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Groundwater resources of the Northern Goldfields, Western Australia

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Cover Photograph: Lawlers Creek, northeast of Pinnacles Station

GROUNDWATER RESOURCES OF THE NORTHERN GOLDFIELDS, WESTERN AUSTRALIA

by

S. L. JOHNSON, D. P. COMMANDER AND C. A. O'BOY

Water and Rivers Commission
Resource Investigations Division

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Abstract

The Northern Goldfields is a major nickel and gold producing area with over 20 operating mines dependent on groundwater for ore processing. The recent construction of the Goldfields gas pipeline through the area, and continuing development in the mining sector, has resulted in the need for a better understanding of the groundwater resources.

The investigation involved a comprehensive review of borefield and exploration data contained in some 440 consultant and company reports, followed by a programme of groundwater exploration including ground-based geophysics, exploration drilling and the installation of monitoring bores. Exploratory air-core drilling was conducted at 17 transects to better define the extent of palaeochannel sand aquifers. Thirty monitoring bores were completed for sampling and monitoring of water levels.

The drilling provided hydrogeological information on the Cainozoic sedimentary sequence within the Carey and Raeside Palaeodrainages. The palaeochannel sand constitutes the most important aquifer in the region and forms the base of the Tertiary sediments. Overlying the palaeochannel sediments is an alluvial aquifer composed of silty and clayey deposits, and locally calcrete.

The groundwater salinity is highly variable with the lower salinities beneath catchment divides, and the higher along the palaeodrainages. There is also a regional trend of increasing groundwater salinity towards the southwest indicating the lower recharge rates in the south of the area. The salinity of the groundwater in the palaeochannel sand ranges from fresh to brackish in the tributaries to hypersaline in the main palaeodrainages.

Small supplies of groundwater of variable salinity, available throughout the region, are used by the pastoral industry. Large groundwater supplies suitable for ore processing are restricted mainly to the palaeochannel sand and calcrete, although there are localised supplies available from well-developed fracture systems in the basement rocks.

Most groundwater is utilised by the mining industry as processing water. There have been 96 groundwater production licences issued in the area with a total allocation of 89 GL/yr, although actual use is estimated at 60% of the licensed allocation. The estimated total groundwater storage of 16 400 GL is considered sufficient for current and projected developments over the next 30 years. Groundwater storage in over 2000 km of palaeochannel sand is estimated at about 3400 GL. There are also substantial groundwater resources within the alluvium aquifer, which may be accessed by leakage into underlying palaeochannels and permeable structures in the basement.

Distribution of groundwater resources is relatively even, with marginally higher resources around Leinster. Although there are large sections of the palaeodrainages and tributaries that are completely utilised by borefields, there is still scope for development throughout the region.

Keywords: Groundwater resources, groundwater development, aquifers, Northern Goldfields.

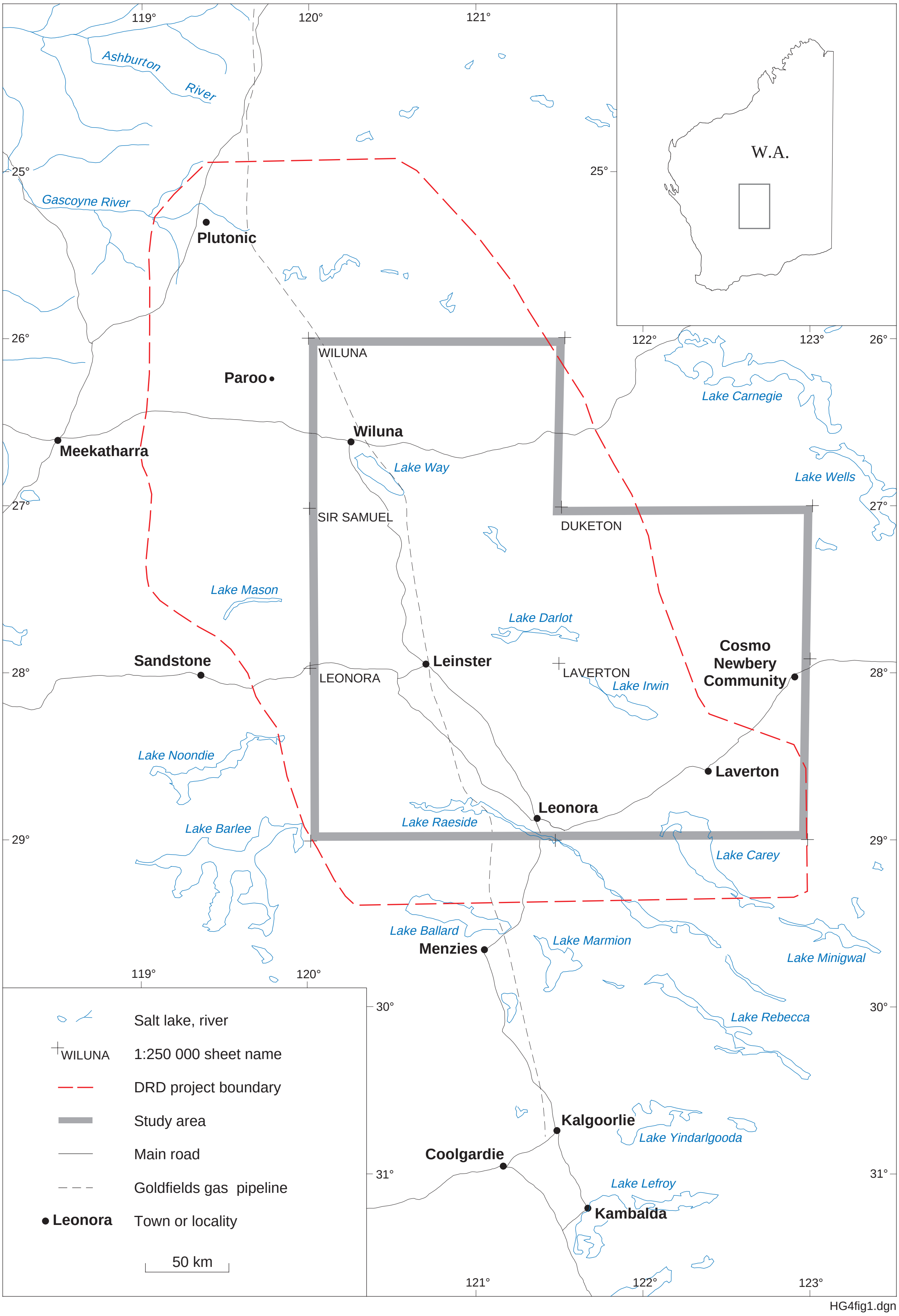

Figure 1. Location map

1 Introduction

1.1 General

The expansion of mining and ore treatment in the Northern Goldfields region since the mid-1980s has led to a large demand for water. Current licensed allocation is about 90 GL/yr[1]. This is supplied wholly from local groundwater with salinity of up to 200 000 mg/L. Projections of water demand, based on the supply of gas from the goldfields gas pipeline (GGP) making ore processing more viable, has led to a need to assess the sufficiency of the groundwater resources.

Preliminary work on the project commenced in 1995 as a result of input by the Association of Mining and Exploration Companies to the Geological Survey of Western Australia (GSWA) work programme, through the Hydrogeology Subcommittee of the GSWA Liaison Committee. In 1996, the Department of Resources Development (DRD) commissioned an infrastructure study of the Northern Goldfields region extending from Laverton to Plutonic along the GGP (Fig. 1). Their consultant (Hardcastle and Richards, 1996) recommended a groundwater resource assessment be carried out. This investigation by the Water and Rivers Commission commenced in September 1996, with geophysical surveys and drilling financed in part by DRD. The investigation concentrated on the area between Laverton and Wiluna, where there is the greatest number of mines.

Groundwater occurs in the bedrock, in Tertiary palaeochannels (former deep drainage lines now filled with sediments), and in overlying alluvial, colluvial and calcrete deposits. The Tertiary palaeochannel aquifers are easier to explore and assess than the bedrock aquifers, and are considered to contain the largest and most readily exploitable groundwater resource. Most of the new mining developments exploit groundwater from the palaeochannels, and it is in these that interference between borefields and allocation problems are likely to occur.

In order to assess the groundwater resources of the region, a review was carried out of the information available from mining developments. As there were large areas lacking information, an exploration programme was formulated to provide a regional understanding of the palaeochannel groundwater resources.

This report presents the results in terms of the distribution and quality of the regional groundwater resources and will be complemented by the compilation of 1:250 000 hydrogeological maps of LEONORA, LAVERTON and SIR SAMUEL[2] which cover the greater part of the region.

1.2 Location

The Northern Goldfields region of the investigation area extends from Leonora and Laverton in the south to Wiluna in the north, including the town of Leinster (Fig. 1). The region has a population of about 5000. The area is a major mineral province with over 20 operating gold mines, two nickel mines, and numerous prospects for uranium, rare earths and base metals. Nickel mining is centred on the deposits at Mount Keith and Leinster, and Murrin Murrin, which commences production in early 1999. Other major mineral deposits include Yakabindie (nickel), Mount Weld (rare earths), Honeymoon Well and Yeelirrie (uranium).

1.3 Climate

The region has a semi-arid climate characterised by low rainfall and a large temperature range. The mean annual rainfall is about 250 mm, but may vary annually from 100 to 500 mm. The winter months of May to August have the highest and most reliable average rainfall, but intense rainfall can occur periodically in the summer months of December to April as a result of tropical cyclones. Potential evaporation totals 2400 mm/year and exceeds rainfall in all months.

1.4 Topography and drainage

The present landscape of the Northern Goldfields is generally of low relief with topography closely related to the underlying geology. The region is characterised by undulating areas of sandplain and granite outcrop with

[1] *1 GL is approximately equivalent to 1 x 10^6 m^3*

[2] *Capitalised names refer to standard map sheets*

northerly trending ridges controlled by the strike of the greenstone belts, and by low-lying broad alluviated valleys containing playa lakes. The topography gradually increases in elevation to the north, ranging from about 350 m in Lake Raeside (south of Leonora) to 600 m above sea level in the Finlayson Ranges (north of Wiluna).

The drainage system of the area comprises three large, broad, sub-parallel, southeasterly trending drainage systems (Fig. 2) known as palaeodrainages. The Carey and Raeside Palaeodrainages extend from a regional divide to the west of the area and drain towards the Eucla Basin. In contrast, the headwaters of the Minigwal Palaeodrainage rise within the area northwest of Cosmo Newbery Community, and discharge into the Carey Palaeodrainage downstream of Lake Carey.

The palaeodrainages have very low gradients and frequently contain small to very large playa lakes such as Lake Carey and Lake Way (up to 1000 km^2). The playa lakes are normally dry, floored by mud or salt crystals, and are commonly fringed by sand and gypsum (kopi) dunes that prevent the flow of surface runoff between lakes. These lakes become inundated during occasional, intense rainfall and in rare cyclonic events. As a result of rainfall from Cyclone Bobby in 1995, Lake Raeside overflowed and discharged eventually onto the Nullarbor Plain (Allen, 1996).

1.5 Vegetation

The vegetation has been mapped and described by Beard (1981). Most of the area comprises low woodland dominated by mulga and mixed eucalypt scrub. Mulga and mallee shrublands thrive towards the south on elevated rocky features such as greenstone ridges. In the northern part of the area, spinifex hummock grasslands with scattered mulga and eucalypt overstorey are prominent on gently undulating sandplain. The drainage lines are often occupied by thick woodland with salt-tolerant halophytes, such as samphire and saltbush, surrounding the playa lakes.

Large areas of mulga and mallee trees around the localities of Laverton and Leonora were cleared for firewood and timber during the initial mining activities; however, this vegetation is regenerating. In the pastoral areas, overstocking and feral animals, such as goats and rabbits, have caused local erosion and land degradation.

1.6 History of water supply

The area was settled after gold was discovered in the early 1890s, and the lack of a water supply became the greatest problem faced by prospectors and early settlers. Between 1902 and 1912, the Mines Water Supply Branch (Department of Mines) constructed various bores, wells and dams to meet the water demands of prospectors and pastoralists. In 1908, supplies of potable groundwater were located at Station Creek, 12 km north of Leonora, with eleven bores commissioned to supply the mining towns of Leonora and Gwalia. In 1929, large supplies of groundwater were located in a calcrete aquifer near Wiluna. Groundwater from this aquifer supplied the mines during the 1930s, until declining gold prices led to a general exodus from the area.

Until the Great Depression of the 1930s, the pastoral industry was restricted mainly to the area near Leonora and Laverton and utilised minor surface water and shallow groundwater supplies. During this time, a decline in mining activity led to the establishment of pastoral properties, with unemployed miners drilling bores using cable-tool rigs and excavating shallow, hand-dug wells to develop pastoral water supplies. Stock water was found throughout the area enabling wells or bores to be sunk at convenient locations, such as paddock corners, with yields sufficient for the installation of windpumps.

The discovery of nickel at Kambalda, south of Kalgoorlie, in the late 1960s led to a resurgence of mineral exploration throughout the region. This intensification of exploration resulted in a number of important discoveries at Mount Windarra, Agnew, Teutonic Bore, Mount Keith and Murrin Murrin (Fig. 3), all of which required extensive groundwater investigations prior to commencement. Consequently, numerous groundwater studies, including geophysical and drilling programmes, have been undertaken by hydrogeological consultants, substantially increasing knowledge of groundwater availability in the region and suggesting that sufficient groundwater was available to meet the potential water demands.

Since the 1980s the introduction of more efficient mineral processing technology, such as carbon-in-pulp and carbon-in-leach processing, together with high gold prices, has intensified mineral exploration with previously low-grade ore deposits now treatable using saline groundwater. In order to meet the increasing

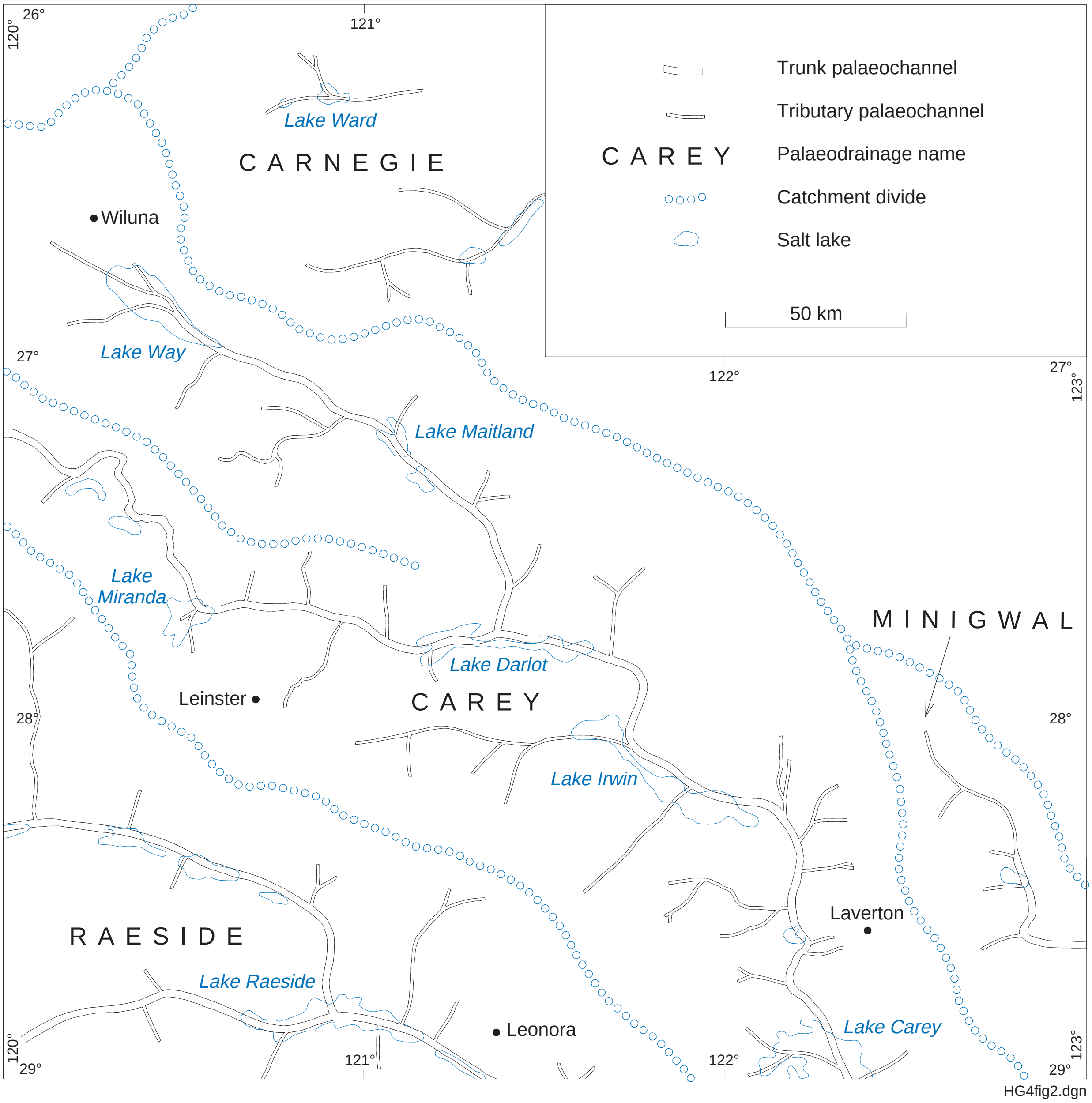

Figure 2. Palaeochannel location

demand for large amounts of water for mineral processing, several large borefields have been established in the Cainozoic sediments of the Raeside and Carey Palaeodrainages. In contrast to the Kalgoorlie region (Commander *et al.*, 1992), the majority of borefields in the Northern Goldfields are located within tributaries of the major palaeodrainages, that contain lower salinity groundwater.

Leonora, Laverton and Wiluna are supplied from groundwater schemes operated by the Water Corporation. The Leinster town supply is obtained from a groundwater scheme operated by Western Mining Corporation (WMC). The only development of groundwater for irrigation has been at Wiluna where, in 1969, Desert Farms commenced the development of irrigated citrus orchards with water from a calcrete aquifer (Sanders, 1971, 1972). Subsequently, the farms have produced, on an intermittent basis, vegetables for local consumption and rock melons for the Perth market. Recently, melons and table grapes have been established within the Millbillillie Pastoral Lease east of Wiluna.

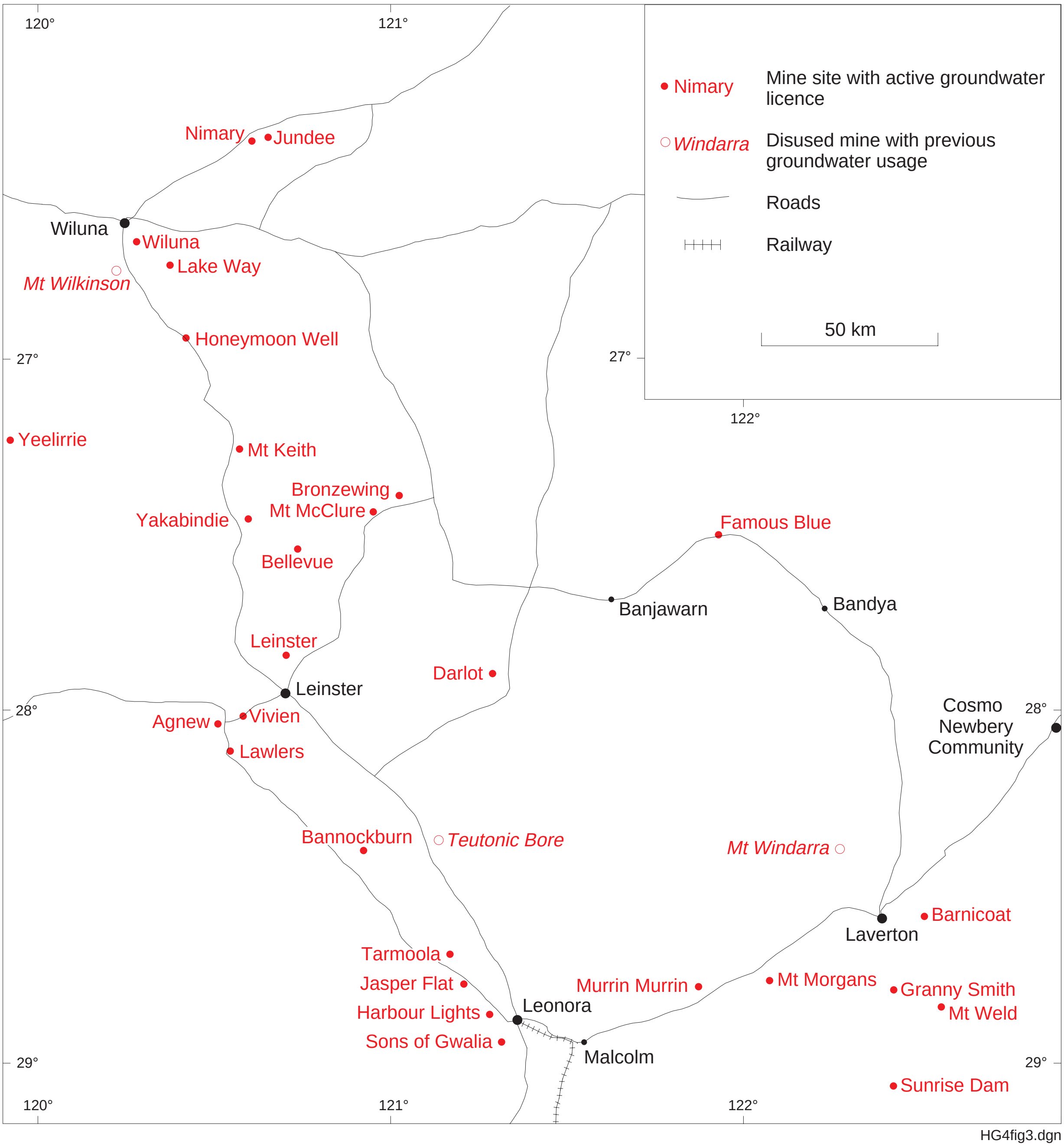

Figure 3. Mines using groundwater supplies

1.7 Demand for water

The mining industry is the major groundwater user and is primarily responsible for the development of groundwater resources in the Northern Goldfields. Since the early 1990s the demand for groundwater has increased with the development of two nickel operations, which are the largest individual consumers of groundwater in the region.

Although the development of new mining operations is closely linked to commodity prices, it is anticipated that the number of operating mines and demand for groundwater is likely to remain constant for the next five to ten years (Hardcastle and Richards, 1996). The total licensed abstraction in the Northern Goldfields is about 90 GL/yr (as at February 1998), and assuming no significant movement in commodity prices, it is anticipated this level of groundwater demand will be maintained. A complete listing of licensed groundwater users in the region is compiled in Appendix 1 with licence number, operator details, aquifer utilised, usage and abstraction rates.

The number of operating gold mines (10–15) is likely to remain static with worked-out mines being progressively replaced by new developments. There is, however, potential for discovering new gold deposits in the Yandal Greenstone Belt and Laverton–Duketon Greenstone Belt areas, which are currently undergoing extensive mineral exploration. Saline to hypersaline groundwater supplies are suitable for gold processing, but small supplies of fresh to brackish groundwater may be required in the stripping plants and for use in refractory processes, such as the Biox method used by Wiluna Mines.

