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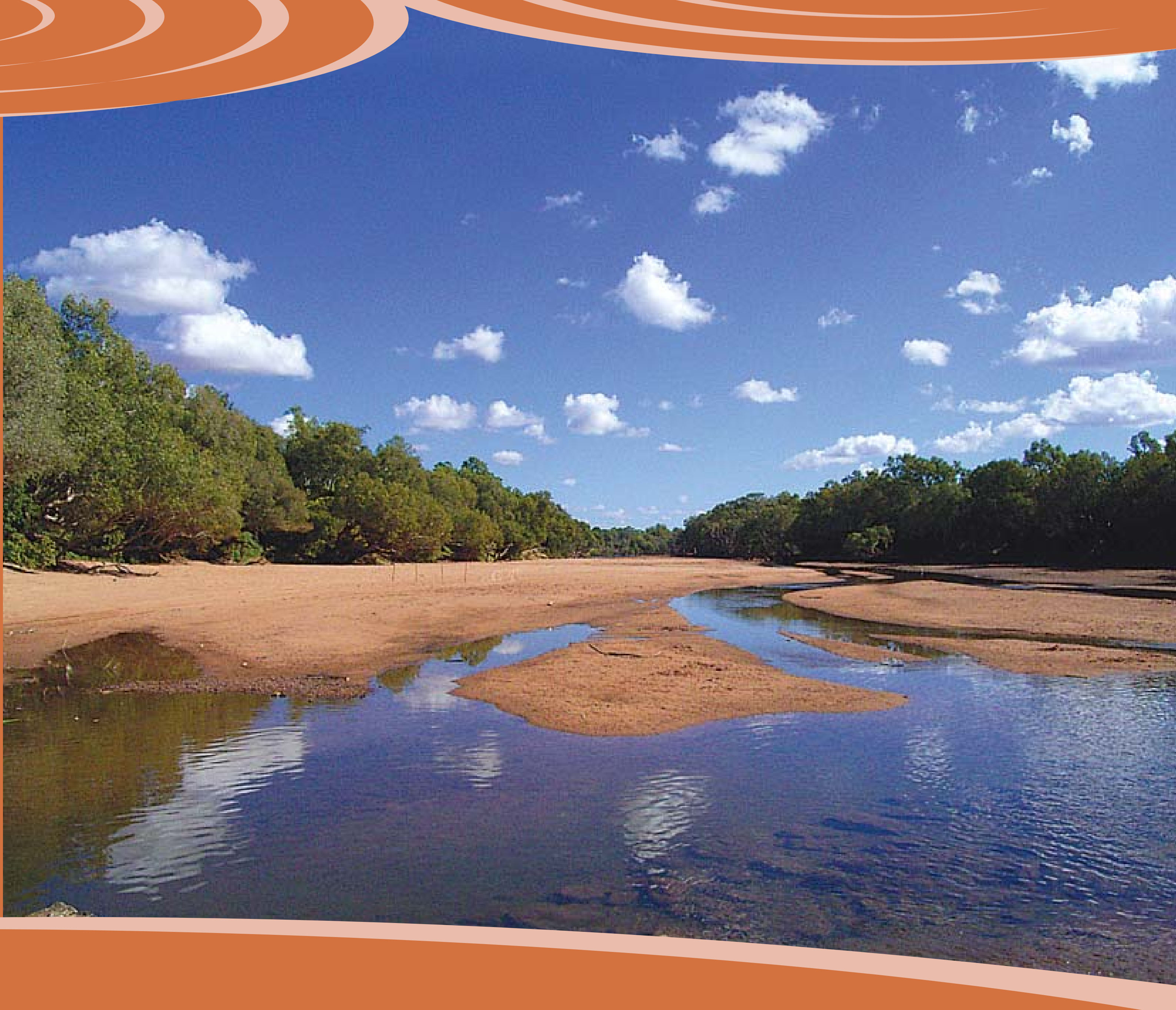

Hydrogeological Assessment of the Fitzroy Alluvium

Hydrogeological Record Series

REPORT NO. HG 16
MAY 2006

Hydrogeological Assessment of the Fitzroy Alluvium

Prepared by

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Water Resources Management

Department of Water

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Hydrogeological Record Series
Report HG 16
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Acknowledgments

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Recommended reference

The recommended reference for this publication is: Lindsay R.P. and Commander, D.P., 2005, *Hydrogeological assessment of the Fitzroy alluvium,* Western Australia, Department of Water, Hydrogeological Record Series HG 16.

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ISSN 1329-542X

Printed on recycled stock.

May 2006

Cover photograph:
Myroodah Crossing in June 2005
R.P. Lindsay

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Summary

The Fitzroy River is one of Australia's largest unregulated rivers characterised by braiding channels within a wide floodplain and significant lower floodplain storage. Annual river discharge measured at Fitzroy Crossing varies between 300 GL (1992) to 25 000 GL (2000) with most of the flow between December and March. The river usually dries up in July or August, leaving a number of permanent pools along the river which are recharged by groundwater during the dry season.

The water resources of the river have been diverted by a barrage for irrigation at Camballin, and a number of other dam sites have been investigated. Previous studies concluded that the cost of bringing surface water to the southwest of the state could not compete with alternatives, and there are severe environmental constraints on damming the river. Assessments of the groundwater resources associated with the river suggested a significant resource; however, there has been little work done to confirm this.

In 2004, the possibility of transporting water from the Kimberley to the southwest was raised again, and a proposal put forward to utilise groundwater from the Fitzroy alluvium via a canal. This proposal highlighted the lack of knowledge about the groundwater resource, and the need for a study to set out current knowledge, and to assess the potential.

Previous exploratory and geotechnical drilling across the floodplain at Willare, Fitzroy Barrage and Gogo had confirmed the presence of an alluvial aquifer composed of a basal zone of gravels and sands about 20–30 m thick, overlain by silts and clays about 10 m thick. If representative of the entire Fitzroy alluvium, the aquifer could contain a groundwater storage of 13 000 GL.

Groundwater recharges the alluvium through the river bed during the wet season. During the dry season, river flow is initially maintained by groundwater discharge, until declining levels drop below the river bed. Permanent pools in the river bed are maintained by groundwater from the alluvium.

The salinity of dry season river flows indicates the groundwater salinity is generally less than 500 mg/L. However, salinity of 500–800 mg/L in a stretch centred on Noonkanbah, corresponding to outcrop of shaley Noonkanbah Formation, indicates that a considerable portion of the alluvial aquifer is brackish. The alluvium receives groundwater discharge from the regional Canning Basin aquifers, which varies in salinity.

Although ecological water requirements have yet to be determined, it is expected that constraints on the consumptive use of the alluvial aquifer will be the need to maintain dry season river flows and permanent pools, which will limit allowable drawdown at the river bed.

In order to quantify likely drawdown, a highly simplified numerical groundwater model was constructed based on assumptions of the hydrogeological parameters of the

aquifer. These, in turn, were based on typical values for river alluvium, as no data are available. This model simulated pumping on a seasonally adjusted schedule from a line of equally spaced bores along the alluvial plain, and indicated that a pumping rate of 2000 m^3/day per kilometre of river could be achieved for a drawdown of about 0.5 m at the river bed. At this rate, a yield of 200 GL/yr could be obtained from the entire 275 km stretch of alluvium between Willare and Fitzroy Crossing.

The available hydrogeological data are limited and the analysis of likely yield is very preliminary. A substantial investigation program consisting of aerial geophysical survey, investigation drilling and pumping tests will need to be carried out to define the extent and properties of the aquifer prior to confirming a sustainable yield.

1 Introduction

1.1 Background

The water resources of the Kimberley have long attracted attention as a source for water supply to the southwest of Western Australia, and the Fitzroy River has been considered in planning for Perth's future water supply. However, it has previously been rejected on grounds of high cost of water transport compared with alternative sources (Western Australia Water Resources Council, 1988). In a study of the major groundwater resources in Western Australia, Allen et al. (1992) made a conceptual estimate of 25 GL/yr for the yield of the Fitzroy alluvium extending 50 km upstream of Willare (Figure 1). A follow-up study of the potential for irrigation in the Fitzroy valley (Kimberley Water Resource Development Office, 1993) concluded from this estimate, together with estimates of yield from underlying regional aquifers in the Canning Basin, that 'substantial reserves of groundwater have been identified under the Fitzroy valley'. The report recommended that an investigation program be undertaken to establish with more accuracy the likely yield, although this has not been carried out.

As a result of record low runoff to Perth's water storages in 2001 and 2002, and the subsequent consideration of southwest groundwater and seawater desalination to augment water supplies, proposals for transporting water from the Kimberley were raised again. In response, the State Government established the Kimberley Water Source Expert Panel to assess proposals to transport water from the Kimberley to the southwest. A proposal to construct a canal from the Fitzroy valley, first reported in 1993 (Pollard, 1993), was resurrected and became a State Election issue in February 2005, with groundwater from the Fitzroy alluvium proposed as a source.

Because of the lack of available information on the groundwater potential of the alluvial aquifer, the Department of Environment (Water and Rivers Commission, now the Department of Water) was commissioned to undertake a desk study of the potential of the Fitzroy alluvium to supply 50 to 200 GL/yr of water. The report was funded by the Office of Water Strategy through the Kimberley Water Expert Panel as part of wider studies into the feasibility of transporting water from the Kimberley Region to the southwest of Western Australia.

1.2 Purpose and scope

Little has previously been published about the groundwater in the Fitzroy River alluvial sediments. The aim of this study is to collate the available groundwater information, and to assess the groundwater resource potential of the alluvial aquifer.

The study area focuses on the Fitzroy alluvial aquifer between Fitzroy Crossing and the estuary at King Sound, a stretch of approximately 275 km (Figure 1). The study area also includes the regional aquifers of the Canning Basin in the groundwater catchment of the Fitzroy River, as these aquifers also discharge into the alluvium.

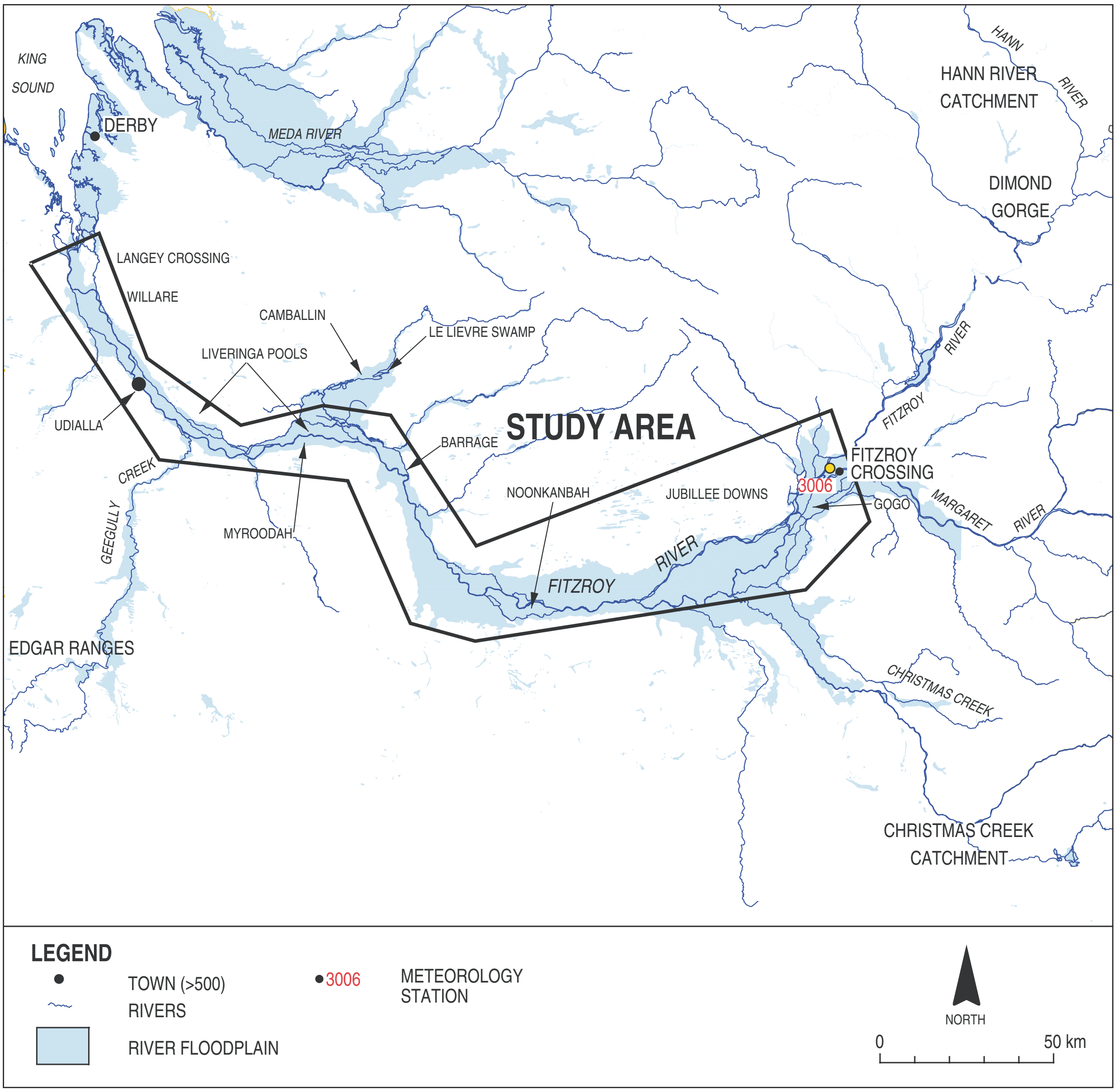

Figure 1. Location map

This study compiles the existing data and draws some preliminary conclusions about the water quality, groundwater movement and the relationship between groundwater and surface water. Preliminary numerical groundwater flow modelling is used to estimate potential borefield yields, taking account of likely environmental constraints on pumping.

Recommendations for investigation work needed to confirm the potential of the alluvial aquifer are also made.

