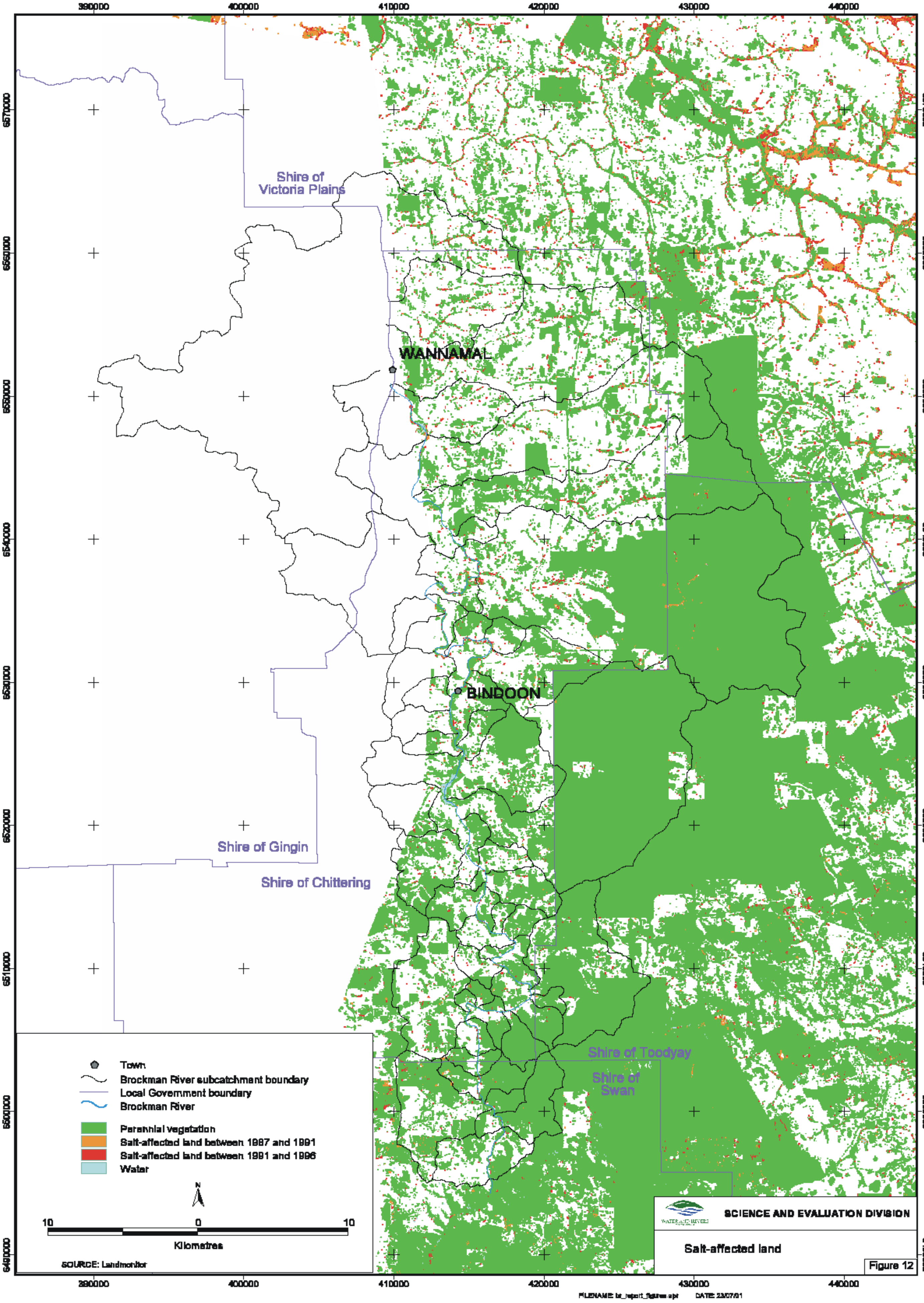


Figure 11. Annual salt load exported by the Brockman River.

Most of the remaining 40% of the salt exported is derived from the catchment south of monitoring station Tanamerah (S616006) (Fig. 10). The results of a Community Monitoring Program between May 1997 and May 1998 suggest there is a distinct variation in water quality along the Brockman River, starting at Julimar Road and moving south during the summer months (Fig. 10). However, the community monitoring program does not indicate whether the water quality measurements were made when the river was flowing. The steady increase in TDS values at site 12 between October 1997 and May 1998 suggests that the Brockman River was not flowing at this point, and that salt concentration was increasing due to evaporation.

At sites 14 and 15 the water quality improved between January 1998 and April 1998, with TDS values ranging from 1122 to 1408 mg/L. The community monitoring at sites 14 and 15 is supported by TDS values measured at Yalliawirra (S616019). The daily TDS values ranged from 577 to 7432 mg/L at monitoring station Yalliawirra (S616019), with a general decrease in TDS values during summer to early autumn. The TDS values increase rapidly around May, when the weir at the southern end of Lake Chittering is lowered (Fig. 10).


Shire of Victoria Plains
WANNAMAL
BINDOON
Shire of Gingin
Shire of Chittering
Shire of Toodyay
Shire of Swan
Town
Brockman River subcatchment boundary
Local Government boundary
Brockman River
Perennial vegetation
Salt-affected land between 1987 and 1991
Salt-affected land between 1991 and 1996
Water
10
0
10
Kilometres
SOURCE: Landmonitor
SCIENCE AND EVALUATION DIVISION
Salt-affected land
Figure 12

3.3.2 Localised trends

Studies in Western Australia have shown that, at a local level, salt storage tends to be low in the upper parts of a surface water catchment and increases down slope with the highest levels generally being alongcreek lines (Salama *et al*., 1994; Salama *et al*., 1999). This is related to the rate at which groundwater moves through the weathered-rock profile and the clays associated with that profile. The groundwater movement tends to be reduced in the lower landscape. Localised high salt concentrations can form along structural barriers such as dykes, and at breaks of slope (Lewis, 1991; Salama *et al*., 1994). Localised areas of high salt concentration in the Brockman River catchment include groundwater seeps in the area bounded by the Great Northern Highway, Maddern Road, Blue Plains Road and Chittering Road.

