Government of **Western Australia**
Department of **Water**

Australian Government
Water for the Future

The Pilbara coast water study

Hydrogeological record series

Looking after all our water needs

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By T. Haig

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Cover Photo: Fortescue River Bridge on the Great Northern Highway by Hazli Koomberi on the 12 February 2009 - a few days after an intense low pressure system had caused heavy rainfall with flood waters going over the bridge.

For more information about this report, contact:
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Summary

The *Pilbara coast water study* is a source review of all groundwater, surface water and supplementary supply options in support of the region's coastal supply schemes. The study highlights the most potential groundwater supply options for development in the near future.

The study area extends from the Carnarvon Basin to the West Canning Basin along the Pilbara coast and extends inland approximately 100 km to include the Millstream Borefield (Figure 1). The study focuses on the three main port facilities associated with Onslow, Dampier and Port Hedland.

Potential groundwater supplies that may be viable for future development are shown in Figure 2. A summary of the options recommended for further investigation is provided in Table 1. The potential yields shown below are approximations based on hydrogeological assessments and do not include provisions for environmental, social and cultural requirements.

Table 1. Potential supply options

Supply scheme	**Overall supply and demand**	**Options**	**Potential yield (GL/yr)**
West Pilbara	Development of a **new 5 GL** source is needed	Lower Fortescue R. alluvium	10
		Upper Harding fractured bedrock	6 (low reliability estimate)
		Maitland River alluvium	Unknown
		George River alluvium	Unknown
		West Pilbara desalination scheme	Demand equivalent
Port Hedland	**New source** likely to be needed in **five years**	West Canning Basin (fresh/brackish portion)	20 (19)
		Turner River (fresh/brackish portion)	<1 GL(unknown)
		De Grey River (Bulgarene Borefield)	3–6
		Yule River (licence increase to 8.5 GL/yr)	2
Onslow	**No immediate need** for new source	Cane R. borefield expansion	Unknown
		Lower Robe River	10

This study was undertaken as part of the development of the *Pilbara regional water plan*. It includes a comprehensive review of the region's existing Water Supply Schemes and infrastructure, and other potential water resources. An appraisal of the overall prospects for supply is presented, as well as potential sources of supplementation to the existing supply schemes. The following general conclusions can be made:

- **Further development** of groundwater resources in the Pilbara coastal region is required to meet projected demand: with the expansion of mining and industry, more water will be required for ore processing and handling. Current water resources are likely to be insufficient to meet long-term demand.
- **Desalination** is an important option because it is independent of climatic variation and is not susceptible to drought. In addition, locally sourced natural gas could be an economically viable source of energy.
- Supplementing existing water-supply schemes by conveying **water from the Kimberley** is not cost-effective when compared with developing groundwater sources and desalination.
- Currently-used groundwater resources have an associated level of uncertainty in regard to **aquifer reliability**. This is primarily due to the infrequency of groundwater recharge events.
- **Surface water** development in the Pilbara is not viable due to complications related to cultural and environmental impacts. The Harding Dam, though currently supplying significant water to the West Pilbara Water Supply Scheme, is subject to these constraints.

A desktop review of potential and existing groundwater resources has been undertaken. Most of the work is based on published investigations and provides a good baseline appraisal of the hydrogeology. The yields reported below do not take into account provision for environmental, social and cultural requirements. The allocation of water from all aquifer systems described below will require further work to define sustainable levels of use consistent with current sustainability guidelines. The following conclusions are made regarding potential supply options for each of the three coastal supply centres:

West Pilbara Water Supply Scheme

- The **Lower Fortescue River** alluvium is a well-documented resource with early estimates of potential yield about **10 GL/yr**. A sustainable yield is probably much less than this: further work to assess possible environmental factors will be required.
- **Fractured bedrock** aquifers associated with the Sholl shear zone in the vicinity of the Upper Harding River have been explored in three locations. Estimates of total potential yield from the three sites range from **3–6 GL/yr**, however significant work is required to prove up the resources.
- Minor groundwater resources associated with the **Maitland River and George River** areas have been identified. The resources are limited and have not

been extensively investigated. The resources may have some potential as supplementary sources and future assessment work is warranted.

- The **Millstream Aquifer** system has been extensively investigated through drilling and test pumping, and is used conjunctively with the Harding Dam as the West Pilbara Water Supply Scheme. It has yielded **4 GL/yr** during drought periods without significant falls in aquifer levels. However, yields at about **9 GL/yr** have been problematic, while yields at **14–15 GL/yr** have resulted in significant falls in aquifer levels. Due to the significance and sensitivity of the dependent ecosystems, the aquifer is managed using a number of criteria including mean minimum aquifer levels and rates of decline. When necessary, supplementation to maintain pools and springs is required. A numerical groundwater model has been developed for the aquifer to assess impacts, but this requires further work.

Port Hedland Water Supply Scheme

- The **West Canning Basin** represents a significant groundwater resource. Water quality is variable within both the **Wallal Sandstone aquifer** and the overlying **Broome Sandstone aquifer**. The total groundwater resource from the Wallal Sandstone aquifer is estimated to be 21 GL/yr, of which about **14 GL is fresh**. The Broome Sandstone aquifer has a total estimated yield of 18 GL/yr, of which only about **6 GL is fresh**.
- The **Turner River** alluvium has the potential for only moderate supplies of fresh water (<1 GL), as increases in salinity and drawdown become limiting factors in production. Alternatively, potential exists for the resource to be used as ‘fit-for-purpose’ brackish water supply. One option may be to use the brackish water as a supply source for desalination. This option also requires further assessment.
- The **De Grey River** alluvial aquifer is one of the sources for the Port Hedland Water Supply Scheme. It is currently operating 10 production bores in the **Namagoorie borefield**, which has a licensed abstraction of **7 GL/yr**. At present, environmental approval is being sought to expand production through the commissioning of the **Bulgarene borefield**. The new borefield may potentially increase the scheme supply by **3–6 GL/yr**, although further work is required to adequately assess the sustainable yield and environmental impacts.
- The **Yule River** alluvium is the second source for the Port Hedland Water Supply Scheme and currently operates nine production bores. It has a temporary licence to increase maximum abstraction from **6 GL/yr to 8.5 GL/yr**. A proposed pumping trial and monitoring program will assess the possible effects of the 2 GL increase in abstraction on groundwater-dependent vegetation.

Onslow Water Supply Scheme

- The **Lower Cane River** alluvium is the source for the Onslow Water Supply Scheme, and currently 16 production bores are operating with a licensed allocation of **0.35 GL/yr**. There is some heterogeneity within the aquifer and consequently the effects of pumping are variable. Saline encroachment is a potential effect of over-pumping; however, the aquifer is currently meeting Onslow's demands. Expansion of the borefield upstream of the current location may increase the available yield, but this has yet to be verified.
- Recharge estimates on the **Lower Robe River** indicate that a reasonable upper-limit annual abstraction may be **10 GL**. This estimate, of course, does not take into consideration the cultural, social and ecological water requirements of the area.
- River-flow volumes on the **Ashburton River** are considerable, with a long-term annual mean of 922 GL. As yet, significant occurrences of alluvial thickness or secondary porosity in bedrock units are unproven. Assessment work will be necessary to prove up a significant supply for development.