1.3 Previous Work

Indigenous communities living along the Fitzroy River have been well aware of its flooding cycle and through the concept of 'living water' understand that groundwater maintains the permanent pools in the dry season (Toussaint et al., 2001).

Attention in the 1950s to 1980s focused on the possibilities of damming or diverting surface water from the river for agriculture and hydro-electricity. The history of dam site investigations has been summarised by WAWA (1993). The first dam site survey was led by C.M. Dimond in 1952, after whom the gorge is now named (Figure 1). The Fitzroy Barrage is the only dam across the Fitzroy River, and was opened in 1962 to divert water for crop irrigation at Camballin. The project was abandoned in the early 1980s owing partly to flood damage, and partly to crop pests and diseases and an insufficient economy of scale. The Fitzroy Plan was the earliest formal documentation of potential dam sites and overview of the irrigation potential of the Fitzroy Valley prepared by the Public Works Department in January 1964 (in: WAWA, 1993). In 1965, the Geological Survey of Western Australia conducted a geotechnical drilling survey at Gogo for a proposed dam site (Swarbrick, 1965). However, the risk of leakage under the dam and possible failure of the abutments was considered too great. The emphasis on surface storage has meant that most hydrographic gauging and recording of river flow has been directed towards flood warning and potential surface water yields.

The immediate area around Camballin was proclaimed a Groundwater Area in 1973 and incorporated into the Canning–Kimberley Groundwater Area in 1996. Drilling carried out at Camballin established high bore yields from the Permian aquifers of the Canning Basin. Subsequent drilling has been carried out to establish groundwater supplies at Fitzroy Crossing and Noonkanbah, and other small communities, and recently for diamond mining at Ellendale.

The first regional groundwater surveys consisted of censuses of pastoral bores carried out during regional geological mapping (Derrick and Playford, 1973; Crowe and Towner, 1981; Gibson and Crowe, 1982). As part of a proposal for regional hydrogeological map compilation (Commander, 1987), a drilling program to specifically investigate the groundwater potential of the Fitzroy alluvium was carried out, consisting of a transect of four exploratory drilling sites along the Great Northern Highway at Willare Crossing (Smith, 1988). The extent of the Fitzroy alluvial aquifer from Willare upstream to Fitzroy Crossing was subsequently recognised on the Hydrogeological Map of WA (Commander, 1989), based on the 1:250 000 geological mapping by Crowe and Towner (1981) and Gibson and Crowe (1982), and the lowermost 50 km is represented on the Derby 1:250 000 hydrogeological map (Smith,1992).

Allen et al. (1992) recognised the potential of the alluvium as a major groundwater source and estimated a conceptual yield of 25 GL/yr from the alluvium below the floodplain extending 50 km upstream of Willare.

There are few pastoral bores intersecting the alluvium, as the floodplain is generally inundated in the wet season. The geotechnical drilling carried out for the Fitzroy Barrage and the proposed Gogo damsite provide the only other information on the characteristics of the alluvium. Taylor (2000) studied the geomorphology of the floodplain and river, and provides a useful insight into the depositional and erosional environment of the river alluvium.

Investigation of the regional aquifers of the Canning Basin was carried out in 1987, consisting of a detailed investigation of the Erskine Sandstone aquifer east of Derby (Laws and Smith, 1989) and exploratory drilling at a further four sites within the Derby

1:250 000 map sheet area, in addition to the four sites in the Fitzroy alluvium (Smith, 1988, 1992). However, these other investigations lie outside the groundwater catchment of the Fitzroy River. Laws (1991) outlined the groundwater resource potential of the Canning Basin, and Allen et al. (1992) provided groundwater resource estimates for the regional aquifers. Commander et al. (2002) discussed development of the groundwater resources of the regional aquifers in the basin.

1.4 Climate

The Fitzroy River area is subject to a pronounced wet season that commonly results in river flooding, and a dry season when river flows reduce to a trickle or cease altogether. High-intensity rainfall resulting from cyclonic activity from the north and northwest and localised thunderstorms usually occurs between November and April, followed by winters with little or no rainfall. Annual rainfall is highly variable, ranging between 200 mm/yr and 1000 mm/yr at Fitzroy Crossing (Figure 2), and is highly seasonal with about 90% of the rain falling between November and March. There is also considerable spatial variation of rainfall in the river catchment area, with less than 400 mm/yr falling in the southeastern, Christmas Creek catchment to about 900 mm/yr in the northerly Hann River catchment (Storey et al., 2001).

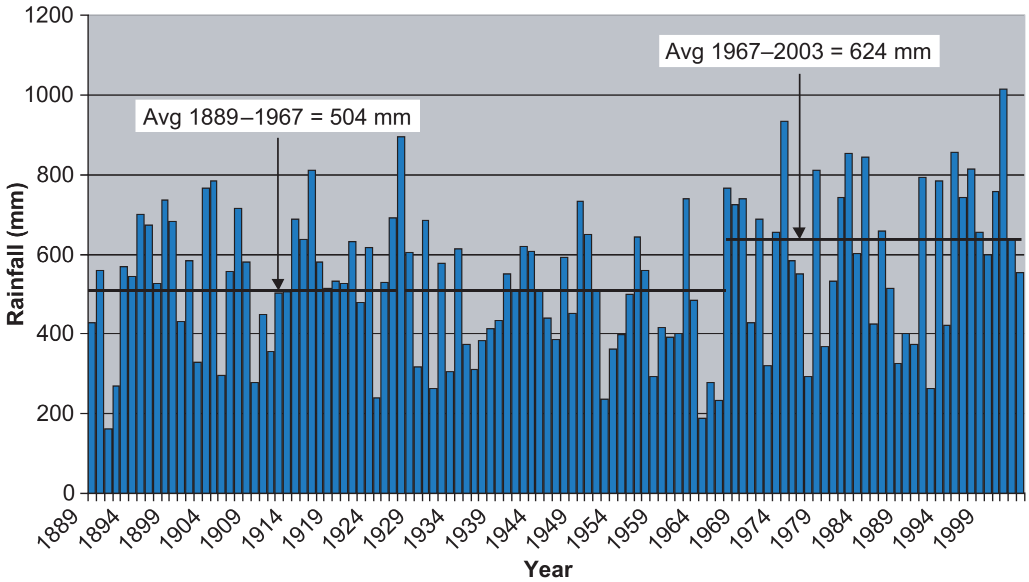

Figure 2. Fitzroy Crossing annual rainfall (Station 3006)

A graph of the mean monthly rainfall compared with evaporation shows that evaporation greatly exceeds rainfall in all months with a net moisture deficit of about 1.75 m/yr (Figure 3). Long-term annual rainfall at Fitzroy Crossing is shown in Figure 3. The average of recent long-term rainfall from 1967 to 2003 is 624 mm/yr, which is higher than the average between 1899 and 1967 of 504 mm/yr.

The region experiences high temperatures in summer, with a mean November minimum in Fitzroy Crossing of 24.2°C and maximum of 40.5°C, compared with a mean July minimum of 10.7°C and maximum of 29.6°

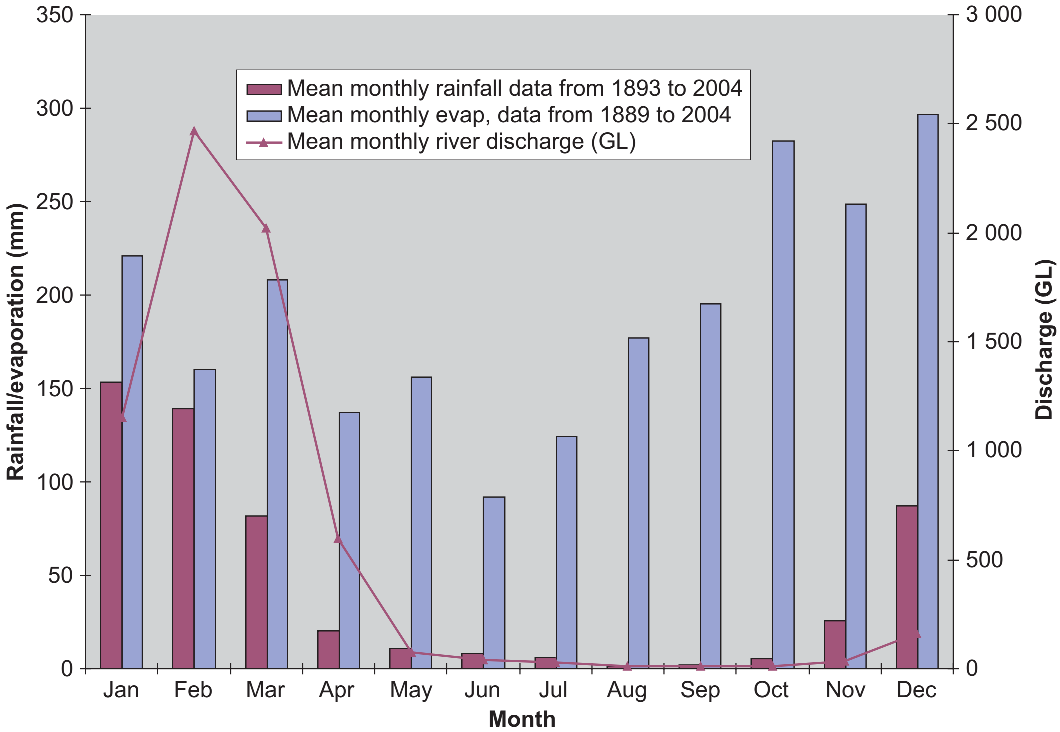

Figure 3. Rainfall, evaporation and mean river discharge at Fitzroy Crossing

1.5 Physiography, vegetation and fauna

There are three major physiographic provinces in the study area that can be subdivided according to their geographical extent (Beard, 1979). These principal physiographic regions are the Fitzroy Plains, the Fitzroy Floodplain and Rangelands. Figure 4 shows the distribution of the physiographic provinces.

Western Sand-Plain Province

The Sand-Plain Province is mainly below 100 m AHD and has little surface drainage and only minor development of dunes. In the eastern part of the Dampier Peninsula and flanking the Meda and May Rivers, this sand masks a landscape of low plateaus and valley plains.

The North Fitzroy Plains

The North Fitzroy Plains consist principally of eolian sand and gravel, underlain by lateritised sandstone and mudstone of the Noonkanbah Formation and Liveringa Group. The area may be an important source area for some of the coarse clastic material that constitutes the Fitzroy alluvium. There are some isolated peaks of Fitzroy Lamproite and Permian rocks. Mt Hardman Creek is the most prominent watercourse, and claypans in the central part occur in small, internal drainage depressions. The plains are mainly broad sandy areas covered with thick pindan scrub, grassland wooded with a sparse layer of trees 5 to 15 m in height and a dense thicket of acacia.

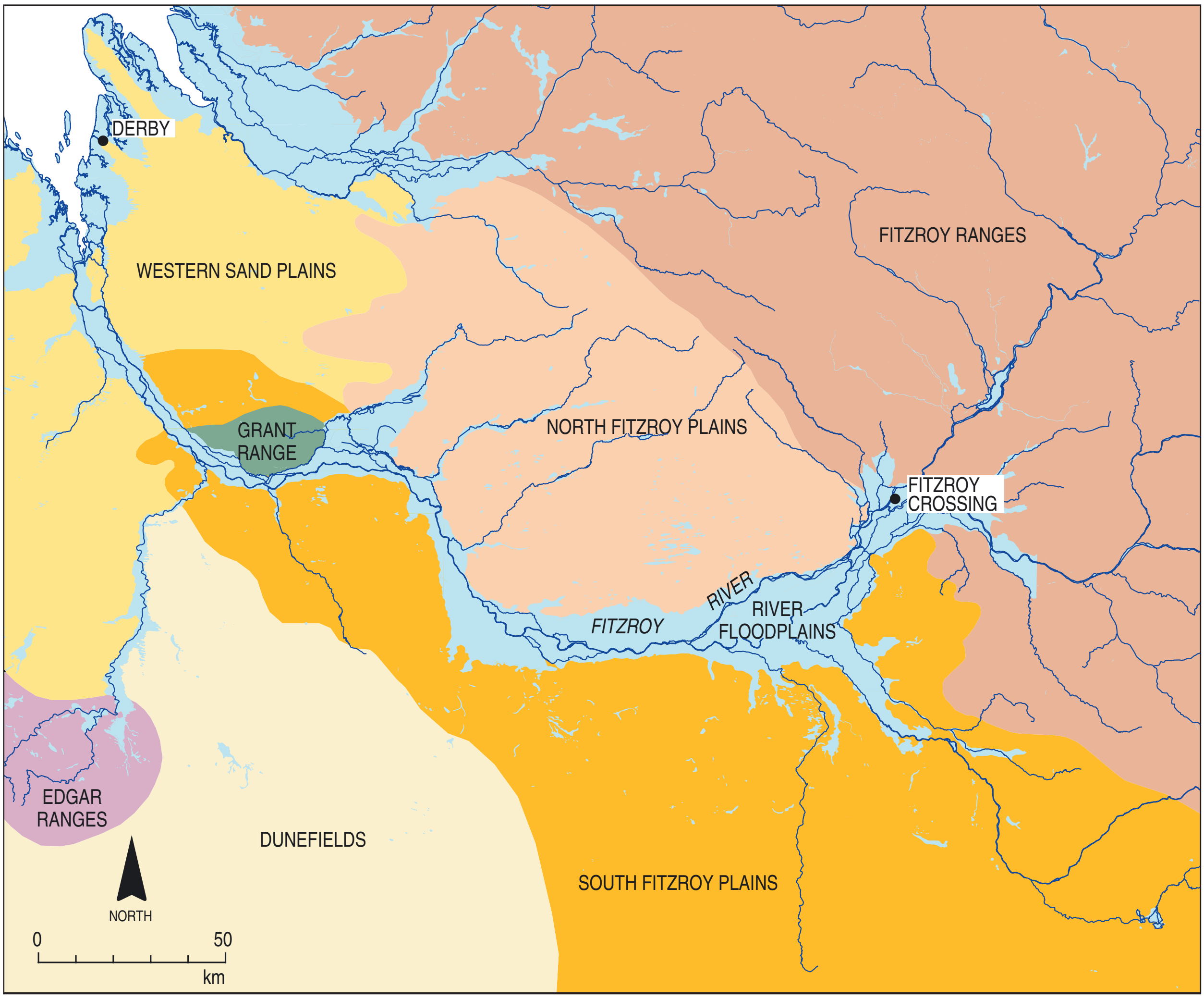

Figure 4. Physiographic regions

The South Fitzroy Plains

The South Fitzroy Plains include the dissected anticlinal highlands of the St George Ranges and Poole Range (up to 190 m above plain level) and are largely rubble covered. Drainage on the plains is sparse and mainly transverse to the main structural trends, although drainage over the Grant Group follows strike-fault and joint-controlled valleys, giving rise to a trellis pattern.