3.4 Discussion of rising groundwater and salt storage

Groundwater levels are rising in the catchment and are evident as groundwater discharge sites and increased base flow into the southern section of the Brockman River. These groundwater discharge sites are evident along topographic depressions such as the broad, open valleys in the north of the catchment and steep ‘v’ shaped valley depressions in fractured-rock aquifer zone A. Mid-slope groundwater discharge sites, evident predominantly but not exclusively within the fractured-rock aquifer zone A, are related to the irregular depth to crystalline bedrock and decreases in the topographic gradient.

About 60% of the salt load exported by the Brockman River is generated north of monitoring station Tanamerah (S616006), and the remaining 40% south of this gauging station. At present, extensive salt stores in the east of the catchment have not been mobilised. The sources of Wootra Brook and Spice Brook drain land covered with native perennial vegetation. Salt stores under areas covered with native perennial vegetation (Fig. 10) will potently not be mobilised. However, the salt stores will have been mobilised in the western sections of these two subcatchments where the land has been cleared for agricultural activities (Fig. 10).

The rising groundwater and salt mobilisation within the catchment threatens the agricultural activities and the biodiversity of the Brockman River. In the future, rising groundwater in fractured-rock aquifer zone A is expected to raise the salinity in the surficial aquifer zones within the Brockman River valley. The surficial aquifer zone contains the best quality groundwater within the catchment on the Darling Plateau, but is threatened by the more brackish groundwater moving down slope from fractured-rock aquifer zone A (Fig. 3a). Such an increase in salinity within the surficial aquifer zone will impact on the horticulturist and orchardist who require fresh to brackish groundwater for irrigation purposes.

4 Management options

The management options are detailed under the two main issues of groundwater resource and salinisation.

The groundwater management objectives are defined, along with priority areas. Recommended actions with related examples are also summarised in Table 4.

4.1 Groundwater resource

Groundwater resources are limited and localised. East of the Darling Fault the best quality groundwater is found in the surficial aquifer zone with additional groundwater supplies being found in the fractured-rock aquifer zone A (Fig. 7)

West of the Darling Fault the groundwater resources are under review by WRC. The shallow unconfined aquifer found on the Dandaragan Plateau is interconnected with the large regional aquifers of the Perth Basin. Few data exist for this zone within the Brockman River catchment.

4.1.1 Groundwater management objectives

The groundwater management objectives should be to use groundwater efficiently and to protect existing groundwater sources.

4.1.2 Priority areas

There are two priority areas comprising

- Environmental Planning Precincts DR2, DR3, DR4, DR5, DR6 DR9 which are predominantly the surficial aquifer zone and fractured-rock aquifer zone A.
- The regional aquifer system located on the Dandaragan Plateau.

4.1.3 Recommended actions

1) *Public awareness and education*

- Educate regarding the storage, usage and disposal of chemicals, fertilisers, pesticides and herbicides at both the household level and business level.
- Encourage the use of native plants in the gardens, which will reduce the use of chemicals such as fertilisers, pesticides and herbicides. Native plants require minimal watering in summer, thus preserving existing groundwater supplies.
- Educate regarding the interdependence between rivers and groundwater, thus revealing the relevance of groundwater quality to a healthy river system.

2) *Industry awareness of best management practices specific to their group*

- Identify groundwater issues related to specific industries, such as nutrient discharge associated with piggeries; fuel leakage from fuel storage tanks, both commercial and private; contamination from waste-disposal sites.
- Ensure that industry is employing best management practices and monitor issues related to groundwater if deemed necessary.
- Facilitate industry education; i.e. workshops and field days.
- Ensure correct disposal of solid and liquid waste, and waste water from existing light industry, agricultural and horticultural activities.

3) Efficient use of groundwater

- This can be achieved by ensuring that appropriate land use activities are carried out within the Brockman River catchment.
- Encourage the use of water of appropriate quality for industrial and agricultural activities; i.e. do not use fresh groundwater if brackish groundwater is suitable.

4.2 Salinisation

Managers should prioritise the developmental, economic and environmental requirements for the catchment before defining targets. The target(s) could be:

- to reduce the amount of saline land
- to improve the water quality of the Brockman River or
- a combination of both depending on the needs of the catchment.

4.2.1 Groundwater management objectives

There are four objectives for groundwater management:

1. manage groundwater recharge
2. lower groundwater levels
3. evaluate options implemented
4. public support of management action.

The options under management objectives 1 to 3, unless otherwise stated, are from *Salinity: a guide for land managers* (State Salinity Council, 2000). Technical advice and additional information is available from Government agencies including WRC, CALM, Agriculture Western Australia (AGWEST), and Department of Environmental Protection (DEP). Contact names and phone numbers these are listed in *Salinity: a guide for land managers.*

4.2.2 Priority areas

Subcatchments within Environmental Planning Precincts DR7, DR8, DR9 and DR13 are priority areas. However, rising groundwater levels and salinisation are evident throughout the catchment.

4.2.3 Recommended actions

4.2.3.1 Manage groundwater recharge

Options to reduce recharge to groundwater include commercial farm forestry; native vegetation management and revegetation; and engineering practices.

- Commercial farm forestry

  Commercial farm forestry introduces deep-rooted perennial vegetation, which use water all year round and extracts water from deeper in the weathered-rock profile. When using trees to reduce groundwater recharge, the following must be considered:

  - the slope (of the ground) and hydraulic conductivity;
  - tree density per hectare; and
  - suitability of the tree for local conditions, such as rainfall and soil type.

The ability of trees to intercept water moving laterally through the weathered-rock profile is dependent on slope of the ground surface and hydraulic conductivity. Documented in Stirzaker *et al*. (2000), Silberstein and others have developed a matrix to help identify combinations of slope and hydraulic conductivity where tree belts would receive laterally moving water (Fig. 13). There is potentially good lateral water movement in the blue zone, some movement in the green zone, but insufficient lateral movement in the yellow zone.