All supply schemes

- Ecosystems with varying degrees of dependency on groundwater occur at all sites reviewed in the study.
- Current estimates of sustainable yield for all sites need to be revised to take into account provisions for environmental, social and cultural requirements. Allocation limits should then be reviewed and adjusted as required.

1 Introduction

Increased consumption of water associated with mining and industrial development in the Pilbara, as well as strong population growth, has created uncertainty about sustainability of existing resources to meet the demand. As a result, additional water resources will need to be developed to supplement the coastal supply schemes.

The main centres of demand are Onslow, Dampier, Karratha, Burrup Peninsula, Cape Lambert, Dampier and Port Hedland (Figure 1). New port facilities have been considered at Ronsard Island and Cape Preston, where there are concerns about future water supply security.

In 2000, the Water and Rivers Commission undertook the *Central Pilbara groundwater study* (Johnson & Wright 2001), funded in part by the former Department of Resources Development, the Australian Federal Government, and the Water and Rivers Commission. The study investigated the management of water resources and water demands from the major mining operations in the Central Pilbara, and has proven a valuable reference for industry, regional developers and government in addressing water-related issues in the region.

In 2004, the Department of Industry and Resources completed the *Pilbara coast petroleum and minerals study*, which addressed potential infrastructure limitations hindering future development. The study provided some long-term projections of water demands; however, these need to be reviewed in light of recent developments and proposed port expansions. A key recommendation of the report, from a water-resource perspective, was to develop a regional master or strategic plan for water. Progress towards any strategic plan requires a comprehensive water-resource assessment to improve the understanding of current resource limitations, resources warranting additional investigation, and any related water-supply issues within the Pilbara region.

In 2006, the Department of Water began the *Pilbara coast water study*. The primary focus of the study has been to consolidate the large body of work and monitoring data on the numerous existing and potential water resources available on the Pilbara coast. The subsequent report will be used to identify and guide future resource investigation and development, and to develop a strategy to secure water supplies to meet the increasing demand in the region.

1.1 Scope and purpose

This report is the culmination of a comprehensive review of technical reports and monitoring data for the major groundwater resources to supply fresh water to the various towns and industrial users on the Pilbara coast. It is intended to summarise all relevant information, as well as provide an objective review of reserve estimates

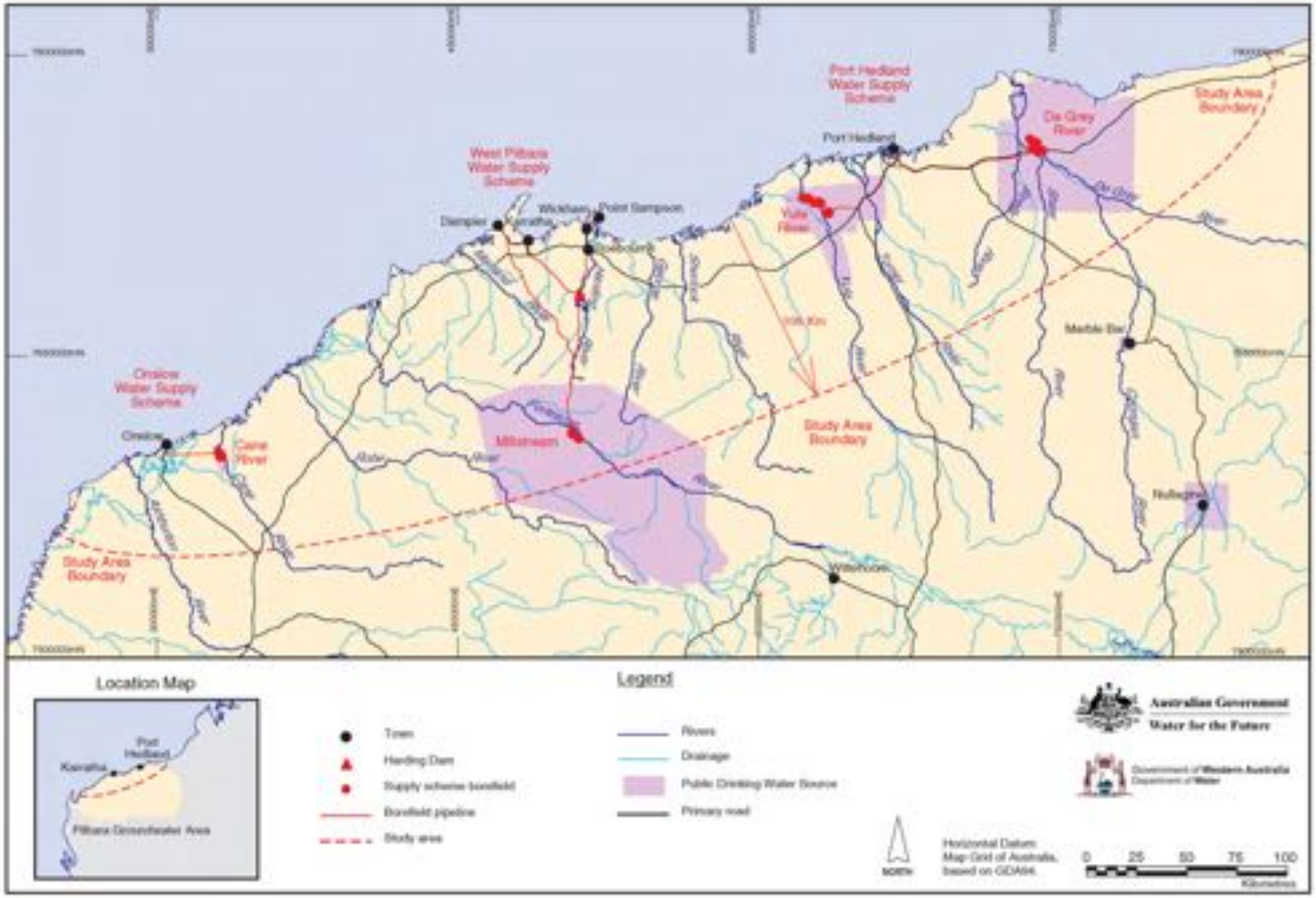


Figure 1: Study area

and the reliability of each supply – in light of the trend toward increased usage and uncertain climate. The main objectives of the work include:

- a review of existing water-supply schemes servicing towns on the Pilbara coast
- a review of groundwater resources, both used and unused
- a review of surface water, desalination and conveyance options
- a quasi-quantitative appraisal of the reliability of aquifers based on their recharge parameters
- a set of recommendations to move forward in securing water supplies for the Pilbara coast.