The Fitzroy Floodplain

The Fitzroy Floodplain is underlain by the alluvial deposits of the Fitzroy River and its tributaries. The floodplain is characterised by broad levees, plains of heavy cracking clays (black soil) with gilgai and active and relict watercourses. Taylor (2000) has studied the geomorphology of the floodplain and river to reconstruct the palaeoflow conditions of the Fitzroy River. Pools and braided channels are common where the river traverses black soil plains. Some pools are perennial and are sustained by groundwater. Ephemeral pools also occur in claypans on the Dampier Peninsula and west of the Fitzroy River, and in wetlands such as Le Lievre Swamp. King Sound is fringed by mudflats which are covered by normal tides, and by silt plains which are inundated only by spring tides or after heavy rainfall.

The floodplain is vegetated by *Eucalyptus microtheca* savanna with fringing woodland composed of eucalypts, acacias and wild figs (Storey et al., 2001). The levees are vegetated with grassy woodlands and the floodplains support grasses, scattered trees and shrubs. The fauna and flora have been described in detail by Storey et al. (2001).

Wetlands and permanent pools along the Fitzroy River support a diverse ecology, including 35 species of fish, some endemic to the Kimberley and the Fitzroy, and 67 species of waterbirds. Ecologically, permanent pools are important refuges for aquatic species enabling them to survive the harsh dry season. Fish include some marine opportunists with limited distribution (eg sawfish and whiprays). Of the remaining species, about 18 are Kimberley endemics and at least three are regional endemics (Storey et al., 2001).

Waterbird usage of the floodplains, particularly at Camballin, is considered sufficient for Ramsar* listing, and many of the waterbird species are listed under international agreements (eg JAMBA/CAMBA) (Storey et al., 2001). The Camballin project has highly modified the local environment and has had serious environmental impacts owing to the alteration in natural flow of the Fitzroy River and its 'boom and bust' cycles (Storey et al., 2001).

The Grant Range

The Grant Range is a rugged area of dissected Permian sandstone that rises from the Fitzroy Floodplain and the Fitzroy Plains. Local relief reaches 250 m, and scarps are common. Vegetation consists of spinifex, grasses, and open woodlands.

The Dunefields

The dunefields consist of eolian dune fields and sand sheets, with little organised drainage. The longitudinal dunes (sief) are up to 30 km long and have an average height of 12 m. They are separated by broad swales, which are, in places floored by a mixture of eolian and alluvial sediments. The dunefields are vegetated with low scrubby woodland and spinifex grassland.

The Edgar Ranges

The Edgar Ranges is an area of dissected Mesozoic sandstone and mudstone composed of Jarlemai Siltstone. The ranges are characterised by steep-sided mesas, and has north-facing scarp at its southern margin. Vegetation consists of spinifex grasslands. Trees are usually present only along the watercourses.

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*Ramsar is an intergovernmental treaty for the protection of wetlands and their fauna, signed in Ramsar, Iran in 1971.

1.6 Landuse

Aboriginal people have occupied the Fitzroy Catchment region at low population densities for tens of thousands of years (O'Connor 1995; McConnell and O'Connor 1997). The Fitzroy River was likely to have been a focus of population during dry periods, and acted as a physiographic and cultural divide between desert clans to the south and clans from the ranges in the north and east (Purcell, 1984).

The migration of Europeans into the Kimberley region was underway by the 1890s, with most of the land of the Fitzroy Catchment under pastoral leases. Sheep numbers peaked in the West Kimberley at 307 000 head in 1941, and cattle at 812 000 in 1970 (KWRDO,1993). Such high livestock numbers led to decreased vegetation densities, compacted soil surfaces and large areas of erosion, especially on river frontages (Bolton, 1953; Payne et al., 1979; AGWA, 1981; Fitzgerald, 1982). Land degradation away from water sources is less severe, and in rocky catchment areas impacts are minimal (Taylor, 2000). A decrease in livestock numbers since 1978, the establishment of watering points away from the river frontage and improved fencing, are reducing the impact of pastoralism on the landscape (KWRDO, 1993) and no river frontage on the Fitzroy is now in very poor condition (WRC, 1997).

Scattered aboriginal communities occur throughout the area; the largest community is at Noonkanbah (population 250), which is located on the edge of the Fitzroy River.

1.7 Geology

The study area lies mainly within the Fitzroy Trough subdivision of the northern Canning Basin (Figure 5), which contains Permian, Triassic and Jurassic sediments, intruded by narrow volcanic plugs of Mesozoic lamproite (Middleton, 1990). The sediments are predominantly sandstones and shales of shallow water marine, deltaic and fluvial origin (Figure 6). The sediments are deposited within the Fitzroy Trough which is the most prominent structural feature of the area. This is a northwest-trending graben bounded on the northeast by the Pinnacle Fault System and to the southwest by the Fenton Fault System (Crowe and Towner, 1981). To the northeast, the Lennard Shelf is an area of relatively shallow basin occupied by Devonian reef and other early Palaeozoic rocks. The Barbwire Terrace, a platform with up to 3000 m of sediments with younger Jurassic sediments at the surface lies to the southeast of the Fitzroy Trough.

The oldest rocks in the study area are late Devonian to late Carboniferous limestones, siltstones, minor sandstones and shales, collectively called the Fairfield Group. These rocks are only exposed to the northeast of the area and are underlain by older rocks of the Devonian reef complex. They are unconformably overlain by the Grant Group, which is dominated by sandstones at the base and top, and by siltstone members in the central part of the sequence. The Grant Group rocks are exposed mostly in anticlinal structures and form prominent ranges of hills, such as Grant Range near Liveringa, and the St George Ranges southeast of Noonkanbah.

The Poole Sandstone (Permian) unconformably overlies the Grant Group but is commonly exposed in association with the lithologically similar Grant Group rocks.

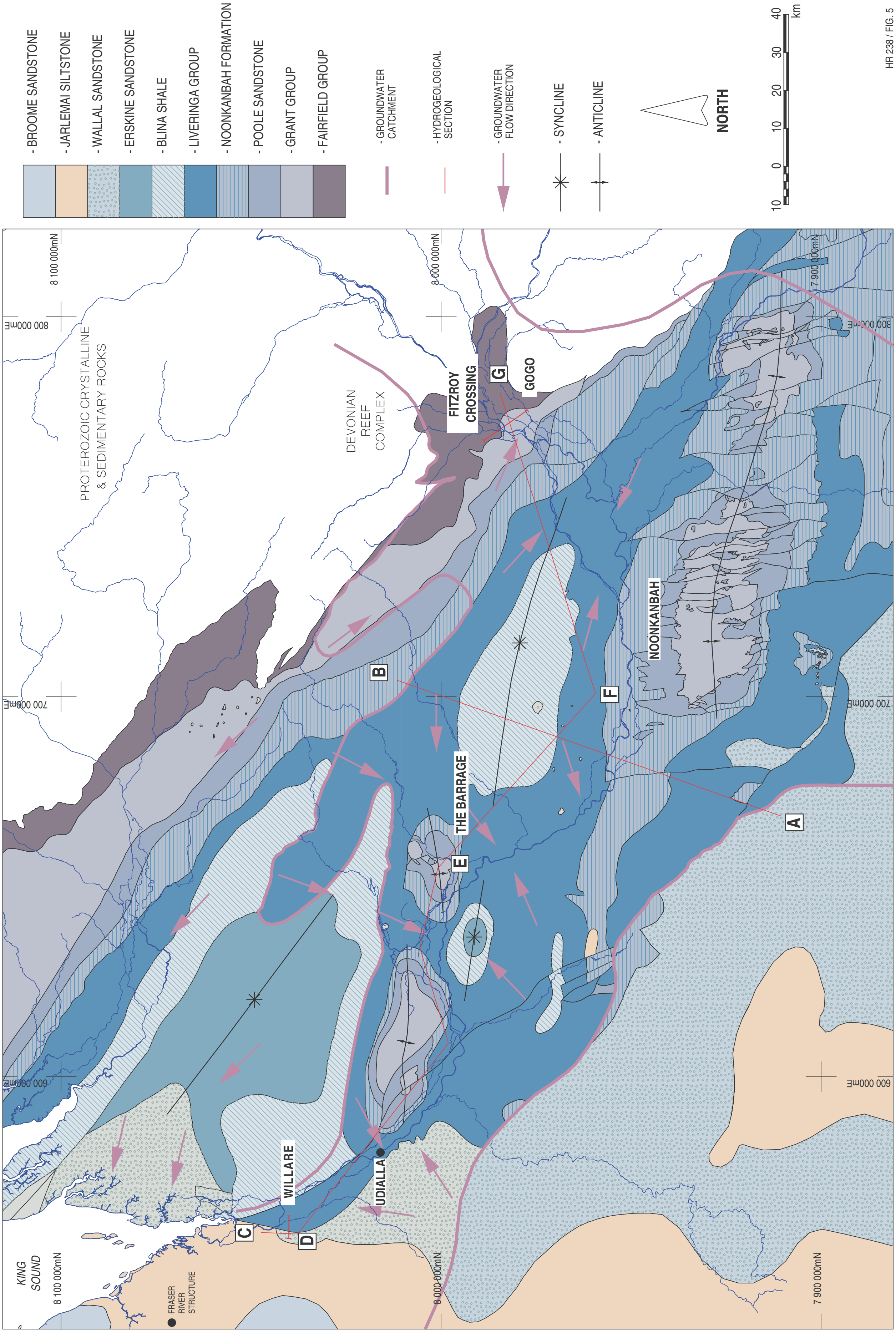

Figure 5. Geology and groundwater catchment of the Fitzroy River

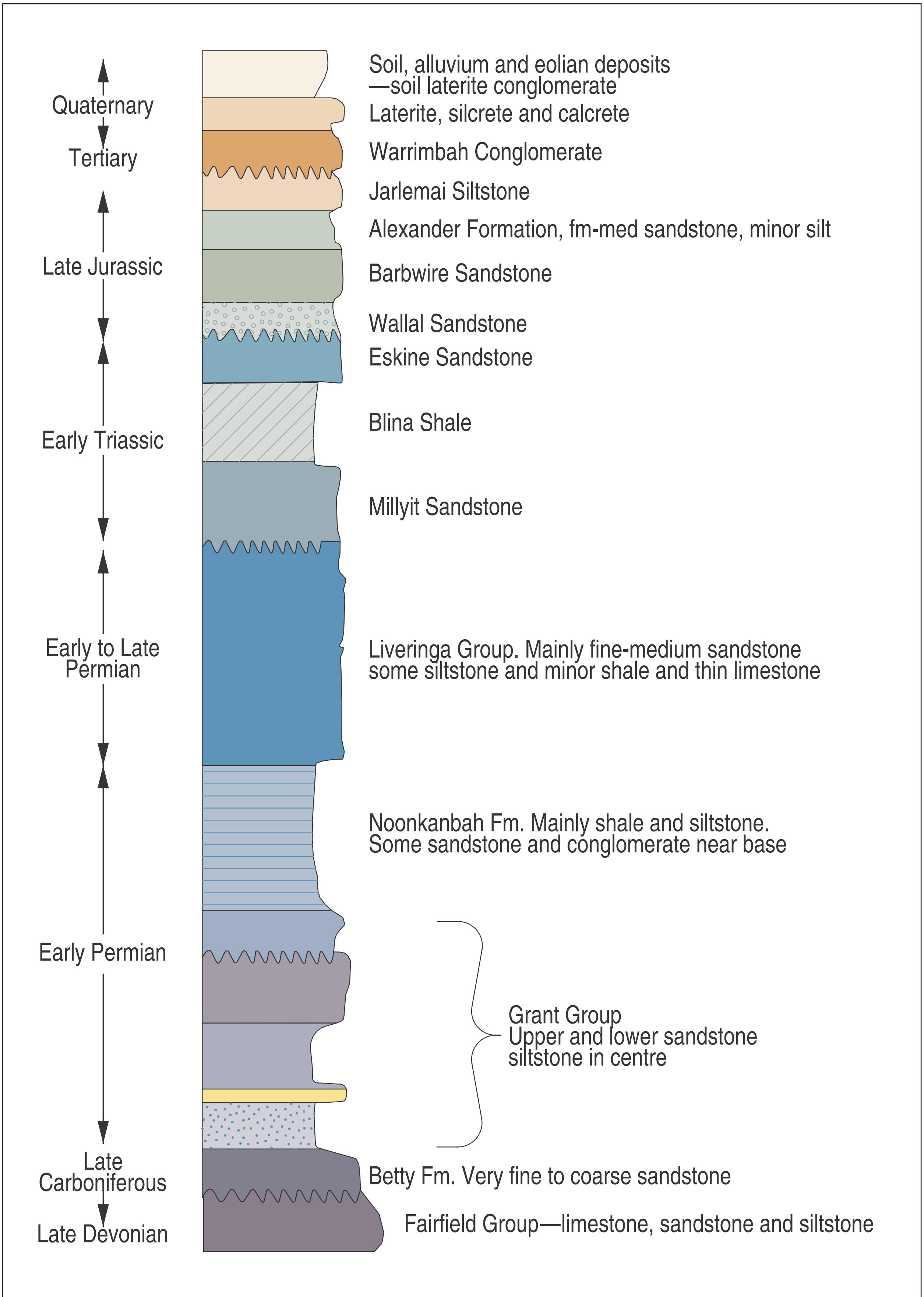

Figure 6. Generalised geological section

The Poole Sandstone appears as a prominent range of hills on top of the Grant Range near Liveringa Homestead. The Poole Sandstone contains two members in the area: the Nura Nura Member, and the overlying Tuckfield Member. There is an angular unconformity between the Nura Nura Member and the underlying Grant Group in the Grant Range, west of Camballin. The Nura Nura Member is composed of fine sandstone with minor mudstone in the middle section. It occurs extensively in the anticlinal structures such as the Grant Range, Mt Hutton and the St Georges Ranges. The Nura Nura member thins out to the east. The Tuckfield Member is also composed mostly of thinly bedded fine sandstone, which forms rounded hills and is a good aquifer.