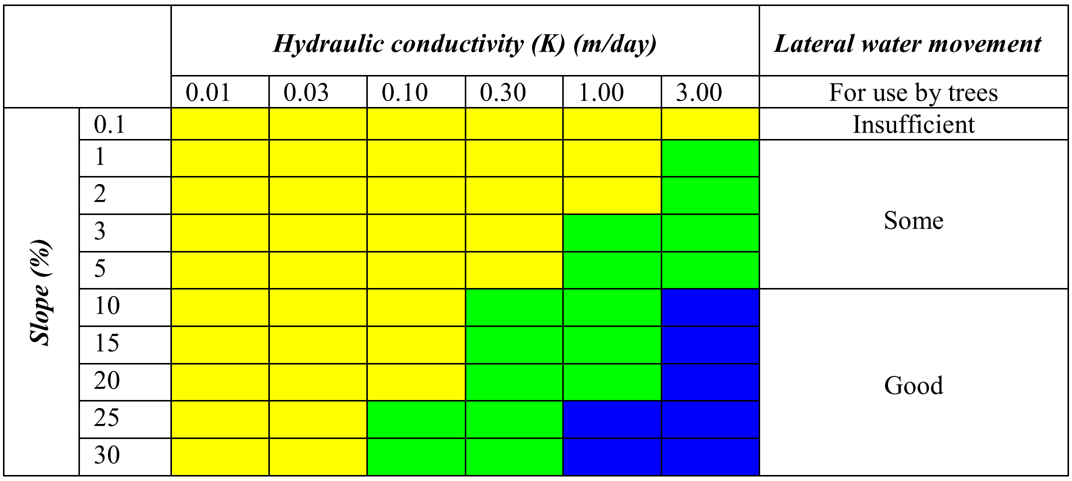


Figure 13. Lateral water movement (Silberstein *et al*., from Stirzaker *et al*., 2000)

In the Brockman River catchment the weathered-rock profile is assumed to have a hydraulic conductivity between 0.06 and 0.09 m/day for the fine-grained saprolite and mottled zone, 0.6 to 0.75 m/d for the coarse-grained saprolite, and 1 m/day for the near-surface soil (Fig. 3b). Thus, trees can potentially utilise some laterally moving water in the Brockman River catchment where the topographic slope is greater than 3% and the soil has a hydraulic conductivity value of at least 1 m/day.

The effectiveness of trees will also depend on tree density per hectare. The planting density (normally quoted as trees per hectare) will depend on the soil type, water availability and tree species. Advice on tree density is available from AGWEST.

Commercial farm forestry is potentially successful at increasing water use and decreasing recharge, while providing an opportunity to diversify farm income, including the possibility of carbon credits. As the time between planting and harvesting can be many years, joint venturing with companies and some government agencies may be possible.

Annual average rainfall in the Brockman River catchment falls between 500 and 900 mm; thus the following trees crops have potential:

Maritime pine (Pinus pinaster)

Maritime pine is suitable for deep sands and deep sandy gravels in areas exceeding 400 mm/year. Existing markets include posts and chip logs from the thinning, which can start at year 15, and the final harvest at 30 to 35 years.

Eucalyptus

Select Western Australian species of the native deep-rooted eucalyptus are suitable for sawlogs and may be successfully grown in rainfall areas exceeding 450 mm/year. Eastern states species require at least 500 mm/year. Additional economic benefits include the option to diversify farm income from carbon trading. Social benefits may include enhanced biodiversity.

Oil mallees

Mallees are a short rotational crop and can be repeatedly harvested on a two to three year cycle. Regular harvesting keeps them in permanent coppicing mode of growth.

Additional trees species

The tree groups listed above are not an exhaustive list. Rural Industries Research and Development Corporation (2000a) has compiled from various published and unpublished sources a list of tree and shrub species currently planted or potentially suited to farm forestry and dryland salinity management in southern Australia (Table 3). In addition Acacias (*Acacia mearnsii*, *A. decurrens*, *A. fulva*) are currently being assessed to determine tannin production and quality, along with their suitability as fire wood (Rural Industries Research and Development Corporation, 2000b). These *acacia* species are also potentially suitable as ‘bush food’ (Rural Industries Research and Development Corporation, 2000b).

Table 3. Tree and shrub species potentially suited to dryland salinity management in southern Australia (Rural Industries Research and Development Corporation, 2000a)

Species	*Mean annual rainfall (mm)*				*Mean annual temperature (ºC)*				*Frost*	*Salinity*	*Acidity*	*Alka-linity*	*Water-logging*
	<400	400-600	600-800	>800	>23	17-22	12-16	<12					
Acacia. saligna		**	***	*		***	***		*	*	*	**	*
A. stenophylla	*	***	**		***	***	***		*	***	*	**	**
Atriplex nummularia	***	***				***	**		*	***	*	**	*
Casuarina cunninghamiana		***	***	***	**	***	***		*	**	**	*	**
C. glauca			***	***	*	***	***		*	***	**	*	***
C. obesa	*	***	***	*		***	***		*	***	*	**	**
Chaemaecytisus palmensis		***	**			**	***		*	*	*	*	
Corymbia maculata		*	***	***		***	**		*	*	*	*	*
Cupressus macrocarpa		**	***	*		***	***		**	*	**	*	*
Eucalyptus camaldulensis (northern)		***	***	***	***	***			*	**	**	**	*
E. camaldulensis (southern)		***	***	***		***	***		**	**	**	**	*
E. cladocalyx	*	***	**			***	***		*	*	**	**	
E. globulus			**	***		***	***	**	**	*	*	*	*
E. largiflorens	**	***	*			***	***		*	**	*	**	**
E. leucoxylon	*	***	***	*		**	***		**	**	**	*	*
E. nitens			**	***		*	***	***	***	*	*	*	*
E. occidentalis	*	***	***			***	***		*	***	*	**	**
E. polybractea	*	***	**			***	***		*	**	*	*	*
E. robusta			*	***		***	**		*	*	*	*	**
E. sideroxylon/tricarpa	*	***	***	*		***	*	*	**	*	**	*	*
E. spathulata	**	***	**			***	***		*	***	*	*	**
E. viminalis			**	***		*	***	**	***	*	**	*	*
Grevillea robusta			**	***		***	**	**	*	*	**	*	
Melaleuca halmaturorum	**	***	***			**	***		**	***	**	**	***
M. uncinata	**	***				*	***		*	**	**	*	
Pinus pinaster	*	***	***	**		**	***	*	**	**	**	*	
P. radiata			**	***		*	***	**	***	**	**	*	*

Notes:

Mean annual rainfall: * = reasonable suitable; ** = suitable; *** = very suitable. The ratings do not imply a particular growth rate: they merely provide a comparison between species of relative performance within zones. In general there is a positive correlation between growth and rainfall. Species rated as very suitable in low rainfall zones will have growth rates, when grown at low rainfall sites, than species rated suitable for high rainfall zones, grown at high rainfall sites. For example, *P. pinaster* grown at a site with 500 mm annual rainfall will not grow as fast as *P. radiata* grown at s site with >800 mm rainfall.