The nickel operations at Mount Keith and Murrin Murrin have long-term groundwater requirements which should remain static over the next 20 years. The licensed abstraction for the Mount Keith and Murrin Murrin nickel mines is 15 GL/yr and 13 GL/yr respectively with most groundwater extracted from the palaeochannel sand aquifer. There is also potential for a new nickel operation at Yakabindie with processing water available from the palaeodrainage downstream of WMC's Albion Downs borefield.

There are further mine developments at the planning stage in the Northern Goldfields, including Mount Weld (rare earths), Yeelirrie (uranium) and Lake Way (uranium). These prospective mines should be able to obtain sufficient groundwater supplies, as the Mount Weld carbonatite is currently being dewatered for use by the Granny Smith Gold Mine, and the two uranium deposits are located in calcrete aquifers.

Groundwater is also used throughout the region for town water supplies, pastoral purposes, and for irrigated horticulture and citrus at Wiluna. It is anticipated that groundwater demand will not increase substantially, although there is potential for further horticultural development in the north of the region. The Paroo calcrete aquifer was explored for this purpose (Sanders, 1973), but has not been developed because suitable soils were not present.

1.8 Allocation and licensing

Groundwater resource utilisation and conservation in Western Australia is administered by the Water and Rivers Commission in accordance with the Rights in Water and Irrigation Act 1914, the Water Authority Act 1984, and the Water Agencies Restructure (Transitional and Consequential Provisions) Act 1995.

The investigation area lies entirely within proclaimed Groundwater Areas. The southern and central part is in the *Goldfields Groundwater Area* (WAWA, 1994), while the northwest portion is in the *East Murchison Groundwater Area* (Water and Rivers Commission, *in prep.).* The management objectives are twofold: to ensure that groundwater resources, and environmental features reliant on them, are not degraded through overuse; and to ensure the resources are allocated in an equitable manner.

Groundwater licences are issued either as exploration or production licences. They are granted on the conditions that the applicant has legal access to the land in question, and that there will be no adverse affect on existing licensed users. The Water and Rivers Commission must be satisfied that the groundwater resources are sufficient for the proposed abstraction. The saline groundwater resources are considered to be non-renewable, and licences allow for the mining of groundwater storage. The mines using groundwater supplies are shown on Figure 3 and licence details of these groundwater users are tabulated in Appendix 1.

1.9 Previous investigations

1.9.1 Geology

The region has been geologically mapped at 1:250 000 scale (Gower, 1976; Thom and Barnes, 1977; Bunting and Chin, 1979; Bunting and Williams, 1979; Elias and Bunting, 1982), and part of the region is covered by recent GSWA and Australia Geological Survey Organisation (AGSO) 1:100 000 scale maps. The Archaean geology is well documented (Griffin, 1990), but the subsurface Tertiary sediments are poorly known and not depicted on any of the geological maps. Commander *et al.* (1992) described the Tertiary sediments in the Kalgoorlie Region to the south, and these have been mapped on 1:250 000 hydrogeological maps (Kern, 1995a,b, 1996a,b). The broad distribution of the palaeodrainages that represent the catchment areas of Early Tertiary rivers was mapped by Beard (1973) from the vegetation pattern. The geomorphology and landscape development associated with the palaeodrainages was further analysed by Bunting *et al.* (1974), van de Graaff *et al.* (1977) and Morgan (1993).

1.9.2 Mineral exploration

Since the 1960s, there has been extensive mineral exploration throughout the region focusing on the Archaean greenstone belts, and on contacts between greenstone and granitoid rocks. Gold mineralisation is widespread within the greenstone belts, and a number of major nickel deposits occur between Agnew and Wiluna, and near Laverton. A base-metal deposit, principally zinc, has been mined at Teutonic Bore. In recent years, mineral exploration has intensified in the northeast of the area, particularly within the Yandal and Duketon Greenstone Belts, and has led to the discovery of economic gold deposits at Bronzewing, Nimary and Jundee.

Exploration has been carried out in the Tertiary palaeodrainages for uranium and gold. Significant resources of uranium have been found in calcrete deposits at Yeelirrie (WMC), and mineralisation occurs also in calcrete around Lake Way, Lake Maitland and Lake Raeside. Exploration has been carried out in Tertiary palaeochannels for roll-front type deposits and lignite-hosted deposits, such as those at Mulga Rock in the Raeside Palaeodrainage 200 km southeast of Laverton (Keats, 1990). Since 1979, Broken Hill Proprietary Ltd (BHP) has carried out extensive exploration for placer and precipitated gold in the Tertiary palaeochannels throughout the Eastern Goldfields (Smyth and Button, 1989).

1.9.3 Groundwater

The hydrogeology of the region has not been studied in detail and knowledge of the bedrock aquifers is limited to a few investigations for mine water supply. The first description of the regional hydrogeology and the availability of groundwater was by Morgan (1966), who undertook bore siting for various pastoral leases in the area. The calcrete aquifers in the north of the area were evaluated by Sanders (1969) and Sanders and Harley (1971) to determine their potential for irrigation and mine water supplies. A brief description of the hydrogeology and general availability of groundwater is included in the geological series explanatory notes (Gower, 1976; Thom and Barnes, 1977; Bunting and Chin, 1979; Bunting and Williams, 1979; Elias and Bunting, 1982).

Forbes (1978) made an assessment of the groundwater resources of the area in response to concerns about the availability of groundwater for mining supplies. This was subsequently revised and updated by Bestow (1992), who provided regional estimates of the renewable and stored groundwater resources for each 1:250 000 sheet area in the Eastern Goldfields. Allen (1996) provided a description of the hydrogeology and groundwater availability but did not assess the groundwater resources. The hydrogeology and the distribution of licensed abstraction was further described in Dames and Moore (1996), although there was no attempt to quantify groundwater resources.

Considerable groundwater exploration and development has been carried out for mining companies in the Northern Goldfields during the past thirty years by hydrogeological consultants. Most of these reports are held by the Water and Rivers Commission.

Geotechnics (1972) conducted a large groundwater exploration programme to evaluate the groundwater resources of the Agnew area for WMC and the Public Works Department (PWD). This study focused on the Depot Springs area and employed resistivity surveys prior to drilling (Cowan and Omnes, 1975). Borefields have been established for mining developments throughout the region (Fig. 3), with a large amount of work having been carried out for the Mount Keith nickel operation. Recent groundwater exploration has concentrated on locating water supplies in palaeodrainages for projects such as Mount Keith and Murrin Murrin, and in calcrete aquifers at Wiluna and Jundee. Groundwater development from fractured-rock environments near Leinster has been described by Whincup and Domahidy (1982a,b).

2 Investigation programme

The purpose of the initial phase of the investigation programme was to gain an understanding of the available information and data distribution within the project area prior to conducting field studies. Exploratory geophysical surveys and drilling were then carried out to acquire new hydrogeological information in areas with few or no data, particularly within the tributaries of the main trunk palaeochannels.

2.1 Assessment of existing information

In addition to the published sources of geological and groundwater information, 440 reports held by the Water and Rivers Commission containing groundwater information relating to mine and town water supplies within the Northern Goldfields were reviewed. Other sources of information included GSWA town water supply investigations, WAMEX open-file mining company reports, and bore information stored in the Water and Rivers Commission's groundwater database (AQWABase).

A brief synopsis of groundwater information for the DUKETON, LAVERTON, LEONORA, SIR SAMUEL and WILUNA 1:250 000 sheets was compiled from these various sources in order to gain an appreciation of the regional hydrogeology and data distribution. This information was transferred onto preliminary hydrogeological maps to show the approximate position of the palaeochannel and calcrete aquifers. These preliminary maps were used for project planning and selection of the exploratory geophysical and drillhole transects.

Twenty transects (A–T) were selected for exploratory geophysics and drilling in areas lacking information to define the distribution of the regional palaeochannel aquifers (Fig. 4). Ten transects were placed across the main trunk palaeochannels, with nine transects positioned to define the tributaries. As additional information from mining companies became available, it was apparent that exploration was not required on Transect S and drilling need not be conducted on Transect N. In order to minimise the amount of geophysics and drilling, the transects were selected where the major drainage lines narrow between areas of exposed bedrock or those of higher relief.

2.2 Geophysical survey

The desk study confirmed that deep palaeochannel aquifers are hidden by overburden within the broad flat featureless valleys of the existing drainage system. In order to reduce drilling costs, targets needed to be defined using surface geophysical methods. Where possible, the surveys were run across the entire valleys, starting and finishing on outcropping rock. Discussions were held with various companies on which techniques would give the most useful results, and tenders for the survey were then requested.

Following assessment of tenders, it was decided to proceed with a combination of gravity and time-domain electromagnetic (TEM) methods. Between March and May 1997, gravity and TEM surveys were carried out by Tesla-10 Pty Ltd using a Scintrex CG-3 gravity meter and Sirotem Mk 3 TEM system. Of the nineteen transects surveyed, the gravity method was used on nine, the TEM system on a further nine and both systems on one. TEM infill was carried out on two of the gravity transects. Station spacing on all transects was 100 m.

The use of gravity and TEM are complementary, with both responding to contrasts in different bulk physical properties of the subsurface geology. The gravity method was used on the deeper main channels where the density contrast between the unconsolidated superficial deposits and the denser bedrock produced an anomaly with distinctly lower gravity readings, and also where the TEM method would be affected by shallow highly conductive hypersaline groundwater. In the palaeochannel tributaries the superficial deposits are thinner and provide a much less distinct gravity anomaly, but the lower salinity groundwater enables the TEM method to distinguish saturated sediments from the bedrock.

Overall, the geophysical survey was very successful, with the identification of targets on all lines surveyed. Most confidence was gained from the use of both methods over the same area as the data from each method can be affected by extraneous influences. Examples include gravity results being affected by deeper geological features, and various shortcomings of the TEM inversion method such as 'equivalence', whereby a thin highly

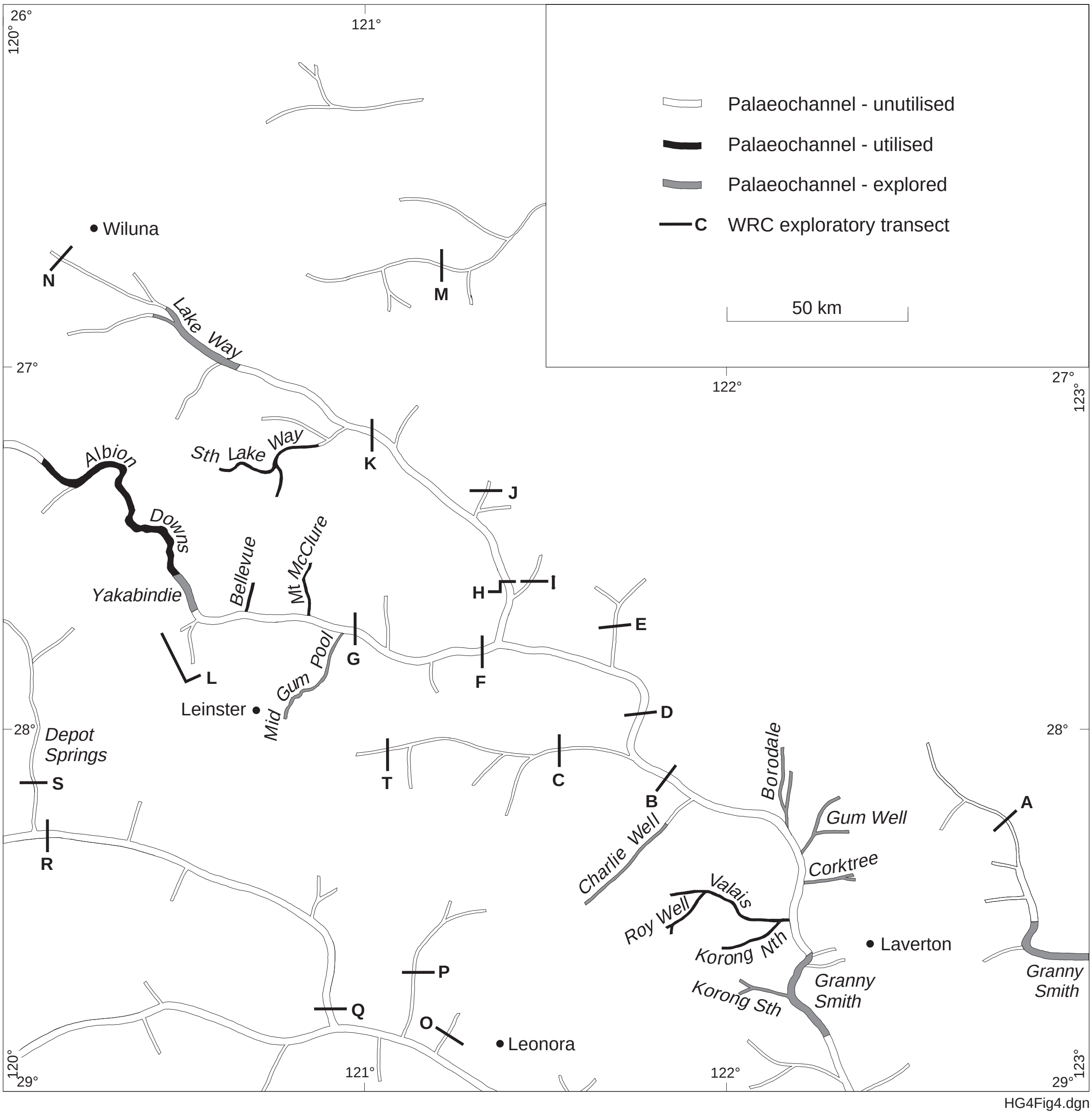

Figure 4. Groundwater development in palaeochannels

conductive layer produces a response similar to that of a thicker, less conductive layer. The geophysical data were reported by Tesla-10 (1997).

2.3 Drilling and bore construction

The drilling commenced in May 1997 and was completed in January 1998. The bore sites are designated by the prefix NE (North Eastern goldfields), followed by the transect letter (A to T), and the bore number in order of drilling. The drilling programme followed the surface geophysical survey and was divided into two phases. The first phase involved exploratory aircore drilling on targets determined from the surface geophysics. This was followed by mud-rotary drilling techniques, where the aircore technique had been unsuccessful at fully penetrating the palaeochannel sand aquifer, and for monitoring bore installation. Full details of the exploration and monitoring bores are given in Johnson *et al.*, 1998.

Aircore drilling was chosen because it has been used extensively in the Goldfields to investigate the palaeochannels, and also because it permitted the collection of representative geological samples. The only drawback was difficulty in drilling loose sand with large differential hydrostatic pressure between the groundwater in the formation and that in the drill rods. This induced sands to flow (running sands) into the drill rods causing blockage leading either to considerable delays because the rods had to be pulled from the hole for cleaning or, in the worst case, to cessation of drilling at the bore site.

The mud-rotary technique was employed where exploratory holes could not be completed due to running sands, as this method enabled the hydrostatic pressure in the formation to be balanced by the column of mud in the bore. In this way the bore was held open to allow geophysical logging to be undertaken and the bore completed. The main drawback to the mud-rotary system was that the geological samples were contaminated and the salinity of the formation water could not be determined during drilling.

GM Smith and Co., using a custom-made rig, commenced the aircore drilling in May 1997. About one-third of the programme was completed by July 1997 with 2548 m drilled on five transects. TDC Drilling Pty Ltd with a GEMCO H13 rig then undertook the remaining two-thirds of the programme. TDC commenced drilling in August 1997 and finished in September 1997, with 5112 m drilled on twelve transects.

At each site the aim was to drill an exploratory bore through the surficial deposits, which could include calcrete and the Tertiary sediments (where present), and then into the highly weathered Archaean bedrock until the rock type was identified. Samples from the drilling returns were taken every metre and geologically logged. Water samples were also taken but the measurements of salinity were unreliable because of probable contamination from the air-mist drilling technique. Overall, the aircore drilling was very successful and showed that the surface geophysics had provided accurate drill targets enabling the palaeochannel geometry to be readily delineated.

The mud-rotary drilling was carried out by Delta Consultancy and Drilling Services Pty Ltd using an Edson 5000W rig. The programme commenced in August 1997 with demobilisation in January 1998. A total of 2086 m was drilled on 15 transects, with 18 deep and 12 shallow monitoring bores completed. The sample returns were geologically logged during drilling, prior to running downhole gamma-ray logs in the open hole to accurately locate the sand aquifer.

Steel casing was installed in the deep monitoring bores when problems were encountered with loss of circulation in calcrete. The remaining monitoring bores were completed with 50 mm diameter PVC blank casing with 0.8 mm slots over the aquifer intervals. After gravel packing, the bores were developed by airlifting until all drilling fluid was removed and the water became clear. During airlifting, the flow rate and salinity were monitored and one-litre water samples taken for chemical analysis at Australian Government Analytical Laboratories (Appendix 2).

3 Geology

3.1 Regional setting

The investigation area is in the Eastern Goldfields Province (Griffin, 1990) of the Archaean Yilgarn Craton. The province is characterised by granite–greenstone rocks that exhibit a prominent northwest tectonic trend and low- to medium-grade metamorphism. The Archaean rocks are intruded by east–west dolerite dykes of Proterozoic age, and in the eastern area there are small, flat-lying outliers of Proterozoic and Permian sedimentary rocks. The basement rocks are generally poorly exposed owing to low relief, extensive superficial cover, and widespread deep weathering. Early Tertiary sediments are preserved in palaeochannels (Fig. 5) within an infilled palaeodrainage system, and are concealed by a thick sequence of Cainozoic deposits.

3.2 Archaean

The Archaean geology comprises metamorphic, igneous and sedimentary rocks (greenstone belts), and intrusive granitoids (Fig. 5). The base of the greenstone sequence consists of mafic and ultramafic rocks that are overlain by felsic volcanic and volcaniclastic rocks. Metamorphosed clastic sedimentary rocks including chert, quartzite and banded iron-formations dominate the upper part of the sequence. Granitoid rocks of mainly monzogranitic composition intrude the older greenstone rocks and occupy broad areas each side of the greenstone belts. The granitoid rocks occur as plutons and form linear belts of granitic gneiss, which are locally intruded by quartz veins, pegmatites and aplites.

Granitoid emplacement has extensively deformed the greenstone sequence resulting in complex geological structures. The contacts are characterised by strong deformation, local high-grade metamorphism, and interleaving of granitoid and greenstone rocks. As a result of their structural deformation, the greenstones are highly sheared and fractured. In contrast, the granitoids are generally massive with only local fracturing, adjacent to the greenstone contacts.

Most of the Archaean rocks in the Northern Goldfields have a weathered profile resulting from chemical breakdown of the crystalline bedrock. The depth of weathering in the greenstones generally extends to about 50 m below the surface but in some areas (particularly along faults and shears and sulfide-bearing zones) it may exceed 100 m (Allen, 1996). The weathering of the granitoid rocks, in contrast, is generally less than 40 m deep, although deeper sections have been observed along shear zones and below the palaeodrainages.

The weathering profiles on the greenstones and granitoids generally comprise a lateritic duricrust at the surface underlain by a variable thickness of dense, kaolinitic clay. The clay grades downward into a zone of weathered and fractured bedrock with fracturing enhanced by secondary chemical dissolution and joints commonly infilled with clay. Below the weathering zone, there is a sharp contact with fresh, sparsely fractured bedrock with fracturing decreasing with depth.

The greenstone belts contain economically important mineral occurrences, including the rich gold deposits at Granny Smith, Darlot and Bronzewing, and the nickel deposits at Mount Keith and Murrin Murrin. Gold has been deposited in a range of host rocks within the greenstone sequence, where it is predominantly structurally controlled, probably very late in the evolution of the granite–greenstone terrane (Wyche, 1997). Economic nickel mineralisation is confined to the thick ultramafic units in the Agnew–Wiluna greenstone belt and in greenstones around the Murrin Murrin deposit near Leonora.

3.3 Cainozoic

Early Tertiary sedimentary deposits of Middle to Late Eocene age have infilled the Cretaceous or Early Tertiary valleys. The sediments typically comprise a basal fluvial sand overlain by lacustrine clay. These are overlain by an interfingering sequence of alluvium and minor colluvium of later age, possibly Late Tertiary, that is locally replaced or displaced by calcrete.

Alluvial deposits form a thin veneer over the majority of Archaean rocks in the area. The alluvium form outwash fans on the flanks of the trunk valleys. Thicker deposits of colluvium also occur in tributaries, especially within the greenstone belts where the valley sides are steep.

3.3.1 Early Tertiary sediments

The stratigraphy of the Early Tertiary sediments in the

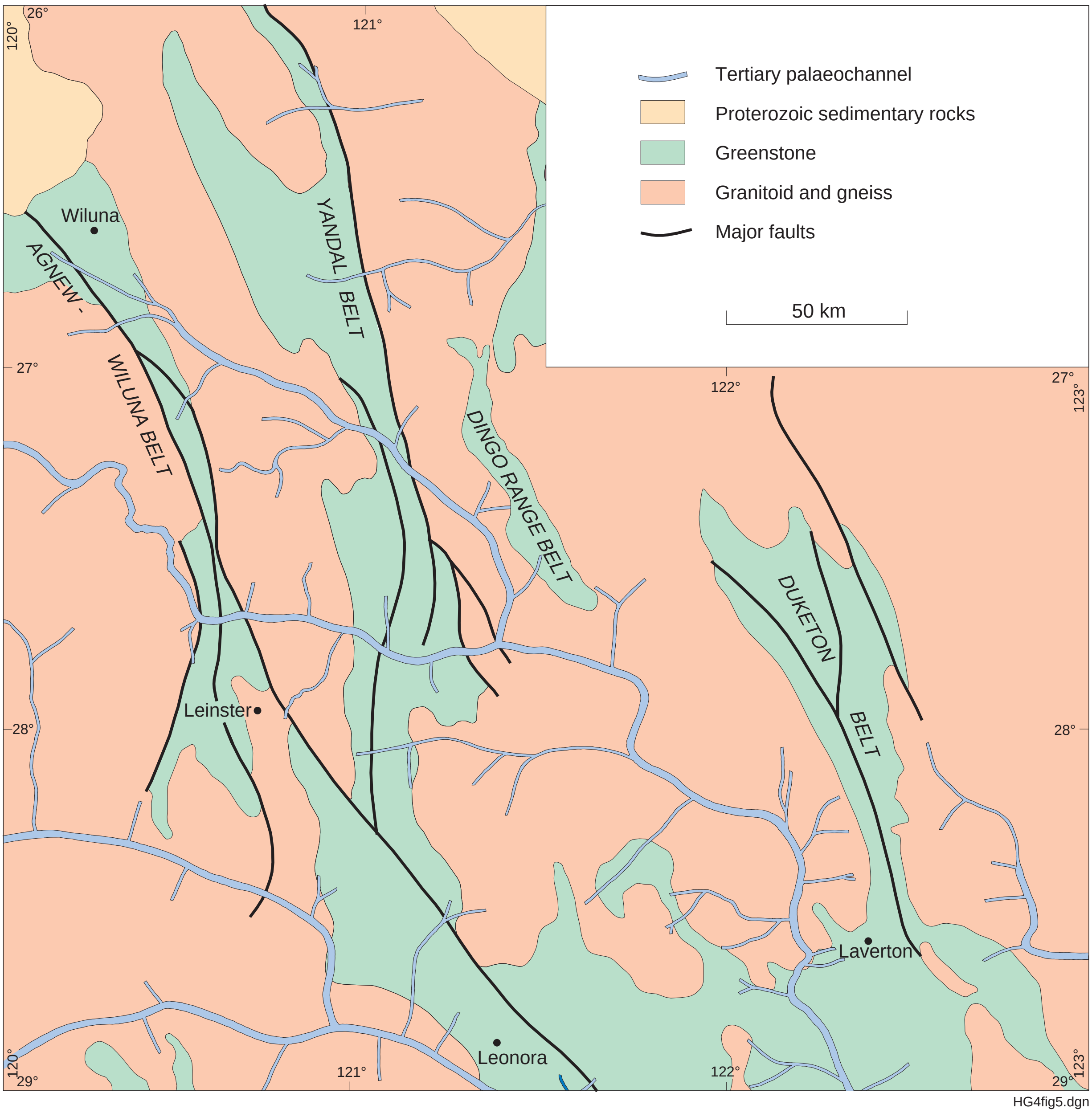

Figure 5. Bedrock geology and palaeochannels

Raeside and Carey Palaeodrainages is similar to that described in Commander *et al.* (1992), and Kern and Commander (1993) for the Roe Palaeodrainage in the Kalgoorlie Region. The sediments comprise a basal sand overlain by an interbedded sequence of dense, plastic clay with minor interfingering sand lenses. The palaeochannel sand at the base of the sequence occurs as a sinuous stringer sand unit, bounded by relatively steep topography, on the underlying Archaean bedrock surface (Fig. 6). Palynological analysis of lignitic material in NER-3 indicates an Eocene age (Milne, 1998), and is equivalent to the Wollubar Sandstone in the Roe Palaeodrainage (Kern and Commander, 1993).