The Noonkanbah Formation (late Permian) is composed predominantly of siltstone and shale and underlies part of the Fitzroy River centred near Noonkanbah aboriginal community. The formation is poorly exposed and known mostly from coal and oil exploration drill holes.

The Liveringa Group conformably overlies the Noonkanbah Formation and is the most extensive unit underlying the Fitzroy River. It is up to 900 m thick and composed of sandstone and siltstone with lenses and minor beds of claystone and shale.

The Blina Shale overlies the Liveringa Group and is about 200 m thick. It subcrops in synclinal stuctures but is poorly exposed. The Blina Shale probably conformably overlies the Liveringa Group in the area immediately east of Derby, but elsewhere the relationship is probably disconformable or unconformable, for example at the Moorodah Syncline south of the barrage (Figure 7), (Crowe and Towner, 1981; Middleton, 1990).

The Erskine Sandstone (Triassic) disconformably overlies the Blina Shale. It covers a wide area to the east of Willare, where it forms low scarps. The formation ranges between 30 m thick in the Erskine Ranges and 269 m at Myalls Bore near Derby.

A major unconformity separates the Erskine Sandstone (late Triassic) and the overlying Wallal Sandstone (late Jurassic). The Wallal Sandstone crops out extensively to the south of the Fitzroy River and east of Derby and is 335 m thick in the WAPET Fraser River No.1 well. The overlying Barbwire and Alexander Formations are similar in lithology and of variable thickness, with a maximum combined thickness of approximately 95 m. The Wallal Sandstone consists of laminated pink and white, very fine to very coarse grained sandstone with minor siltstone, conglomerate and lignite. The Alexander Formation comprises sandstone, siltstone and minor conglomerate.

The Jarlemai Siltstone conformably overlies the Alexander Formation and is predominantly a mudstone with scattered coarse sand grains and granules. It forms the Edgar Ranges in the southwest of the study area and typically forms mesas and breakaways with steep sides and slopes.

Cainozoic sediments are thickest in the Fitzroy Valley. The Warrimbah Conglomerate (Cainozoic) is a thin (approx. 10 m thick) cobble and pebble conglomerate that unconformably overlies older Permian and Triassic rocks. Its distribution is limited to within 15 km of the Fitzroy River and may represent a previous course of the Fitzroy River. It forms scattered gravel plains between Myroodah Homestead and Noonkanbah. The alluvium of the Fitzroy River underlies the floodplain, is 30 to 40 m thick, and

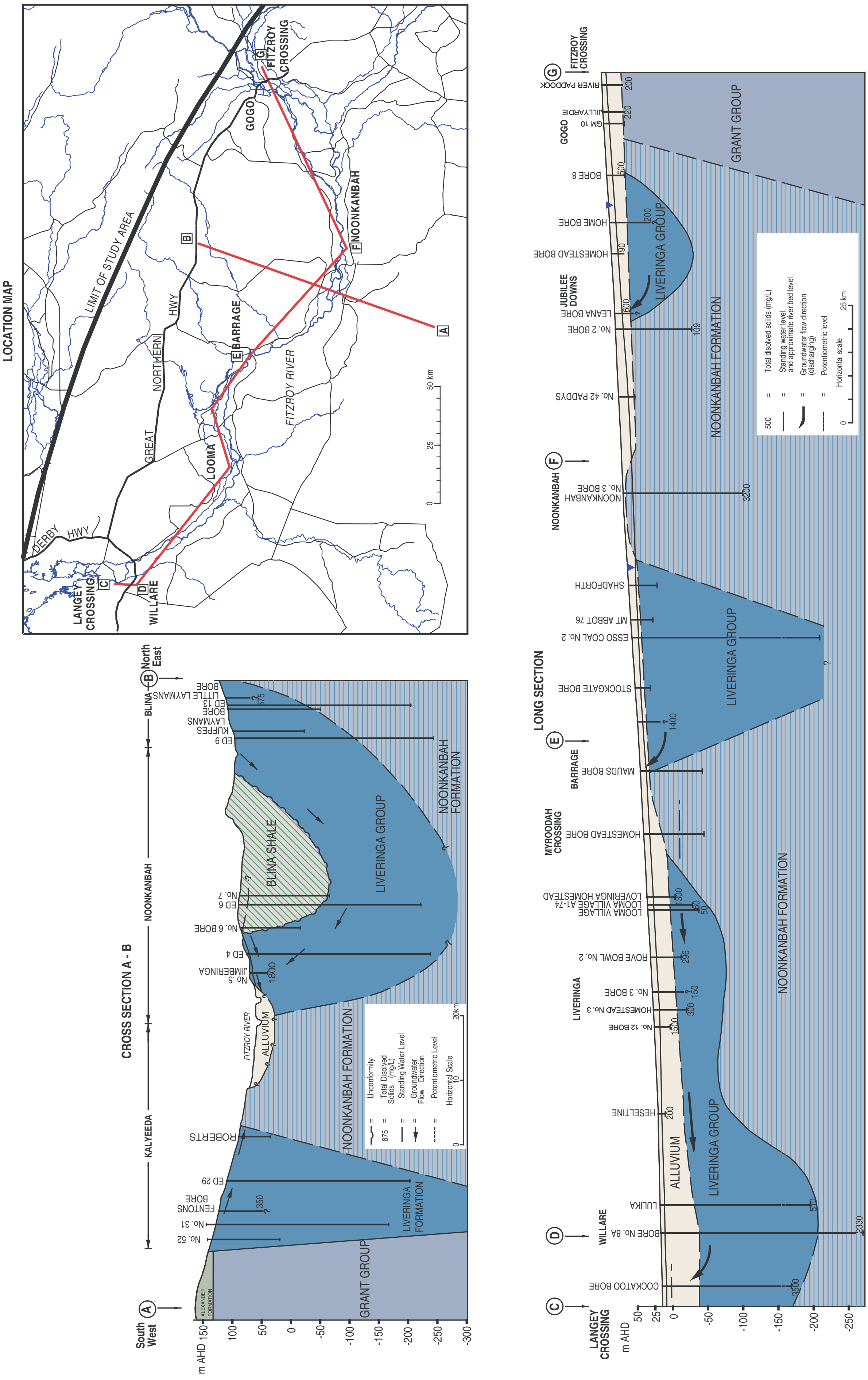

Figure 7. Regional hydrogeological sections

composed of a basal sand gravel representing the river bed load deposits, overlain by up to 10 m of silt/clay overbank deposits.

The Permian to Jurassic rocks are faulted and gently folded. The most prominent anticlines give rise to the Grant and St George Ranges, which are west-northwesterly trending structures whose areas of closure are marked by ranges of hills acting as a barrier around which the Fitzroy River flows. These, as well as other smaller associated folds, are cross cut by numerous north-northwesterly trending transverse faults creating a trellised drainage system (Crowe and Towner, 1981; Gibson and Crowe, 1982).

2 Hydrology

2.1 Runoff

Runoff is highly variable within the Fitzroy River catchment, with 50 mm/yr on the permeable sands of the southern plains to about 150 mm/yr on the bedrock and rocky hills in the northern region (Ruprecht and Rodgers, 1998 in Storey et al., 2001). Runoff therefore depends on where the rain falls in the catchment, as well as the intensity and duration. River flow is highly seasonal, with flooding in the wet season from December to March. The river contracts to pools with very low flows from about June to October.

The meteorology and hydrology of flood events have been examined by Main Roads Western Australia (MWWA) for engineering and design purposes (eg Goh and Joyce, 1986, 1990; Goh, 1993a,b). Taylor (2000) has described the flood geomorphology of the Fitzroy River to reconstruct the palaeoclimatic record. The Water Authority (WAWA) recorded the flood discharges that occurred in the Fitzroy Catchment from 1957 to 1993 and modelled the hypothetical scenarios associated with plans for dam construction in the catchment. The later work is included in a desktop assessment of the capacity of the Fitzroy Valley to support irrigated agriculture (Kimberley Water Resources Development Office, 1993).

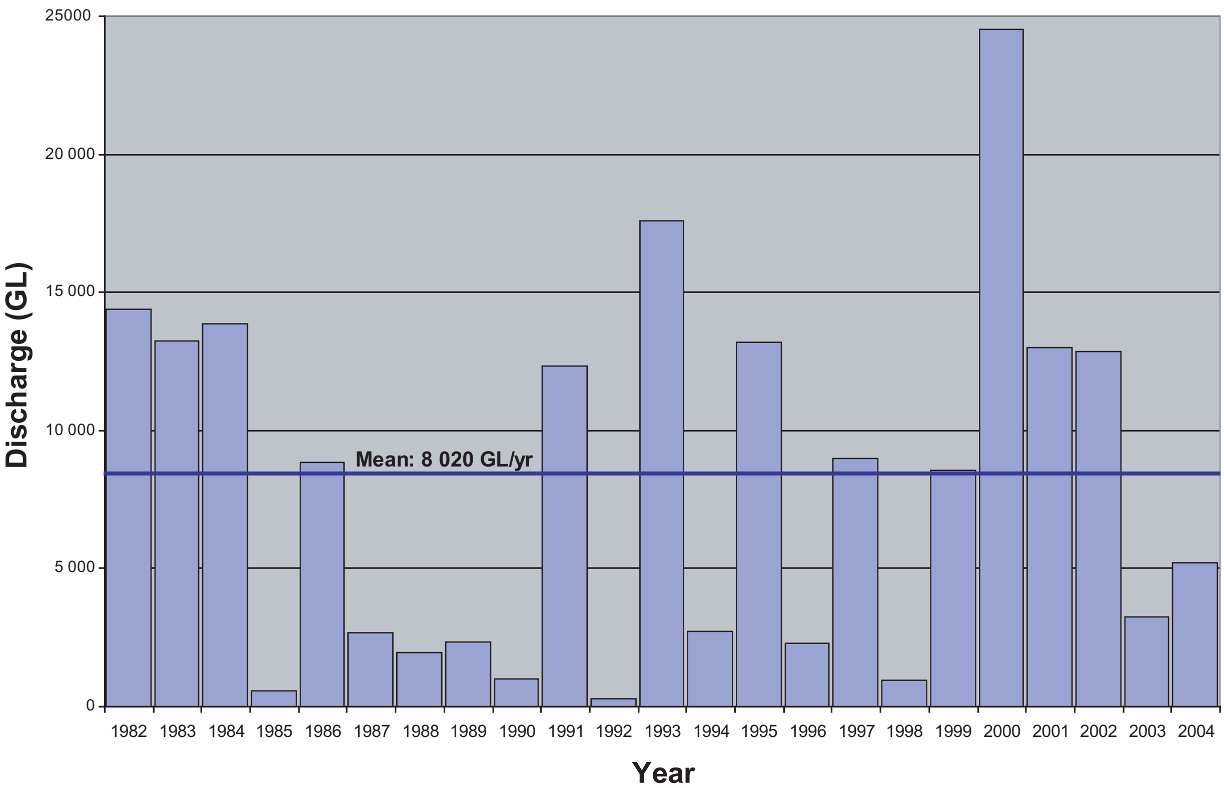

Figure 8. Fitzroy River annual discharge at Fitzroy Crossing (Station 802055)

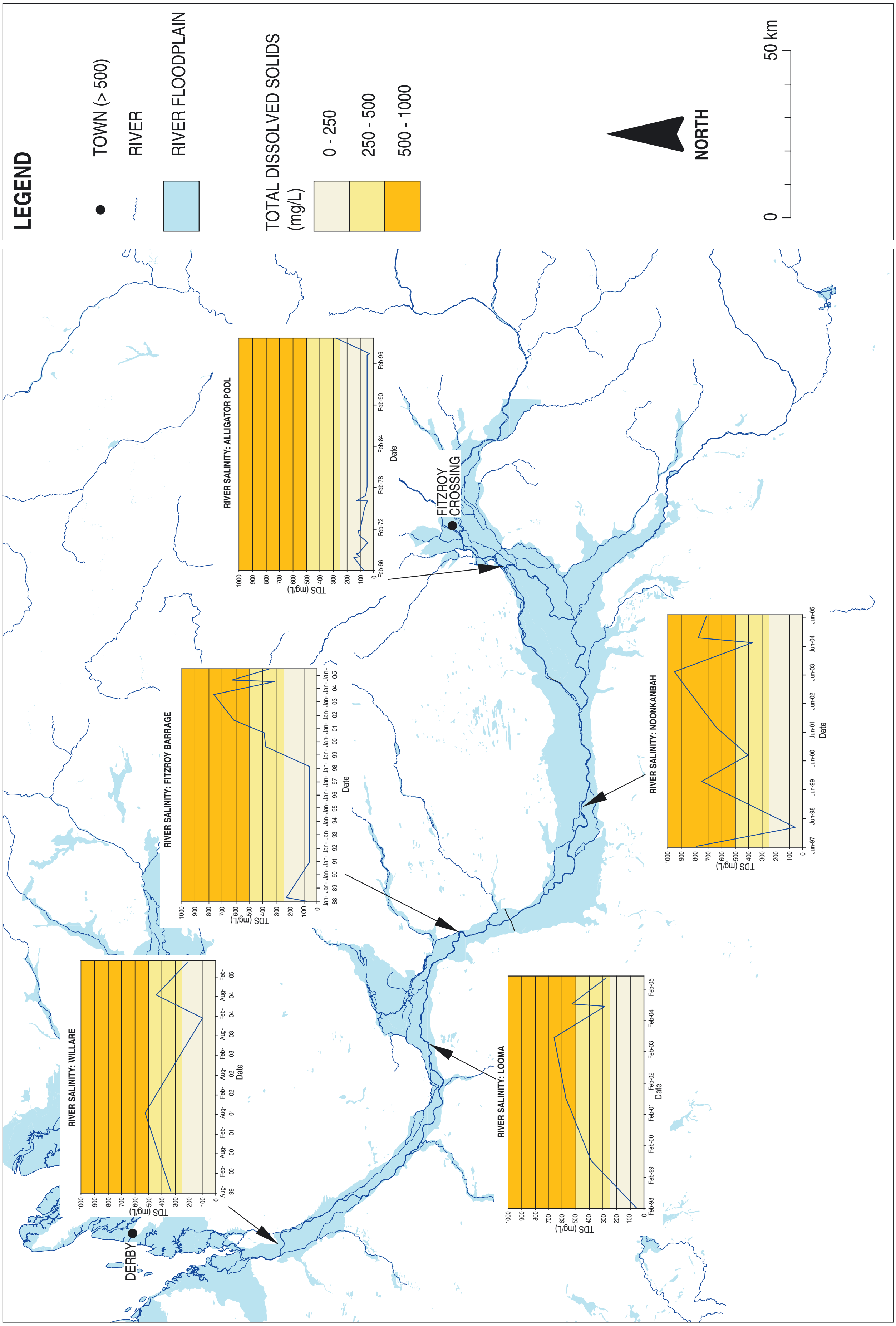

Figure 9. Fitzroy River salinity

The annual discharge of the Fitzroy River at Fitzroy Crossing ranges from 300 GL (1992) to almost 25 000 GL (2000). Figure 8 shows the annual discharge from 1982 to 2004.