Mean annual temperature: * = reasonable; ** = suitable; *** = very suitable

Frost risk: * = slightly tolerant (< 5 frost days per year); ** = moderately tolerant (5–20 frost days); *** = very tolerant (> 20 frost days with up to –5–10°C)

Saline: refers to electrical conductivity of a saturated soil paste of the average root- zone (approx. 0-60 cm) * = ECe 2–4 dS/m; ** = ECe 4–8 dS/m; *** = ECe > 8 dS/m

- Native vegetation management and revegetation

Improving the health and diversity of remnant vegetation will help increase water use and lowers recharge. Remnant vegetation also provides habitat for native fauna and maintains biodiversity. To create or extend wildlife corridors revegetation may be needed. Locally occurring native species that are appropriate for the soil type should be used and the natural flora structure should be recreated. Native vegetation needs to be protected from grazing and fencing subsidies may be available.

Economic benefits are possible through such activities as tourism, wildflower picking and seed collecting.

- Engineering options to manage groundwater recharge

Surface-water management will decrease the amount of water available for groundwater recharge, with management options including shallow interceptor drains or grade banks. Good design and planning of the water management systems can reduce the incidence of seasonal water-logging and improve the reliability of on-farm water supplies. The earthworks are generally implemented on a whole-of-farm basis and should be integrated with catchment water-management strategies. The best design involves shallow drains or banks built along grade lines channelling water into a series of dams or a stable, safe disposal point. Several rows of trees or shrubs planted on the lower side of the drains add to the resilience of the system.

4.2.3.2 Reducing the groundwater level

All the options used for reducing recharge to the groundwater have the potential to lower the groundwater level. For high-value land, engineering options may be appropriate, including deep drains and groundwater pumping. Relief wells and syphons many also be considered but these are still in the research stages. These engineering options are not appropriate for all locations and, therefore, need to be designed by professionals. With all engineering works the following must be considered:

- ➢ safe disposal of water;
- ➢ potential off-site and downstream impacts;
- ➢ are your neighbours aware of, and in agreement with, your proposal?
- ➢ do you need to submit a Notice of Intent to drain?

- Deep drains

Deep drains are defined as those deeper than 1.5 m and are notifiable under the Soil Conservation Act. Shallow drains and banks are not notifiable. Effective drainage design accounts for slope, soil type and hydrology. The design must also reduce the risk of negative downstream impacts including flooding, waterlogging, erosion, sedimentation, salinity and eutrophication. Deep drainage is most effective in material that allows water to move laterally, such as in stable sands. Such drainage is not effective in deep clays.

- Groundwater pumping

Groundwater pumping requires production bores to be drilled into the coarse-grained saprolite just above the bedrock. The efficiency of production bores is dependent on the hydraulic conductivity of the regolith and spacing of those bores.

- Relief wells

Relief wells involve groundwater flowing under pressure from a production bore. This method requires knowledge of potentiometric levels on site, and these are best determined with a nest of piezometers. As with groundwater pumping, the efficiency of production bores is dependent on the hydraulic conductivity of the regolith and spacing of the bores.

- Siphons

This system involves a self-priming syphon that draws groundwater from a production bore or a set of production bores. This bore, or set of bores, is primed daily by a small groundwater pump and irrigation controller(s). Efficient groundwater abstraction from such bores is effectively limited to those with water levels less than 4 m below ground level that are located on topographic gradients greater than 3%.

4.2.3.3 Evaluation

When implementing change, an integral part of the plan must be the monitoring of biophysical changes. Monitoring can be at a particular site or on an integrated catchment basis, thus allowing land managers to assess whether the changes are effective and, if necessary, to make adjustments. Monitoring requirements will be dictated by the objectives of the remedial plan and may need to include watertable depths, change in percent cover and health of perennial vegetation, and change in farming practice.

4.2.3.4 Increased public education and awareness

Private landholders, catchment groups and landcare groups within the catchment have started dealing with the issues of rising groundwater within the catchment, but increased awareness and information exchange between these groups will encourage remedial action to continue, especially since the results of any action taken may not become evident for a few years.

- Public information on catchment targets set, and why they were selected.
- Education on causes and management of salinisation.
- Reinforce the key message that the whole community benefits from reducing salinity.
- Encourage formation of active subcatchments groups (some already active) and community participation.
- Encourage tours of remedial sites, both successful and unsuccessful

Table 4a. Summary of management options for limited groundwater resource

Groundwater management objective	*Priority areas*	*Recommended actions*	*Examples/actions*
Use groundwater efficiently.	A) Environmental Planning Precincts DR2, DR3, DR4, DR5, DR6 and DR9 which are predominantly within the surficial aquifer zone and fractured-rock aquifer zone A. B) The regional aquifer system located on the Dandaragan Plateau.	**Efficient use of groundwater**	Ensure that appropriate land use activities are carried out within the Brockman River catchment. Encourage the use of appropriate quality water for industrial and agricultural activities; i.e. do not use low salinity/fresh groundwater if brackish groundwater is suitable.
Protect existing groundwater sources	As above	**Industry awareness of best management practices**	Identify groundwater issues related to specific industries, such as nutrient discharge associated with piggeries; fuel leakage from fuel storage tanks (commercial and private); and contamination from waste disposal sites. Ensure that industry is employing best management practices and monitor issues related to groundwater if deemed necessary Facilitate industry education; i.e. workshops and field days Ensure correct disposal of solid and liquid waste, and waste water from existing light industry, agricultural and horticultural activities.
		Public awareness and education	Education regarding the storage, usage and disposal of chemicals, fertilisers, pesticides and herbicides at both the household and business levels. Encourage the use of native plants in the gardens to reduce the use of chemicals like fertilisers, pesticides and herbicides. Native plants also require minimal watering in summer, thus preserving existing groundwater supplies. Education on the interdependence of rivers and groundwater, to illustrate the relevance of groundwater quality to a healthy river system.