The palaeochannel sand consists of predominantly very fine to coarse-grained quartz sand with minor silt, gravel and carbonaceous horizons, which were deposited in a combination of fan-type and braided channel-type alluvial structures. They may be up to 40 m thick, from 100 to 1000 m in width and in particular sections of the palaeodrainage become thicker, broader and coarser downstream, such as in the Albion Downs Borefield (Berry, 1994). Several upward-fining sequences have been observed at Transects B, D and R comprising a

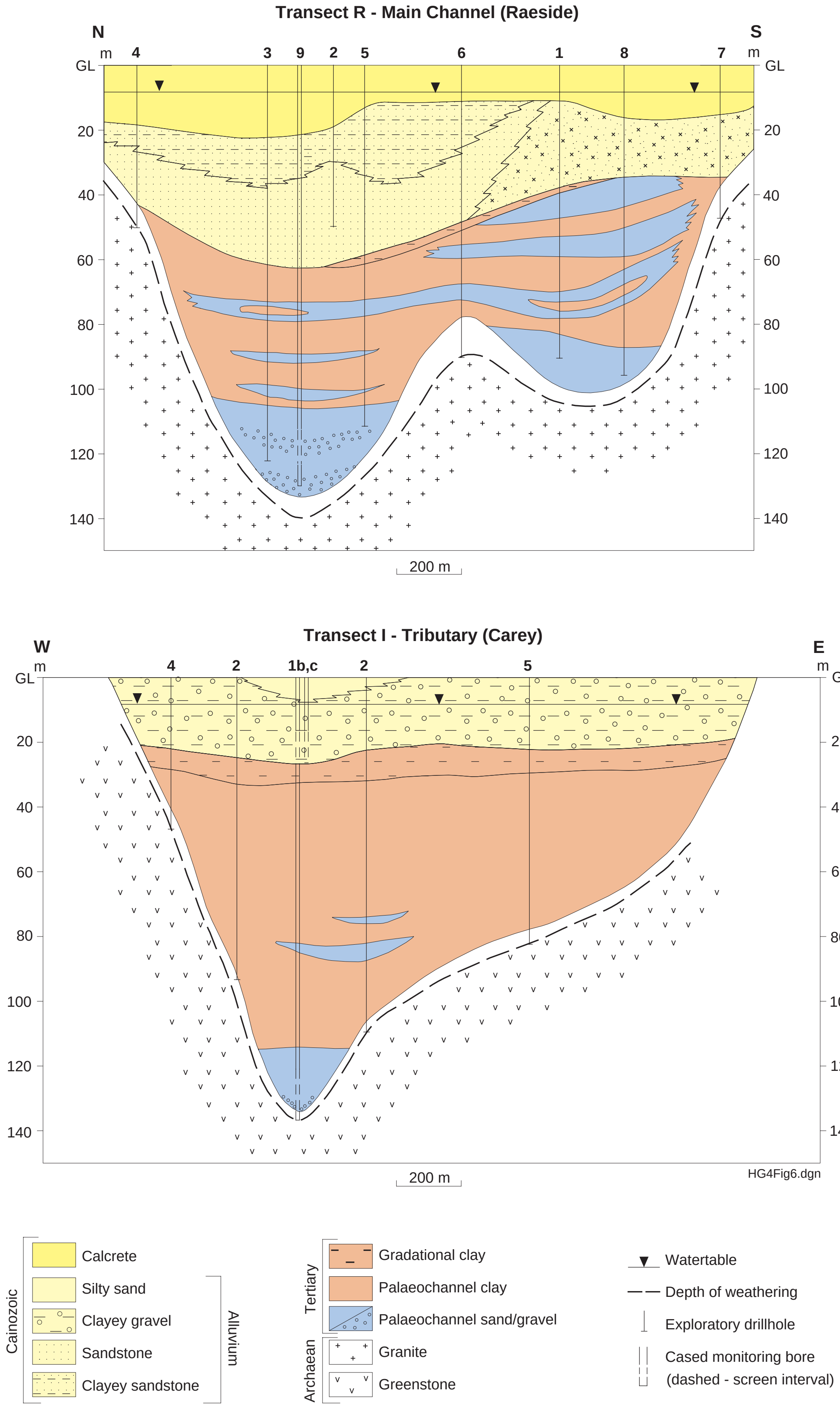

Figure 6. Hydrogeological cross sections

lower very coarse subangular to subrounded quartz sand grading into an upper sequence of fine to medium sand, which is commonly clayey. A thin bed of rounded grey quartz cobbles commonly occurs at the base of the unit.

The thickness and presence of the palaeochannel sand is related to their origin, with the thickest sequences of sand occurring in granitoid catchments, that are capable of providing more quartz-rich, clastic material than the predominantly greenstone catchments. The best example of this relationship to provenance is to the north of Laverton, where the Valais and Roy Well tributaries contain thick sequences of sand, gravel and clastic material resulting from weathering of the granitoid catchments. In contrast, the Borodale and Gum Well tributaries to the northeast contain clay-rich sequences with little or no sand, and is believed to be related to the fine-grained nature of the surrounding greenstone and gneissic rocks.

The palaeochannel sand is inferred to be continuous along the main trunk drainages. However, the continuity of the sand is poorly understood and the basal sand may be absent where the palaeochannel crosses greenstone belts, such as in the Carey Palaeodrainage near Lake Miranda. In the upper reaches of the Carey and Minigwal Palaeodrainages, the sand is finer grained, clay-bounded and cemented, indicating lower energy fluvial deposition and poor sediment development near the drainage headwaters. The palaeochannel sand is generally absent in the upper reaches of the tributaries; in Transect J, only thin sand lenses were intersected. However, as in the main trunk drainages, it is anticipated that the sand sections in the tributaries will thicken farther downstream.

The overlying clay, possibly of lacustrine origin, rests on the basal sand with a gradational contact comprising several metres of dark-grey clayey sand. The unit reaches a maximum thickness of 78 m in bore NED-9 (Johnson *et al.*, 1998) and grades downward from sandy clay to a uniform, light-grey plastic clay. Minor interfingering sand horizons up to 10 m thick occur throughout the clay and are believed to have been contributed from lateral tributaries. In the Northern Goldfields, the clay is present only in palaeochannels and is not known to outcrop.

3.3.2 Alluvium

Alluvial deposits form the upper portion of the Cainozoic sequence within the palaeodrainages, and include interfingering minor colluvium. The deposits consist of silty sand (with minor gravel in granitoid areas) and are characterised by ferruginisation and poor sorting of the predominantly quartzose grains. Alluvium occurs as channel fill associated with palaeodrainages and the lower parts of the tributary valleys.

The thickness was found to be highly variable, with over 60 m in the Raeside Palaeodrainage at Transect R (Fig. 6). The variation in thickness is largely dependent on position in the drainage system with the thickest sequences often coinciding with the axes of the Tertiary palaeochannels. The depositional environment is probably similar to that found in present-day outwash alluvial fans and minor creeks.

Thin deposits of colluvium form along the flanks of greenstone ridges and comprise subrounded, iron-stained basaltic gravels and angular basalt fragments, up to 100 mm diameter, within a clayey matrix. The colluvium has a variable thickness that rarely exceeds 20 m with the thickest sequences developed towards the base of basalt outcrops, such as at Transects I (Fig. 6), H and O. It was probably deposited in a debris-flow environment with a component of sheetwash, which may account for the subrounding of the gravels.

3.3.3 Calcrete

Calcrete is a carbonate rock formed by the *in situ* replacement or displacement of the alluvial and colluvial deposits by magnesium and calcium carbonate precipitated from percolating carbonate-saturated groundwater (Mann and Horwitz, 1979). The source of the carbonate-rich groundwater is believed to be related to the alteration and decomposition of ultramafic minerals in greenstone rocks, and the precipitated carbonate mineral is generally calcite rather than dolomite (Geotechnics, 1972).

Bodies of calcrete generally occurs at the margins of present-day salt lakes, and locally in some of the main tributaries in the palaeodrainages (Sanders, 1974). The occurrence of calcrete tends to be restricted to the northern part of the investigation area, although it is known to extend as far south as 30°S (Butt *et al.*, 1977). The calcrete rarely exceeds 10 m in thickness, except in the Depot Springs Palaeodrainage where up to 40 m of calcretised alluvium has been identified (Geotechnics, 1972). Areas of calcrete outcrop range from less than 1 km^2 to over 100 km^2 in the Raeside Palaeodrainage.

Karstic features, including sinkholes and gilgai structures, are often developed due to the susceptibility of the calcrete to chemical dissolution via percolating surface water and groundwater movement. Solution cavities are mostly developed near the present watertable and are also well developed in deltaic situations, where tributaries adjoin the main trunk drainages.

4 Hydrogeology

4.1 Groundwater occurrence

The Northern Goldfields area is underlain by weathered and fractured Archaean bedrock, which forms the northern portion of the Yilgarn Goldfields fractured-rock groundwater province. The bedrock is covered locally by palaeochannel deposits and by widespread alluvium, colluvium and lake deposits (Fig. 7).

The fractured bedrock is characterised by secondary permeability resulting from chemical weathering of tectonic and decompression fracture systems. Fractured-rock aquifers are developed in greenstone rocks, such as mafic and ultramafic volcanic rocks, with minor groundwater supplies present within fractured granitoid rocks. Vuggy weathering profiles are developed in ultramafic and carbonatite rocks. The maximum depth of open fractures reported in the area is 120 m in greenstones at Granny Smith Gold Mine (Dames and Moore, 1993). Groundwater can be inferred to occur to a similar depth along major faults and shear zones.

The base of the Tertiary sedimentary sequence in the palaeochannels is marked by a fluvial sand aquifer confined beneath a dense clay layer. The palaeochannel sand is highly permeable and contains significant supplies of groundwater, which are fresh to brackish in the tributaries and saline to hypersaline in the main trunk drainages. The sand, however, has limited groundwater storage with most groundwater abstracted being the result of induced leakage from overlying sediments and surrounding fractured-rock aquifers.

The presence of aquifers overlying the Early Tertiary palaeochannels, which include alluvium and calcrete deposits, is an important hydrogeological difference when compared with the Roe Palaeodrainage, as described by Commander *et al*. (1992). Groundwater occurs within the primary porosity of the alluvium, whereas calcrete exhibits increased secondary permeability through chemical dissolution. The alluvium aquifer has by low permeability due to its clayey nature, whereas the calcrete can often provide large local supplies of fresh to brackish groundwater from solution cavities.

The groundwater occurs in regional flow systems within the major palaeodrainages. It moves under gravity from about the drainage divides towards the salt lakes, and then downstream in the palaeochannels. As observed in the Roe Palaeodrainage (Commander *et al.*, 1992), it is inferred that groundwater movement is controlled by the location of salt lakes, which determine local discharge areas, and the recharge sites of dense, reflux brine plumes. Hydraulic gradients along the palaeodrainages are generally very low, with steeper gradients occurring in the upper reaches of the catchments, and where the palaeochannel crosses greenstone ridges, such as south of Transect H.

The groundwater flow systems in the Northern Goldfields are maintained by rainfall recharge (Allen, 1996). Groundwater recharge is difficult to estimate as it constitutes a very small proportion of rainfall, most of which is either directly evaporated or utilised by the native vegetation, with a small component of runoff into claypans and playa lakes. Most recharge is likely to occur during heavy rainfall when it is augmented by recharge from surface runoff and local flooding. Groundwater discharge occurs mainly by evaporation from playa lakes, and a relatively small amount by throughflow within the palaeochannels.

4.2 Alluvium

4.2.1 Aquifer characteristics

The alluvium forms an unconfined aquifer with a shallow watertable often less than 5 m below ground level and an average saturated thickness of between 5 and 15 m. The permeability of the alluvium is generally low, with a hydraulic conductivity of less than 2.5 m/day in the Albion Downs Borefield (Berry, 1997), owing to its silty nature. The hydraulic conductivity can, however, increase quite significantly in permeable sand and gravel horizons, and calcretised sections. In addition, the alluvial aquifer is often partly indurated by siliceous and ferruginous cementation, possibly representing previous watertable positions, which have secondary porosity and high permeability developed in bands.

Bore yields from the alluvium can range from 50 to 600 kL/day in the Lake Way and Albion Downs Borefields, reflecting the variability in hydraulic

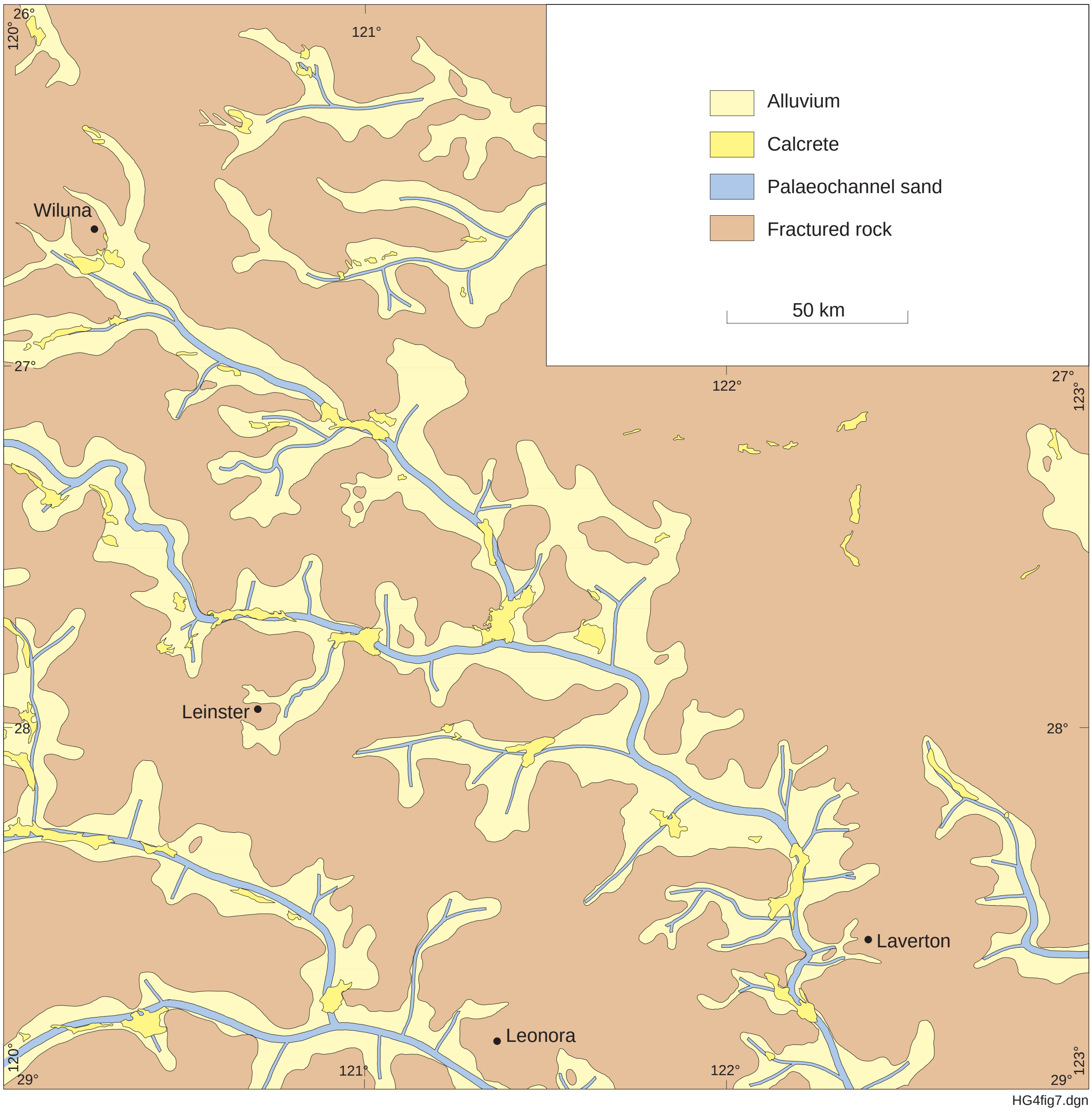

Figure 7. Major hydrogeological units

conductivity. The largest yields are from the unconsolidated, clayey, rounded basaltic gravels that form colluvial deposits at the base of greenstone ridges, such as at Transects H and O. Groundwater salinity of the alluvial aquifer ranges from 1000 to 4000 mg/L TDS on the flanks of the palaeodrainages and below alluvial fans, with higher salinity water encountered in the lower parts of the drainage system and towards salt lakes.

The alluvial aquifer is an important component of the hydrogeological cycle and contains significant quantities of low-salinity groundwater. Owing to its low permeability, the aquifer is not directly utilised, and most groundwater is obtained via leakage into underlying palaeochannel and fractured-rock aquifers.

4.2.2 Groundwater resources

4.2.2.1 Renewable

Groundwater resources in the alluvium are recharged from irregular, episodic rainfall events. Forbes (1978), Hickman *et al.* (1986) and Bestow (1992) have all made estimates of renewable groundwater resources throughout the Northern Goldfields by assuming a percentage of rainfall contributing to groundwater recharge on an areal basis. As there are no new data on recharge, it was decided to use the recharge estimations by Bestow (1992) for comparison between renewable and stored groundwater resources in alluvium, as well as for the fractured-rock aquifer.

Bestow (1992) used the chlorinity method, outlined by Hingston and Gailitis (1976), to estimate recharge rates on an areal basis for a number of groundwater salinity ranges. His estimate of 0.9% recharge for fresh groundwater (<1500 mg/L) correlated closely with Sanders' (1971, 1972) estimates derived by the hydraulic method, and was similar to the 1% rainfall recharge figure used by Forbes (1978). Bestow further estimated that recharge to groundwater of 1500–7000 mg/L was 0.23%, and that for groundwater of 7000–14 000 mg/L was 0.09% of rainfall.

In order to estimate the renewable groundwater resources to the alluvium, the percentage area of alluvium for each 1:250 000 sheet was estimated from published geological maps and multiplied by Bestow's renewable estimates. The renewable groundwater resource into the alluvium is estimated at 43 GL/yr with higher values towards the north reflecting the increase in rainfall (Table 1). There are, also, likely to be additional recharge contributions through runoff, particularly where runoff is concentrated beneath alluvial fans.

4.2.2.2 Stored

The stored groundwater resources have been estimated using assumptions of the saturated thickness and specific yield based on drilling and pumping-test information. The groundwater resources in storage have been estimated by multiplying the areal extent of the aquifer, saturated thickness, and specific yield. The saturated extent of the alluvium was mapped using pastoral bore data and geological maps. The distribution was compiled and digitised, and the polygonal area of the alluvium aquifer calculated using ArcView GIS software.

The saturated thickness is variable, depending on its topographic position, with the thicker sequences occurring along the palaeochannel axis. The saturated thickness of the aquifer ranges from 5 to 60 m in the various transects, but an average thickness of 10 m is an appropriate value on an areal basis.

Estimation of the specific yield is based on lithology. Berry (1994) assumed a specific yield of 0.05 and an initial thickness of 32 m for the upper unconfined aquifer with leakage into the palaeochannel sand. However, the specific yield was modified to 0.03 during a review of the numerical model of the Albion Downs Borefield (Berry, 1997). A specific yield of 0.05 is therefore considered appropriate in terms of the water that could be available for use, directly or by leakage to other aquifers.

The total stored groundwater resources in the alluvium is estimated at 11 300 GL and is summarised for each 1:250 000 sheet in Table 1. The groundwater resources are evenly distributed throughout the region. The largest resources lie within the Carey Palaeodrainage, particularly downstream of Lake Way, and where major tributaries adjoin the main trunk drainages.

The salinity distribution in the alluvium highlights the general trend of increasing salinity towards the south.

Table 1. Groundwater storage and recharge in the alluvium aquifer

1:250 000 Map sheet	*Groundwater storage within salinity divisions (GL)* 0–1000	1000–3000	3000–14000	>14000	*Groundwater storage (GL)*	*Renewable groundwater resources[1] (GL/yr)*
	mg/L TDS					
Wiluna	384	1007	758	171	2320	11
Sir Samuel	304	1154	1326	347	3131	10
Duketon	285	354	142	172	953	8
Leonora	17	735	1338	410	2500	8
Laverton	36	595	1226	539	2396	6
Total	**1026**	**3845**	**4790**	**1639**	**11300**	**43**

[1] Estimations of groundwater recharge taken from Bestow (1992).

The largest fresh to brackish resources are generally located to the north of Leinster. The aquifer in the south is typically brackish to saline with minor fresh groundwater present in the upper catchment areas of tributaries, such as in the Valais Borefield. The salinity divisions used in the calculations were selected on potential groundwater usage for potable (0–1000 mg/L), horticultural (1000–3000 mg/L), pastoral and nickel processing (3000–14 000 mg/L), and mining purposes (>14 000 mg/L).

4.3 Calcrete

4.3.1 Aquifer characteristics

Owing to its well-developed secondary porosity and high permeability, calcrete forms a locally high-yielding aquifer. The calcrete occurs low in the drainage systems where the watertable is generally shallow, less than 5 m below ground level, and saturated thickness is mostly between 5 and 10 m. Bore yields are highly variable depending on the nature and extent of karstic development. Yields at Depot Springs (Geotechnics, 1972) ranged from less than 100 kL/day in massive calcrete to 4400 kL/day in highly karstic calcrete.

Groundwater in the calcrete is commonly brackish to saline, between 2000 and 6000 mg/L TDS, because of its position in the lower reaches of drainages (Sanders, 1969). There are, however, small potable supplies, such as at Wiluna and Yeelirrie, where the calcrete receives enhanced groundwater recharge via direct rainfall infiltration, and more particularly inundation from surface runoff surrounding catchments during intense rainfall events.

Calcrete is an important local aquifer in the Northern Goldfields capable of providing large supplies of shallow, brackish groundwater for use in town water schemes, and pastoral and mining industries.