2.2 Salinity

Salinity levels in the Fitzroy River have not been routinely measured; however, some records are available from five stations from 1996 to 2005. Figures 9 and 10 show wet season salinity levels of less than 250 mg/L, compared with dry season levels which range up to 900 mg/L. The river is fresh (< 500 mg/L) between Fitzroy Crossing and Noonkanbah, it is marginal (500–1000 mg/L TDS) between Noonkanbah and Myroodah, and fresh from Myroodah to Willare. Dry season salinity of the river water can be interpreted to reflect the salinity of the groundwater, as contribution from surface runoff is negligible and river flows are supported by baseflow. The brackish stretch of river at Noonkanbah may reflect the baseflow contribution both from the alluvial aquifer, and possibly from the Noonkanbah Formation, over which the river flows along that section. There may also be an influence of the Blina Shale upstream from Noonkanbah. As can be seen from the individual graphs at each of the five sampling points, the salinity of river water often exceeds the desirable potable water limit of 500 mg/L during the dry season, which, if a true reflection of the groundwater in the alluvial aquifer, may provide some constraints as a potable water supply source.

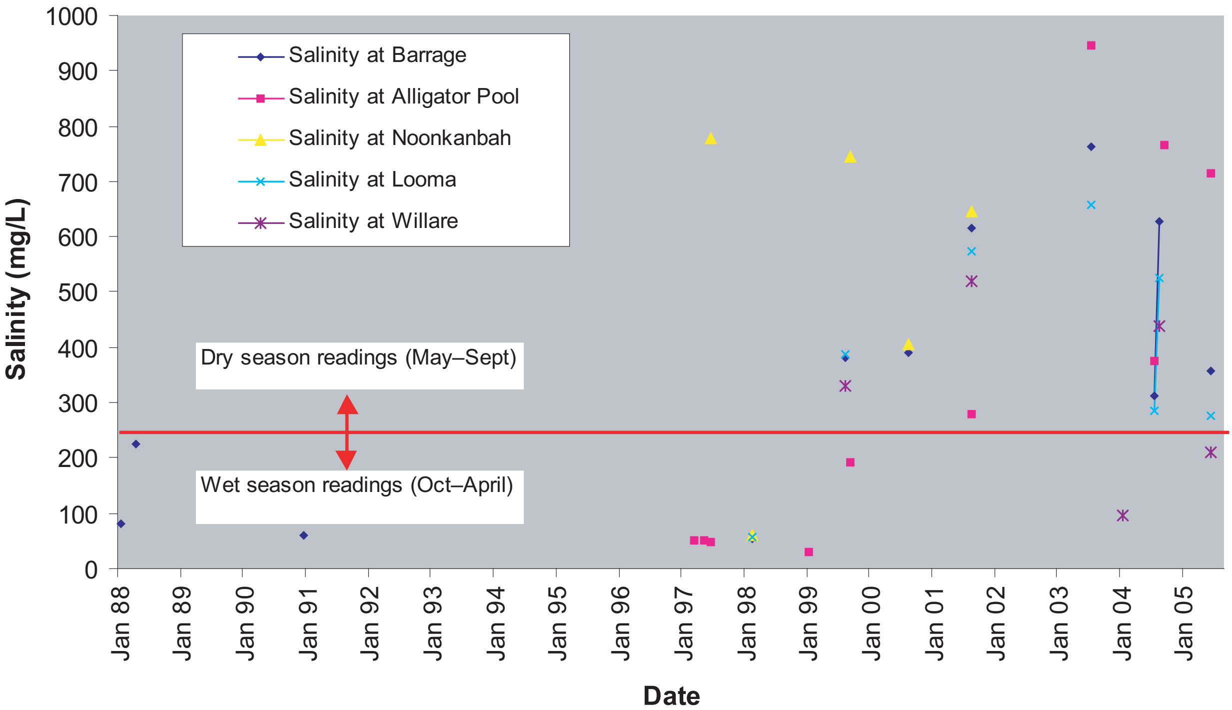

Figure 10. Comparison of wet and dry season salinity along Fitzroy River

3 Hydrogeology

3.1 Alluvium

3.1.1 Composition

Three drill sections, at Gogo, Willare and the Fitzroy Barrage, provide some indication as to the stratigraphic composition of the alluvial aquifer (Figure 11). The section at the barrage is a generalised section based on drilling in 1959 reconstructed from drawings and integrated with stratigraphic data from drill logs compiled by the Public Works Department. However, the drill hole locations appear to have been lost. The three sections, coupled with observations of the present river banks and bed, provide a picture of the stratigraphy of the alluvium.

The alluvium appears to be approximately 30 m thick, with a predominantly sandy/gravelly basal section about 20 m thick, overlain by approximately 10 m of silts and clays above the river bed level. This succession would indicate that the river is working back and forth within a wider alluvial valley, carving out its older deposits of sand and silt and depositing new deposits in approximately the same sequence. This is supported by Taylor (2000) who concluded that the bank erosion and channel migration are limited by stable channel banks, based on stratigraphic and geomorphic evidence. The sands and gravels within the alluvial plain are associated with the active river bed and channel, whereas the silts and clays are associated with floodplain and levee deposits. Cobbles in the river bed may be reworked from the Warrimbah Conglomerate. For this study, the alluvial plain has been measured as the area covered by an 'average' flood as mapped by Geoscience Australia.

3.1.2 Groundwater recharge

Recharge to the alluvial aquifer is from two main sources. The main source of recharge can be inferred to be from the river during the flood season. Flood water percolates downwards and laterally away from the river into the aquifer. Natural recharge is limited by the available storage of unsaturated sand/gravel. If the sand/gravel does not extend above river bed level, the aquifer is likely to be full, and there is not spare storage capacity of unsaturated gravels.

The second principal source of recharge is by groundwater discharging from regional aquifer systems of the Canning Basin, principally from the Liveringa Group, which underlies the greater part of the alluvium (Figure 7). Recharge from this source is likely to be greater during the dry season as potentiometric head levels in the alluvial aquifer fall, allowing the rate of inflow to increase.

3.1.3 Groundwater storage

The groundwater storage in the alluvium can be estimated from the volume of saturated sand/gravel. Based on an aquifer thickness of 20 m, a floodplain area of 3200 km^2

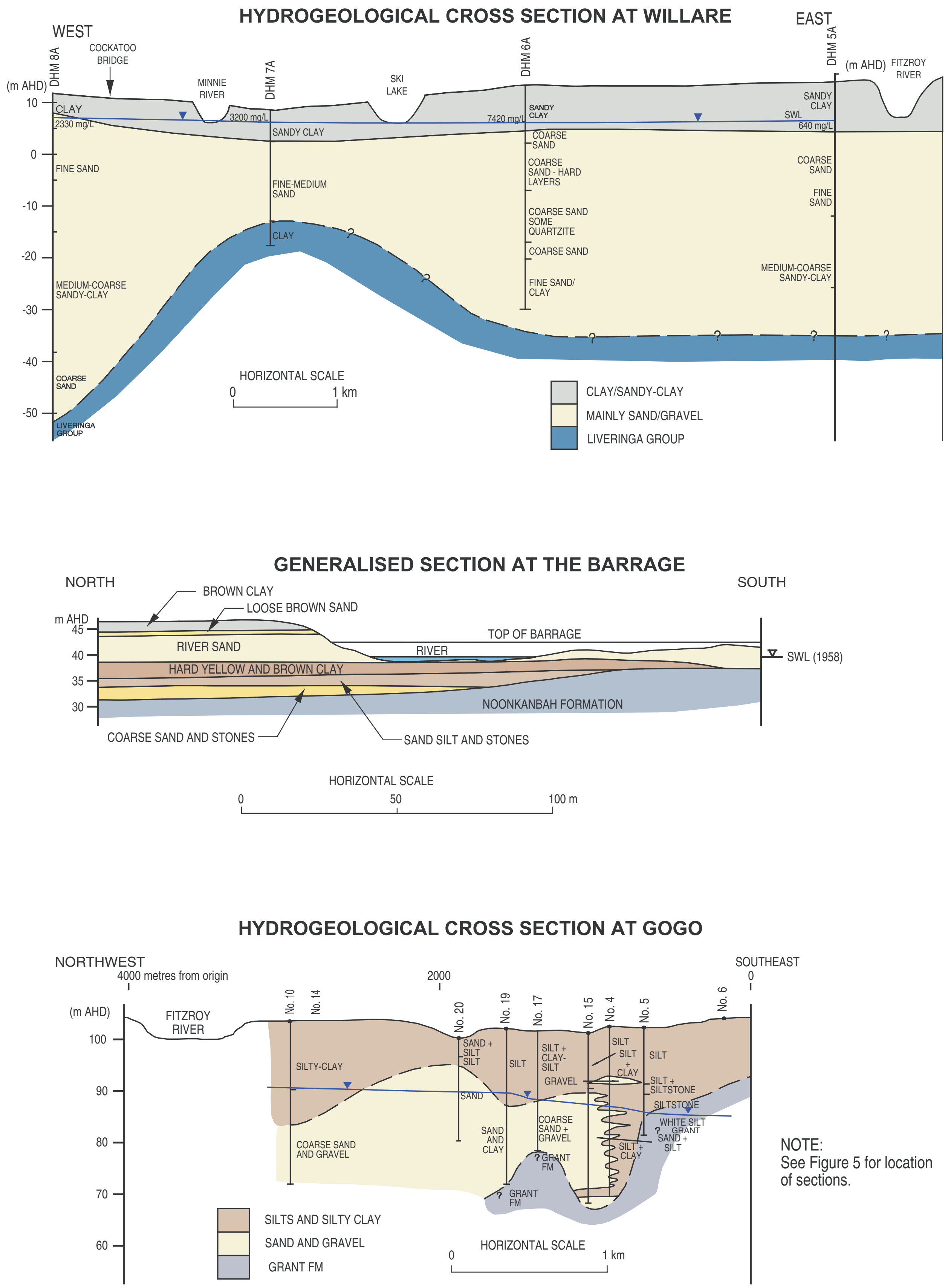

Figure 11. Hydrogeological sections at Willare, Fitzroy Barrage and Gogo

and a porosity of 0.2, the Fitzroy alluvium contains an estimated total groundwater storage of 13 000 GL. This represents 50 GL per kilometre length of the river. Of this groundwater in storage, a portion in the middle reaches around Noonkanbah is likely to have a salinity over 500 mg/L owing to ingress of brackish or saline groundwater from the sedimentary bedrock aquifers.

3.1.4 Groundwater salinity

Salinity in the alluvial aquifer has been measured only in the Western Australia Geological Survey's investigation bores at Willare Crossing (Smith, 1992), The salinity ranged from 690 mg/L (DHM5A), close to the main river channel, to 2910 mg/L (DHM8C) near Minnie River and Cockatoo Creek, which are stagnant and possibly tidal during the dry season.

Some indication of salinity in the alluvial aquifer in other areas might be gained from dry season river water salinities, as it is likely that most of the flow in the dry season is derived from groundwater baseflow. Comparison between wet season and dry season salinities (Figure 10) shows that wet season salinity is usually less than 250 mg/L (flood waters), whereas dry season salinity ranges from 250 to 950 mg/L. It is assumed that dry season flows are derived from groundwater baseflow, whereas during the wet season river water is almost entirely derived from surface runoff; thus, the salinity of the river may reflect the underlying salinity of the groundwater in the alluvial aquifer. Hence, the higher salinity inferred for the alluvium near Noonkanbah (Figure 12), based on the dry season river salinity, reflects the groundwater salinity in the underlying Noonkanbah Formation.

3.1.5 Groundwater surface water interaction

A model for the interaction between surface water and groundwater at the Fitzroy River is shown diagrammatically in Figure 13. During the wet season, flood water recharges the alluvial aquifer through the river bed, distributary channels and also through the floodplain. The alluvial aquifer receives limited recharge from the regional aquifers because the hydraulic head of water in the alluvial aquifer is greatest under flood conditions.

During the dry season the groundwater contributes base flow to the river bed, progressively declining until the river ceases to flow. Groundwater maintains water levels in the pools, but levels decline with increasing evaporation. The rate of groundwater level decline may reduce once the river bed dries up, owing to decreased evaporation, combined with increased flow from the regional aquifers.