Table 4b. Summary of management options for dry land salinisation

Groundwater management objective	*Priority areas*	*Recommended actions*	*Examples/actions*
Reduce groundwater recharge	Subcatchments within Environmental Planning Precincts DR7, DR8, DR9 and DR13. However, rising groundwater levels and salinisation are evident throughout the catchment.	**Manage groundwater recharge**	Commercial farm forestry, Maritime pine, Eucalyptus, Oil mallees, Acacias, and other tree species. Management of native vegetation and revegetation. Engineering practices: surface-water management via shallow interceptor banks or grade banks.
Lower groundwater level	As above	**Manage the groundwater recharge and engineering options**	Reducing groundwater recharge as above. Engineering options: deep drains (> 1.5m deep), not effective in deep clays; groundwater pumping; relief wells or syphons where depth to groundwater is less than 4 m and land surface has slope greater than ~3%.
Evaluate remedial actions	As above	**Monitoring**	Monitoring program either site specific or at catchment level.
Public support of management actions	As above	**Increased public education and awareness**	Public information on catchment targets and why they were selected. Education on the causes and management of salinisation. Reinforce the key message that the whole community benefits from reducing salinity. Encourage active subcatchment groups and community participation. Encourage tours of remedial sites, both positive and negative.

5 Recommendations for future work

1) Groundwater flows between the Wannamal Lake system should be investigated. At present the surface flows between Wannamal Lake and the Brockman River are intermittent. If Wannamal Lake is collecting saline water it is important to understand the groundwater flows into, and possibly out of, the lake and the impact this will have on the Brockman River.

2) Rising groundwater is known to increase the risk of flooding. At present, flood risk within the catchment has not been addressed. Flood prediction within the catchment should to addressed with special regard being paid to the flood plains of the Chittering–Needoonga lake system, and any impact of flood water on the Swan Coastal Plain.

3) Determine if geophysical methods will provide additional information and be cost effective. Curtin University Geophysics Department has an Honours project that is looking at different ground geophysical method to resolve a localised groundwater seep within the catchment.

References and recommended reading

AUSTRALIAN NATURE CONSERVATION AGENCY, 1993, A directory of important wetlands in Australia: Australian Nature Conservation Agency.

AUSTRALIAN WATER RESOURCES COUNCIL, 1988, Guidelines for the preparation of Australian hydrogeological maps: Department of Primary Industries and Energy, Australian Water Resources Council, Water Management Series no. 13.

BOYD, D. W., 1979, Bindoon Town Water Supply — Groundwater investigations 1978: Water Resources Section, Planning, Design and Investigation Branch, Public Works Department, Hydrogeology Accession no. 311 (unpublished).

BSD CONSULTANTS PTY LTD, 1985, Chittering Country Club Estate bore completion report–bores CCC1 and CCC2: BSD Consulting Pty. Ltd (unpublished).

CACCETTA, P. A., WALLACE, J. F., BEETSON, B., and CROSSLEY, N., 1999, Mapping salinity in the Swan–Avon Region: CSIRO Mathematical and Information Sciences and AGWEST (unpublished).

CHURCHWARD, H. M., and McARTHUR, W. M., 1980, Landforms and soil of the Darling System, Western Australia, *in* Atlas of Natural Resources Darling System, Western Australia: Department of Conservation and Environment, p. 25–33.

CLARKE, C. J., GEORGE, R. J., BENNETT, D. L., and BELL, R., 2000, Geologically related variations in saturated hydraulic conductivity in the regolith of the western wheatbelt of Western Australia and its implications for the development of dry land salinity: Australian Journal of Soil Research, v. 38, p. 555–568.

COCKBAIN, A. E., and HOCKING, R. M., 1990, Geological Evolution — Phanerozoic, *in* Geology and mineral resources of Western Australia, Western Australia Geological Survey, Memoir 3, p. 750–755.

COPE, R. N., 1975, Tertiary epeirogeny in the southern part of Western Australia: Western Australia Geological Survey, Annual Report for 1974, p. 80–86.

CORAM, J. E., 1998, National classification of catchments for land and river salinity control: Water and Salinity Issues, *in* Agroforestry no. 3.

DAVIDSON, W. A., 1995, Hydrogeology and groundwater resources of the Perth Region, Western Australia: Western Australia Geological Survey, Bulletin 142, 257p.

EVANGELISTI & ASSOCIATES, 1998, Environmental input into structure, land capability and catchment management plans within the Ellen Brook Catchment and surrounds — Shire of Chittering Land Capability and Management Plan — Part 1 — working paper: Evangelisti & Associates (unpublished).

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 1978, The New Norcia Prospect — Annual Report: Shell Minerals Exploration (Australia) Pty Ltd, Wamex Database, Item no. 2327, Accession no. 7824.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 1981, Bindoon Town water supply — groundwater investigations 1979–80, File GS134/78 (unpublished).

GEORGE, R. J., 1992, Hydraulic properties of groundwater systems in the saprolite and sediments of the wheatbelt, Western Australia: Journal of Hydrology, v. 130, p. 251–278.

KAY, T., and DIAMOND, R., 2001, A hydrogeological assessment of the Victoria Plains, Red Gully, Gingin Townsite and Eclipse Hill Subareas of the Gingin Groundwater Area: Water and Rivers Commission, Hydrogeological Report HR 156 (unpublished).

LEWIS, M. F., 1991, Lineaments and salinity in Western Australia — Carriers or barriers?, *in* Challenges for sustainable development — International Hydrology and Water Resources Symposium 1991, Perth, Western Australia: Institution of Engineers Australia, National Conferences Publications no. 91/22, Preprints of Papers, v. 1, p. 202–209.

MYERS, J. S., 1990a, Geological evolution — Precambrian, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 737–749.

MYERS, J. S., 1990b, Mafic dyke swarms, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 126–127.

NAHON, D., and TARDY, Y., 1992, The ferruginous laterites, *in* Regolith exploration geochemistry in the tropical and subtropical terrains, *edited by* C. R. M. BUTT, and H. ZEEGERS: Elsevier, p. 41–55.

RURAL INDUSTRIES RESEARCH AND DEVELOPMENT CORPORATION, 2000a, Trees, water and salt–An Australian guide to using trees for healthy catchments and productive farms–research update: Rural Industries Research and Development Corporation, Publication no. 00/170.

RURAL INDUSTRIES RESEARCH AND DEVELOPMENT CORPORATION, 2000b, Emerging products and services from trees in lower rainfall areas: Rural Industries Research and Development Corporation, Publication no. 00/171.

SALAMA, R. B., BARTLE, G., FARRINGTON, P., and WILSON, V., 1994, Basin geomorphological controls on the mechanism of recharge and discharge and its effect on salt storage and mobilization — comparative study using geophysical surveys: Journal of Hydrology, v. 155, p. 1–26.