1.2 Study area

1.2.1 Location

The study area extends along the Pilbara coast from the edge of the Carnarvon Basin to the West Canning Basin and extends inland from the coast for approximately 100 km (Figure 1). Within the study area three existing major supply schemes are currently operated: the West Pilbara Water Supply Scheme, the Port Hedland Water Supply Scheme and the Onslow Water Supply Scheme. Recognised groundwater areas are shown in Figure 2, including those that are currently in use and others that may be feasible as new supply options.

1.2.2 Climate

The Pilbara coast climate is arid-tropical: it is influenced by both tropical maritime air from the Indian Ocean and continental air from the interior. These influences result in a climate of extremes, with severe droughts and major floods occurring at close intervals. The weather patterns can be generalised into summer weather patterns, extending from October through to April, and winter patterns, extending from May through to September. Summer patterns are characterised by very hot daytime temperatures, often exceeding 40ºC between November and February, and highly episodic intense rainfall. Winter weather patterns are characterised by low rainfall and moderate temperatures (average daytime 25ºC). Coastal temperatures in both seasons tend to be moderated by the influence of onshore winds.

The average annual rainfall ranges from 230–350 mm and mainly falls between the months of January and April. Rainfall patterns can vary dramatically due to the influence of tropical cyclones, which cause major flows in most rivers every one to three years. River flows are typically short lived. Rainfall can be erratic and very localised due to thunderstorm activity, hence rainfall from a single monitoring site is seldom representative of an entire catchment.

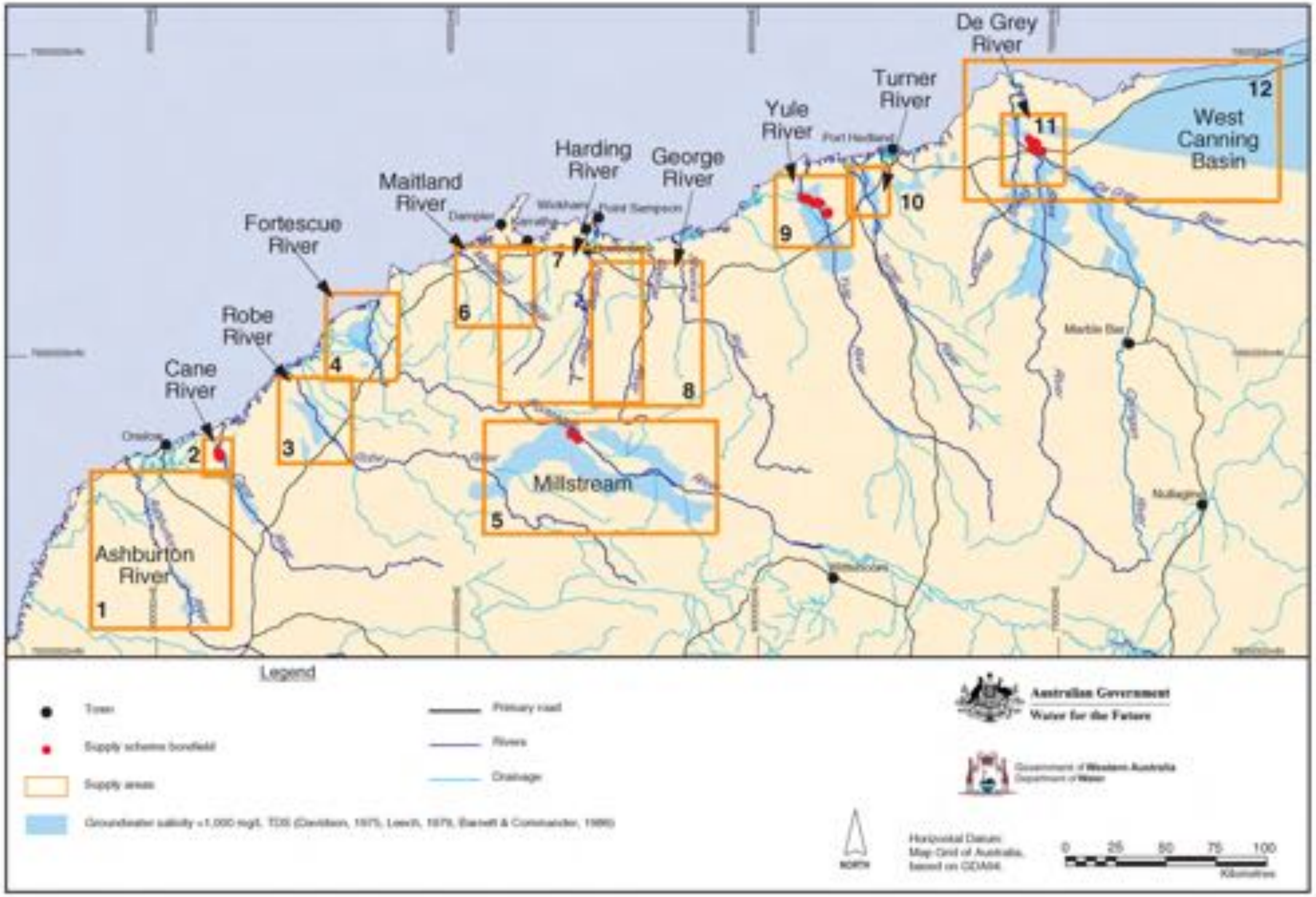


Figure 2: Study options

Rainfall data for selected sites in the Pilbara region is presented in Table 2.

Table 2. Mean annual rainfall in the Pilbara region

Recording station	Mean annual rainfall (mm)	Maximum monthly mean (mm)	Minimum monthly mean (mm)	Start of records
Port Hedland	313	94.3 (February)	0.9 (October)	1942
Karratha	269	69.5 (February)	0.3 (October)	1971
Dampier	310	97.0 (February)	0.1 (November)	1991
Onslow	274	50.5 (February)	0.7 (October)	1886
Pannawonica	395	99.1 (February)	1.4 (September)	1971
Wittenoom	460	109.8 (February)	2.4 (September)	1949
Paraburdoo	283	56.1 (February)	2.9 (September)	1971
Newman	310	80.1 (February)	3.9 (September)	1965

Evaporation greatly exceeds mean annual rainfall. Average pan evaporation rates along the coast are approximately 3400 mm/yr.

1.2.3 Physiography

The westernmost part of the study area includes a low-lying coastal plain, which overlies Carnarvon Basin sediments near Onslow. Broad depositional areas of limited elevation overlie eroded bedrock and form two large peneplains in the northern and western areas. The Hamersley and Chichester ranges form the areas of higher elevation, and are separated by the Fortescue River valley. To the north-east of the study area, the Canning Basin is overlain by a large aeolian sand plain.

1.2.4 Land use

Most inland areas are covered by mining and exploration leases due to the vast iron ore reserves in the Hamersley Basin, and to a lesser extent, minor deposits of other commodities to the north. Large areas of the Pilbara are also used as pastoral land.