4.3.2 Groundwater resources

4.3.2.1 Renewable

There have been relatively few studies of recharge rates to calcrete aquifers in the Northern Goldfields, and most of the work has focused on the calcrete aquifers around Wiluna. The first recharge studies were undertaken by Chapman (1962) who determined rainfall recharge proportions of 1.3% and 3.3% for calcrete catchments at Lorna Glen (east of Wiluna) and at Wiluna respectively. Later, Sanders (1971, 1972) determined recharge rates of 0.7% and 0.79% of rainfall for calcrete catchments at East Wiluna, and 0.98% for the calcrete aquifer at Paroo.

There is also some increased infiltration through sheet flooding and stream flow that occurs after intense rainfall events; however, these runoff contributions are difficult to quantify. Sanders (1972) noted that storm events with greater than 50 mm of rainfall generate significant runoff from the catchment areas that inundates the calcrete. Infiltration is very rapid into the calcrete via solution cavities, although this process of recharge probably only occurs during sheet flooding.

Based on the estimates by Chapman and Sanders, recharge directly from rainfall or local runoff in areas of outcropping permeable calcrete would constitute at least 1% and possibly as much as 5% of the total rainfall in these areas. The renewable groundwater resources were estimated by multiplying the areal extent of the individual calcrete bodies, the annual rainfall (assumed as 200 mm/yr) and a recharge figure of 1% of rainfall. The areal extent of calcrete was determined using planimetric techniques, with aquifer boundaries taken from GSWA 1:250 000 geological maps, Agriculture WA landform maps (Pringle *et al.*, 1994), and various groundwater consultants' reports.

The total renewable groundwater resources in the calcrete is estimated at 30 GL/yr and is summarised in Table 2 for each 1:250 000 sheet. The resources increase towards the north with larger calcrete bodies occurring in the Wiluna and Yeelirrie area. These estimates are conservative because only the areas of outcropping calcrete were used in the calculation.

4.3.2.2 Stored

The groundwater resources in the calcrete aquifer are also given in terms of groundwater in storage. Estimates of total storage are shown in Table 2 and include several areas of calcrete that have been studied in detail by Sanders (1969, 1973, 1974) and by groundwater consultants.

Where possible, groundwater storage in the calcrete was estimated from the volume of saturated aquifer defined by drilling. The saturated thickness of calcrete is highly variable, up to 30 m thick, with an estimated average of 5 m. For the purpose of groundwater resources estimation, this value is applied to unexplored calcrete bodies.

Table 2. Groundwater storage and recharge in the calcrete aquifer

1:250 000 Map sheet	*Groundwater storage within salinity divisions (GL) 0–1000*	*1000–3000*	*3000–14000*	*>14000*	*Groundwater storage (GL)*	*Renewable groundwater resources[1] (GL/yr)*
	mg/L TDS					
Wiluna (south)	55	62	70	3	190	5
Sir Samuel	11	106	184	27	328	12
Duketon	-	12	12	-	24	1
Leonora	-	16	214	15	245	8
Laverton	-	19	81	2	102	4
Total	**66**	**215**	**561**	**47**	**889**	**30**

Note: Wiluna (south) is the southern half of the Wiluna 1:250 000 map.

The specific yield of calcrete is highly variable (ranging from 0.05 to 0.25) due to its karstic nature. Specific yields are high where associated with karstic development, commonly close to or at the watertable, and lowest where the calcrete is massive. Specific yield also generally decreases with depth below the watertable. In calcrete bodies with no aquifer testing information, the applied specific yield of 0.10 is based on pumping-test results around Wiluna (Sanders, 1973), Depot Springs (Geotechnics, 1972), and at Yeelirrie (Australian Groundwater Consultants, 1981).

The storage estimates for each calcrete body (Appendix 2) are summarised for each 1:250 000 map sheet in Table 2 and shown on Figure 8. The total groundwater resource in the calcrete aquifer for the Northern Goldfields area, including the Yeelirrie calcrete aquifer, is estimated to be about 890 GL. The largest groundwater resources are located in the northern areas, in particular near Wiluna and Yeelirrie, with groundwater salinity also decreasing northward.

4.4 Palaeochannel sand

4.4.1 Aquifer characteristics

The palaeochannel sand is the most important aquifer in the Northern Goldfields, capable of providing significant groundwater supplies. The sand aquifer is up to 1 km wide, and up to 40 m thick in the trunk palaeochannels, reducing to several hundred metres wide in the tributaries. The sand is confined beneath as much as 80 m of structureless, kaolinitic clay, although relationships are not certain in the upper parts of those tributaries that have not been explored. The confining clay layers in the tributaries are often contain silt and several sandy horizons. Results of pump testing at the Valais Borefield shows that pumping from the lower sand aquifer induces leakage from the overlying sediments and adjacent bedrock (Rust PPK, 1996).

The sand is inferred to be continuous along the main trunk drainages throughout the Northern Goldfields. However, the sand may be absent where the palaeochannel crosses greenstone belts, such as in the Carey Palaeodrainage near Lake Miranda. The continuity of the sand is poorly understood.

The hydraulic conductivity of the sand has been established by pumping-tests at several localities along the Carey Palaeodrainage and ranges from 1 to 40 m/day with an average of 10 m/day. The variation in hydraulic conductivity along the palaeodrainages is poorly understood owing to the lack of aquifer testing in the main trunk drainages. There are, however, sections in the Carey Palaeodrainage, such as in the Albion Downs Borefield (Berry, 1994), which exhibit increasing hydraulic conductivity downstream as the sand becomes coarser. However, this may apply only in the upper sections of the palaeochannels, as elsewhere the sand is coarse grained and relatively uniform.

Although the palaeochannel sand is the most productive and reliable aquifer in the Northern Goldfields, they have limited storage and long-term pumping will induce leakage from the overlying lithologies and surrounding weathered bedrock. As most of the groundwater is hypersaline its usefulness is restricted to mining activities, although the presence of fresh to brackish

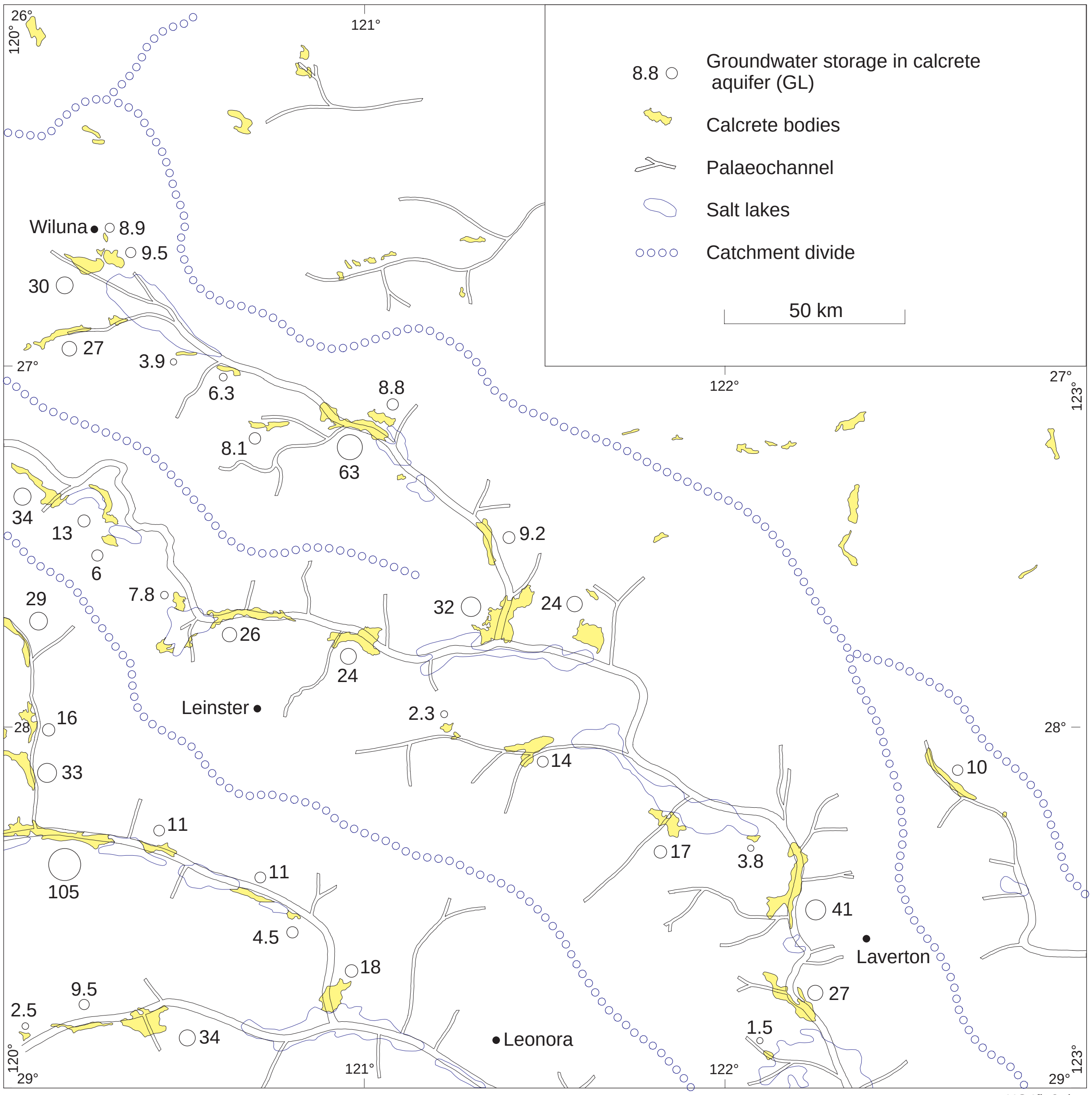

Figure 8. Groundwater storage in calcrete

groundwater in the tributaries implies that there may be local potential for potable supplies and irrigation usage.

4.4.2 Recharge

Commander *et al.* (1992) noted that direct recharge to the Wollubar Sandtone only takes place in the upper reaches of the palaeochannel where the confining layer is absent. There is no evidence suggesting the palaeochannel sand aquifer in the Carey and Raeside Palaeodrainages is unconfined, hence it is assumed most recharge is by inflow from the weathered and fractured bedrock flanking the palaeochannel, and by vertical leakage through the confining layer where downward heads occur.

There is input to the main palaeochannels from minor tributaries, which are distributed along the Carey and Raeside Palaeodrainages. It is difficult to estimate the rate of accession of lower salinity groundwater from the tributaries, although the process is inferred to occur at several localities along the palaeodrainages.

Recharge to the palaeochannel sand aquifer is inferred to be very small reflecting the high evaporation, thick vegetation, and low permeability of the confining clay, and the low permeability of the weathered bedrock. There have been no recharge studies during this investigation; previous works by Commander *et al.* (1992) and Turner *et al.* (1994) in the Roe Palaeodrainage suggested that recharge through direct infiltration of rainfall was negligible. Commander *et al.* (1992) inferred from calculations of discharge that groundwater recharge to the Wollubar Sandstone contributing to groundwater outflow is about 0.003% of rainfall. Isotopic and geochemical analysis by Turner *et al.* (1994) estimated that only about 0.01 mm/year of rainfall over the catchment area actually recharges the sand aquifer.

4.4.3 Groundwater flow

Groundwater in the sand aquifer is along the axes of the palaeochannel. The hydraulic head in the sand is generally lower than in the Archaean bedrock indicating that the palaeochannels are regional drains receiving groundwater flow from the surrounding areas of bedrock. The elevation of the regional potentiometric surfaces in the palaeochannel sand of the Carey Palaeodrainage falls from about 500 m in the north to 390 m in the southeast near Lake Carey, a distance of 260 km (Fig. 9). In the Raeside Palaeodrainage, the regional potentiometric surface falls from 460 m in the west near Kaluwiri Station to 360 m in the east beneath Lake Raeside, a distance of 130 km.

In the Carey and Raeside Palaeodrainages, groundwater flows eastwards in the direction of the original drainage. The hydraulic gradient in the Carey Palaeodrainage steepens to the south of Transect H (0.8 m/km), where the palaeochannel narrows and passes through the more resistant belts of mafic rocks. In the vicinity of salt lakes (Fig. 9), the hydraulic gradient is very low (0.2 m/km between Transects B, D and G) suggesting groundwater discharge through evaporation at lake surfaces.

Steeper hydraulic gradients (2 m/km) occur within the tributaries reflecting significant groundwater flow of actively recharged low-salinity groundwater, as well as narrower channel widths, thinner sand sections and lower hydraulic conductivity.

Groundwater flow (Q) in the trunk palaeochannels can be estimated using the Darcy equation $Q = k\ i\ a$, where k is hydraulic conductivity (estimated), i is the hydraulic gradient (from Fig. 9), and a is the cross-sectional area of the palaeochannel sand (derived from the drilling transects). Calculations for each segment of the palaeochannel are tabulated in Appendix 4. These calculations indicate that groundwater throughflow is 0.01 GL/yr in the Carey Palaeochannel and 0.02 GL/yr in the Raeside Palaeochannel.

The rate of groundwater flow can also be estimated from the equation for seepage velocity (v_s), $v_s = k\ i/n$, where n is porosity. At k =10 m/d, i = 0.0002, and n = 0.2, the seepage velocity is about 0.01 m/d, representing a travel time along 300 km of palaeochannel of about 100 000 years. This is supported by dividing the total storage (3359 GL) by the total throughflow (0.03 GL/yr) which again equals about 100 000 years, a measure of the groundwater residence time.

The groundwater throughflow is small in relation to the total storage, and is a very small component of the water balance. Groundwater flow, however, is likely to be continuous along the full length of the palaeochannels, with local recharge (through the tributaries) and local discharge occurring at the salt lakes.

4.4.4 Discharge

Groundwater discharge from the area is principally by evaporation from the salt lakes, with a relatively small amount of groundwater outflow in the palaeochannel sand. The groundwater outflow from Carey and Raeside Palaeodrainages is ultimately towards the Eucla Basin, which is about 350 km to the southeast of the area.

Commander *et al.* (1992) suggested that discharge to the salt lakes from the palaeochannel sand aquifer takes place through the overlying clay layer, and through the adjacent weathered Archaean bedrock. As the salt lakes generally overlie areas of bedrock, rather than overlying the palaeochannels, most of the discharge from the sand is inferred to be through the weathered bedrock.

In areas of salt lakes, there is a decrease in the hydraulic gradient and the potentiometric head in the palaeochannel sand is close to the lake surface. As in the Roe Palaeodrainage, there is also an increase in groundwater salinity in the palaeochannel sand downstream of salt lakes indicating the salt lakes are areas of groundwater discharge and behave as evaporative basins (Commander *et al.*, 1992). Turner *et al.* (1993) noted that the rate of salinity increase along parts of the Roe Palaeodrainage implied

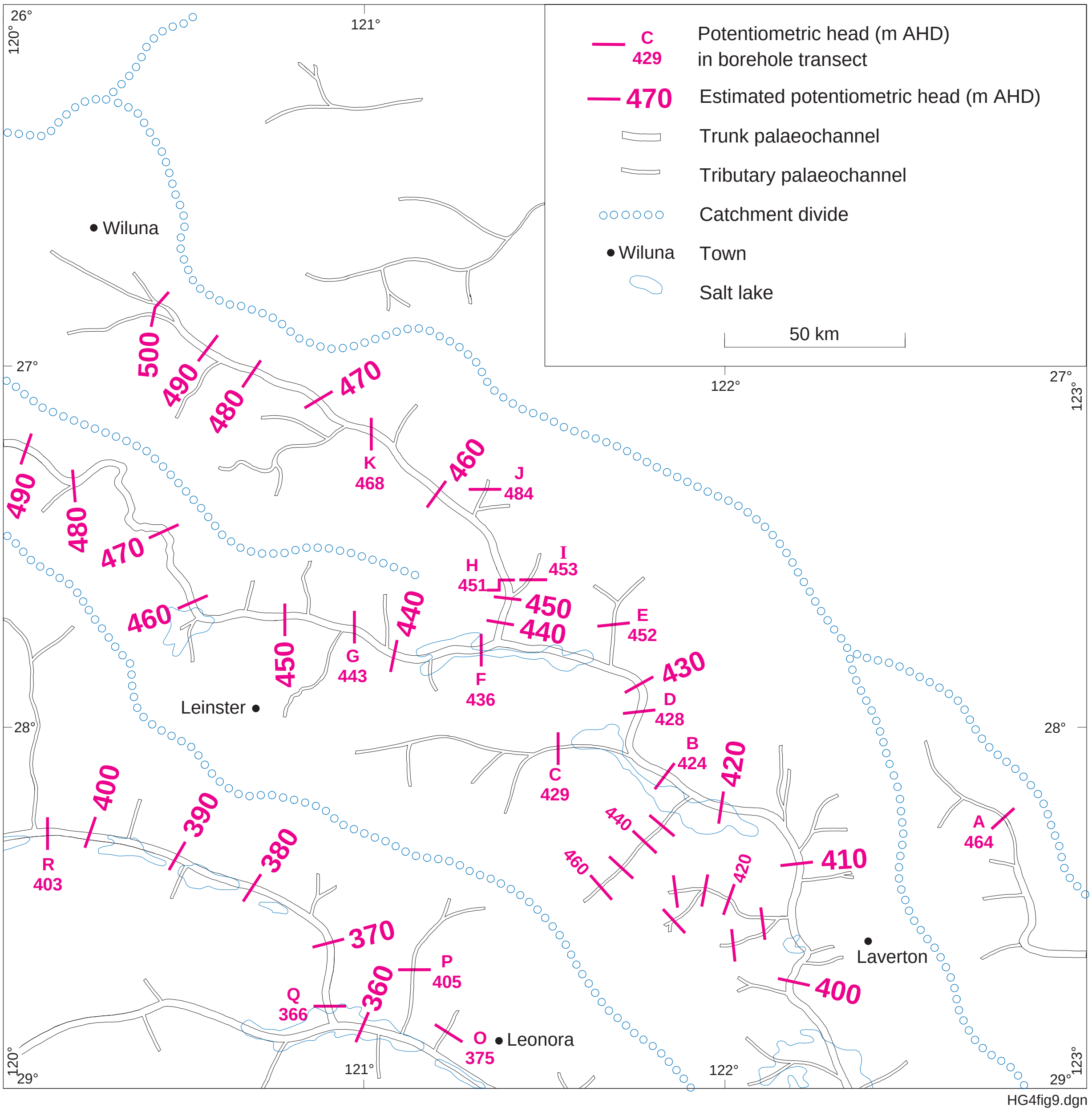

Figure 9. Potentiometric head in the palaeochannel aquifer prior to groundwater abstraction

that evaporation must account for more than 96% of water loss from the aquifer. Although the process is poorly understood, Commander *et al.* (1992) suggested that there were areas of upstream groundwater discharge into the salt lakes from the palaeochannels and areas of downstream recharge to the palaeochannels of more concentrated brines.

4.4.5 Trends in groundwater salinity

Groundwater salinity within the palaeochannel sand ranges from fresh to brackish (1000 to 3000 mg/L) in the tributaries, to hypersaline (as much as 238 000 mg/L) in the main palaeochannels (Fig. 10). There are also variations in salinity along the palaeochannels suggesting increases associated with groundwater discharge at salt lakes resulting in reflux brine plumes downstream (Commander *et al.*, 1992), and decreases in salinity related to the accession of lower salinity groundwater from tributaries. These variations can be observed in a small section of the Carey Palaeodrainage, where the salinity in the palaeochannel sand falls from 223 000 mg/L beneath Lake Miranda to 27 000 mg/L at

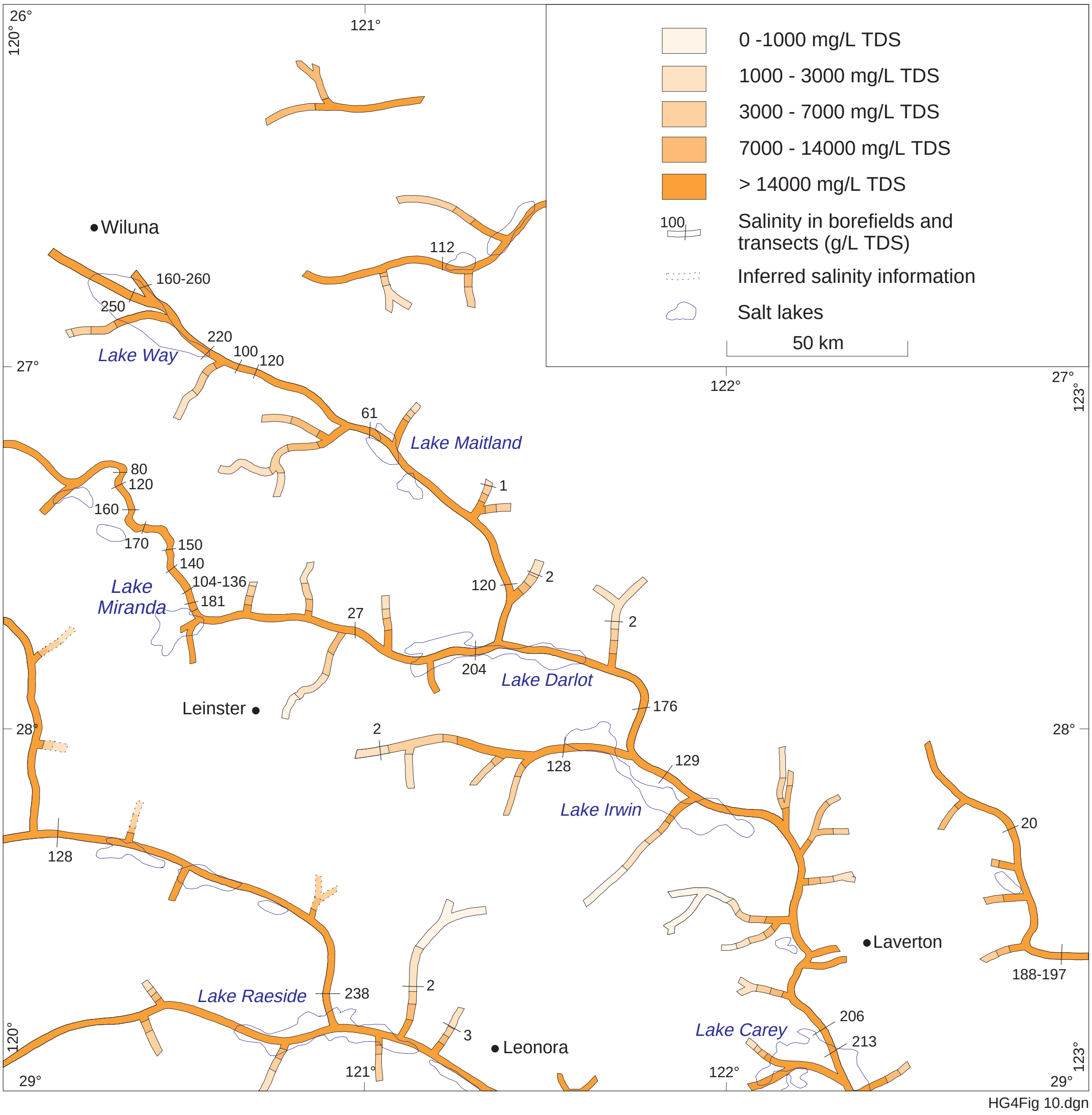

Figure 10. Groundwater salinity – palaeochannels

Transect G, probably because of recharge of fresh to brackish groundwater from the Gum Pool tributary.

As observed in the Roe Palaeodrainage (Commander *et al.*, 1992), there is apparent stratification of groundwater in the palaeochannel sand, with denser higher salinity groundwater at the base of the aquifer, such as at Transect K. The presence of the lower salinity groundwater towards and at the palaeochannel edges may indicate groundwater inflow to the channels from the adjoining bedrock aquifers.