SALAMA, R. B., OTTO, C. J., and FITZPATRICK, R. W., 1999, Contributions of groundwater conditions to soil and water salinization: Hydrogeology Journal, v. 7, p. 46–64.

STATE SALINITY COUNCIL, 2000, Natural Resource Management in Western Australia — Salinity–a guide for land managers: Western Australia, State Salinity Council.

STIRZAKER, R., LEFROY, T., KEATING, B., and WILLIAMS, J., 2000, A revolution in land use–Emerging land use systems for managing dryland salinity: CSIRO, Land and Water.

SWAN RIVER TRUST and WATER AND RIVERS COMMISSION, 1999, Swan–Canning Cleanup Program — Action plan: Western Australia Swan River Trust.

WATER AND RIVERS COMMISSION, 1999, Barns Road aquifer — A review: Western Australia, Water and Rivers Commission, Trim no. 09937 (unpublished).

WATER AND RIVERS COMMISSION, 2000, Managing the groundwater resources of the Gingin Groundwater Area in the period prior to approval of the revised Allocation Plan (Draft): Western Australia, Water and Rivers Commission.

WATER AUTHORITY OF WESTERN AUSTRALIA, 1993, Gingin Groundwater Area Management Plan: Water Authority of Western Australia, Report no. WG 160.

WILDE, S. A., and LOW, G. H., 1978, Perth, Western Australia, Sheet SH/50-14: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

Appendix 1. Surface water flows and rainfall for the Brockman River Catchment

Table 1.1. Stream discharge volume (megalitres) recorded at monitoring station Glen Darran (S616179)

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Monthly*	*Total*	*Days*
1963	[]	[]	[]	[0.0]	441.1	34467	61560	58660	28197	5818	652.7	3.8	[21089]	[189803]	119
1964	0	0	0	380.4'	9.1'	13427	81903	66209	19271	10241	1949	[387.5]	[16148]	[193779]	3
1965	[17.1]	0.0'	0	0	49.2	1977	33823	16766	10708'	20251	3034	331.3	[7246]	[86960]	15
1966	103.1	0	0	0	71	466.3	8962	7083	3860	1259	272.1'	33.4'	1842'	22112'	0
1967	0	0	0	0	2622'	14076	33262	30199	11726	1771	134.4	11.6'	7817'	93804'	0
1968	0.1	0	0	44.3	80.7	4326	18643	[23756]	20595	5982	807.4	74.6	[6192]	[74311]	2
1969	32.7	2.5	0	[14.1]	[126.7]	600.3'	1094	1834	381.3	71.5	30	0	[349.0]	[4188]	10
1970	0	0	0	0	49.5	2502'	6885	5430	2896	3014	279.0'	1.4	1754'	21058'	0
1971	[0]	[]	[64]	[13]	[7]	[179]	[315]	1893	2686	3342	[427]	[]	[893]	[8926]	181
1972	[]	[]	[]	[]	[]	[218]	1202'	15051'	5659'	1035	138	4	[3330]	[23308]	164
1973	0	0	0	0	89	[1036]	13949	[7288]	[10196]	4190	698	58	[3125]	[37505]	46
1974	2	46	2	1269*	5451	15708	35191	49360	7131	2089	573	76	9742*	116899*	0
1975	21	0	10	60	176	723	13548	20264	4863	2065	347	24	3508	42101	0
1976	6	3	10	83	193	448	895	6428	2713	605	394	49	986	11827	0
1977	9	0	3	18	107	290	480	4669	1009	361	110	9	589	7067	0
1978	0	0	0	4	120	1443	18187'	3484'	1305'	886"	92	22	2129"	25544"	0
1979	0	0	2	24"	67	586	1972'	3392'	1546	[368]	[]	[]	[796]	[7957]	75
Mean	[13]	4'	[6]	[119]	[604]	[5440]	[19522]	[18928]	[7926]	[3727]	[621]	[72]	[5149]	[56891]	Mean
Med.	[0]	0'	[0]	[14]	[98]	[1036]	[13548]	[7288]	[4863]	[2065]	[371]	[24]	Med.		
Max	[103]	46'	[64]	[1269]	[5451]	[34468]	[81904]	[66210]	[28198]	[20252]	[3035]	[387]	[21089]	[193780]	Max
Min	[0]	0'	[0]	[0]	[7]	[179]	[315]	[1835]	[381]	[72]	[30]	[0]	[349]	[4188]	Min
OK	91%	100%	95%	86%	94%	93%	99%	96%	98%	97%	100%	99%	96%	96%	OK
Cnt	15	14	15	16	16	17	17	17	17	17	16	15	17	17	Cnt

All recorded data is continuous and reliable except where the following tags are used:

" Faulty, some doubt in corrected trace

' Faulty, confident in corrected trace

* Estimated record

[ ] Data not recorded

Table 1.2. Stream discharge volume (megalitres) recorded at monitoring station Yalliawirra (S616019)