1.3 Previous studies

The existing groundwater schemes along the Pilbara coast came about through systematic groundwater investigations of the major aquifers as part of a geological survey that began in 1965. This involved exploratory drilling on the Turner River “(Farbridge 1967) and Yule River (Whincup 1967). Investigations at Millstream began in 1968 and were completed in 1983 (Davidson 1969a, 1969b; Barnett & Commander 1986), while investigations at the De Grey River began in 1971 (Davidson 1975b).

Davidson (1975a) carried out a bore census that led to potential fresh groundwater resources being identified. Potential sources that have not yet been developed were investigated in 1971–75 in the West Canning Basin (Leech 1979), along the Lower Fortescue and Lower Robe rivers in 1984–85 (Commander 1994a, 1994b) and at the Upper Cane and Ashburton rivers in 1994 (Yesertener & Prangley 1996, 1997).

These investigations have all been in alluvial or sedimentary aquifers. Investigations of the dolerite bedrock occurred at Cooya Pooya (Barnes 1973). The Water Corporation has carried out further investigations at the De Grey River and in fractured bedrock in the Karratha/Roebourne area.

Reassessments of the groundwater resources have also been made for the Yule River (Forth 1972a; Davidson 1976), Millstream (Forth 1972b) and Cane River borefields (Martin 1996).

An assessment of the surface-water hydrology of the Pilbara was made by Ruprecht and Ivanescu (2000).

1.4 Supply potential

1.4.1 Groundwater

Yield estimates from various groundwater sources in the Pilbara have been reported since the 1970s. The estimates have been referred to as ‘potential yield’, ‘preferred yield’ and ‘safe yield’.

The various yield estimates have been based on standard hydrogeological analysis, such as percentage of recharge, simple analytical calculations or numerical modelling. The various estimates of yield did not take into consideration the economic, social and environmental values associated with the supplies. As a result, any estimates of yield based on these methods will be referred to in this document as ‘potential yield’.

Recommendations have been made to investigate and assess potential supply options along the Pilbara coast. The proposed work will provide a better understanding of the economic, social and environmental values associated with these supplies. Until better information about groundwater-dependent ecosystems is available, fairly broad assumptions have to be made about these requirements. The objective is to estimate a ‘sustainable yield’ for each new groundwater option to support future planning and management strategies.

1.4.2 Surface water

Previous investigations (Sadler & Parker 1974a, 1974b; Dames & Moore 1979; Forrest & Coleman 1996a, 1996b) have concluded that surface-water sources in the Pilbara should only be developed in conjunction with a groundwater supply. More recent work has shown that surface water sources are possible as water supplies, but given cultural and environmental concerns are unlikely to be investigated further.

Surface-water resources are subject to long lead times because of requirements for environmental approval, land acquisition, construction and development of infrastructure. These long lead times are, in themselves, a restriction to the development of surface-water sites.

A cost comparison of developing groundwater versus surface-water sites was undertaken by Woodward-Clyde AGC (1996). It was reported that the development of groundwater resources to support the Port Hedland Water Supply Scheme would be more cost-effective than the development of surface-water sites. The report concluded that the cost of developing surface-water sites – compared with other supply options – might be a restriction to development.

1.4.3 Desalination

Forrest (1995a) assessed the potential for desalination plants located at Cape Lambert and Maitland Estate. Two scenarios for feedwater were discussed: using brackish groundwater from wellfields near the coast facilities or using seawater. The option of using brackish groundwater was unlikely to be feasible. The option of using seawater was considered to be feasible, considering the potential availability of economically viable local energy and advances in reverse osmosis technology.

The Water Corporation has successfully developed new desalination technology at Kwinana in the South West and on the Burrup Peninsula in the Pilbara. Compared with groundwater development, desalination provides a higher degree of reliability. Desalination has fewer restrictions in relation to climatic variation. The increasing costs of developing conventional water sources have made desalination more economically viable.

A desalination facility near the coastal port facilities to support the supply schemes is a viable option. The major risk or restriction associated with the development of desalination is the continuing cost and availability of inexpensive energy sources. If the cost and availability of gas in the Pilbara region changes in the future, the economic viability of desalination will need to be reviewed.

1.4.4 Kimberley water

Forrest (1995b) reviewed the option of obtaining water from the Kimberley for use in the Pilbara. Previously the Western Australian Water Resources Council and consultants Wilson Sayer Core P/L and Binnie & Partners had released a study entitled *Water for the 21st century*. This 1988 study assessed the option of obtaining water from the Kimberley for use in the Pilbara. In 1990, the Infrastructure Development Corporation also undertook a feasibility study of the same scheme, which included a review of previous studies.

Forrest reported that the regional groundwater supplies available in the Pilbara would be the most economic option for demands of less than 200 GL/yr. For the Kimberley option to be economically feasible, the demand in the Pilbara needed to be more than 400 GL/yr. It was reported that this option would be more applicable to the eastern portion of the Pilbara than the west. Along the Pilbara coast, desalination would be the less expensive option. Forrest concluded that water from the Kimberley would not be an option for the Pilbara.

In 2004, GHD P/L completed a study for the Water Corporation on the option of supplying the Perth region with fresh water from the Fitzroy River in the Kimberley. The study also compared the relative cost of a pipeline to the cost of desalination.

The GHD (2004) report concluded that the project was technically feasible but the cost was prohibitively expensive when compared with alternative options, specifically desalination. The pipeline’s construction would have led to a range of social issues with various stakeholders including pastoral, agricultural, mining and aboriginal interests. The most significant social impact was related to Aboriginal heritage and Native Title.

More recently, Western Australia’s Department of Premier and Cabinet commissioned GHD to revisit this option. In the 2006 report entitled *Options for bringing water to Perth from the Kimberley, An independent review*, it was concluded that the cost of supplying Perth with water from the Kimberley was prohibitively expensive and other sources like from desalination is more cost effective.

1.4.5 Mine dewatering

Significant volumes of water are involved in the dewatering of mine sites and excess water is often the main issue with operational water balances. The option of making excess groundwater from mine sites available to supplement public supplies should be thoroughly investigated. Groundwater occurrences related to mining activities was considered outside the scope of this study.

1.4.6 Public policy for drinking water sources

The Department of Water is responsible for protecting the state’s existing and future drinking water sources. These sources are protected through the declaration of water reserves and catchment areas over existing groundwater or surface-water Public Drinking Water Source Areas (PDWSAs) and potential groundwater and surface-water catchments. PDWSAs are established under the *Country Areas Water Supply Act 1947* (WA). Several sources discussed in this study are existing PDWSAs (Figure 1).

PDWSA proclamation is an important step in developing the possible future sources identified in this study. It will help ensure these sources are protected to provide a safe, good-quality water supply. Guidance on the type of land uses appropriate within these areas is provided by the area Water Quality Protection Note: *Land use compatibility in Public Drinking Water Source Areas*.