4.4.6 Groundwater resources

4.4.6.1 Renewable

The palaeochannel sand is recharged in the upper reaches of the tributaries with the presence of low-salinity groundwater and steeper hydraulic gradients, when compared with the trunk palaeochannels. As direct recharge from rainfall is considered to be negligible, it is thought that the tributaries may receive indirect recharge via leakage of groundwater from the fractured-rock aquifers. Whereas, the trunk palaeochannels are

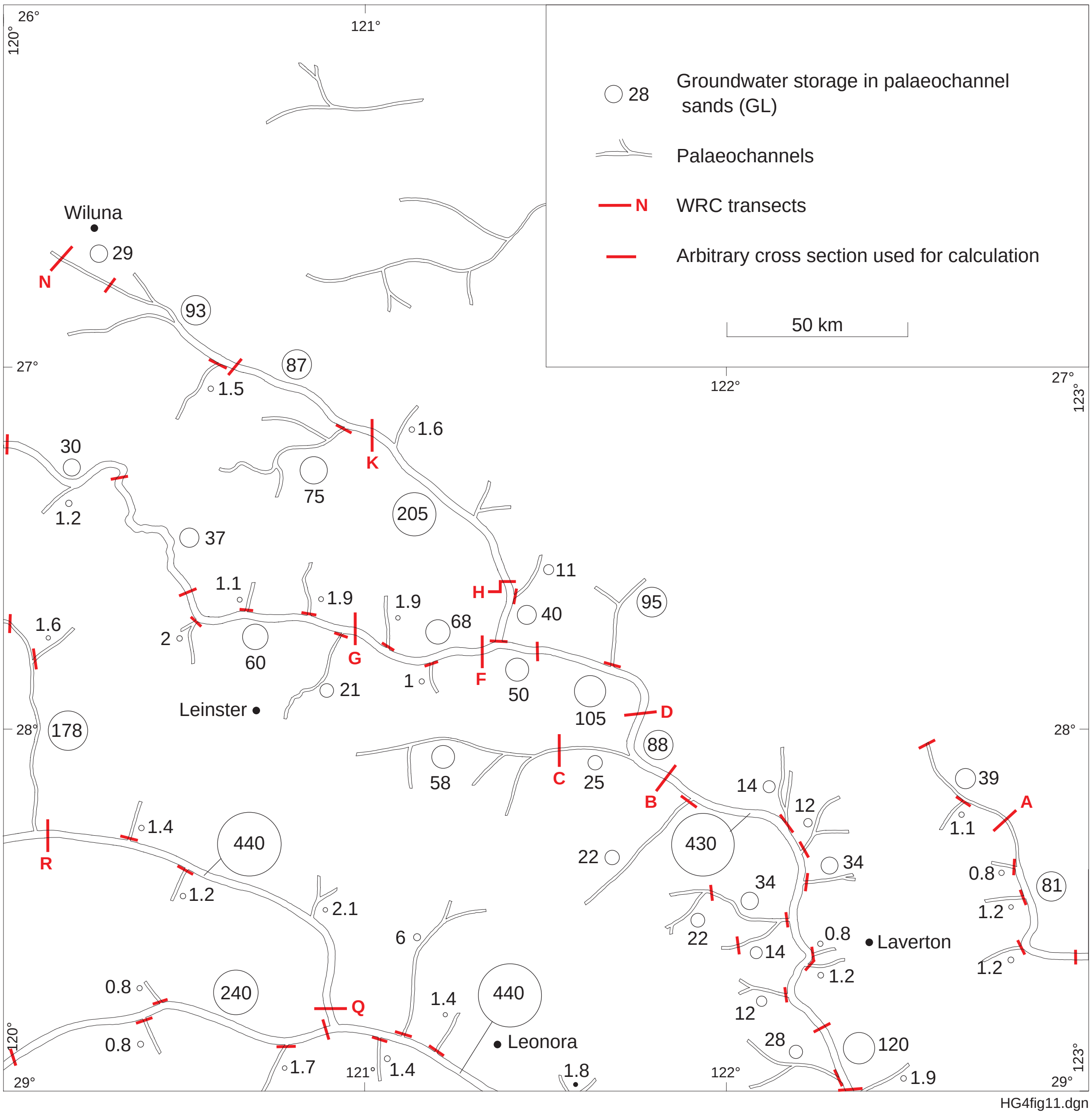

Figure 11. Groundwater storage in palaeochannels

essentially non-renewable, except for minor groundwater derived from leakage from bedrock and contribution from the tributaries. As a result of these indirect recharge mechanisms, it is not possible to quantify groundwater recharge (and renewable resources) with current knowledge.

4.4.6.2 Stored

Groundwater storage in the palaeochannel sand is estimated from the volume of sand defined by mine water supply drilling programmes and by the 1996-97 exploration programme undertaken as part of this investigation. The volume was calculated by multiplying the length of the palaeochannels between drilling lines by the average cross-sectional area of the saturated sand and applying a specific yield of 0.2. The length (sector) between each cross section was measured from the mapped extent of the palaeochannels (Fig. 11), and the area of the saturated sand measured from the cross sections.

In the calculations, it was assumed with one exception (Transect Q) that the orientation of the cross sections is at right angles to the palaeochannel and that the palaeochannel length is a relatively straight line between transects. It was also assumed that the sand is continuous and that the cross-sectional area of the sand can be interpolated between transects. However, it is known that some sections are not at right angles to the palaeochannels, the palaeochannels are likely to be sinuous, and the palaeochannels thin where the channels traverse resistant bedrock, or thicken where tributaries enter the palaeochannels. Furthermore, only the resources of the main palaeochannels and tributaries have been estimated, and there are likely to be significant resources in the unexplored minor tributaries.

The estimates of storage, groundwater salinity and throughflow for each segment of the palaeochannels are tabulated in Appendix 4. The total groundwater stored in the sand aquifer is estimated at 3359 GL for 2021 km of palaeochannel length (Table 3). The groundwater storage of 1.7 GL per kilometre of palaeochannel is similar to estimates by Commander *et al.* (1992) in the Roe Palaeodrainage. These estimations are representative of groundwater storage in the palaeochannel sand, although long-term pumping of these aquifers suggests that significant groundwater inflow can be induced through leakage from adjacent fractured-rock aquifers and overlying lithologies.

There are significant resources of saline to hypersaline groundwater in the main trunk section of the Carey and Raeside Palaeodrainages. The largest groundwater resources are in the thicker and wider downstream parts of the palaeodrainage, as the sand aquifer in the upper reaches is often thin.

As well as the trunk drainages, there are also important resources of fresh to brackish groundwater within tributaries, that are located along the Carey and Raeside Palaeodrainages. There are large low-salinity resources within the South Lake Way and Valais tributaries, although significant fresh groundwater resources have also been located in the tributary beneath Transect E. Many of these tributaries are remote from current centres of demand and are often in granitic areas that are unprospective for mineral deposits.

4.5 Fractured-rock aquifers

4.5.1 Aquifer characteristics

The fractured-rock aquifers comprise greenstones, granitoids and minor intrusive rocks that are characterised by secondary porosity and permeability. This results from complex fracturing systems being enhanced by chemical dissolution along fracture lines. The storativity and hydraulic conductivity of these aquifers is largely related to the degree of fracture intensity. Rock solution associated with fracturing is rare below the weathered zone owing to fracture closure, although significant groundwater has been intersected at depth within localised fracture and fault systems.

The local geological structure is the dominant feature controlling the occurrence of fractured-rock aquifers, with the lithology of the rocks having limited influence and affecting only the extent of structural development. The lateral continuity of the aquifer systems along the dominant geological structures is poorly understood, although ellipsoidal drawdowns associated with mine dewatering suggest that the aquifers are strongly anisotropic with the greatest permeability parallel to the major structures.

Table 3. Groundwater storage in the palaeochannel aquifer

1:250 000	*Groundwater storage within salinity divisions (GL)*				*Groundwater storage*
Map sheet	*0–1000*	*1000–3000*	*3000–14000*	*>14000*	*(GL)*
	mg/L TDS				
Wiluna	0	0	0	122	122
Sir Samuel	6	28	58	645	737
Duketon	0	24	48	151	223
Leonora	2	10	30	1275	1317
Laverton	38	35	78	809	960
Total	**46**	**97**	**214**	**3002**	**3359**

The fractured-rock aquifers have an associated weathering profile of variable thickness and extent that is in hydraulic connection with the underlying fractured rocks. There are large volumes of groundwater in the weathered profile with the depth and extent of oxidation related to geological structure and rock type. In general the zone of oxidation is deepest where associated with mineralised ore zones, along lithological contacts and shear zones.

The main differences between the rock groupings of greenstones and granitoids relate to weathering profiles, fracturing systems and structural relationships. In general, the greenstone rocks are more prospective for groundwater supplies than the granitoids, which are more homogeneous and sparsely fractured.

The greenstones form linear, arcuate belts of interbedded mafic and ultramafic volcanic, felsic volcanic and metasedimentary rocks, including cherts and banded iron-formation. They are locally deeply weathered with a weathering profile consisting predominantly of dense clay, except when associated with some ultramafic rocks and mineralised zones that have locally well-developed secondary permeability.

The weathering profile in greenstone rocks is generally low yielding owing to its clay content. However, moderate supplies of up to 500 kL/day are obtainable from the transitional zone. There are large, localised groundwater supplies from weathered profiles over specific rock types, such as the vuggy, siliceous caprock in the Leinster area (Whincup and Domahidy, 1982a), and from highly altered carbonatite at Weld Range (Dames and Moore, 1995). There are several borefields, including Perseverance Borefield at WMC's Leinster nickel operations (Meyer and Richards, 1990) and Fairyland Borefield at Lawlers Gold Mine, that are developed in weathered and cavernous dunite. These aquifers are capable of bore yields up to 2500 kL/day; however, they have limited areal extent and are largely restricted to the greenstone sequence near Leinster.

Large groundwater supplies of up to 1500 kL/day are obtainable from regional fault and shear zones in the greenstone belts. These may be at lithological contacts, subsidiary structures transecting or coalescing with the regional structures (such as faults, tensional displacements and fold axes), and where there is brittle deformation of quartz veins, chert and banded iron-formations. Large yields have also been obtained from intrusive contact zones around granitoid, dolerite dyke or porphyry intrusions. Mineralised zones are often important local aquifers, and groundwater has been found in auriferous quartz veins at Darlot Gold Mine (K.H. Morgan and Assoc., 1994) and shear zones at Granny Smith Gold Mine (Dames and Moore, 1993).

The granitoids comprise multiple intrusions of medium-grained monzogranite, with minor granite and granodiorite. They are locally intruded by pegmatites, quartz veins and by dolerite dykes, some of which are up to 10 m wide and have strike lengths of several kilometres. The granitoids have been lateritised and deeply weathered, and subsequently partly exposed by erosion. The weathering profile characterised by sandy clay may be up to 30 m thick, with the thicker profiles occurring along shear zones or beneath the palaeodrainages.

Groundwater supplies of up to 100 kL/day are obtained from the base of the granitoid weathering profile and from underlying veined or fractured rock. Larger supplies of groundwater are available from lineaments, probably faults or shear zones, within the granitoids and at the contact with greenstones, where supplies of up to 1500 kL/day have been obtained. The granitoids are intruded by pegmatite dykes and quartz veins that tend to be well fractured and may form small but locally important aquifers. The granitoids are poorly explored throughout the area owing both to their poor mineral prospectivity and poor groundwater prospects due to their homogeneity and sparse fracturing.

The 11-Mile Well Borefield, part of WMC's Nickel Operations water supply, is the only borefield in the investigation area established in weathered and fractured granite (Whincup and Domahidy, 1982a). The borefield has been located along two major structural lineaments resulting from displacement along the Perseverance Fault. The aquifer is locally weathered down to 80 m, with the largest yields from the transitional zone where the fracturing has been enhanced by secondary weathering, and also from interstitial lenses of mafic and ultramafic rock (Groundwater Resources Consultants, 1989).

4.5.2 Groundwater resources

4.5.2.1 Renewable

The fractured-rock aquifers are recharged infrequently by rainfall and runoff from ephemeral drainages into open fractures and weathered zones. Morgan (1966) suggested that recharge is increased in areas of high-level laterite and in areas of exposed fractured rock. As these recharge areas are generally restricted to catchment divides, it can be inferred that infiltration of rainfall and runoff is likely to be small.

As there are no new data on recharge, the same methodology is used as that employed for the alluvium. The estimation was conducted by multiplying the percentage area of outcropping Archaean bedrock for each 1:250 000 sheet and the renewable resource figures in Bestow (1992). The renewable groundwater resource is estimated at 27 GL/yr with the highest value in the north related to the increase in rainfall.

4.5.2.2 Stored

Groundwater in the fractured-rock aquifers is contained within the weathering profile and fractures in the basement rocks. Forbes (1978) and Bestow (1992) have estimated stored groundwater resources in fractured-rock aquifers on an areal basis with assumptions of a uniform saturated thickness and specific yields. However, borefields can be established only in a small proportion of the area where there is extensive fracturing or development of permeability in the weathered profile.

It is therefore considered more appropriate to evaluate these resources based on regional fracture systems, rather than by taking an areal approach. A conceptual model outlined below shows the parameters that are assumed to apply to fracture systems capable of providing groundwater supplies. The model is based on information from pumping tests, long-term monitoring of borefields and dewatering schemes in fractured-rock aquifers, field investigations of mine dewatering, and discussions with various groundwater specialists.

The essentials of the interpretation are that: the watertable is generally located 10 m below ground level, the weathered zone forms a semi-confining layer, and two distinct aquifer zones are present within the fractured rock (Table 4). The weathered zone comprises a thick sequence, up to 60 m, of dense clay in greenstones to firm, lightly coloured, sandy clay in granitoid weathering profiles. For the purpose of resources estimation, a saturated thickness of 40 m and storativity of 0.001 for the weathered zone have been applied.

The upper aquifer consists of fractured and oxidised bedrock with improved secondary porosity due to preferential weathering. It has a saturated thickness of between 10 and 30 m in the 11-Mile Well Borefield (Groundwater Resources Consultants, 1989). The specific yield can range up to 0.10 in vuggy ultramafics (Allen, 1996), but a value of 0.05 is used for resource estimation.

The basal aquifer comprises relatively fresh, fractured bedrock with groundwater present in regional fracture structures. The hydraulic conductivity of this aquifer is related to the intensity of fracturing and structural deformation, fracture closure, and the presence of clay minerals along fracture planes. Allen (1996) noted that large supplies of groundwater may be obtained from bores to 100 m depth, where these intersect fractured chert and banded iron-formations, regional structural features, fault and shear zones. A saturated thickness of 30 m and specific yield of 0.01 are considered representative for resource estimation.

The geometry of the fracture systems may be quite complex, hence a number of assumptions were made to approximate fracture dimensions. The length of regional fracture systems, in particular shear zones along granitoid and greenstone contacts, cross-cutting faults and regional lineaments, were measured from the 1:500 000 interpreted geology map of the Northern Goldfields (Farrell, 1997). Only the length within the greenstone belts has been considered as it is not proven that these fractures can be exploited within the granitoid areas. The depth of these fracture systems is often less than 80 m, but they may extend to 140 m (K.H. Morgan and Assoc., 1995a). An aggregate length of 1083 km was

Table 4. Fractured rock aquifer characteristics

Zone	*Specific yield*	*Saturated thickness (m)*	*Depth below surface (m)*
Weathered bedrock	0.001	40	0 – 50
Fractured, oxidised bedrock	0.05	20	0 – 70
Fractured, fresh bedrock	0.01	30	0 – 100

Table 5. Groundwater storage and recharge in the fractured-rock aquifer

1:250 000 Map sheet	*Fracture length (km)*	*Groundwater storage within salinity divisions (GL)*				*Groundwater storage (GL)*	*Renewable groundwater resources[1] (GL)*
		0–1000 mg/L TDS	*1000–3000 mg/L TDS*	*3000–14000 mg/L TDS*	*>14000 mg/L TDS*		
Wiluna	1083	56	41	41	12	150	7
Sir Samuel	1320	94	48	29	9	180	6
Duketon	914	51	54	17	4	126	5
Leonora	1467[2]	60	70	50	20	200	5
Laverton	1467[2]	60	70	50	20	200	4
Total		**321**	**283**	**187**	**65**	**856**	**27**

[1] Estimations of groundwater recharge taken from Bestow (1992).

[2] Fracture length determined from unpublished AGSO data.

determined for WILUNA, 1320 km for SIR SAMUEL, and 914 km for DUKETON. A width of 100 m and depth of 100 m have been used in the calculations.

The storage estimates for the fractured-rock aquifers in the northern portion of the investigation area are tabulated in Table 5. The total groundwater storage in the fractured-rock aquifers is estimated to be 850 GL, assuming a storage of 0.14 GL per linear kilometre of fracture.

Owing to lack of information, the resources on the LAVERTON and LEONORA sheets were not calculated. It is however anticipated that the southern sheets will have slightly larger groundwater resources than those on SIR SAMUEL, owing to the presence of more extensive greenstone exposure. It can also be inferred that the groundwater salinity may be marginally higher. The resource estimates for the southern area, shown in Table 5, are interpretative and are intended to gain an appreciation of total storage in the fractured-rock environment compared to palaeochannels.

The estimates of fresh to brackish groundwater resources are considered representative, although the saline and hypersaline groundwater resources are slightly underestimated. The reason for the underestimation is that the regional fracture systems are usually exposed in elevated areas of greenstone rocks, where there is lower groundwater salinity, including the upper reaches of catchments and along drainage divides. There is a general trend of increasing salinity towards the south in the fractured-rock aquifers, and although salinity commonly increases with depth in fracture systems, this is not shown on Figure 12, where the salinity is for the upper parts of the fracture systems.

4.6 Groundwater salinity

The distribution of groundwater salinity in all aquifers in the Northern Goldfields is related to topography (Fig. 12). Regionally, there is a general trend of increasing groundwater salinity towards the southwest highlighting the lower recharge rates in the south of the area (Allen, 1996). Groundwater tends to increase in salinity towards and along the drainage lines, particularly the palaeo-drainages, with the lowest salinity groundwater occurring along the catchment divides. Sanders (1969) noted that groundwater salinity also varies seasonally, particularly in calcrete, with slow increases in salinity during the dry periods due to evapotranspiration, and decreasing with the influx of fresh water during recharge events.

Potable groundwater (<1000 mg/L TDS) occurs in elevated areas of enhanced recharge including weathered and fractured bedrock along catchment divides, and in the upper reaches of palaeodrainages, such as Transect J. Alluvium and colluvium deposits adjacent to bedrock outcrops commonly contain small supplies of low-salinity groundwater. Calcrete in the Wiluna area locally contain large supplies of fresh groundwater where the calcrete receives increased recharge via stream runoff and local flooding.

Brackish groundwater (1000–3000 mg/L TDS) is widely distributed throughout the Northern Goldfields. The tributaries comprising alluvium, colluvium and palaeochannel sand deposits often contain brackish groundwater, such as in Transects I, O and P, that progressively increases in salinity downstream towards the main trunk drainages. The presence of fresh groundwater in the upper parts of the palaeochannel tributaries is indicative of modern recharge. As calcrete is

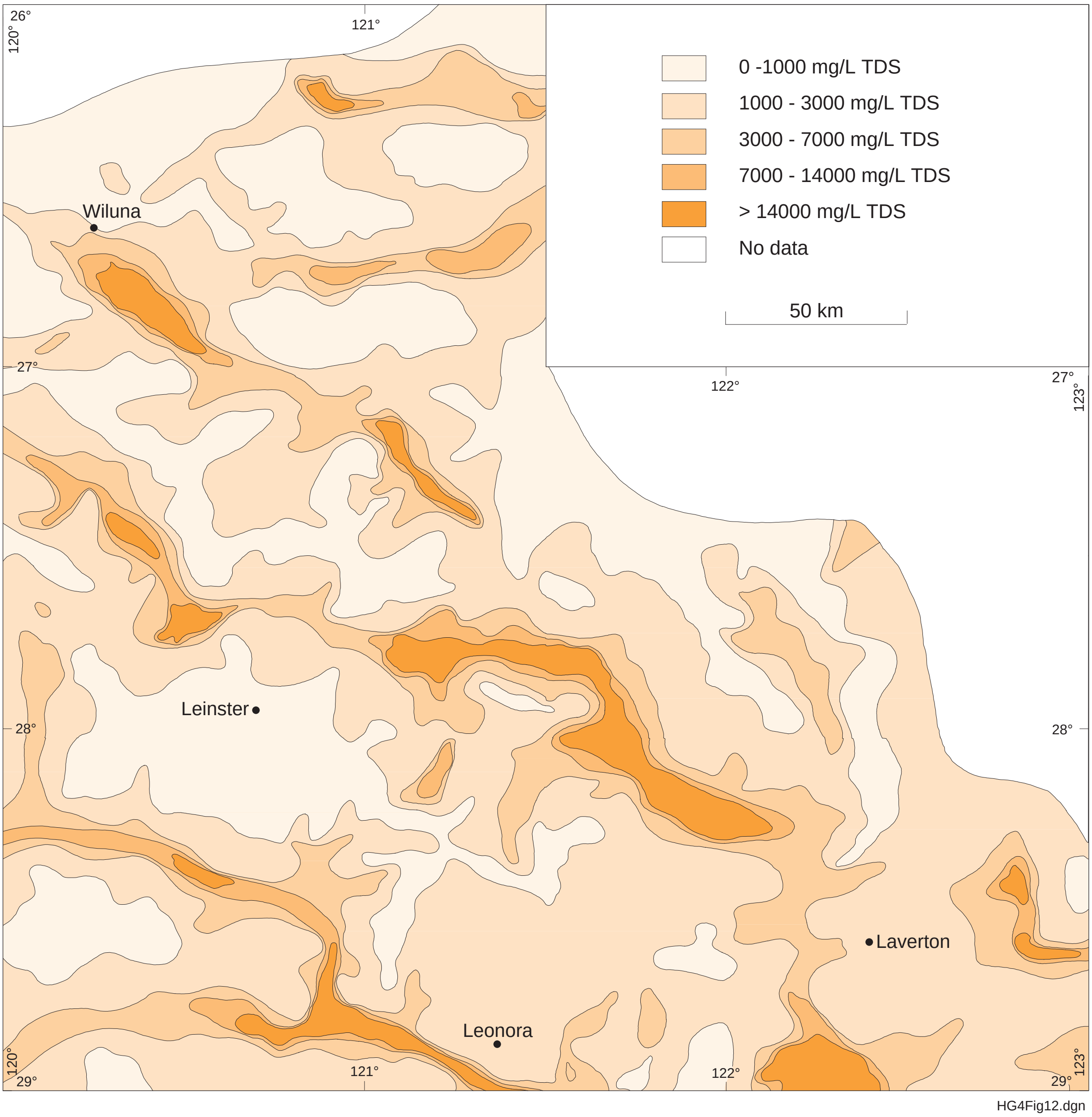

Figure 12. Groundwater salinity – watertable

generally located in the lower reaches of the palaeodrainages, it commonly contains brackish groundwater of 2000 to 6000 mg/L TDS (Sanders, 1969).

Saline groundwater (3000–35 000 mg/L TDS) is associated with the lower reaches of the tributaries, and within alluvium and colluvium deposits in the palaeodrainages. The weathered and fractured bedrock contains variable supplies of saline groundwater with the higher salinity groundwater occurring in greenstone rocks. Dames and Moore (1994) noted that groundwater in the fractured-rock aquifers at Granny Smith Gold Mine is often stratified, and consequently the salinity of the abstracted groundwater increases as drawdowns increase.