3.2 Canning Basin aquifers

The major regional aquifers are the Grant Group (including the Poole Sandstone), the Liveringa Group, and the Wallal and Alexander Formations. These aquifers are composed predominantly of coarse sands with minor silt and claystone. These aquifers underlie the alluvial aquifer and discharge into it; hence, the salinity in the alluvium is affected by the salinity in the regional aquifers. The groundwater salinity distribution,

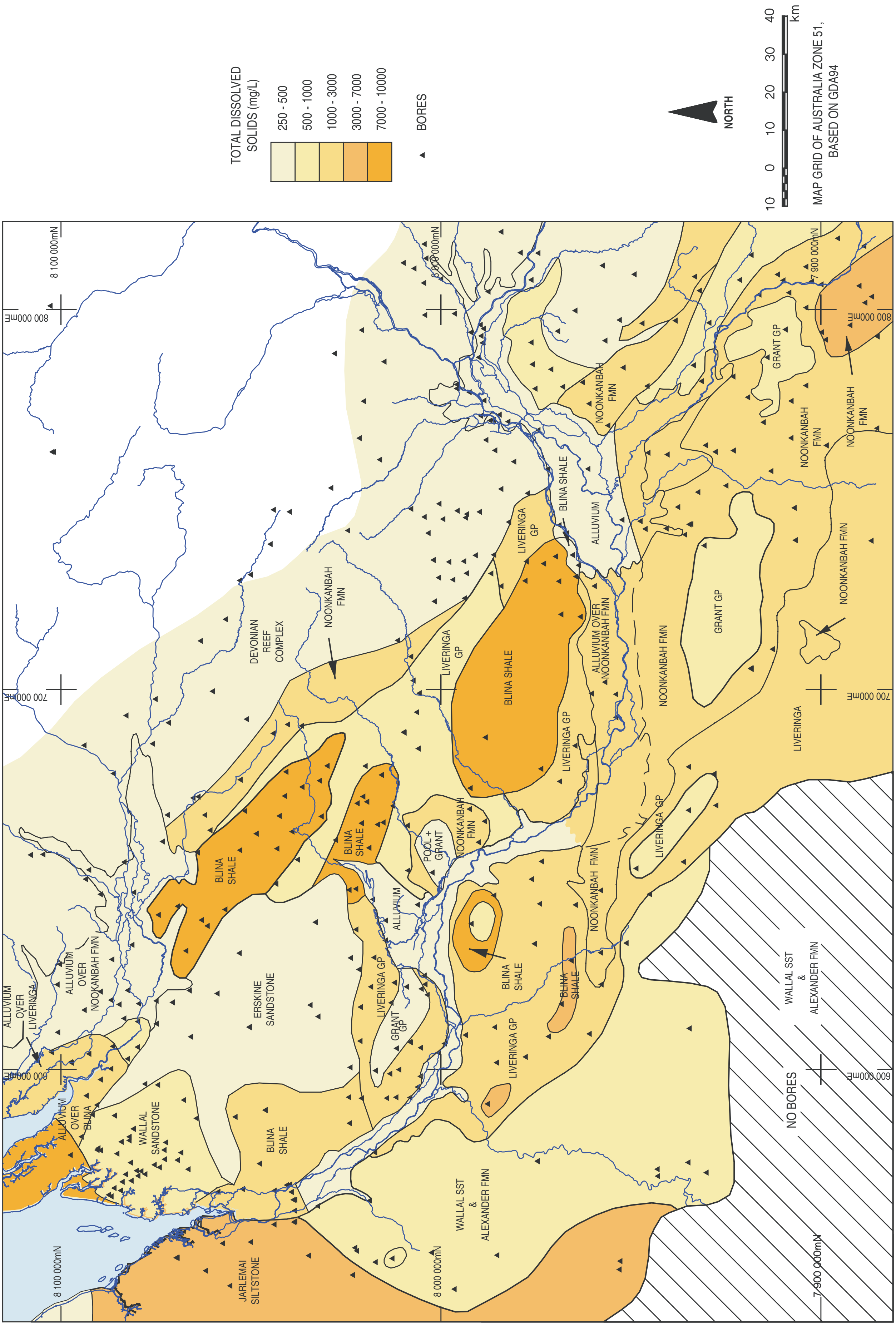

Figure 12. Groundwater salinity of the Fitzroy Area

mainly derived from pastoral bores (Figure 12), indicates low-salinity groundwater in the Wallal and Erskine Sandstones and in the sandstone aquifers of the Liveringa and Grant Groups, and brackish to saline groundwater in the Jarlemai Siltstone, Blina Shale, and Noonkanbah Formation.

3.2.1 Wallal Sandstone and Alexander Formation

The Wallal Sandstone and Alexander Formation consist of sandstone with minor siltstone, conglomerate and lignite. The formations are in hydraulic continuity and are therefore considered as a single aquifer.

The formations occur in the subsurface in the western part of the Fitzroy Catchment but outcrop only in small areas, including the west bank of the Fitzroy River at Langey Crossing. The maximum thicknesses of Wallal Sandstone (286 m) and Alexander Formation (219 m) occur in the Fraser River structure to the northwest of the Fitzroy River (Figure 5).

The Wallal Sandstone unconformably overlies the Triassic formations, is overlain conformably by the Jarlemai Siltstone in the west, and unconformably by Quaternary sediments elsewhere.

There are two discreet flow systems. The western flow system (Figure 5) is mainly confined beneath the Jarlemai Siltstone but it appears to be unconfined southwest of the Fitzroy River. Bores may flow on the low-lying silt plains bordering the coast.

The groundwater salinity in the western flow system is variable. In some areas near Udialla Homestead, where the flow system is unconfined, salinities are less than 1000 mg/L (Figure 9). Where the Wallal Sandstone is confined by the Jarlemai Siltstone salinities are about 2000 mg/L, and to the west of Willare (the Logue River) salinities are in the range 2800 to 3800 mg/L. The western flow system provides pastoral water supplies in the area southwest of the Fitzroy River.

3.2.2 Blina Shale

The Blina Shale consists mainly of dark grey-green shale and siltstone with minor sandy claystone and fine sandstone. The maximum thickness is 462 m in Kora 1 (Esso, 1983). The Blina Shale is a confining bed to the Liveringa Group. A few small, generally saline supplies have been developed from the Blina Shale in the Derby area, for example at bore 1/85, which obtained a supply of 100 m^3/day from the Blina Shale.

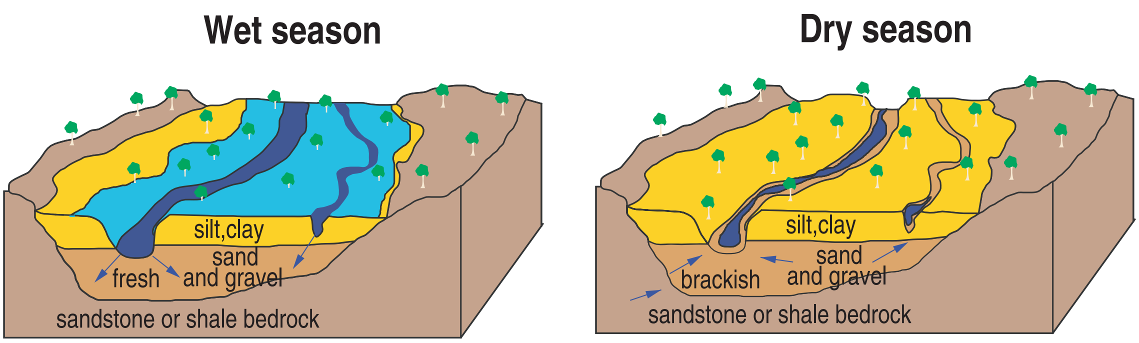

Figure 13. Conceptual model of the alluvial aquifer

Reported groundwater salinities are 1100 mg/L for Bore 1/85 at Willare Bridge Roadhouse but are in the range 7–10 000 mg/L in pastoral bores in other areas underlain by Blina Shale (Figure 13).

3.2.3 Liveringa Group

The Liveringa Group, comprising the Hardman and Lightjack Formations separated by the Condren Sandstone, consists of interbedded sandstones, siltstones and shales. The thickness of the Liveringa Group varies from 319 m in East Yeeda-1 (Bridge, 1986) to nearly 900 m (Crowe and Towner, 1981), although it is commonly about 600 m thick in the central part of the catchment area as intersected by coal exploration drill holes. The Liveringa Group lies conformably on the Noonkanbah Formation and is overlain disconformably by the Blina Shale and unconformably by the Wallal Sandstone. The Condren Sandstone is the best aquifer of the Group, but its distribution is limited to the western part of the area (Derby 1:250 000 map sheet area) and pinches out in the Noonkanbah 1:250 000 map sheet area.

Recharge occurs mainly from rainfall on areas of outcrop, and locally from surface runoff and leakage through alluvium in Le Lievre Swamp near the Fitzroy River east of Camballin (Figure 1). In the Grant Range area, groundwater flow is westward and discharge may take place through the alluvium to Lower Liveringa Pool. Groundwater may discharge to the Fitzroy River alluvium south of bore DHM 7 (Figures 1 and 11) and there may be upward leakage into the overlying Wallal Sandstone west of Fitzroy River. In the northeast, groundwater probably flows in a northwesterly direction and discharges into the Meda River (Figure 1).

The groundwater salinity in the Liveringa Group is generally marginal to brackish (500–3000 mg/L). Low-salinity groundwater is present in the aquifer near Le Lievre Swamp possibly because of recharge from the floodwaters. Groundwater salinity increases westwards towards Willare, where it is 7000 mg/L in bore DHM 8 (Figure 11). Salinities probably vary with the nature of the formation in which the bore is screened, being fresher in sandstone members than those screened in shale or siltstone members.

3.2.4 Noonkanbah Formation

The Noonkanbah Formation, consisting of siltstone, limestone and minor sandstone, has a wide distribution over the study area but is very poorly exposed. It does outcrop in the river at Noonkanbah Crossing where it is composed of fine sandstone, siltstone and shale. The formation ranges between 310 and 415 m thick and is a poor aquifer. The few pastoral bores that appear to produce from the formation are mostly brackish to saline (Figure 12).

3.2.5 Poole Sandstone and Grant Group

The Poole Sandstone and the Grant Group are considered hydrogeologically similar as they are composed predominantly of sandstone and are good aquifers. They are the

Figure 14. Landsat (TM) image of Fitzroy River with recommended drill traverses and targets

oldest rocks known in the area and are found in anticlinal structures and towards the northeast, at Gogo and Fitzroy Crossing.

Recharge can be inferred to take place in the outcrop areas of the Grant and St Georges Ranges, and on the northern margin of the basin, but elsewhere the aquifer is confined by the Noonkanbah Formation, so the mechanism for groundwater discharge is unknown.

Groundwater salinity in the Grant Group and Poole Sandstone is lowest on the northern margin (300 mg/L at Ellendale) but is usually in the range 500–2000 mg/L elsewhere. Geophysical logs of oil exploration wells indicate low salinity persisting at depth.

The thickness and widespread distribution make the aquifer potentially important. Bore yields of 2000 m^3/day have been achieved at Ellendale, and 500 m^3/day for Fitzroy Crossing town water supply. Because the formations mainly outcrop only in rugged areas within the Fitzroy catchment, there are few bores.

4 Groundwater resource potential

4.1 Environmental factors

The alluvial aquifer supports dry season river flows and permanent pools in the main channel, which persist until the commencement of wet season river flows. The aquifer may also support pools away from the main channels, such as Liveringa Pool. The pools in the dry season represent the only permanent water source for terrestrial, aquatic and avian wildlife, and they also support fringing vegetation. The river and pools are culturally significant for the local communities. Under the Environmental Water Provisions Policy for Western Australia (Water and Rivers Commission, 2000), provision must be made for the protection of water-dependent ecosystems, while allowing for the management of water resources for their sustainable use and development to meet the needs of current and future users. The sustainable yield for consumptive use has to account for the Ecological Water Requirements (EWRs), which are water regimes required to maintain the ecological values at a low level of risk. EWRs have not been formally determined nor have Environmental Water Provisions been set. The Department of Water has commenced the determination of EWRs with the report on environmental values of the Fitzroy River system (Storey et al., 2001).

Storey et al. (2001) found that the general ecological variety and health of the riverine ecosystem is good, despite unrestricted stock access. The authors reported diverse fish fauna containing species endemic to the Kimberley and to the Fitzroy. Waterbird usage of the floodplains, particularly Camballin, is listed with Ramsar and several species are protected under international agreements.

Storey et al. (2001) also evaluated the potential effects on the ecology of interrupting the flooding (by damming the river). They found that reduced energy flows could lead to infilling of pools, and terrestrialisation of vegetation. This would also reduce stimuli for spawning runs and return migrations, and change the balance between vertebrate and invertebrate communities. Interruption of floods would reduce the suitability of the floodplain as a habitat for water birds, and reduced flushing of the estuary would increase the erosion rate of the mangroves and reduce the wet–dry season changes in salinity, with corresponding changes in the variability of aquatic fauna.

Toussaint et al. (2001) emphasised that indigenous groups have expressed their dependence upon the river and the cyclical relationship of water, such as importance of the warramba, or annual flood which cleans out the river system. The importance of water to local indigenous people is communicated by knowledge exchange, song, stories and film, and traditional owners constantly reaffirm that the Fitzroy Valley rivers, waters and riverine resources are central to their lives. Some communities supplement their food sources by fishing and gathering aquatic fauna.

There is also a deeply felt feeling among local communities that any controls on the natural flows or water level reduction induced by groundwater abstraction will negatively alter traditional food sources that some communities still rely upon (Toussaint et al., 2001). The indigenous communities consider permanent pools in the Fitzroy as 'living water'. Ecologically, permanent pools are important refuges for aquatic species enabling them to survive the harsh dry season. Therefore, any process which impacts on pools (eg infilling by sediment or lowering of water levels by abstraction) can have substantial impacts on fauna. The traditional owners emphasised that infilling made pools unsuitable for fishing and that floods are critical to flush these pools and 'cleanse the country'. Overall, there is a clear linkage between ecological and cultural values of specific freshwater habitats, particularly the permanent pools.