2 Geology

This summary is predominantly based on the Water and Rivers Commission Hydrogeology Report No. 61, *Groundwater resources of the Pilbara region, Western Australia,* March 1997 by A. Wright. Information has also been sourced from Hydrogeology Report No. HR 35 (unpublished), *Groundwater resources of major catchments in the Pilbara region, Western Australia*, 1996 by D.J.P Skidmore.

2.1 Pre-Cambrian basement rocks

The basement rocks along the Pilbara coast can be broadly divided into the Archaean greenstones and granites of the Pilbara Craton and the Early to Middle Proterozoic Hamersley Basin (figures 3 and 4).

2.1.1 Pilbara Craton

The Pilbara Craton represents the oldest rocks in the region. It is subdivided into the Archaean granite-greenstone terrain and the Proterozoic Hamersley Basin.

The granite-greenstone terrain underlies younger sediments along the coastal area from Cape Preston in the west to Goldsworthy in the east. It extends inland as far as Nullagine and Marble Bar. The general distribution of granite to greenstone is about 60 to 40. The granite forms ovoid bodies and domes that may be up to 120 km across. The granite contains a range of deformed and metamorphosed granitic phases and may be intruded by younger veins and dykes. The greenstone sequences comprise metasedimentary and volcanic rocks that have been intruded by significant volumes of granite. The greenstones have undergone a complex history of deformation and metamorphism.

The Hamersley Basin overlies the older granite-greenstone terrain. The northern boundary of the basin is present inland from Karratha. It extends from Cape Preston and the Lower Fortescue River in the west to the mid to upper catchments of the Harding and George rivers to the east. The rocks of the Hamersley Basin form hills and ridges inland of the coastal plain and are present as isolated outliers over the granite-greenstone terrain. The basin comprises a sequence of rocks including mafic and felsic volcanic and intrusive rocks, shale, siltstone, sandstone, conglomerate, dolomite and banded iron formation. A period of intense tectonic activity centred in the south of the Pilbara Craton resulted in faulting and folding of the sediments. The rocks have also undergone low-grade burial metamorphism which decreases in intensity from the south to the north of the basin.

2.1.2 Early and Middle Proterozoic basins

The Capricorn Orogen broadly coincides with the southern margin of the Pilbara region and separates the Pilbara Craton from the Yilgarn Craton to the south. In this area, it comprises the Proterozoic rocks of the Ashburton Basin and the Gascoyne Complex.

The rocks of the Ashburton Basin comprise metamorphosed sandstone, siltstone, mudstone, conglomerate, dolostone, and mafic and felsic volcanic rocks of the Wyloo Group. It underlies much of the Upper Ashburton River catchment and extends northward to underlie the Lower Cane and Robe rivers.

The Gascoyne Complex consists of metamorphic schists, granite and granitic gneiss. It lies to the south of the Ashburton Basin and extends north to underlie the Lower Ashburton River and parts of the Lower Cane River.

The western limit the Ashburton Basin and the Gascoyne Complex outcrop is the edge of the foothills approximately 60 km inland from Onslow. The western limit outcrops along either side of the North West Coastal Highway as far north as the Pannawonica turnoff. Outliers of the Proterozoic-aged Mount Minnie Basin and Edmund Basin are present in the foothills east of Onslow. The Proterozoic basement rocks drop to depths of greater than 200 m along the coast.

2.1.3 Intrusive veins and dykes

Mafic dykes of dolerite have intruded the basement rock. Most of the dykes were intruded over the period before the greenstones' deformation to after the Hamersley Basin's development. Felsic dykes and veins also intrude Archaean and Proterozoic rocks, but are less common.

2.2 Phanerozoic sedimentary basins

The sedimentary basins within the study area are the Canning to the east and the Carnarvon to the west. They were formed around the northern and southern margins of the Pilbara Craton and contain relatively unconsolidated and gently dipping Phanerozoic sediments. The sediments were deposited in intercratonic or marginal basins as part of the break-up of the Gondwana super-continent.

2.2.1 Canning Basin

The south-western part of the Canning Basin onlaps the north-eastern margin of the Pilbara Craton to the east of Port Hedland (Figure 3). The sediments are deposited on basement rocks of the Anketell Shelf, which runs to the east along the coast for 200 km. The shelf extends inland towards the Pilbara Craton near the Oakover River valley. The West Canning Basin is more than 700 m thick and comprises Permian, Jurassic and Cretaceous sediments. The main geologic units of interest to this study