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Monthly*	*Total*	*Days*
1975	[]	[]	[]	[45.2]	248.1	803.2	15918'	22849'	4962'	2290'	415.7	63.3	[5288]	[47595]	98
1976	15.8	0	0	82.7	237.3"	535.8"	990.4"	8135"	3305"	652.1"	420.2"	72.4"	1204"	14448"	0
1977	7.1"	0	0	0	128.9*	347.3"	627.6"	5719"	1072"	418.7"	136.7"	18.2"	706.3*	8476*	0
1978	0	0	0	0	122.6"	1581"	19764"	5915"	2254"	1734"	112.1"	43.0"	2627"	31527"	0
1979	0.6"	0	0	64.9*	125.8"	1022"	3400"	5788"	2430"	669.8"	202.9"	24.6"	1144*	13729*	0
1980	0	0	0	14.5"	223.9"	772.7"	6166"	6819'	3561'	1316	280.4	51.7	1600"	19206"	0
1981	7.5	0	0	12.2*	1225"	24433"	20935"	44753'	6819'	2453'	[484.3]	[]	[9193]	[101125]	39
1982	[140.3]	22.8'	15.1'	43.6'	207.4	3632	6721	12605	4946	1853	255.9'	92.5'	[2544]	[30537]	6
1983	16.7	22.6	114.2	212.1'	142.0'	3222'	21776'	20446	25645	2588	1694	346	6352'	76227'	0
1984	136.4	4.1	119.9	393.7"	2596	4267	6532"	14027	7677'	1153	648.5	143.8	3141"	37702"	0
1985	63	130.8	43	85.7	143.1	415.3	2589	5075	2343	877.2	202.1	59.6	1002	12028	0
1986	8	287	124	61	415*	2411	16521*	18172*	7411*	2815	513	81	4068*	48817*	0
1987	24	4	14	119	654"	3338*	10215	15592	6100	2023	382	149	3218*	38614*	0
1988	30	0	1	54	379	3873'	15694'	19295'	7822	4955	1034	180	4443'	53318'	0
1989	61	18	21	69	418	1152	5546	7311'	2805	2608	449	76	1711'	20534'	0
1990	1363	1573"	454	519	448	1178	7775	10447*	3770*	1293*	676*	443*	2495*	29940*	0
1991	34*	3	11	81*	244*	6472	29793	21906	9323	3098	1351	1028*	6112*	73344*	0
1992	1211*	1324*	400*	118	750	3934	11061'	26826*	22654*	4241	1329	494	6195*	74343*	0
1993	131	39	29	66	3696	3478	5904	19638'	13914	4090	761	216	4330'	51961'	0
1994	46	38	35	121	972'	5176	15324	9107	3728	1202	150	48	2996'	35947'	0
1995	5	14	32	88	705	9441	42428	30236	10251	2902	940	121	8097	97163	0
1996	29	8	21	64	126	1834	19285	31178	19743	6522	1922	216	6746	80948	0
1997	24	24	80	224	323	2651	3426	11514	8534	1697	262	66	2402	28825	0
1998	12	2	18	50	178	2402	9861	10387	16008	[3304]	[]	[]	[4222]	[42220]	66
Mean	[146]	153*	67*	[108]	613*	3682*	12427*	15989*	8212*	[2365]	[636]	183*	[3827]	[44524]	Mean
Med.	[24]	8*	21*	[67]	285*	2531*	10038*	13317*	6460*	[2157]	[449]	87*			Med.
Max	[1363]	1573*	454*	[519]	3696*	24433*	42428*	44754*	25646*	[6522]	[1922]	1028*	[9193]	[101125]	Max
Min	[0]	0*	0*	[0]	123*	347*	628*	5075*	1073*	[419]	[112]	18*	[706]	[8476]	Min
OK	99%	100%	100%	99%	100%	100%	100%	100%	100%	99%	99%	100%	100%	100%	OK
Cnt	23	23	23	24	24	24	24	24	24	24	23	22	24	24	Cnt

All recorded data is continuous and reliable except where the following tags are used:

" Faulty, some doubt in corrected trace

' Faulty, confident in corrected trace

* Estimated record

[] Data not recorded

Table 1.3. Stream discharge volume (megalitres) recorded at monitoring station Tanamerah (S616006)

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Monthly*	*Total*	*Days*
1980	[]	[]	[]	[]	[]	[219.6]	2611	2779	1550	471.3	30.4"	0.2"	[1094]	[7662]	157
1981	0	0	0	0	296.0"	7299*	7680	19351'	3630	874.5	474.4	196.3	3317*	39804*	0
1982	27.8	0	0	0	23.6'	1578'	2231	4751	2402	931.3	32.0'	0.0'	998.3'	11979'	0
1983	0	0	0.9	0.4	0	1798	9679	9855	10013	1578	741.7	59.1	2810	33727	0
1984	147.7	0	0	0	1851	2347	3211	6372	2834	585.8	174.6	0.1	1460	17525	0
1985	12.5"	1.6"	0	0	9.2"	91.9	1036	1707	860.7	168.3"	3.1"	0	324.3"	3891"	0
1986	0	99.1	5.3'	0	78.8	1243'	6219	10074	3451	1133	44.3*	0.1"	1862*	22350*	0
1987	0	0	0	95	803.5	1947	5445	9291	3697	886.7'	58.1"	10.5	1852	22235"	
1988	0	0	0	2.8	519.9	2819	8011	9445'	3578'	1493	190	0.8	2171'	26062'	0
1989	0	0	0	0	435	944.2	3398	3138	[734.0]	851.3	35.7	0	[794.8]	[9537]	13
1990	662.9	590.1	23.3	83.7	144	506.5	3648	4794	2094	798.7	55.7	0	1116	13403	0
1991	0	0	0	0	0	2038	11374	8933	3767	1271	424	26*	2320*	27834*	0
1992	19*	90*	234*	326	397	1660	4876	10331	8885	2237	681	79	2485*	29816*	0
1993	0	0	0	0	3637	1649	3057	8786	5566	1834	299	3	2069	24832	0
1994	0	0	0	0	429	2328	5728	3162	1517	399	6	0	1131	13569	0
1995	0	0	0	0	757	6481'	25919	15252	5924	1695	411	33	4706'	56472'	0
1996	0	0	0	0	40	1154	7139	12207	7619	2574	850	94	2640	31676	0
1997	0	0	0	30	677	1392	1530	4523	3199	787	62	3	1017	12203	0
1998	0	0	0	0	31	2191	5547	4595	5451	[1561]	[]	[]	[1938]	[19377]	66
Mean	48*	43*	15*	30	563"	[2089]	6229	7861'	[4041]	[1165]	254*	28*	[1900]	[22313]	Mean
Med.	0*	0*	0*	0	346"	[1660]	5445	8786'	[3578]	[931]	118*	2*			Med.
Max	663*	590*	234*	326	3637"	[7300]	25919	19351'	[10013]	[2574]	850*	196*	[4706]	[56472]	Max
Min	0*	0*	0*	0	0"	[92]	1036	1708'	[734]	[168]	3*	0*	[324]	[3892]	Min
OK	100%	100%	100%	100%	100%	99%	100%	100%	98%	99%	100%	100%	100%	100%	OK
Cnt	18	18	18	18	18	19	19	19	19	19	18	18	19	19	Cnt

All recorded data is continuous and reliable except where the following tags are used:

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' Faulty, confident in corrected trace

* Estimated record

[ ] Data not recorded

Table 1.4. Total monthly and annual rainfall (mm) measured at meteorological station Yalliawirra North (509388)