Hypersaline groundwater (>35 000 mg/L TDS) occurs mainly in palaeochannels and in bedrock adjacent to playa lakes. The high salinities of groundwater in playa lakes result from the concentration of salts as water evaporates from the lake surface. Most noticeable is that groundwater in the main trunk drainages is generally hypersaline where it enters the investigation area, which is downstream of such large salt lakes as Lake Mason, Lake Noondie and Lake Barlee (Fig. 1).

5 Groundwater development

5.1 Overview of groundwater resources

Estimates of renewable and stored groundwater resources have been calculated for the Northern Goldfields (Table 6). Previous estimates of renewable resources made by Forbes (1978) and Bestow (1992) were considered representative, and the estimations by Bestow (1992) were used in these calculations. However, as noted by Allen (1996), their estimates of stored resources are questionable.

Both authors used an areal approach for estimating stored groundwater resources with assumptions of saturated thickness and a specific yield. Bestow (1992) implied that stored groundwater resources of about 49 000 GL were available, although it is known that only a small proportion of this groundwater can be utilised. The major difference between our estimation of 16 400 GL and that of Bestow is primarily related to the estimation methodology used in the fractured-rock environment. Bestow used a saturated thickness of 6 m over the whole area and a specific yield of 0.10. For this investigation, it was considered more appropriate to estimate groundwater resources that were readily obtainable and could be utilised by large-scale developments.

The largest resources of fresh to brackish groundwater exist in the north, particularly near Wiluna and Leinster, with progressively increasing salinity towards the south (Fig. 13). The alluvium and palaeochannel sand aquifers both contain the significant stored groundwater resources (Table 7), with groundwater more readily

Table 6. Stored and renewable groundwater resources within 1:250 000 sheets

1:250 000 Map sheet	*Groundwater storage within salinity divisions (GL)*				*Groundwater storage (GL)*	*Renewable groundwater resources (GL/yr)*
	0–1000 mg/L TDS	*1000–3000 mg/L TDS*	*3000–14000 mg/L TDS*	*>14000 mg/L TDS*		
Wiluna	495	1110	869	308	2782	23
Sir Samuel	415	1336	1597	1025	4373	28
Duketon	336	444	219	327	1326	14
Leonora	79	831	1632	1720	4262	21
Laverton	134	719	1435	1370	3658	14
Total	**1459**	**4440**	**5752**	**4750**	**16401**	**100**

Table 7. Groundwater resources and licensed abstraction in each aquifer type

Aquifers	*Groundwater storage within salinity divisions (GL)*				*Groundwater storage (GL)*	*Licensed abstraction (GL/yr)*
	0–1000 mg/L TDS	*1000–3000 mg/L TDS*	*3000–14000 mg/L TDS*	*>14000 mg/L TDS*		
Alluvium	1026	3845	4790	1639	11300	10
Calcrete	66	215	561	47	889	8
Palaeochannel sand	46	97	214	3002	3359	37
Fractured-rock	321	283	187	65	856	34
Total	**1459**	**4440**	**5752**	**4753**	**16404**	**89**

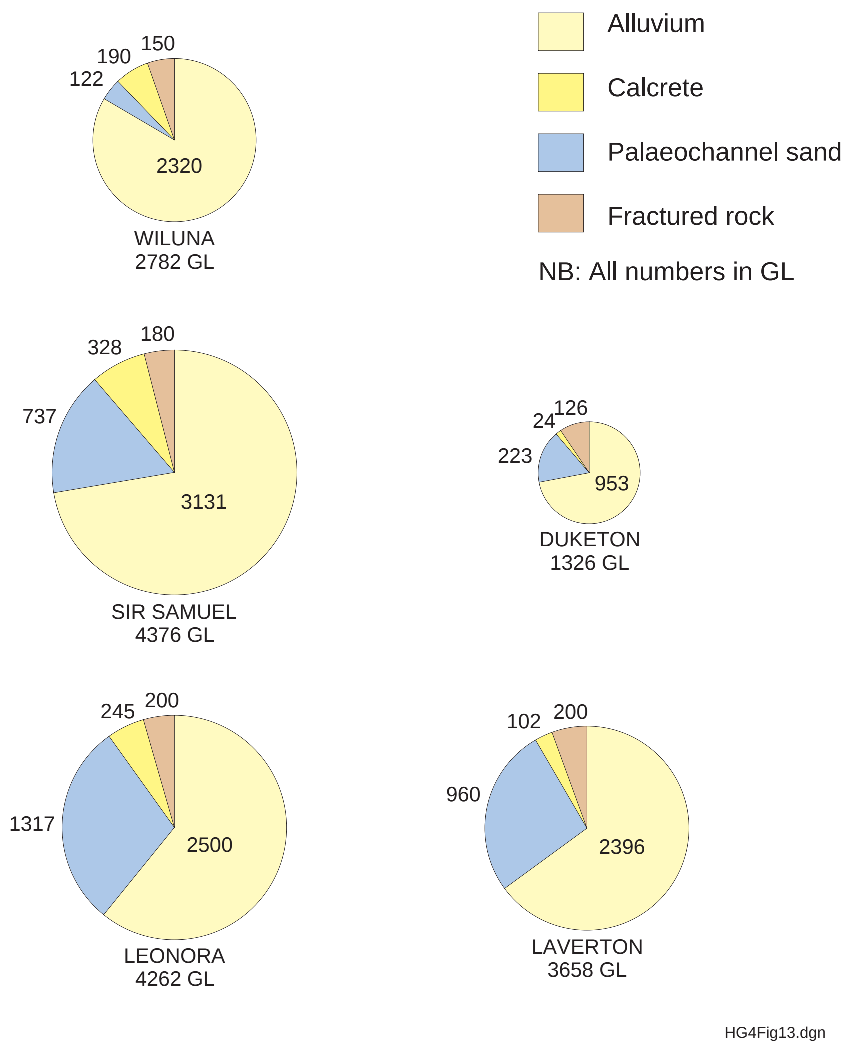

Figure 13. Distribution of stored groundwater resources

utilisable from the palaeochannel sand owing to its high transmissivity. The groundwater resources in the alluvium aquifer, which occurs around the valley flanks, are generally of low salinity, whereas the palaeochannel sand, that occupy the centre of the palaeodrainages, typically contains saline to hypersaline groundwater.

The calcrete contains large, localised groundwater resources, which can readily be utilised due to its karstic nature. Groundwater within the calcrete is generally brackish to saline, although local areas of fresh groundwater are present around Wiluna. The groundwater resources in the fractured-rock environment occur in localised, structurally controlled zones, with the larger resources of this type being associated with the greenstone belts.

The total stored groundwater resource of all aquifers in the Northern Goldfields is estimated to be 16 400 GL. However, only a portion of this total storage of groundwater can be economically extracted by boreholes. BHP and AGC (1988) introduced the concept of a commandable storage in the Roe Palaeodrainage and considered this to be about 80% of the total storage for the palaeochannel sand. A commandable storage of 60% is considered more appropriate in the Northern Goldfields to allow for the silty nature of the alluvium aquifer, and this figure has been used by Groundwater Resources Consultants (1989) at the 11-Mile Well Borefield. The total commandable groundwater storage in the Northern Goldfields is therefore estimated to be about 60% of 16 400 GL, i.e. about 10 000 GL.

As of February 1998, there were 96 groundwater production licences issued in the Northern Goldfields for a total allocation of about 89 GL/yr (Table 7). Most of this allocation is for the mining industry at levels of between 0.1 and 1 GL/yr, and is used for mineral processing, mine dewatering and camp water supplies. The annual recharge to the region is estimated to be 100 GL/yr, and slightly exceeds all current estimated abstraction. In conjunction with the substantial groundwater resources held in storage, it is anticipated that processing requirements for the next 30 years are attainable, mostly by abstraction from a combination of deep palaeochannel sand and the overlying alluvium.

5.2 Potable water supplies

The town water supplies of Leonora, Laverton and Wiluna are obtained through groundwater schemes operated by the Water Corporation, whereas the Leinster supply is operated by Western Mining Corporation. The potable water requirements for all the mine sites throughout the region are obtained from groundwater, mainly from elevated weathered and fractured-rock aquifers.

Leonora town water supply is obtained from the Station Creek borefield to the north of the town and contains 12 production bores completed in alluvium, minor calcrete, and weathered and fractured bedrock aquifers. Groundwater abstraction in 1991–92 was 0.53 GL with the salinity of the scheme ranging from 1200 to 1800 mg/L TDS during periods of high demand (WAWA, 1992a).

Martin (1991) identified areas to the north of Station Creek borefield with the potential to supply fresh to brackish groundwater from fractured-chert aquifer. There is further potential for moderate supplies of brackish groundwater at Transect O, 3 km west of the Station Creek borefield, in alluvium and palaeochannel sand. The palaeochannel sand in NEO-2 (Johnson *et al.*, 1998) contains brackish groundwater with a salinity of 1800 mg/L TDS and airlift yields of 210 kL/day. The overlying alluvial aquifer comprises clayey gravel and fragments of greenstone rock with groundwater salinity ranging from 1100 to 1400 mg/L TDS and small airlift yields.

The water supply for Laverton is obtained from the Beasley Creek borefield to the north of the town in weathered and fractured greenstones, and from the Telegraph shaft at the Lancefield mine. Total abstraction has reduced from 0.45 GL in 1989–90 to 0.27 GL in 1994–95 highlighting the population reduction following the closure of the Mount Windarra mine (WAWA, 1992b). The salinity of the supply ranges from about 800 mg/L TDS in the Telegraph Shaft to 1400 mg/L TDS from Beasley Creek. The current water supply is adequate to meet the present requirements for Laverton. However, additional bores have been developed around the Skull Creek area to assure future water demands (WAWA, 1992b).

The water supply for Leinster is obtained from a borefield along 11-Mile Creek with groundwater abstracted from a contact zone between weathered granite and greenstones. The water is also used for mine operations and annual production is about 0.3 GL (Allen, 1996). Salinity ranges between 600 and 900 mg/L TDS. There are adequate supplies to meet the water requirements of Leinster.

The Wiluna town water supply is currently drawn from two wells located about 7 km east of the town. The wells are developed in calcrete of the East Wiluna Aquifer (Sanders, 1971), and comprise alluvium and massive calcrete overlying weathered Archaean greenstone and granite. Groundwater abstraction has increased from 0.05 GL in 1977–78 to about 0.1 GL in 1994–95 as a result of the Wiluna Dumps Project that commenced during 1983 (WAWA, 1988). The salinity of the supply is stable at about 750 mg/L TDS. Although the current water supply is adequate to meet the present demands for Wiluna, additional supplies would be readily available by recommissioning and upgrading other wells in the town wellfield.

There are relatively high concentrations of nitrate in all the town water supplies, at levels exceeding the 45 mg/L standard for drinking water. It can be inferred that most potable groundwater in the Northern Goldfields contains similar high nitrate levels. The analyses listed in Appendix 2 show that nitrate generally exceeds 30 mg/L, with a maximum concentration of 130 mg/L. The likely sources of the nitrates may be related to nitrate-fixing bacteria associated with soil crusts and termite mounds (Jacobson, 1993) and to nitrate-fixing vegetation. Locally, around stock watering points, there may be nitrate contamination from animal faeces.

The location of potable water supplies for prospective mine sites is an important consideration during the initial phase of mine development. In general, there are sufficient supplies of potable to marginal groundwater available reasonably close to mine sites throughout the area, with the majority of domestic water supplies on mine sites abstracted from fractured-rock and calcrete aquifers. In localities where there are poor prospects for locating potable water, small-scale desalination of groundwater can also be used for some domestic supplies.

Domestic supplies on pastoral stations are usually provided by rainwater tanks supplemented by potable groundwater, if available. Low-salinity groundwater is often used for sanitary purposes and for maintaining the gardens and orchards around the homestead.

5.3 Irrigation water supplies

The presence of suitable groundwater supplies is only one factor in the prospective development of horticulture. A number of other socioeconomic and environmental factors must be taken into account prior to development, such as climate, soil type, soil structure, infrastructure requirements, labour and market proximity.

There is local potential for irrigation development throughout the Northern Goldfields area. Although the only development of groundwater for irrigation has been at Wiluna, where in 1969 Desert Farms established citrus orchards irrigated from a calcrete aquifer (Sanders, 1972). Subsequently, there has been intermittent production of vegetables for local consumption and rock melons for the Perth market. Recently a pilot vineyard has been established on the Millbillillie Lease, east of Wiluna.

It is suggested that for commercial irrigation, aquifers with production bores capable of yielding at least 500 kL/day are required to ensure peak demand during dry periods. The groundwater salinity requirements are dependent on crop type: citrus requires less than 1000 mg/L TDS, whereas fodder crops such as lucerne and rhodes grass use groundwater up to 3000 mg/L TDS. Groundwater supplies capable of meeting these criteria are restricted to local areas within the calcrete, alluvium and palaeochannel sand.

Calcrete is the most prospective aquifer for horticultural development as the watertable is generally less than 10 m below ground level, bores yield up to 1000 kL/day and groundwater salinity is often fresh to brackish. The best prospects for low-salinity groundwater for citrus plantations are around the Wiluna area, where the calcrete is recharged via direct infiltration of rainfall and surface runoff along drainage lines. The calcrete aquifer to the north of latitude 28°S contains variable supplies of brackish to saline groundwater that may be suitable for fodder crops.

The alluvium aquifer has limited potential due to its silty nature, although large supplies of groundwater between 1000 and 3000 mg/L TDS may be available from debris-flow deposits adjacent to greenstone outcrop, such as at Transect H. The groundwater salinity is highly variable with lower salinity areas present where sediments receive increased surface runoff from outcropping bedrock, and increasing salinity towards drainage lines.

The palaeochannel sand aquifers in the upper reaches of the tributaries, such as those at Transects I, J, O and P, contain significant supplies of marginally fresh to brackish groundwater. Aquifer depressurisation of the palaeochannel sand may induce downward leakage of low-salinity groundwater from the overlying alluvium aquifer. The capital costs associated with establishing deep production bores in the palaeochannel sand aquifers may be relatively high as would be running costs related to pumping. However, these costs would be mitigated by the need for fewer (high-yielding) bores in the sand aquifer, than in the alluvium to achieve the same result. Geophysical techniques may have to be employed to locate the aquifer, and drilling may exceed 120 m to fully penetrate the basal sand. Production bores may be screened within both the alluvium and palaeochannel sand aquifers to reduce drawdowns and the number of bores required.

The Centre of Arid Zone Research at CSIRO is conducting a five-year study into the potential for horticultural development in the region. The Water and Rivers Commission has provided hydrogeological information, including descriptions and maps of the hydrogeology and groundwater salinity. This information is to be incorporated with topographic, landform and soil mapping by Agriculture WA into a GIS to assist in evaluating horticultural potential.

5.4 Pastoral industry

The pastoral industry is one of the major users of groundwater with about 3000 bores and wells throughout the Northern Goldfields. The large number of pastoral bores and wells highlights the suitability of the area for raising sheep, and the past economically buoyant conditions of the pastoral industry. The distribution of stock-watering points has been dictated more by the foraging range and by the paddock system on the pastoral properties than by the availability of groundwater (Allen, 1996). In general, groundwater supplies are easily obtained, but many exploratory sites have been abandoned due to poor drilling conditions, inadequate supplies, or unacceptable salinity (Morgan, 1966).

Most bores and wells used by the pastoral industry are less than 30 m deep, and are typically equipped with windmill-powered pumps which yield up to 20 kL/day. The alluvium and calcrete deposits are the most extensively utilised aquifers owing to shallow watertable, less than 10 m below surface, and low groundwater salinity. The alluvium is poorly sorted and characterised by low yields of groundwater, although larger yields exceeding 20 kL/day may be available from karstic calcrete and scree-slope deposits adjacent to greenstone belts.

Groundwater suitable for stock-watering, up to 5000 mg/L TDS, is readily obtainable throughout the area except in the centres of the palaeodrainages, where water of salinity of 8000 mg/L TDS is used. Shallow wells penetrating a few metres below watertable may be effective in producing lower salinity water. Groundwater salinity in calcrete is generally stock quality, but the salinity rises towards the centre of calcrete bodies and along the palaeodrainages. Where the salinity rises with depth, pumping at large abstraction rates may cause increases in salinity.

There are sufficient resources of groundwater within shallow alluvium and calcrete deposits throughout the area suitable for utilisation by the pastoral industry. The potential for future development of pastoral supplies is unlikely to be hindered by groundwater availability. However, it is important that the groundwater resources are protected from pollution and overpumping by neighbouring borefields.

5.5 Mining industry

The mining industry is the largest groundwater user in the Northern Goldfields region. There are over 100 operating gold mines and two operating nickel mines with a number of new projects planned for the next five to ten years. An important consideration in the economic viability of any mine operation is the securing of adequate, long-term groundwater supplies. During the early phase of mine development, it is often critical to locate and establish substantial groundwater resources of suitable quality for ore processing and smaller supplies of low-salinity groundwater for domestic purposes. In addition, the distance of the water supply from the mill site and water-quality limitations are also important considerations.

The groundwater requirements of mine operations are highly variable, ranging from 2000 kL/yr for small-scale gold deposits to over 15 GL/yr for large-scale nickel operations (Appendix 1). The groundwater is obtained from shafts and borefields and is used for dust suppression, ore beneficiation, ore processing (gold and nickel), domestic usage and specialised industrial use after desalination (Allen, 1996).

The variability in groundwater usage for ore treatment is largely related to the metallurgical process, and the quantity and type of mineralised ore. The carbon-in-pulp and carbon-in-leach techniques for processing of gold ore are capable of using saline to hypersaline groundwater. However, there is increasing cost (with increasing salinity and magnesium content) associated with the need to add reagents to raise pH. Saline to hypersaline groundwater is used for nickel processing at Mount Keith, but the lateritic nickel deposits at Murrin Murrin will require water of salinity less than 10 000 mg/L.

The groundwater requirement for gold mines in the Northern Goldfields is generally less than 1 GL/yr over periods of five to ten years, whereas the large-scale nickel operations will use up to 15 GL/yr over periods of 20 to 30 years. The current nickel operations in the region are the largest groundwater consumers with a combined licensed abstraction of about 30 GL/yr, which is about 30% of the total allocation for the Northern Goldfields. Their borefields obtain groundwater from whole tributaries and large sections of the trunk palaeochannels to ensure their long-term sustainability. Groundwater abstraction can be optimised by utilising alternate water supplies including pit dewatering, reclaimed water from tailings, and water from inundated mine voids.

There are significant groundwater resources available for utilisation by the mining industry throughout the region. It is anticipated these estimated resources are sufficient to ensure the long-term supply of groundwater to the mining sector for at least the next thirty years. Most of the groundwater is drawn from the palaeochannel sand aquifer and is the favoured source of supply for large-scale operations. There are also groundwater supplies abstracted from borefields established in calcrete and fractured-rock aquifers. In contrast, there are only two borefields developed in the alluvium (Appendix 1).

5.5.1 Alluvium

The presence of a significant alluvium aquifer in the Northern Goldfields is an important hydrogeological difference compared with the Roe Palaeodrainage in the Kalgoorlie Region. In the Northern Goldfields, the surficial deposits contain significant stored resources of low-salinity groundwater that are actively recharged by rainfall runoff from surrounding bedrock outcrop. The aquifer is directly used only by Bannockburn and Tarmoola (Snowys Well Borefield), but is basically underutilised due largely to its low permeability. The large groundwater storage is generally abstracted via downward leakage into underlying palaeochannel and fractured-rock aquifers during aquifer depressurisation. It is inferred that most leakage into the palaeochannel sand occurs through the weathered bedrock profile, rather than through the confining plastic clay.

The Snowys Well Borefield comprises nine production bores developed in a shallow alluvial aquifer with an average saturated thickness of 40 m. The total abstraction for 1995–96 was 0.46 GL/yr with an average salinity of 1590 mg/L TDS (Mount Edon Tarmoola Operations, 1996). The aquifer needs to be managed as higher abstraction rates could lead to local dewatering and increasing salinity. There has also been significant waterlevel response after cyclonic rainfall events, such as Cyclone Bobby, highlighting the importance of recharge to maintaining water quality in the aquifer.

The alluvium aquifer is currently utilised via leakage in the majority of borefields established in the palaeochannel sand, including Albion Downs Borefield at Mount Keith and Valais Borefield at Murrin Murrin. The majority of production bores in these borefields typically have both aquifers screened to maximise yields, and minimise costs through decreasing the number of bores required.

Low bore yields limit the potential for locating groundwater supplies suitable for ore processing in the alluvium aquifer because supplies can be often obtained from other sources at lower cost. There are localised areas, particularly adjacent to greenstone belts, where the clayey gravel sediments may be suitable for developing a small-scale groundwater supply, such as at Transect H. Any borehole established in the sediments should be properly constructed and well developed with a graded-sand annulus to prevent siltation.

Most of the groundwater abstracted from the surficial aquifers is used for pastoral purposes. It is, therefore, important to ensure this resource is protected from contamination, and that the effect of pumping from deeper aquifers is considered. The disposal of tailings at mine sites, and seepage of highly concentrated saline water from leaking pipelines and storage ponds may cause local contamination. As these tailings storages contain contaminants that include cyanide and metal-cyanide compounds, it is important that these potential point-sources of pollution are monitored, in accordance with current regulations, to protect this shallow groundwater resource.

5.5.2 Calcrete

A number of borefields are currently established in the calcrete aquifer including the Southern and Eastern Borefields at the Wiluna Mines operation (K.H. Morgan and Assoc., 1996), Sandhill Borefield at Jundee Gold Mine (K.H. Morgan and Assoc., 1995b), and Mount Morgan Gold Mine (Coffey and Partners, 1987). The current licensed abstractions range from 0.2 to 3 GL/yr and it appears that most mining operations only use about 60% of their licensed allocation. The Wiluna Gold operation is the largest user of groundwater from the calcrete aquifer abstracting 1.57 GL in 1996 (K.H. Morgan and Assoc., 1996). Most of their groundwater usage is from the Eastern Borefield, which is also utilised for the Wiluna town water supply, as it satisfies their requirement for low chloride concentrations for its Biox gold-processing method.

The calcrete aquifer has potential for further development in the Northern Goldfields. There are significant local groundwater resources to the north of Leinster, and within the thick calcrete deposits at Yeelirrie (Australian Groundwater Consultants, 1981) and Depot Springs (Geotechnics, 1972). The current licensed allocation from the calcrete is estimated at 7.7 GL/yr, compared with a stored groundwater resource inferred to be 888 GL. In most borefields, abstraction from the calcrete aquifer could be increased, as additional groundwater is often available from recharge via rainfall and surface runoff, and groundwater inflows from the adjacent superficial aquifer. Groundwater within the calcrete generally ranges between 3000 and 5000 mg/L TDS. Fresh to brackish groundwater, up to 3000 mg/L TDS, is also available but generally restricted to the north of the region.

The calcrete aquifers throughout the region are capable of producing large yields from shallow individual bores, although the aquifers may be susceptible to dewatering due to overpumping, particularly during extended periods of drought. Pumping tests of production bores in the calcrete indicate short-term yields of up to 1500 kL/day, but sustainable yields are generally substantially lower with an average of 500 kL/day being typical. The sustainable yields are usually low because the highly transmissive zones, which are best developed near the watertable, cannot be overpumped without causing drawdown and possible dewatering.