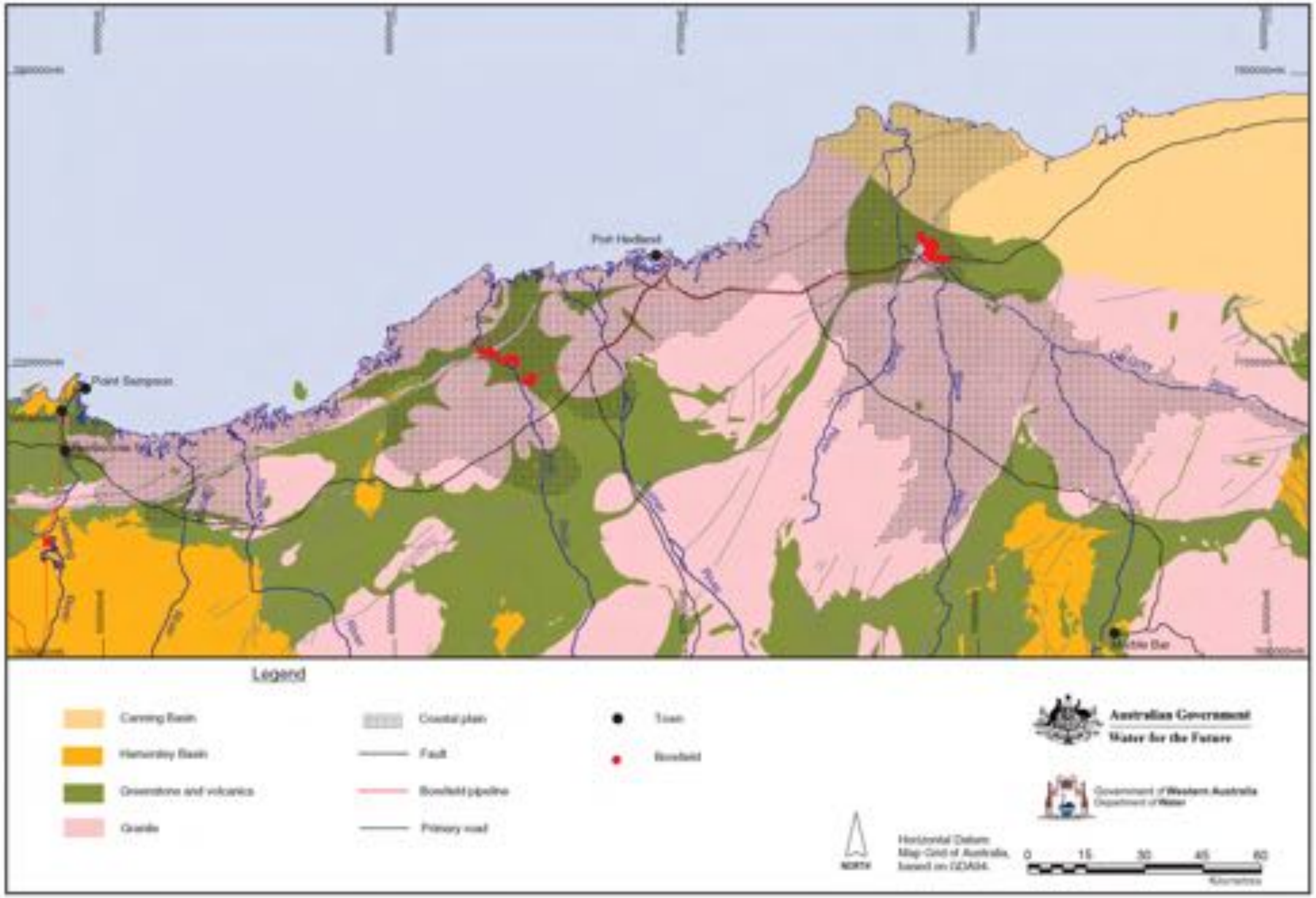


Figure 3: Port Hedland Coastal Plain bedrock geology

are the Cretaceous/Jurassic-aged Broome Sandstone, Jurassic-aged Jarlemai Siltstone and Wallal Sandstone.

2.2.2 Carnarvon Basin

The Carnarvon Basin onlaps the western edge of the Pilbara Craton and Capricorn Orogen to the south and east of Onslow (Figure 4). The sediments overlie Proterozoic basement rocks of the Peedamullah Shelf, which runs along the Onslow coast and extends inland for up to 60 km. The sedimentary sequence is mostly less than 500 m thick, but increases to 700 m to the south-west. Along the Robe River the thickness can increase to greater than 1000 m within the structural depression called the Robe River embayment.

The units of the Carnarvon Basin comprise Late Devonian to Cretaceous sediments of the Winning Group and Late Carboniferous to Early Permian Lyons Group. The stratigraphy is summarised below in Table 3.

Table 3. Carnarvon Basin stratigraphy

Group	Age	Unit	Thickness
Winning	Later Cretaceous	Toolunga Calcilutite	<100 m
		Muderong Shale (Mardie Greensand Member)	150 m
		Windalia Radiolarite	
		Gearle Siltstone	
	Early Cretaceous	Yarraloola Conglomerate	<300 m
		(Nanutarra Formation and Birdrong Sandstone)	
Lyons	Late Carboniferous to Early Permian	Limestone, dolomite, claystone, shale, siltstone and sandstone	>280 m

The Lyons Group rests on Proterozoic basement rocks and is present deep along most of the Onslow coast. The top of the sequence is within 150 m of the surface in the north and about 400 m bgl in the south.

The Winning Group comprises a basal coarse-grained section overlain by finer-grained sediments dominated by shale. The Nanutarra Formation and the Birdrong Formation are lateral equivalents of the Yarraloola Conglomerate. The three units are often undifferentiated in borehole logs and are often referred to as the basal Cretaceous sand and conglomerate. The units typically occupy buried channels where the major drainages enter the coastal plain. The units may lie over the Lyons Group units or directly on the Proterozoic basement rock.

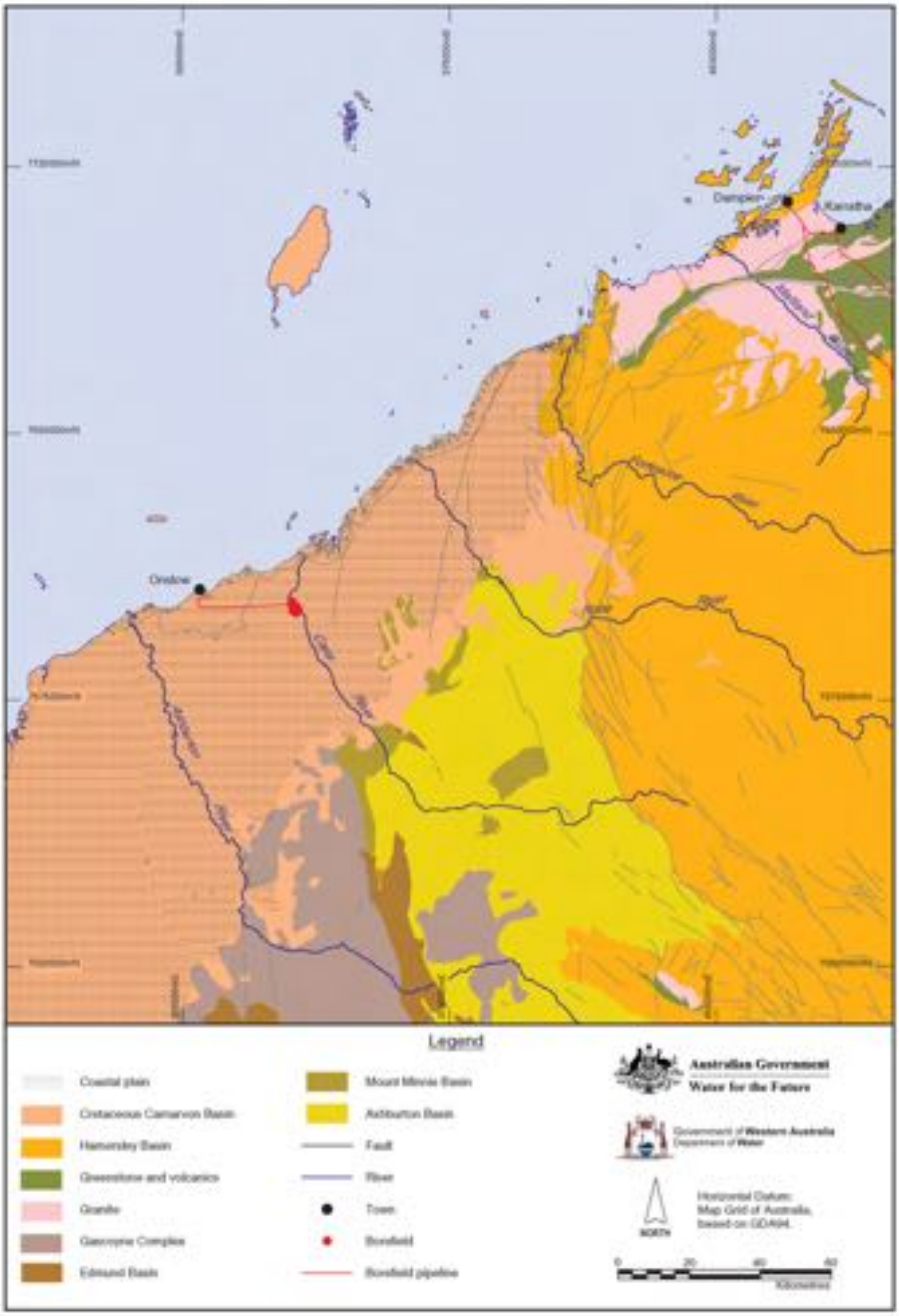


Figure 4: Ashburton Coastal Plain bedrock geology

The various members of the Winning Group have been intersected in groundwater exploration wells along the Pilbara coast between the Ashburton and Fortescue rivers. Overlying the Carnarvon Basin sediments is a thin veneer of Cainozoic superficial sediments.