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Monthly*	*Total*	*Number of days data missing*
1979	[]	[]	[]	[59.0]	75	157.3	112	94.9	37.2	32.8	59.6	4	[70.2]	[631.7]	100
1980		7	4.8	78.3	111.5	132.3	154.3*	103.0*	82.4*	38.5*	20.3	[5.0]	[61.4]	[737.4]	2
1981	[0]	[0.0]	5.6	24.8	187	195.7	132.1	141.8'	[51.4]	[]	[]	[]	[82.1]	[738.5]	105
1982	[65.4]	[2.3]	17	10.6	48	185.2	122.1	116.8	93.2	23.8	3.2	11	[58.2]	[698.4]	7
1983	0.4	9	19.2	7.4	22.4	[91.6]	[125.5]	122.1"	90.0"	20.2"	61.9	21.6	[49.3]	[591.3]	35
1984		3.8	41.6	68.5	185.4	74	108.1	131	109.7	32.1	66.5	24.4	70.4	845.3	0
1985	29.7	5.7	21.4	40.1	34.3	140.3	116.7	[123.4]	[17.7]	24.3	21.9	4.5	[48.3]	[580.0]	15
1986	1.6	92	34.7	1.6	125.4	162	170.5	119.6	47.1	43.2	19.4	[0]	[68.1]	[817.1]	1
1987	1		13.8	70.8	95	166.8	175.8	76.2	48.6	58.2	45.4	25	64.7	776.6	0
1988		[0]	[]	[36.2]	149.2	104.6	144.8	123.4	104.4'	71.3	36.6	8.0'	[70.8]	[778.5]	43
1989	15.5	19	0.8	38.6	79.2	77	147.2	73	86.4'	90.2	6.0'	7.4	53.4'	640.3'	0
1990	138	51.1'	51.2	68.0'	59.6	66	173.4	120.6	57.8	65.8	8.4	11.6	72.6'	871.5'	0
1991	0.4	18.6	3.2	59	101.4	251.4	204.8	69.6	113	41.4	56.8	58.4*	81.5*	978.0*	0
1992	11.9*	52.3*	19.0*	17	80.6'	163.7	104.2	220.6	83	17.4	72	5.8	70.6*	847.7*	0
1993	0.6	1.2	4.3'	8.9	131.6	106.3	123.1	171	119.6	43.5	5.0'		59.6'	715.3'	0
1994	0.6		2.7	1.4	132.2	157.1	100.3	92.7	48.3	11.1	4.8		45.9	551.2	0
1995		29.3	5.7	6.2	158.7	141.9	217.1	98.5	69	72.8	26.8	9.7	69.6	835.8	0
1996	3.1		1.4	12.8	61.8	226.6	210.6	137.2	123.8	60.6	54.6	15.8	75.7	908.2	0
1997	0.8	22.8	57.6	45.9	82.6	78.6	101.4	141.8	84.1*	33.9*	7.6*		54.8*	657.2*	0
1998	0.8	0.8	30	18.1	90.3	181	94.2	145.1	92.7	[28.1]	[]	[]	[68.1]	[681.1]	66
Mean	[14.2]	[16.6]	18.6*	[33.7]	100.6'	[143.0]	[141.9]	[121.1]	[78.0]	[42.6]	32.1*	[11.8]	[64.8]	[744.0]	Mean
Median	[0.8]	[5.7]	15.4*	[30.5]	92.6'	[149.5]	[128.8]	[121.4]	[83.5]	[38.5]	24.4*	[7.7]			Med.
Max	[138.0]	[92.0]	57.6*	[78.3]	187.0'	[251.4]	[217.1]	[220.6]	[123.8]	[90.2]	72.0*	[58.4]	[82.1]	[978.0]	Max
Min	[0.0]	[0.0]	0.8*	[1.4]	22.4'	[66.0]	[94.2]	[69.6]	[17.7]	[11.1]	3.2*	[0.0]	[45.9]	[551.2]	Min
OK	99%	98%	100%	98%	100%	96%	98%	100%	97%	99%	100%	99%	99%	99%	OK
Count	19	19	18	20	20	20	20	20	20	19	18	18	20	20	Cnt

All recorded data is continuous and reliable except where the following tags are used:

" Faulty, some doubt in corrected trace

' Faulty, confident in corrected trace

* Estimated record

[ ] Data not recorded

Notes: This station has been recording rain fall since 1979, the length of which is less than the long tern rainfall. Mean annual rainfall includes estimated data and missing records, thus the value given is lower than expected.

Appendix 2. Community monitoring of water quality along the Brockman River

Table 2.1. Surface water quality (TDS mg/L) at various sites along the Brockman River

Site number	*5/05/97*	*5/06/97*	*7/07/97*	*4/08/97*	*1/09/97*	*6/10/97*	*3/11/97*	*1/12/97*	*5/01/98*	*2/02/98*	*2/03/98*	*2/04/98*	*1/05/98*
1	11000	11000	11000	11000	7887	7865	10065	11000	-	-	-	-	-
2	-	6358	-	4565	2860	3933	5434	5940	-	-	-	-	-
3	-	6215	-	4593	2822	3449	4235	7920	-	-	-	-	-
4	8525	5242	4884	4059	2965	-	5005	6028	11000	-	-	-	-
5	8360	5203	4730	3889	2970	-	5033	6160	11000	-	-	-	-
6	8195	5390	4494	3630	3025	3647	4906	-	-	-	-	-	-
7	5280	4906	3988	3432	2932	3361	4164	4950	-	-	-	-	-
8	5940	5181	3740	3768	-	3377	4153	4835	-	-	-	-	-
9	6655	5071	4989	3889	2937	3300	3746	4197	5440	6584	9075	-	-
10	-	5165	4917	4125	-	3278	3729	-	-	-	-	-	-
11	-	5104	4912	4070	-	3278	3790	-	-	-	-	-	-
12	5280	3977	4576	3504	2866	3168	3740	4301	5341	5973	6353	6573	6199
13	2310	3960	3256	3812	2789	3163	-	2992	2915	2618	2860	2602	2376
14	2475	3124	5055	2547	2184	3141	-	2970	1177	1568	1155	1122	1859
15	2860	3339	3916	3449	2635	2965	2739	1925	1359	1221	1265	1408	1496

All values converted from electrical conductivity values (uS/cm) to TDS values (mg/L) using a conversion factor of 0.55.
Hand held electrical conductivity meter had a maximum reading of 20 000 uS/cm
- no recorded data given

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