In summary, if groundwater from the Fitzroy alluvial aquifer is to be used, there should be limited impact upon the groundwater level in the active channel and perennial pools. Although any abstraction in the alluvial aquifer will affect the groundwater levels to some extent, the ecological balance in and around perennial pools should be maintained as well as access to shallow groundwater in the river bed for animals that depend upon digging for water during the dry season.

4.2 Groundwater potential

The alluvium has the potential to be replenished each year as it is recharged by direct infiltration from the river bed when the river is flowing. Recharge from the river is limited by the amount of river flow in low-flow years; the minimum annual flow on record is 300 GL. In the natural condition, recharge may also be limited by the available storage capacity of unsaturated aquifer.

Constraints on consumptive use of the aquifer in the wet season while the river is flowing would be minimal, except in low-flow years, as there is a need to maintain flow to King Sound. The aquifer could be used essentially as a filter for river water, avoiding the need to settle the high sediment load and turbidity, if bores could be sited and maintained in a floodplain environment.

There may be greater potential to utilise the aquifer if there are parts of the gravel aquifer which are not well connected to the river bed, such as those which can be pumped in the dry season without affecting the pools in the main channel, but which have sufficient connection with floodways to be recharged in the wet season. Such conditions would have to be determined by a comprehensive drilling program. Pumping could be possible from bores sited away from the river, using aquifer water to artificially maintain flows and pool levels.

If the aquifer were to be utilised, recharge could be artificially enhanced by raising the river level, as has occurred at the Fitzroy Barrage, which would increase the hydraulic gradient and hence the rate of groundwater flow into the aquifer. A conjunctive use could consist of a series of barrages from which surface water could also be drawn. However, there may be strong environmental and social–cultural reasons against this proposition, as outlined by Storey et al. (2001) and Toussaint et al. (2001).

For any proposed groundwater pumping, an objective of borefield design would be to pump the aquifer distant from the river, minimising impacts close to the river. In the wet season, bores might also be pumped close to the river to maximise infiltration.

4.3 Groundwater flow modelling

In order to assess the likely drawdown at the river from a borefield in the alluvium, a 3-D finite difference groundwater flow model to represent the Fitzroy River alluvium was developed using the GMS-Modflow package. The model area covered a 15 km width of aquifer over a 10 km length of the river. A 1000 m × 1000 m square model grid was used to represent the area. The alluvium was represented by two model layers, the upper layer being the silty floodplain deposits, whilst the lower layer represented the more transmissive river bed sand and gravel. A horizontal hydraulic conductivity of 1 m/d and a leakance of 0.01 L/d were adopted for the upper layer. The lower layer was given a transmissivity of 300 m^2/d, representing a 30 m thickness of aquifer with a hydraulic conductivity of 10 m/d. The Fitzroy River was represented by the Modflow River Package to allow both groundwater recharge from the river during the high flows and the discharge to the river from the river during low flows. The hydraulic conductance of 1000 m^2/d per unit length of the river adopted for the river bed was based on an assumption of 10 m/d for the hydraulic conductivity and about 100 m width of the river.

The pumping scenario comprised one bore per kilometre stretch on one side only of the river. Pumping was applied only to the bottom sandy layer and was varied seasonally, with higher pumping in the wet season (Figure 1 in Appendix 1). The model was run in transient mode for 10 years and the final watertable was compared with the watertable from a base case (no-pumping scenario) to obtain net drawdowns. The drawdown contours were constructed using Surfer (Figures 2–5 in Appendix 1) for average pumping rates of 1000 and 2000 kL/d from each bore. Drawdowns at the river bed of 0.4 to 0.5 m resulted from the pumping, and were considered to be the likely upper acceptable range. However, detailed environmental impact studies are required before any acceptable drawdown can be determined.

The modelling therefore shows that pumping rates of 2000 m^3/day per kilometre could theoretically be achieved from a borefield on one side of the river, with a drawdown of only 0.5 m at the river bed at the end of the dry season. This represents a total abstraction of 200 GL/yr for the entire 275 km length of river alluvium.

5 Conclusions

Existing drilling data indicate that the alluvial aquifer along the Fitzroy River consists of a basal 20 to 30 m of cobbles, gravel and sand, overlain by overbank deposits consisting of approximately 10 m of silt and clay. The alluvium between Fitzroy Crossing and Langey Crossing has a large groundwater storage of approximately 13 000 GL.

The alluvial aquifer receives most of its recharge from the river during the flood season, and is also a discharge area for regional aquifers in the Canning Basin. Baseflow from the aquifer supports dry season flows and permanent pools. The alluvial aquifer is probably almost fully saturated throughout the year with water levels in the aquifer falling by a small amount during the dry season.

The aquifer is highly transmissive and groundwater levels would likely fall by approximately 0.5 m adjacent to the active river channel in the dry season if 200 GL/yr were abstracted from regularly spaced bores along the aquifer. The potential environmental impacts of a fall in the groundwater level by this amount could considerably alter the balance of the ecosystem.

The ultimate yield of groundwater from the alluvium is limited by the flow of the Fitzroy River, which is as low as 300 GL/yr. The constraint on utilising groundwater storage in a low-flow year is the need to maintain river pools. Preliminary groundwater flow modelling indicates that a yield of 2000 m^3/day per kilometre length of the river could be obtained for a drawdown of around 0.5 m in the river bed at the end of the dry season. Extrapolated along the entire length of the river, this represents a yield of 200 GL/yr from the 275 km of alluvium.

The salinity in the alluvial aquifer is only partially understood. Indications from dry season river flows are that parts of the alluvium contain groundwater of salinity exceeding 500 mg/L, partially as a result of discharge from the underlying regional aquifers.

Prospects for a large, sustainable groundwater source would depend upon there being parts of the alluvial aquifer that can readily be recharged but have limited hydraulic connection with river pools, so that any abstraction impacts would be localised. Given the variable nature of the alluvium, substantial exploration will be needed to locate suitable conditions.

6 Recommendations

The conclusion that the river alluvium has the potential to supply up to 200 GL/yr of water under normal flood conditions from evenly spaced bores along the entire length of the river is a theoretical proposition, based on very limited data. A practical borefield location would require a comprehensive exploration program to look for stretches of abandoned river gravels or sediments at tributary confluences that have seasonal recharge but mitigated hydraulic connection with the permanent pools. To assess both the hydraulic parameters of the river alluvium and the groundwater resource potential for the Fitzroy alluvium, the following field investigations are required:

1. Trial the use of transient electromagnetic techniques to map the thickness and distribution of the alluvium. As the environment is fresh water, an appropriate technique is required.
2. Drill investigation bore traverses in accessible areas across the river (as shown in Figure 14) to establish the thickness and characteristics of the alluvial aquifer, and the groundwater salinity and chemistry.
3. Determine the response over a year of groundwater levels to river flow events, and determine the seasonal change in storage in the sand/gravel aquifer.
4. Construct and test pump a bore to determine the likely bore yield, and to determine through observation bores the transmissivity of the aquifer. This will aid the modelling of impacts of abstraction on the river bed.
5. Establish ecological water requirements for the riverine environment of the Fitzroy River as part of the study to determine sustainable yield for the alluvial aquifer.

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Glossary

abstraction	removal of water by pumping from an aquifer.
aquiclude	a geological material, stratum, or formation that contains water (ie has porosity) but does not transmit it (ie has zero or negligible permeability).
aquifer	a consolidated or unconsolidated geological unit (material, stratum, or formation) or set of connected units that yields a significant quantity of water of suitable quality to wells or springs.
confined	an aquifer that that is immediately overlain by a low-permeability stratum, such that the aquifer is fully saturated
unconfined	an aquifer the upper surface of which is a watertable at atmospheric pressure.
aquifer system	intercalated permeable and poorly permeable materials that comprise two or more permeable units separated by aquitards, which impede vertical groundwater movement but do not affect the regional hydraulic continuity of the system.
drawdown	the drop in potentiometric head, or elevation of watertable, from the initial head, caused by pumping from a well or set of wells.
head	fluid mechanical energy per unit weight of fluid, which correlates to the elevation that water will rise to in a well.
potentiometric surface	a surface of equal hydraulic heads or potentials, typically depicted by a map of equipotentials such as a map of watertable elevations.
pumping test	one of a series of techniques to evaluate the hydraulic properties of an aquifer by observing how water levels change with space and time when water is pumped from the aquifer.
storage	water contained within an aquifer.
transmissivity	the discharge through a unit width of the entire saturated thickness of an aquifer for a unit hydraulic gradient normal to the unit width. Sometimes termed the coefficient of transmissibility.
unsaturated	the condition when the pores of a rock or soil are not fully filled with water.

watertable	a surface at or near the top of the phreatic zone (zone of saturation) where the fluid pressure is equal to atmospheric pressure. In the field this is defined by the level of water in wells that barely penetrate the phreatic (saturated) zone.
well yield	the discharge of a well at (nearly) steady flow.

Appendix 1

Groundwater modelling
by S. Varma

A 3-D finite difference groundwater flow model to represent the Fitzroy River alluvium was developed using the GMS-Modflow package. The model area covered a 15 km width of aquifer over a 10 km length of the river. A 1000 m × 1000 m square model grid was used to represent the area. The alluvium was represented by two model layers: the upper layer represented the silty floodplain deposits, and the lower layer represented the more transmissive river bed sand and gravel. A horizontal hydraulic conductivity of 1 m/d and a leakance of 0.01 L/day was adopted for the upper layer. The lower layer was given a transmissivity of 300 m^2/day, representing a 30 m thickness of aquifer with a hydraulic condutivity of 10 m/day. The Fitzroy River was represented by the Modflow River Package to allow both groundwater recharge from the river during the high flows and the discharge to the river from the river during low flows. The hydraulic conductance of 1000 m^2/day adopted for the river bed was based on an assumption of 10 m/day for the hydraulic conductivity and 100 m width of the river.

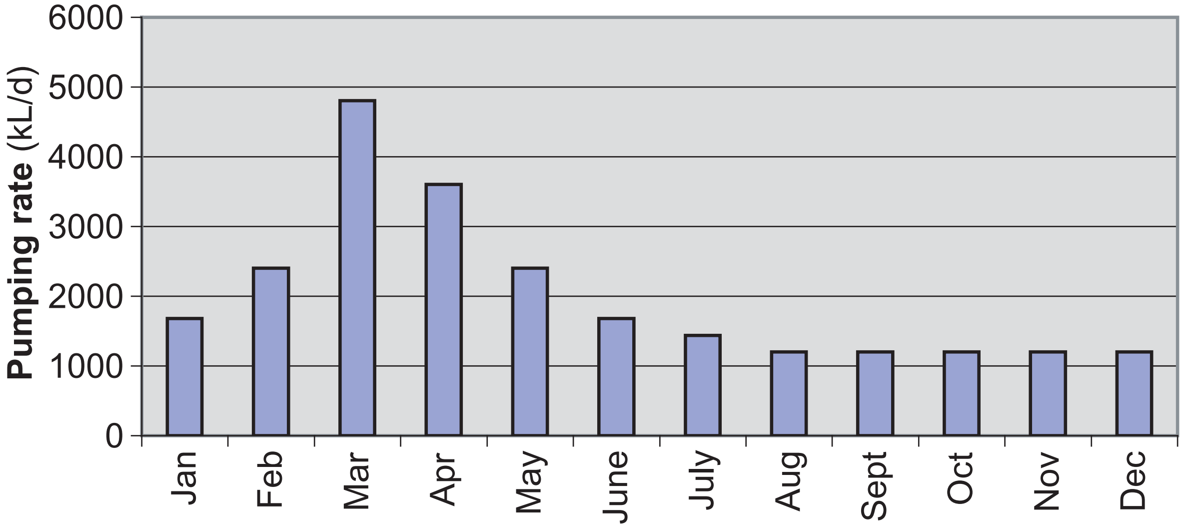
The pumping scenario comprised one bore per kilometre stretch on one side only of the river. Pumping was applied only to the bottom sandy layer and was varied seasonally (Figure A). The model was run in transient mode for 10 years and the final watertable was compared with the watertable from a base case (no-pumping scenario) to obtain net drawdowns. The drawdown contours were constructed using Surfer (Figures B–E) for average pumping rates of 1000 and 2000 kL/d from each bore. Drawdowns at the river bed of 0.4 to 0.5 m resulted from the pumping, and were considered to be the likely upper acceptable range.