2.3 Cainozoic deposits

2.3.1 Pisolitic limonite

Pisolitic limonite is correlated with the Robe Pisolite and represents dissected remnants of Tertiary drainage deposits. The pisolites fill channels incised into basement rock by earlier drainages and are strongly cemented with secondary goethite and silica. Solution channels and fractures can be extensively developed and are sometimes filled with detrital sand and clay.

Pisolitic limonite occurs on the Onslow plain where bores have intersected discontinuous deposits in the subsurface that unconformably overlie Cretaceous sediments. Most deposits are between 4 and 7 m thick. The river channels of pisolitic limonite are currently mined as channel iron deposits along the Robe River, inland from the coastal plain.

Pisolitic limonite also occurs in the upland areas where it forms disconnected and isolated low hills and mesas, dissected by younger drainages. Mesas of pisolitic limonite are along the Onslow Plain near Yarraloola Station.

2.3.2 Trealla Limestone

Trealla Limestone is a Tertiary-aged unit of the Carnarvon Basin sequence. It occurs over most of the subsurface of the Onslow coastal plain and outcrops in small, isolated patches. It unconformably overlies pisolitic limonite or Cretaceous sediments and has not been detected in boreholes to the east of the Fortescue River floodplain. It is a fine-grained crystalline limestone, clay and marl that may be fractured and is variably weathered. The Trealla Limestone ranges in thickness from 10 to 41 m, but is mostly about 15 m thick.

2.3.3 Calcrete

Chemical precipitates are deposited in the Pilbara as calcrete, dolomite, limestone and river calcrete. The formation of the precipitates is usually associated with drainage channels where the cemented material occurs in outcrops or in the subsurface below the alluvial material.

The most common deposits comprise carbonate cemented clay, silt, sand and gravel. The cementation likely occurs as a result of the precipitation of carbonate material derived from basement rocks. Solution channels of up to 0.5 m in diameter have been developed in calcrete, but it can also be massive and hard.

Deposits in the main drainage channels or in the larger valleys may be up to 54 m thick and up to 20 km wide (Millstream). Outside of the main drainages, deposits tend to be thin and have limited lateral extent.

2.3.4 Alluvium

Rivers traverse the coastal plain and deposit large amounts of alluvial material. Along the Onslow coastal plain, alluvial sediments are deposited on older sediments of the Carnarvon Basin or on the Proterozoic basement rock. To the east, along the Port Hedland coastal plain, alluvium overlies weathered Archaean basement rocks. Alluvial thickness can be greater than 50 m, but decreases in thickness away from the major drainage channels.

Older paleochannels of earlier drainages can occur away from the present position of active river channels. Thick sections of alluvial material representing paleochannels have been intersected away from current riverbeds in the Ashburton, Fortescue, Maitland, Yule and De Grey rivers.

Alluvium is occasionally cemented by calcium carbonate into calcrete. The calcrete zones are developed at various depths by hydrochemical activity in the zone of groundwater fluctuation.

Inland of the coastal plain, alluvium varies it its lateral extent and thickness and occupies present drainage channels. Inland river channels are typically less than 1 km wide, but along some sections of the main rivers the width can be up to 10 km. Thicknesses are generally less than 10 m, but deposits of up to 30 m are common in the inland valleys of the Hamersley Range.

3 Hydrogeology

3.1 Unconsolidated sediment aquifers

3.1.1 Coastal alluvial aquifers

Alluvial aquifers occur across the Port Hedland and Onslow coastal plains with groundwater generally contained in unconfined conditions in Quaternary sediments. Groundwater in the Port Hedland coastal plain aquifer is in hydraulic connection with underlying weathered fractured-rock aquifers, whereas groundwater in the Onslow coastal plain aquifer is in hydraulic connection with the confined aquifers of the underlying Carnarvon Basin sediments.

Recharge to the coastal alluvial aquifers occurs mostly from river flow. Consequently, the most important areas for groundwater resources are where the major surface watercourses cross the coastal plain. Groundwater salinity is also lowest in these zones. Paleochannels and abandoned river channels represent the thickest part of the alluvial aquifer. Wellfields have been developed in the alluvial aquifers along the Cane River (in conjunction with the underlying Trealla Limestone) to supply Onslow with water. Alluvial aquifers along the Yule and De Grey rivers have been developed to supply Port Hedland with water.

3.1.2 Valley fill aquifers

Valley fill aquifers are present in the Fortescue River valley and the valleys within the Hamersley Range. Valley fill deposits, typically consisting of alluvium and colluvium, overlying pisolitic limonite and calcrete, can be over 100 m thick in places. They generally form unconfined aquifers, but can be confined or semi-confined locally by overlying sediments of low hydraulic conductivity. As with the coastal alluvial aquifers, aquifer recharge is predominantly through riverbed leakage from surface watercourses, with only a minor component being from direct rainfall infiltration. Groundwater flow is typically away from the recharge areas, along the valley centres or sides and in the direction of the surface-water flow.

Valley fill aquifers are commonly exploited in conjunction with the underlying aquifers (e.g. calcrete or pisolite). Bore yields along the Fortescue River valley range from 100–1500 m^3/d. Yields of greater than 3000 kL/day are possible in bores constructed in the calcrete or fractured basement rocks in conjunction with the valley fill deposits (Wright 1997).

3.1.3 Calcrete aquifers

Calcrete can occur with alluvial aquifers as massive calcrete aquifers, concretionous deposits, pedogenic calcrete, exposed mounds and weathered precipitate in granite.

Massive valley calcrete occurs at Millstream and in other alluvial valleys in the Hamersley Range. These are significant aquifers that commonly occur in Miocene sediments and typically overlie pisolite. The calcrete at Millstream is up to 46 m thick, but on average is generally less than 10 m thick (Barnett & Commander 1986).

Concretionous calcrete deposits occur in the zone of watertable fluctuation and may not necessarily form significant aquifers, as the cementation reduces permeability.

Pedogenic calcrete occurs as soil development over basic rocks: examples can be found around the Yule and De Grey rivers. The calcrete occurrence at the top of the bedrock is not necessarily considered to be a significant aquifer, but it is recommended that this interval be screened in conjunction with overlying alluvial sediments to maximise bore yields.