Water levels and groundwater salinity in the aquifer can often fluctuate significantly throughout the year with variations generally related to groundwater abstraction and climatic conditions. It is, therefore, important to monitor waterlevels and groundwater salinity in order to minimise the impact of abstraction, assess aquifer performance, prevent aquifer dewatering, and evaluate recharge events. There are often high concentrations of sodium, nitrate, and fluoride in groundwater obtained from the calcrete aquifer; hence it is also important to monitor the quality of water used for potable water supplies.

There has been extensive groundwater exploration in the calcrete aquifer throughout the area by mining companies. Most of the exploration has concentrated on areas of outcropping calcrete, whereas there may be significant stored groundwater resources concealed beneath superficial deposits. The use of surface geophysics, including seismic and resistivity (Geotechnics, 1972) and satellite imagery have proved useful in locating groundwater supplies within the calcrete.

The presence of karstic features on the surface can assist in the identification of high-yielding solution cavities in the calcrete. Most production bores established in the calcrete aquifer are designed to have screens set adjacent karstic and vuggy features. The use of downhole geophysics, particularly gamma–gamma, temperature and caliper logging, has proven useful in locating solution cavities for screen positioning.

5.5.3 Palaeochannel sand

The palaeochannel sand aquifer is the prime target of groundwater exploration and the best aquifer for mining supplies throughout the Northern Goldfields. It comprises coarse sand and gravel which form a narrow sinuous sand unit at the base of the palaeodrainages. The thick sand deposits are the most favoured source of processing water supplies owing to their high transmissivity, large storage and sustainability through leakage from overlying sediments and surrounding bedrock aquifers.

The water supplies for several large-scale mines are obtained from the palaeochannel sand aquifer. The majority of borefields are positioned in the tributaries of the Carey and Raeside Palaeodrainages, such as Valais Borefield at Murrin Murrin (Rust PPK, 1996), Mid Gum Pool Borefield near Leinster (Meyer and Richards, 1990), and the Mount McClure Borefield (Mackie Martin and Assoc., 1989). The tributaries are preferred for borefield development because they contain groundwater of much lower salinity than that in the main trunk drainages. The only borefield established in the main trunk of the Carey Palaeodrainage is the Albion Downs Borefield at Mount Keith, which supplies large quantities of hypersaline groundwater for nickel processing.

There are significant stored resources of saline to hypersaline groundwater available in the main trunk section of the Raeside and Carey Palaeodrainages. The palaeochannels between Leinster and Wiluna are partially utilised, and it is evident that there is potential for development along the Raeside and Carey Palaeodrainages. There are also prospects of locating lower salinity areas within the main trunk drainages, where lower salinity groundwater discharges from the tributaries such as at Transect G.

There are about ten borefields established in the tributaries of the Raeside and Carey Palaeodrainages. There is potential for locating additional groundwater resources in the tributaries, which are relatively well distributed along the palaeodrainages. The water supply for the proposed Murrin Murrin nickel operation is to be abstracted from two tributaries that appear to contain significant stored groundwater resources of less than 10 000 mg/L. The drilling results at Transect E, H and I confirmed that low-salinity groundwater is available from the palaeochannel sand in the tributaries.

The basal sand units in the palaeochannels are considered to be the most prospective aquifer for further development in the Northern Goldfields. The current licensed abstraction from the palaeochannels is about 37 GL/yr with mining operations using approximately 60% of their total allocation. In contrast, most mining operations with borefields positioned in the Roe Palaeodrainage only use 52% of their total allocation (Ion, 1998). Groundwater storage in the palaeochannel sand is inferred to be approximately 3400 GL with most of the groundwater ranging between saline and hypersaline, although there are significant volumes of lower salinity groundwater available from the tributaries. It is therefore considered that groundwater resources in the Carey and Raeside Palaeodrainages are sufficient for current and planned mining developments.

Production bores are usually located in the deepest parts of the palaeochannel, with a bore spacing of 1 to 1.5 km often used. In order to maximise yields, the production bores are typically constructed with PVC slotted sections through the alluvium and wire-wound stainless steel screen in the palaeochannel basal sand aquifer. The use of downhole geophysics, particularly gamma-ray logging, has been employed to locate the main sand intervals for optimum screen settings.

Pumping-test results of production bores in the palaeochannel sand indicate short-term yields from 200 to 1600 kL/day with yields depending on grain size, thickness, and extent of sand. Monitoring results from major borefields in the Northern Goldfields have indicated that confined conditions apply after several years of pumping. By comparison in the Roe Palaeodrainage (Commander *et al.,* 1992) drawdowns in borefields have been lower than predicted from short-term pumping tests, indicating that significant groundwater inflow occurs from tributaries, weathered and fractured bedrock, and by leakage from the overlying sediments. Turner *et al.* (1994) estimated that about 60 to 70% of groundwater abstracted from the palaeochannel sand in the Roe Palaeodrainage is derived from leakage.

The groundwater resources within the palaeochannels throughout the Northern Goldfields are considered to be underutilised, although there are existing borefields which completely the groundwater from tributaries and large sections of palaeodrainage. As direct recharge is minimal, and there is the prospect for conflict between neighbouring mine operations, it is important to manage the resource and ensure care is taken when allocating new licences. It is also important to install monitoring bores to monitor the regional depressurisation of the aquifers, and to allow a continual assessment of aquifer storage properties.

There has been extensive groundwater exploration for palaeochannels over the past ten years. A number of surface and airborne geophysical techniques have proved useful in locating the palaeochannel and initial drilling targets. Surface geophysics, including transient electromagnetic and gravity methods, provides profiles across the palaeochannel highlighting prospective drillsites. Airborne EM techniques show the areal extent of the palaeochannel, and have been used successfully to locate the South Lake Way Borefield at Mount Keith. The air-core drilling technique is a cheap and effective method for groundwater exploration, giving good penetration and sampling, with production bores generally installed using a mud-rotary drilling method.

5.5.4 Fractured-rock aquifers

There are a few borefields established in the fractured-rock environment with most developed in permeable zones of the weathering profile, including the carbonatite at Mount Weld (Dames and Moore, 1995) and vuggy siliceous caprock over ultramafic lithologies near Leinster. Some borefields are developed in relatively fresh, fractured-rock aquifers that generally induce downward leakage from the weathering profile and overlying sediments, such as WMC's 11-Mile Well Borefield (Whincup and Domahidy, 1982a). There are also large volumes of groundwater obtained from the fractured-rock aquifers when associated with mine dewatering.

Groundwater storage in the main fracture zones within the fractured-rock aquifer is estimated to be about 860 GL. The current licensed abstraction is about 34 GL/yr, with the majority of mining operations using between 50 and 100% of their licensed allocation. There appears to be little potential for further large-scale development in the current borefields established. There are localised supplies of fresh groundwater available in the elevated areas of the greenstone belts that are suitable for meeting potable requirements. The best prospects for locating large supplies of processing water are along the contact zones between granitoid and greenstone rocks.

The long-term sustainability of fractured-rock aquifers is constrained by their limited storage and availability of direct recharge. Consequently, the sustainability of fractured-rock aquifers depends on leakage from groundwater storage in overlying alluvial deposits. It is therefore important to manage abstraction so as not to adversely affect other bores in the borefield.

Groundwater exploration in the fractured-rock environment is difficult and costly. It is best conducted in a staged approach by using local experience and remote sensing techniques to identify prospective structural zones. Observations of water flow and fractures during mineral exploration drilling is often useful in locating water-bearing structures and aquifer zones. Remote sensing has been used successfully in the Northern Goldfields with the 11-Mile Well Borefield located near Leinster (Whincup and Domahidy, 1982a), where Landsat imagery assisted in identifying structural lineaments. Surface geophysical techniques can also be useful in drillsite selection.

5.6 Mine dewatering

The dewatering of opencut mines is necessary to gain access to mineralised zones and to ensure wall and slope stability during excavation. The amount of dewatering required is dependent on the presence of water-bearing structures with groundwater abstracted using perimeter bores, in-pit sumps, horizontal drainage holes and pumping from abandoned shafts. Allen (1996) noted that the presence of groundwater in shear zones and in highly weathered mineralised zones has also lead to many dewatering problems in underground mines.

Groundwater obtained from mine dewatering is used for ore processing and mining requirements, principally dust suppression. There are twenty-two licences issued for dewatering covering a total quantity of 23 GL/yr (Appendix 1), although actual abstraction is much less. Inconsistencies in the collection of licensing statistics do not allow assessment of quantities discharged from the minesite, only those used within the mine.

The major individual mine-dewatering activities in the region are: Granny Pit (Granny Smith), 0.9 GL/yr (Dames and Moore, 1997a); Tarmoola Pit, 0.5 GL/yr (Ultramafics, 1996); and Keringal deposit, 0.4 GL/yr (Dames and Moore, 1997b). In addition, abstraction from the Mount Weld ore deposit, not included in dewatering statistics, is used to supply the Granny Smith mine.

Major changes to the groundwater flow system are made where pits are being excavated below the watertable. After mining and dewatering is complete, there will be gradual inundation to a level at which groundwater inflow is balanced by evaporative loss. Because of the high evaporation, the salinity of open water in the pit will gradually rise until a dynamic equilibrium is reached.

5.7 Mine voids

There is also scope for abandoned mine voids to act as surface-water reservoirs for the long-term capture of stream flow and rainfall associated with intense rainfall events. Following Cyclone Bobby the Bannockburn pit was flooded, thus demonstrating the reservoir potential. However, a storm event of this magnitude occurs on average once in twenty years.

Various mining companies throughout the region use these supplies to supplement process water. The Back and Beyond pit at the Mount Morgans Gold Mine is partially inundated and contains about 0.1 GL of impounded water.

Potential is greatest for pits low in the landscape, such as at Granny Smith, where surface flows can be diverted. However, many of the pits are relatively high in the landscape, and therefore do not have large catchments; Mount Keith, for example, is close to a surface-water divide.

Water quality is an issue that may depend on interaction of water with the pit material. There is potential to create acidic conditions and take into solution heavy metals, as well as an increase in salinity. Where groundwater flows into pits, stratification may also occur with lower salinity surface water overlying more-saline groundwater.

There may also be geotechnical considerations with utilising pits as water storages, with rapid changes in water levels possibly compromising the stability of pit walls.

While there are no specific legislative requirements for utilising water in mine voids, the matter has been under consideration by the Departments of Minerals and Energy and Environmental Protection, and by the Water and Rivers Commission, in conjunction with the Chamber of Minerals and Energy. There are environmental and geotechnical guidelines to be followed under Department of Minerals and Energy legislation in respect to mine rehabilitation and closure, and water abstraction has to be licensed by the Water and Rivers Commission.

6 Conclusions

The palaeochannels are the most important aquifer in the region. There are also localised groundwater resources in the alluvium, colluvium, calcrete and fractured-rock aquifers.

The groundwater salinity is highly variable with the lower salinities occurring beneath catchment divides, and the higher salinities along the palaeodrainages. Groundwater is generally of lower salinity in the northern part of the region. The groundwater salinity in the palaeochannels decreases where lower salinity groundwater enters from the tributaries, and increases below salt lakes. Previously unrecognised, fresh groundwater has been discovered in the upper parts of palaeochannel tributaries in the north of the area.

Large groundwater supplies suitable for processing water are restricted mainly to the palaeochannel sand and calcrete, although there are localised supplies available from well-developed fracture systems in the basement rocks. Small supplies of variable salinity groundwater are utilised by the pastoral industry throughout the region. There are limited prospects of locating large, fresh groundwater supplies, but brackish to hypersaline supplies are more readily available.

The total natural groundwater recharge to the region has been estimated to be about 100 GL/yr but there are significant groundwater resources, mainly saline, held in storage. The total groundwater storage for the area is estimated at 16 400 GL, which is considered sufficient for current and projected mining developments over the next 30 years. The stored groundwater resource in the palaeochannel sand is about 3400 GL in some 2000 km of palaeochannel, and is comparable with estimates for the Roe Palaeodrainage in the Kalgoorlie region. There are substantial groundwater resources present within the alluvium aquifer, that are best utilised via downward leakage into either underlying palaeochannel sand, or permeable structures in the basement.

Current licensed abstraction is about 89 GL/yr with most groundwater utilised by the mining industry for processing water, although actual use is only about 60% of the licensed allocation. In most areas currently utilised, groundwater abstraction exceeds recharge and groundwater from the palaeochannels, in particular, is being mined. Periodic assessment of groundwater storage is therefore a necessary part of groundwater management.

The distribution of the groundwater resources is relatively even, with marginally higher resources surrounding Leinster. Although sections of the palaeochannels and tributaries are completely utilised by borefields, there is scope for development throughout the region.

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Appendix 1
Licensed groundwater users in the Northern Goldfields region

No	*Borefield or project name*	*Operator*	*Licence number*	*Expiry date*	*Aquifer*	*Usage*	*Licensed abstraction (GL/yr)*
1	Sunrise Dam Project	Acacia Resources Limited	56388	28/05/01	Fr	Dw, Mn	1.46
2	Sunrise Dam Project	Acacia Resources Limited	59644	22/04/02	Fr	Cp	0.124
3	Sunrise Dam Project	Acacia Resources Limited	59651	22/04/02	Ps	Mn	0.654
4	Murrin Murrin	Anaconda Nickel	60768	19/08/02	Ps?	Cp	0.073
5	Murrin Murrin	Anaconda Nickel	60769	19/08/02	Ps?	Cp	0.328
6	Murrin Murrin	Anaconda Nickel	61171	8/08/07	Ps	Mn	12.775
7	Mount McClure	Arimco Mining Pty Ltd	57783	26/11/01	Fr	Dw	0.7
8	Jundee–Gourdis Pit	Asarco Australia Ltd	45067	30/06/98	Fr	Mn	0.146
9	Mt Wilkinson, Wiluna	Asarco Gold Ltd	32065	31/12/98	Fr	Cp	0.037
10	Mt Wilkinson, Wiluna	Asarco Gold Pty Ltd	32082	31/12/98	Ps	Mn	0.7
11	Mt Morgans Gold Mine	Austwhim Resources	57914	7/01/02	Fr	Dw	0.0438
12	Wiluna Town Reserve	Bowler P	54857	30/06/05	Ca	Hort	0.016
13	Reserve 23797 Wiluna	Building Management Authority	52212	31/12/04	Ca	TWS	0.009
14	Bannockburn	Consolidated Gold Mines Pty Ltd	54824	30/06/03	Fr	Mn, Dw, Cp	1.06
15	Bannockburn	Consolidated Gold Mines Pty Ltd	55986	30/06/03	Al	Dw	1.6
16	Vivien Gold Mine	Consolidated Gold Mines Pty Ltd	60829	26/08/02	Fr	Dw, Cp, Ds	0.289
17	Mining lease 36/58 and 36/59	David John	57626	11/09/01	Fr	Mn	0.02
18	Mining lease 39/12	Dellacqua	55644	30/11/98	Fr	Mn	0.008
19	Mining lease 37/2200	DM Daniels	47196	30/09/99	Fr	Mn	0.001
20	Mount Morgans	Dominion Mining Limited	46609	30/06/98	Fr	Mn, Ds	0.18
21	Mount Morgans	Dominion Mining Limited	46615	30/06/98	Ca	Mn, Ds	1.15
22	Yakabindie Station	Dominion Mining Limited	56844	6/03/02	Fr	Mn, Ds, Cp	0.505
23	Yakabindie	Dominion Mining Limited	56845	6/03/02	Ps	Mn	6.2
24	Mt Morgans	Dominion Mining Limited	46610	30/06/98	Fr	Dw	0.024
25	Jundee	Eagle Mining Corporation	54993	30/06/05	Ca	Mn	1.05

Notes: Al = Alluvium; Ca = Calcrete; Ps = Palaeochannel sand; Fr = Fractured-rock aquifer

Cp = Camp; Ds = Dust; Dw = Dewatering; Ex = Exploration; Mn = Mine; Tl = Tailings; TWS= Town water supply

Appendix 1 (cont.)

No	*Borefield or project name*	*Operator*	*Licence number*	*Expiry date*	*Aquifer*	*Usage*	*Licensed abstraction (GL/yr)*
26	Jundee	Eagle Mining Corporation	56346	31/12/05	Fr	Mn	0.11
27	Nimary Gold Project	Eagle Mining Corporation	57737	18/09/01	Al, Ca	Mn, Ds	1.2
28	Fairyland, Daisy	Forsayth NL	44967	30/09/97	Fr	Mn	1
29	Darlot	Forsayth NL	47360	31/03/99	Al, Ca	Mn, Dw	0.805
30	Darlot	Forsayth NL	48238	31/03/99	Fr	Dw	0.165
31	Mining lease 38/2758	Goldleach	55851	30/06/03	Fr	Tl	0.1
32	Bronzewing	Great Central Mines NL	56847	3/09/01	Al, Fr	Mn, Dw	2.75
33	Jundee, Wiluna	Great Central Mines NL	54784	30/06/05	Al, Fr	Mn, Ds	0.46
34	Jundee, Wiluna	Great Central Mines NL	54785	30/06/05	Fr	Mn	0.075
35	Jundee, Wiluna	Great Central Mines NL	55050	30/06/05	Fr	Ds	0.1
36	Jundee, Wiluna	Great Central Mines NL	55454	30/06/05	Al, Ca	Mn	3
37	Jundee, Wiluna	Great Central Mines NL	56022	30/06/05	Fr	Ds	0.4
38	Jundee, Wiluna	Great Central Mines NL	56719	31/12/05	Fr	Mn, Ds	0.3
39	Harbour Lights	Harbour Lights Mining Ltd	45763	30/12/98	Al	Mn	1.01
40	Duketon	Johnsons Well Mining NL	55822	30/06/05	Fr	Dw	0.009
41	Goanna Patch, Leonora	Leader Resources NL	45699	30/03/98	Fr	Mn	0.12
42	Famous Blue	Maiden Gold NL	52611	31/12/04	Fr	Mn, Dw, Ds	0.657
43	Tarmoola	Mount Edon Gold Mines (Aust) Ltd	57834	4/10/01	Al	Mn	1
44	Tarmoola	Mount Edon Gold Mines (Aust) Ltd	57833	4/10/01	Fr	Mn, Dw	1.3
45	Mount McClure	Mount McClure Mining Pty Ltd	57176	19/06/01	Ps	Mn	1.5
46	Honeymoon Well, Wiluna	Outokumpu Mining AustrAlia Pty Ltd	62306	5/02/08	Al	Cp	0.002
47	Honeymoon Well, Wiluna	Outokumpu Mining AustrAlia Pty Ltd	62308	5/02/08	Ca, Al	Mn, Cp	0.438
48	Mining lease 37/54	PD Green	55455	30/11/98	Fr	Mn	0.1
49	Granny Smith	Placer (Granny Smith) Pty Ltd	43348	30/09/98	Fr	Dw, Ds	4
50	Sunrise Dam	Placer (Granny Smith) Pty Ltd	53794	30/06/05	Fr	Dw, Ds	2

Notes: Al = Alluvium; Ca = Calcrete; Ps = Palaeochannel sand; Fr = Fractured-rock aquifer
Cp = Camp; Ds = Dust; Dw = Dewatering; Ex = Exploration; Mn = Mine; Tl = Tailings; TWS= Town water supply

Appendix 1 (cont.)

No	*Borefield or project name*	*Operator*	*Licence number*	*Expiry date*	*Aquifer*	*Usage*	*Licensed abstraction (GL/yr)*
51	Mt Weld	Placer (Granny Smith) Pty Ltd	54928	30/06/05	Fr	Dw	0.54
52	Mt Weld	Placer (Granny Smith) Pty Ltd	54929	12/02/07	Fr	Mn	4
53	Childe Harold / Phoenix	Placer (Granny Smith) Pty Ltd	58252	8/01/02	Fr	Dw	0.2
54	Bellevue	Plutonic	43484	31/10/98	Fr, Al	Dw, Mn	0.578
55	Genesis	Plutonic Lawlers	53558	30/06/98	Fr	Dw	0.5
56	Hidden Secret	Plutonic Lawlers	55839	30/06/03	Fr	Mn	0.5
57	New Holland	Plutonic Lawlers	57246	24/09/01	Fr	Mn	0.5
58	Caroline and Hell Purgatory	Plutonic Lawlers	55840	30/06/03	Fr	Mn	0.3
59	New Holland	Plutonic Lawlers	57246	24/09/01	Fr	Dw	0.5
60	Laverton town	Shire of Laverton	43533	30/09/98	Fr	TWS	0.01
61	Wiluna Town	Shire of Wiluna	47277	31/12/03	Ca	TWS	0.01
62	Wiluna Town	Shire of Wiluna	61218	30/06/07	Ca	TWS	0.035
63	Wiluna Town	Shire of Wiluna	61219	30/06/07	Ca	TWS	0.035
64	Jasper Flat	Sons of Gwalia	58684	26/02/98	Al, Fr	Dw	1
65	Barnicoat	Sons of Gwalia	55836	30/06/05	Fr	Mn	0.3
66	Barnicoat	Sons of Gwalia	58964	29/05/02	Fr	Mn	0.26
67	Barnicoat	Sons of Gwalia	59341	4/07/01	Fr	Mn	0.66
68	Barnicoat	Sons of Gwalia	59340	4/07/01	Fr	Mn	0.65
69	Eastern Borefield	Sons of Gwalia	50068	30/06/03	Fr	Mn, Dw	1.2045
70	Leonora	Sons of Gwalia	50069	30/06/03	Al, Fr	Mn	0.875
71	Leonora	Sons of Gwalia	59333	4/07/01	Ca	Mn	0.12
72	Station Creek Wellfield	Water Corporation	55606	22/04/01	Al	TWS	0.6
73	Beasley Ck/Telegraph Shaft	Water Corporation	55607	22/04/01	Fr	TWS	0.3
74	Wiluna Wellfield	Water Corporation	55383	22/04/01	Ca	TWS	0.12
75	Gourdis Pit	Wiluna Gold Pty Ltd	51508	30/06/04	Fr	Dw	0.5

Notes: Al = Alluvium; Ca = Calcrete; Ps = Palaeochannel sand; Fr = Fractured-rock aquifer

Cp = Camp; Ds = Dust; Dw = Dewatering; Ex = Exploration; Mn = Mine; Tl = Tailings; TWS= Town water supply

Appendix 1 (cont.)