Two pumping scenarios were selected and run in Modflow:

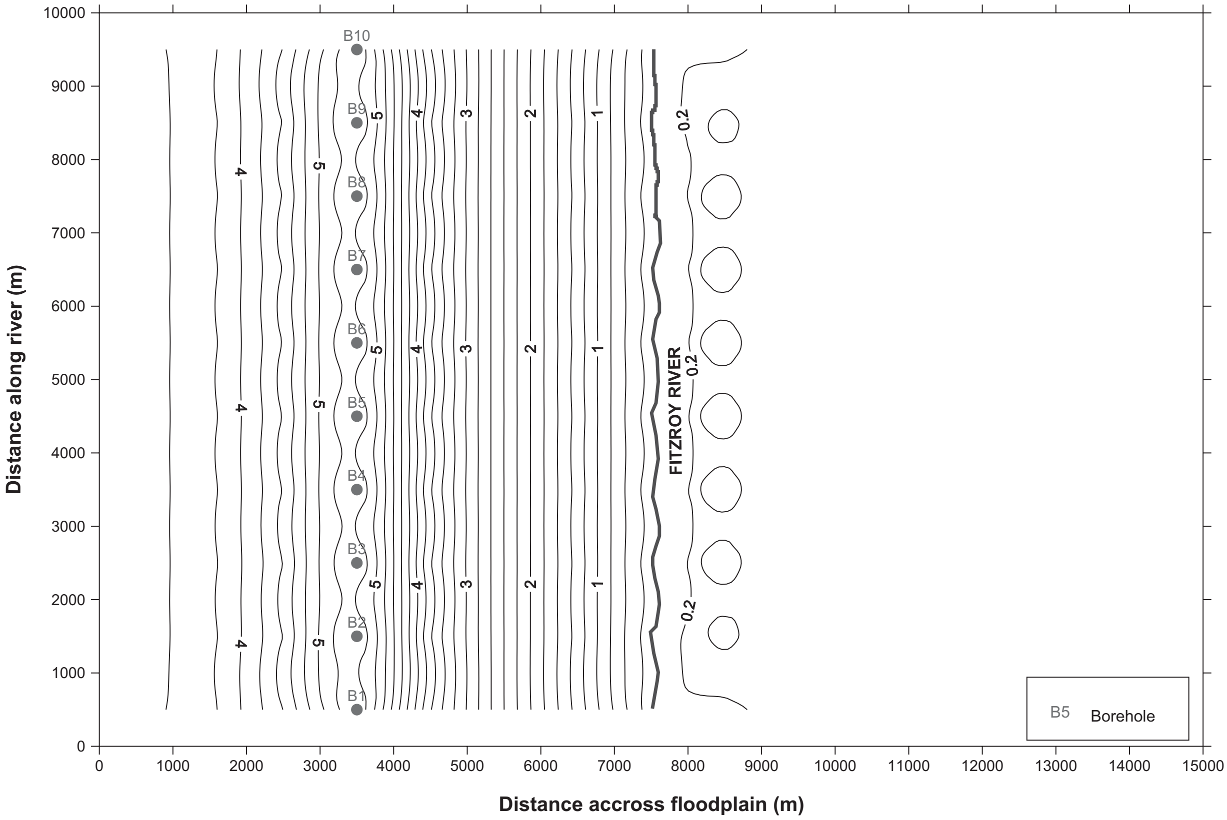
1. Average pumping rate of 1000 kL/day for 12 months for 10 bores spaced at 1 km centres along the alluvial plain, approximately 4 km from the river.
2. Average pumping rate of 2000 kL/day for 12 months for 10 bores spaced at 1 km centres along the alluvial plain, approximately 4 km from the river.

Figures B to E show two time snap shots for each pumping scenario corresponding to the end of the wet season (March) and the end of the dry season (November).

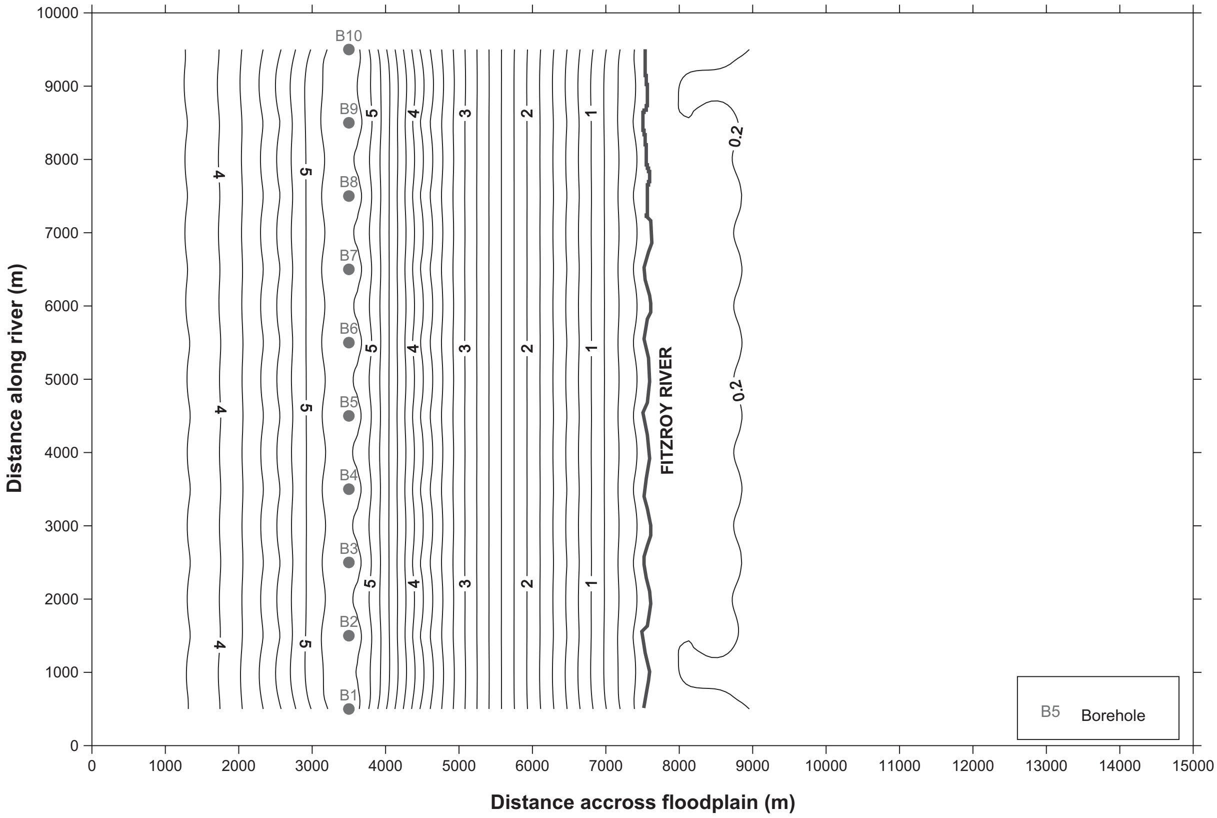
The pumping rate was scheduled to complement the season, with lower pumping rates during the dry season and higher rates during the wet season. The pumping schedule for 2000 kL/day average is shown in Figure A.



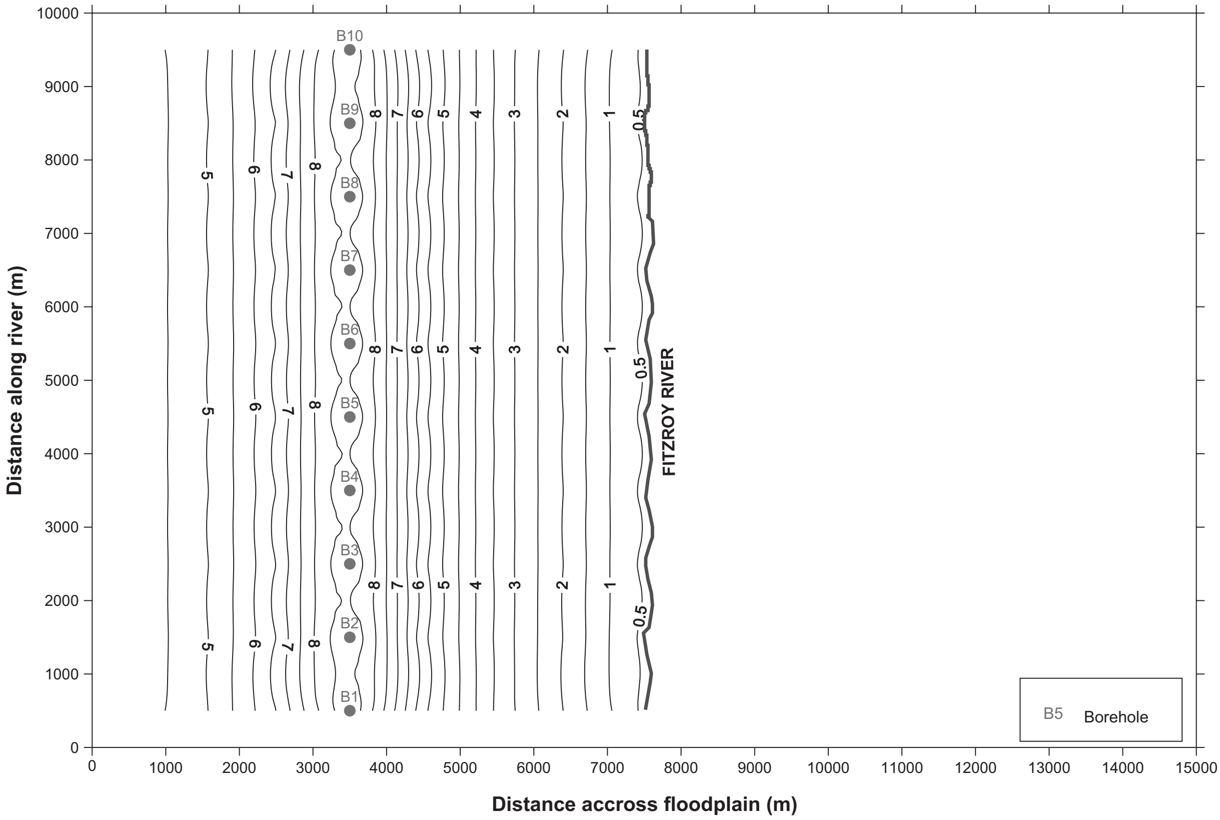
Appendix 1: Figure A. Pumping schedule for an average of 2000 kL/d over 12 months



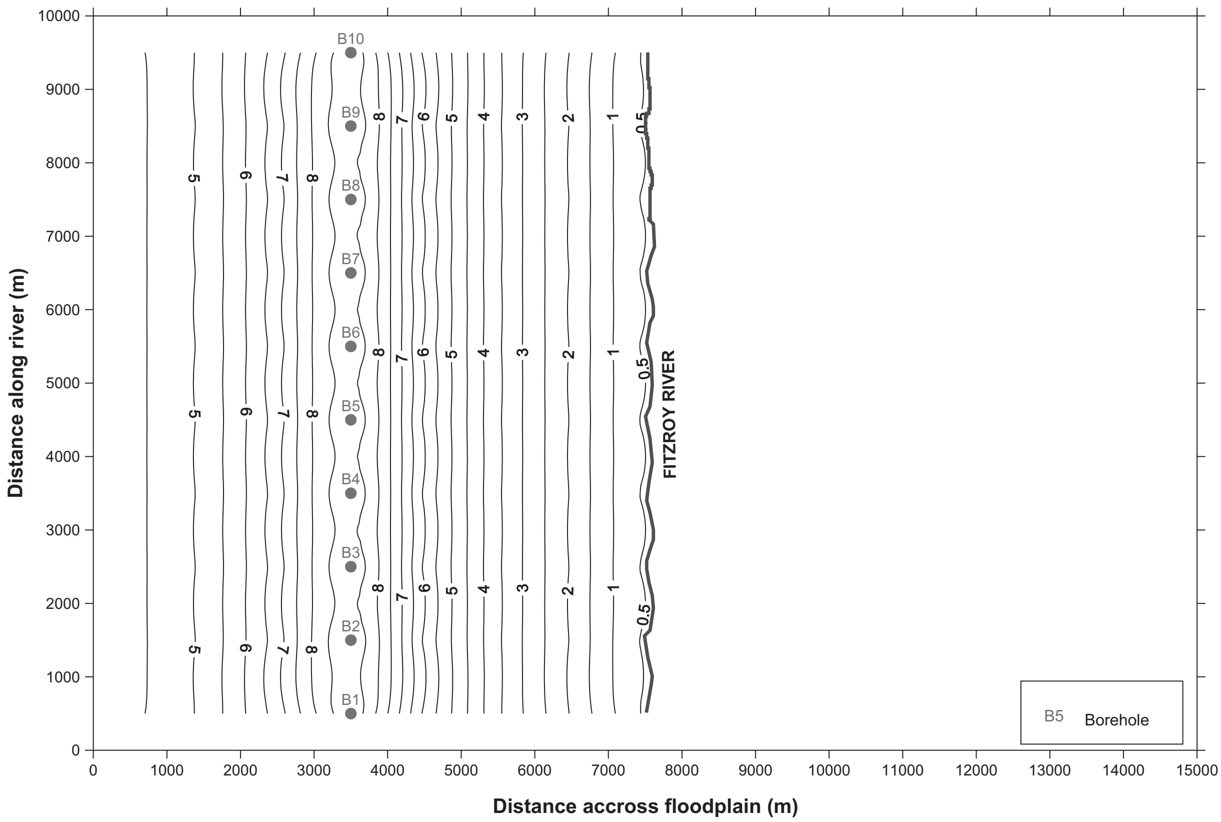
Appendix 1: Figure B. Fitzroy River—Abstraction model for 1000 kL/d (March)



Appendix 1: Figure C. Fitzroy River—Abstraction model for 1000 kL/d (November)



Appendix 1: Figure D. Fitzroy River—Abstraction model for 2000 kL/d (March)



Appendix 1: Figure E. Fitzroy River—Abstraction model for 2000 kL/d (November)

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S HG 2	Groundwater resources of the Northern Goldfields, Western Australia	Johnson, Seth L.; Commander, D. P.; O'Boy, Christopher A.;	Groundwater; Bores (water); Water resources; Goldfields and Agricultural Water Supply; Goldfields; Hydrogeology;	Perth: Water and Rivers Commission	1999	Hydrogeological Record Series	HG 2
S HG 3	Hydrogeology of the Swan Coastal Plain between Cervantes and Leeman, Perth Basin	Kern, A. M.;	Hydrogeology; Cervantes; Leeman; Swan Coastal Plain; Groundwater;	Perth: Department of Environment	2005 [1997]	Hydrogeological Record Series	HG 3
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S HG 5	Hydrogeology and groundwater resources of Collie Basin, Western Australia	Varma, S.;	Hydrogeology; Groundwater; Collie; Bores (water); Monitoring; Electrical power supply; Collieries; Coal;	Perth: Water and Rivers Commission	2002	Hydrogeological Record Series	HG 5
S HG 6	Hydrogeology of the Blackwood River catchment, Western Australia	Ye, L.; Smith, R. A.; Rutherford, J. L.; De Silva, Jayath;	Hydrogeology; Groundwater; Blackwood River; Soil salinity; Salinity; Hydrographic surveys;	Perth: Water and Rivers Commission	2001	Hydrogeological Record Series	HG 6
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S HG 16 This report	Hydrogeological assessment of the Fitzroy Alluvium	Department of Water; Lindsay, R. P.; Commander, D. P.	Groundwater; Groundwater resources; Water quality;	Perth: Department of Water	2006	Hydrogeological Record Series	HG 16

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