No	*Borefield or project name*	*Operator*	*Licence number*	*Expiry date*	*Aquifer*	*Usage*	*Licensed abstraction (GL/yr)*
76	Empire Project, Wiluna	Wiluna Gold Pty Ltd	51510	30/06/04	Fr?	Ds	0.02
77	Caledonian Pit, Wiluna	Wiluna Gold Pty Ltd	56080	31/12/05	Fr	Mn	0.15
78	Wiluna	Wiluna Gold Pty Ltd	57360	23/07/01	Ca	Mn	1.13
79	Wiluna	Wiluna Gold Pty Ltd	57622	3/09/01	Ca	Mn	1.15
80	Empire Project, Wiluna	Wiluna Gold Pty Ltd	51509	30/06/04	Fr?	Ds	0.035
81	Lake Miranda	Wiluna Mines	49390	31/03/98	Ca?	Dw	0.2
82	Emu -Agnew -Leinster	WMC Resources Ltd	40994	31/10/97	Fr	Mn	1.9
83	Emu Main Shaft	WMC Resources Ltd	41477	31/10/97	Fr	Mn	0.5
84	Perserverence Fault	WMC Resources Ltd	41750	31/10/97	Fr, Al	TWS	0.37
85	Beasley Creek Laverton	WMC Resources Ltd	42178	31/10/97	Fr	Ds	0.11
86	Leinster Downs and Weebo	WMC Resources Ltd	46519	30/09/98	Fr?	Ex	0.3
87	Caprock Wellfield, Mt Keith	WMC Resources Ltd	50299	30/06/05	Fr	Mn	1.5
88	Redeemer and Crusader	WMC Resources Ltd	51944	30/07/04	Fr	Dw, Ds	0.535
89	Redeemer Pit – Agnew	WMC Resources Ltd	54116	30/06/04	Fr	Dw	0.2
90	South Lake Way	WMC Resources Ltd	60382	14/07/02	Ps	Mn	3.285
91	Mt Keith Pit	WMC Resources Ltd	58596	13/08/02	Fr	Dw	2
92	Agnew, Deliverer Pit	WMC Resources Ltd	61267		Fr	Ds	0.2
93	Emu Gold Mine	WMC Resources Ltd	54595	30/06/05	Fr	Cp	0.0015
94	Midgum Pool and Alan Pool	WMC Resources Ltd	58111	20/03/02	Ps	Mn	0.205
95	Village Wellfield	WMC Resources Ltd	60628	13/08/02	Fr, Al	Cp	0.275
96	Albion downs	WMC Resources Ltd	60629	13/08/02	Ps	Mn	8.76
						Total	**88.8778**

Notes: Al = Alluvium; Ca = Calcrete; Ps = Palaeochannel sand; Fr = Fractured-rock aquifer

Cp = Camp; Ds = Dust; Dw = Dewatering; Ex = Exploration; Mn = Mine; Tl = Tailings; TWS= Town water supply

Appendix 2
Selected chemical analyses of groundwater

Bore/well	pH	EC (a) (mS/m at 25°C)	TDS (b)	Total hardness (as $CaCO_3$)	Total alkalinity (as $CaCO_3$)	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	SiO_2	B	F
			(mg/L)													
Alluvium																
NEA-6c	7.9	16000	9100	2880	160	310	490	2600	190	160	2800	1500	65	92	-	-
NEB-6c	7.5	112000	73600	8400	120	380	1800	28000	730	120	36000	6500	44	41	-	-
NEC-5c	7.8	84000	67600	7700	190	220	1740	24000	540	190	24000	6900	130	21	-	-
NED-9c	8.2	19000	10300	2500	190	320	410	3200	160	190	5400	530	65	83	-	-
NEE-3c	8.5	1730	1080	290	91	57	37	190	11	81	460	100	64	94	0.75	1.9
NEF-4c	7.3	208000	187700	24000	88	410	5500	65000	2700	88	97000	17000	47	36	-	-
NEG-1c	8.1	5800	2810	430	180	56	70	860	30	180	1300	230	82	77	-	-
NER-4 @ 50m	7.0	77000	44160	8300	250	690	1600	17000	510	250	21000	3100	46	64	-	-
Colluvium																
NEH-6c	8.3	3500	1830	360	220	45	62	510	44	220	680	180	87	68	1.10	1.0
NEI-1c	8.3	2900	1820	600	170	100	62	380	34	170	610	350	85	81	1.10	0.7
NEJ-1c	8.1	1600	970	310	180	60	39	200	28	180	220	150	79	90	0.97	0.9
NEP-1c	8.1	2800	1860	520	200	70	83	450	38	200	660	260	81	94	1.90	0.8
Calcrete																
CAL-6b	7.8	3300	1760	430	260	70	62	480	37	260	610	210	50	83	1.10	1.9
CAL-8	8.2	6200	3500	810	230	97	140	1000	62	230	1400	450	87	73	1.30	1
NEK-1c	8.2	15000	5700	1600	250	160	290	2600	180	250	3900	1200	110	96	-	-
NEQ-9b	7.6	64000	55600	10000	230	290	2300	19000	520	230	29000	4200	50	73	-	-
Palaeochannel sand																
NEA-6b	8.0	35000	19600	5080	320	360	1000	5600	590	320	8400	3300	110	49	-	-
NEB-6b	7.2	169000	128700	12000	48	350	2800	48000	1500	48	65000	11000	39	28	-	-
NEC-5b	7.5	217000	128400	21000	59	340	5000	69000	2900	59	11000	20000	110	14	-	-
NED-9b	7.5	194000	176500	19000	51	380	4400	63000	1700	51	91000	16000	22	13	-	-
NED-12	7.6	162000	170800	17000	69	340	3900	55000	1500	69	93000	17000	36	19	-	-
NEE-3b	8.5	4100	2400	550	200	68	80	670	29	200	950	400	<1	32	0.88	1.3
NEF-4b	7.4	206000	203900	23000	92	96	5600	79000	2900	92	98000	18000	37	24	-	-
NEG-1b	8.0	44000	26900	4700	220	370	910	9500	270	220	13000	2700	23	28	-	-
NEI-1b	8.1	2100	1180	460	160	75	66	230	23	160	360	230	62	41	0.96	0.7
NEJ-1b	8.1	1800	1010	370	130	70	48	210	17	130	290	180	71	47	1.00	0.7
NEK-1b	7.9	108000	86500	15000	330	400	3400	27000	1400	330	41000	13000	73	47	-	-
NEO-1	8.0	3200	1850	460	270	43	85	500	17	270	560	350	78	58	1.90	0.6
NEP-1b	8.0	3200	1860	560	290	67	84	420	24	290	670	310	67	28	2.50	1.6
NEQ-9a	7.2	223000	238700	41000	50	430	9800	98000	2400	50	110000	18000	<1	11	-	-
NER-9	7.4	167000	127500	17000	100	900	3700	47000	1200	100	68300	6600	2.5	19	-	-

Appendix 2 (cont.)

Bore/well	*pH*	*EC (a) (mS/m at 25°C)*	*TDS (b)*	*Total hardness (as $CaCO_3$)*	*Total alkalinity (as $CaCO_3$)*	*Ca*	*Mg*	*Na*	*K*	*HCO_3*	*Cl*	*SO_4*	*NO_3*	*SiO_2*	*B*	*F*
			(mg/L)													
Palaeochannel sediments																
NEL-6 @ 57m	7.3	163000	125510	18000	75	740	4000	48000	1900	75	61000	9700	95	30	-	-
NEL-14 @ 54m	7.3	190000	167300	22000	84	700	4900	64000	2600	84	83000	12000	57	21	-	-
NEM-4 @ 29m	7.5	137000	112000	19000	100	390	4500	38000	1000	100	48000	20000	31	19	-	-
NEM-9 @ 36m	7.7	118000	91100	16000	130	340	3800	30000	850	130	36000	20000	42	26	-	-

Notes: (a) EC=Electrical conductivity; (b) TDS=Total dissolved solids

Appendix 3
Calculations of groundwater storage in calcrete aquifers

Map sheet 1:250 000	*Calcrete reference*	*Saturated thickness (m)*	*Specific yield*	*Area (km²)*	*Storage in salinity divisions* 0–1000	1000–3000	3000–14000	>14000	*Calculated storage*	*Reference*
					(GL with ranges in mg/L)					
Wiluna	Kukabubba Creek	4.57	0.15	13.0	6.2	2.2	0.4		8.9	Sanders (1972)
	Negara Creek	6.7	0.05	28.5	6.7	2.4	0.5		9.5	Sanders (1972)
	Wiluna – South	5	0.1	60.0		6.0	21.0	3.0	30.0	Coffey and Partners (1987)
	Wiluna #1	7	0.1	5.6		0.4	3.5		3.9	AGC (1992)
	Wiluna #2	5	0.1	12.5		0.6	5.6		6.3	
	Wiluna #3	7	0.1	38.3		18.7	8.0		26.8	AGC (1981)
				Total	**12.9**	**30.4**	**39.1**	**3.0**	**85.4**	
Sir Samuel	Sir Sam #1	7	0.1	48.5	3.4	23.8	6.8		34.0	AGC (1981)
	Sir Sam #2	5	0.1	26.3			10.5	2.6	13.1	
	Sir Sam #3	5	0.1	12.0			4.8	1.2	6.0	
	Sir Sam #4	5	0.1	15.6			4.7	3.1	7.8	
	Sir Sam #5	3	0.1	88.1		2.6	18.5	5.3	26.4	Geotechnics (1972c)
	Sir Sam #6	10	0.1	29.4		14.7	14.7		29.4	Geotechnics (1972b)
	Sir Sam #7	10	0.1	16.3		4.9	11.4		16.3	Geotechnics (1972b)
	Sir Sam #8	5	0.1	16.3	3.3	4.9			8.1	
	Sir Sam #9	10	0.1	63.1			50.5	12.6	63.1	Johnson *et al.* (1998)
	Sir Sam #10	5	0.1	17.5		1.8	5.3	1.8	8.8	
	Sir Sam #11	3	0.1	30.6		9.2			9.2	Johnson *et al.* (1998)
	Sir Sam #12	4	0.1	60.0			24.0		24.0	Geotechnics (1972c)
	Sir Sam #13	3	0.1	105.6		9.5	22.2		31.7	Johnson *et al.* (1998)
	Sir Sam #14	4	0.1	5.6		1.4	0.9		2.3	Dames and Moore (1996)
				Total	**6.6**	**72.6**	**174.2**	**26.6**	**280.1**	

Appendix 3 (cont.)

Map sheet 1:250 000	*Calcrete reference*	*Saturated thickness (m)*	*Specific yield*	*Area (km²)*	*Storage in salinity divisions* 0–1000	1000–3000	3000–14000	>14000	*Calculated storage*	*Reference*
					(GL with ranges in mg/L)					
Leonora	Leon #1	10	0.1	33.0		9.9	23.1		33.0	Geotechnics (1972b)
	Leon #2	10	0.1	107.5			107.5		107.5	Geotechnics (1972b)
	Leon #3	5	0.1	22.5			11.3		11.3	
	Leon #4	5	0.1	23.0			9.2	2.3	11.5	
	Leon #5	5	0.1	9.0			4.5		4.5	
	Leon #6	4	0.1	46.0		1.8	3.7	12.9	18.4	Johnson *et al.* (1998)
	Leon #7	3	0.1	47.0		1.4	12.7		14.1	Johnson *et al.* (1998)
	Leon #8	5	0.1	67.5		3.4	30.4		33.8	
	Leon #9	5	0.1	19.0			9.5		9.5	
	Leon #10	5	0.1	5.0			2.5		2.5	
				Total	**0.0**	**16.5**	**214.3**	**15.2**	**246.0**	
Laverton	Quandong	5	0.1	82.0			41.0		41.0	Rust PPK (1996)
	Jupiter	3	0.2	45.0		8.1	18.9		27.0	Mackie Martin (1990)
	Lav #1	5	0.1	35.0			15.8	1.8	17.5	
	Lav #2	5	0.1	7.5			3.8		3.8	
	Lav #3	5	0.1	3.0			1.2	0.3	1.5	
	Lav #4	3	0.1	35.0		10.5			10.5	Johnson *et al.* (1998)
				Total	**0.0**	**18.6**	**80.6**	**2.1**	**101.3**	

Appendix 3 (cont.)

Map sheet 1:250 000	*Calcrete reference*	*Saturated thickness (m)*	*Specific yield*	*Area (km²)*	*Storage in salinity divisions (GL with ranges in mg/L)*				*Calculated storage*	*Reference*
					0–1000	*1000–3000*	*3000–14000*	*>14000*		
Duketon	Duketon #1	5	0.1	47.5		11.9	11.9		23.8	Johnson *et al.* (1998)
				Total	**0.0**	**11.9**	**11.9**	**0.0**	**23.8**	
Yeelirree	Yeelirrie	7	0.1	67.0	4.7	32.8	9.4		46.9	AGC (1981)
				Total	**4.7**	**32.8**	**9.4**	**0.0**	**46.9**	
Glengarry	Paroo	4.46	0.26	90.0	41.7	31.3	31.3	0.0	104.4	Sanders (1969)
				Total	**41.7**	**31.3**	**31.3**	**0.0**	**104.4**	

Appendix 4
Calculations of groundwater storage in palaeochannels

Drainage	Sector	Sector Nr	Length l (km)	Cross-sectional area (m²): Start a_s	Finish af	Average a_a	Specific yield	Storage (GL within ranges in mg/L): 0–1,000	1,000–3,000	3,000–7,000	7,000–14,000	> 14,000	Total Storage (GL)	Storage per km (GL/km)	Hydraulic conductivity K (m/d)	Hydraulic gradient i	Throughflow Q (GL/yr)
Laverton 1:250 000 sheet																	
Minigwal	MIN1 to NEA	1	30	5000	7880	6440	0.2					38.6	38.6	1.3	10	0.0003	0.007
	Deep Well	2	11	500	500	500	0.2			0.5	0.5		1.1	0.1			
	NEA to Western Well Line	3	55	7880	6825	7353	0.2					80.9	80.9	1.5			
	27 Mile Bore	4	8	500	500	500	0.2			0.4	0.4		0.8	0.1			
	Lake Well	5	12	500	500	500	0.2			0.6	0.6		1.2	0.1			
	Waitara Well	6	12	500	500	500	0.2			0.6	0.6		1.2	0.1			
Carey	CAR1 to NEB	7	20	15000	17450	16225	0.2					64.9	64.9	3.2	10	0.0002	0.012
	Weebo	8	25	5000	5000	5000	0.2					25.0	25.0	1.0			
	NEB to Transect A	9	105	17450	23400	20425	0.2					428.9	428.9	4.1	10	0.0002	0.015
	Charlie Well	10	45	2410	2410	2410	0.2	4.0	4.0	4.0	4.0	5.7	21.7	0.5			
	Borodale	11	38	1865	1865	1865	0.2		4.0	2.0	3.0	5.2	14.2	0.4			
	Gumwell	12	30	2000	2000	2000	0.2			2.0	8.0	2.0	12.0	0.4			
	Corktree	13	17	9945	9945	9945	0.2		10.0	7.0	7.0	9.8	33.8	2.0			
	Valais	14	28	6050	6050	6050	0.2	10.0	5.0	5.0	5.0	8.9	33.9	1.2			
	Roy Well	15	28	3900	3900	3900	0.2	21.8					21.8	0.8			
	Korong North	16	19	3650	3650	3650	0.2	2.0	2.0	2.0	2.0	5.8	13.9	0.7			
	Beasley Creek	17	8	500	500	500	0.2				0.4	0.4	0.8	0.1			
	Skull Creek	18	12	500	500	500	0.2				0.6	0.6	1.2	0.1			
	Korong South	19	20	3000	3000	3000	0.2		3.0	3.0	3.0	3.0	12.0	0.6			
	Transect A to CAR2	20	25	23500	25000	24250	0.2					121.3	121.3	4.9	10	0.0002	0.018
	Brewery Well	21	46	3000	3000	3000	0.2		7.0	7.0	7.0	6.6	27.6	0.6			
	Mount Weld	22	19	500	500	500	0.2			0.5	0.5	0.9	1.9	0.1			
Raeside	Cardinia Creek	23	18	500	500	500	0.2			1.8			1.8	0.1			
Total			**631**					**37.8**	**35.0**	**36.4**	**42.6**	**808.5**	**960.5**				

Note: Annual throughflow = 365 K i a_a

Appendix 4 (cont.)

Drainage	Sector	Sector Nr	Length l (km)	Cross-sectional area Start a_s (m^2)	Cross-sectional area Finish af (m^2)	Cross-sectional area Average a_a (m^2)	Specific yield	Storage 0–1,000 (GL within ranges in mg/L)	Storage 1,000–3,000 (GL within ranges in mg/L)	Storage 3,000–7,000 (GL within ranges in mg/L)	Storage 7,000–14,000 (GL within ranges in mg/L)	Storage > 14,000 (GL within ranges in mg/L)	Total Storage (GL)	Storage per km (GL/km)	Hydraulic conductivity K (m/d)	Hydraulic gradient i	Throughflow Q (GL/yr)
Leonora 1:250 000 sheet																	
Raeside	RAE1 to RAE2	1	96	10000	15000	12500	0.2					240.0	240.0	2.5	10	0.0004	0.018
	Gum Well	2	8	500	500	500	0.2			0.3	0.2	0.3	0.8	0.1			
	Middle Well	3	8	500	500	500	0.2		0.3	0.2	0.2	0.1	0.8	0.1			
	Granite Creek	4	17	500	500	500	0.2		0.4	0.4	0.5	0.4	1.7	0.1			
	NEQ to RAE3	5	68	25000	40000	32500	0.2					442.0	442.0	6.5	10	0.0002	0.024
	Emu Well	6	14	500	500	500	0.2			0.7	0.3	0.4	1.4	0.1			
	Sullivan Creek	7	60	500	500	500	0.2	2.0	1.0	1.0	1.0	1.0	6.0	0.1			
	Stratton Creek	8	14	500	500	500	0.2		0.4	0.4	0.3	0.3	1.4	0.1			
	Jeffries Well	9	5	500	500	500	0.2				0.2	0.3	0.5	0.1			
Noondie	NER to NEQ	10	103	17900	25000	21450	0.2					442.0	441.9	4.3	10	0.0003	0.023
	Lawlers creek	11	14	500	500	500	0.2		0.5	0.5	0.2	0.2	1.4	0.1			
	Bulga Water Well	12	12	500	500	500	0.2			0.4	0.4	0.4	1.2	0.1			
	Wilson Creek	13	21	500	500	500	0.2			1.1	0.5	0.5	2.1	0.1			
Mason / Noondie	MAS1 to NER	14	42	10000	17900	13950	0.2					117.2	117.2	2.8	10	0.0002	0.010
Carey	Weebo	15	100	800	5000	2900	0.2		7.0	14.0	7.0	30.0	58.0	0.6			
Total			**582**					**2.0**	**9.6**	**19.0**	**10.8**	**1275.1**	**1316.3**				

Note: Annual throughflow = 365 K i a_a

Appendix 4 (cont.)

Drainage	Sector	Sector Nr	Length l (km)	Cross-sectional area Start a_s (m²)	Finish af (m²)	Average a_a (m²)	Specific yield	Storage 0–1,000 (GL within ranges in mg/L)	1,000–3,000	3,000–7,000	7,000–14,000	> 14,000	Total Storage (GL)	Storage per km (GL/km)	Hydraulic conductivity K (m/d)	Hydraulic gradient i	Throughflow Q (GL/yr)
Sir Samuel 1:250 000 sheet																	
Way	Line 6 to NEK	1	32	12200	15000	13600	0.2					87.0	87.0	2.7	10	0.0001	0.005
	Charlie Well	2	15	500	500	500	0.2		0.4	0.4	0.4	0.3	1.5	0.1			
	South Lake Way	3	75	5000	5,000	5000	0.2		20.0	20.0	20.0	15.0	75.0	1.0			
	NEK to NEH	4	59	15000	19600	17300	0.2					204.1	204.1	3.5	10	0.0001	0.006
	Maitland	5	16	500	500	500	0.2		0.4	0.4	0.4	0.4	1.6	0.1			
	Wangganoo Creek	6	24	0	0	0	0.2						0.0	0.0			
	WAY2	7	25	2000	2000	2000	0.2					10.0	10.0	0.4	10	0.001	0.007
	Kujelan Creek – NEI	8	18	3050	3050	3050	0.2	2.0	2.0	2.0	2.0	3.0	11.0	0.6			
Carey	CAR4 to Line G1	8	46	3000	3450	3225	0.2					29.7	29.7	0.6			
	Little Well	10	12	500	500	500	0.2				0.8	0.4	1.2	0.1			
	G1 to Yakabindie	11	43	3540	5000	4270	0.2					36.7	36.7	0.9			
	Yakabindie to NEG	12	52	5180	6220	5700	0.2					59.3	59.3	1.1	10	0.0002	0.004
	Miranda	13	20	500	500	500	0.2					2.0	2.0	0.1			
	Townsend Well	14	11	500	500	500	0.2		0.3	0.3	0.3	0.2	1.1	0.1			
	Yandal Bore	15	19	500	500	500	0.2		0.5	0.5	0.5	0.4	1.9	0.1			
	Gum Pool	16	34	3000	3000	3000	0.2	4.0	4.0	4.0	4.0	4.4	20.4	0.6			
	NEG to NEF	17	38	6220	11620	8920	0.2					67.8	67.8	1.8	10	0.0002	0.007
	Kara Creek	18	19	500	500	500	0.2		0.5	0.5	0.5	0.4	1.9	0.1			
	Melrose	19	10	500	500	500	0.2					1.0	1.0	0.1			
	NEF to CAR3	20	20	11620	13000	12310	0.2					49.2	49.2	2.5			
Mason	MAS2 to MAS1	21	42	7500	10000	8750	0.2					73.5	73.5	1.8			
	Coffeys Well	22	16	500	500	500	0.2		0.4	0.4	0.4	0.4	1.6	0.1			
Carey	Weebo (On Leonora sheet)		16														
Total			**662**					**6.0**	**28.5**	**28.5**	**29.3**	**645.2**	**737.6**				

Note: Annual throughflow = 365 K i a_a

Appendix 4 (cont.)

Drainage	*Sector*	*Sector Nr*	*Length l (km)*	*Cross-sectional area Start a_s (m²)*	*Cross-sectional area Finish af (m²)*	*Cross-sectional area Average a_a (m²)*	*Specific yield*	*Storage 0–1,000 (GL within ranges in mg/L)*	*Storage 1,000–3,000 (GL within ranges in mg/L)*	*Storage 3,000–7,000 (GL within ranges in mg/L)*	*Storage 7,000–14,000 (GL within ranges in mg/L)*	*Storage > 14,000 (GL within ranges in mg/L)*	*Total Storage (GL)*	*Storage per km (GL/km)*	*Hydraulic conductivity K (m/d)*	*Hydraulic gradient i*	*Throughflow Q (GL/yr)*
Duketon 1:250 000 sheet																	
Carey	CAR3 to NED	1	39	13000	13840	13420	0.2					104.7	104.7	2.7	10	0.0001	0.005
	Erlistoun Creek	2	41	11620	11620	11620	0.2		24.0	24.0	24.0	23.3	95.3	2.3			
	NED to CAR1	3	8	13840	15000	14420	0.2					23.1	23.1	2.9			
TOTAL			**88**					**0.0**	**24.0**	**24.0**	**24.0**	**151.1**	**223.0**				

Note: Annual throughflow = 365 K i a_a

Drainage	*Sector*	*Sector Nr*	*Length l (km)*	*Cross-sectional area Start a_s (m²)*	*Cross-sectional area Finish af (m²)*	*Cross-sectional area Average a_a (m²)*	*Specific yield*	*Storage 0–1,000 (GL within ranges in mg/L)*	*Storage 1,000–3,000 (GL within ranges in mg/L)*	*Storage 3,000–7,000 (GL within ranges in mg/L)*	*Storage 7,000–14,000 (GL within ranges in mg/L)*	*Storage > 14,000 (GL within ranges in mg/L)*	*Total Storage (GL)*	*Storage per km (GL/km)*	*Hydraulic conductivity K (m/d)*	*Hydraulic gradient i*	*Throughflow Q (GL/yr)*
Wiluna 1:250 000 sheet																	
Way	Line 3 to Line 6	1	38	12360	12200	12280	0.2					93.3	93.3	2.5	10	0.0001	0.004
	Way	2	20	1920	12360	7140	0.2					28.6	28.6	1.4			
Total			**58**									**121.9**	**121.9**				

Note: Annual throughflow = 365 K i a_a