Calcrete commonly outcrops within drainage areas as exposed mounds near groundwater-discharge areas. It is often discontinuous in outcrop and can occur as remnants of larger areas that have been cut through by surface-water flows.

Calcrete also forms as a chemical precipitate in the weathered horizon of Archaean granites. Davidson (1976) reported the occurrence of ‘kunker’ or calcrete at the top of the weathered zone in the Yule River. Whincup (1967) reported appreciable amounts of water from the bedrock aquifer at Yule River that is associated with joints, fractures and quartz veining in granite.

Recharge to calcrete aquifers is predominantly through bed leakage from surface-water courses and less so through direct precipitation infiltration. Calcrete can have high hydraulic conductivity through the development of secondary porosity. Yields of up to 5000 kL/day have been recorded at Millstream (Water Corporation 1997).

3.1.4 Pisolitic limonite aquifer

Pisolitic limonite can form significant local-scale aquifers where it is situated close to and beneath drainage lines. It does not outcrop widely and usually only forms an aquifer where it is deposited in subsurface channels previously cut into basement rocks by earlier watercourses. Eroded remnants are exposed as mesas that are unsaturated (e.g. Robe River).

Recharge is often through direct infiltration from overlying alluvium and can be low. Skidmore (1995) noted that salinity in bores completed in the pisolite on the Robe River had elevated values, indicating low recharge. Pisolite aquifers along the Onslow coast may contain brackish groundwater. On the Fortescue River, pisolites at Deepdale in the Millstream area give bore yields of 350–1700 m^3/d. However, Commander (1994a) reported that potential yields from pisolites in the Lower Fortescue and Robe rivers might be low and less than 100 m^3/d.

3.2 Sedimentary rock aquifers — West Canning Basin

The West Canning Basin is a multi-layer aquifer system with the main aquifer units being the Broome and Wallal sandstones. The sandstone aquifers are both confined and unconfined, with primary porosity providing storage capacity. Recharge is through direct precipitation infiltration onto the unconfined portions of the sediments. Groundwater flow patterns occur on a regional scale away from the recharge areas (Leech 1979).

3.2.1 Broome Sandstone aquifer

The Broome Sandstone is a major unconfined aquifer that is recharged from direct infiltration of rainfall when outcropping or indirectly through thin layers of overlying sandy sediments. Groundwater flow is to the north and north-west and there is a general increase in salinity in the direction of groundwater flow (Leech 1979). The Broome Sandstone has the potential to supply a significant volume of groundwater.

3.2.2 Wallal Sandstone aquifer

The Wallal Sandstone is predominantly confined and separated from the overlying unconfined Broome Sandstone by the Jarlemai Siltstone. The mechanism of recharge is not clearly defined, as differentiation between the Broome Sandstone and the Wallal Sandstone in the unconfined portions of the basin is unclear. Recharge may occur to the Wallal Sandstone from direct precipitation where it is unconfined and the Broome Sandstone is not present. Recharge may also occur as direct infiltration from the overlying Broome Sandstone where the Jarlemai Siltstone is not present. Groundwater is fresh to saline, but is often less than 1000 mg/L TDS, indicating relatively rapid recharge (Leech 1979). Salinity increases down the groundwater gradient. In places the Wallal Sandstone aquifer has the potential for relatively high-yielding abstraction bores of between 1000–2000 kL/day (Leech 1979). The Wallal Sandstone has a greater volume and generally better water quality than the Broome Sandstone aquifer.

3.3 Sedimentary rock aquifers – Carnarvon Basin

3.3.1 Trealla Limestone aquifer

The Trealla Limestone aquifer occurs predominantly in the subsurface along the coastal plain from the Ashburton River to the Lower Robe River. It occurs in outcrops in rare, small, isolated patches. Recharge is from leakage of the overlying alluvial sediments. In general, the salinity is similar to that of the overlying sediment (Skidmore 1996). Away from the river channels and source of recharge, the Trealla Limestone has low potential as a regional aquifer.

There is limited information on yields from bores completed in the limestone. At the Robe River, yields of 980 kL/day have been reported where fissured limestone is in contact with the overlying alluvial sediments. In the Cane River, yields of up to 300 kL/day have been reported where the limestone is fractured, but most yields are less than 100 m^3/d. In general, most yields from bores completed in the Trealla Limestone will be less than 100 kL/day and yields up to 1000 kL/day will be very rare (Skidmore

1996). In the Lower Fortescue River, the Trealla Limestone forms a confining bed over the Yarraloola Conglomerate aquifer (Commander 1994a).

There is little potential for the Trealla Limestone to provide significant water supplies for town or agricultural use. However, it could provide small stock and domestic supplies if bores are located close to drainages.

3.3.2 Yarraloola Conglomerate aquifer

The Yarraloola Conglomerate aquifer consists of the Yarraloola Conglomerate, the Birdrong Sandstone and the Nanutarra Formation. In bore logs, it is generally referred to as basal Cretaceous sand and conglomerate. It lies above the Lyons Group sediments and is confined by the Muderong Shale over much of the coastal plain. Throughout much of the Onslow coast, the formations are within 200 m of the ground surface (Wright 1997).

Groundwater recharge is by leakage from overlying alluvial aquifers. Where the aquifer outcrops, recharge occurs by direct rainfall infiltration – but this is considered to be minimal compared with leakage from overlying formations. Groundwater quality is fresh near the recharge points, but declines rapidly away from them, which implies that recharge to the aquifer is relatively minor and localised. On the Onslow coastal plain, groundwater flow in the Yarraloola Conglomerate is generally from the recharge areas, outward from the rivers and down towards the west. Allen (1988) estimated groundwater-flow velocities to be as low as 4 m/year.

Salinity generally increases with depth and along the groundwater-flow direction. Where the Yarraloola Conglomerate lies immediately beneath alluvial deposits of the major drainage lines, the salinity may be fresh to marginal. Commander (1994a) reported salinities that ranged from 454–492 mg/L TDS from the Yarraloola Conglomerate in the Lower Fortescue River area. The conglomerate is confined by up to 30 m of Trealla Limestone.

Bore information is available from investigative drilling associated with the Manyingee uranium project. Testing completed in the Yarraloola Conglomerate and the Birdrong Sandstone found the bores could potentially produce more than 1000 m^3/d (Skidmore 1996). Data is also available from two bores in the Fortescue River subcatchment, where yields of 120–1063 kL/day have been reported (Commander 1994a). Artesian bores drilled during petroleum exploration were reported to have flows ranging from 50 to 4546 m^3/d, (Skidmore 1996). Skidmore also reported that bores constructed by screening 10 m or more of the aquifer should be capable of producing up to 1000 m^3/d. At the time of writing, Pilbara Iron is planning to develop a borefield in the Yarraloola Conglomerate near the proposed Mesa A mine site, the Robe River and the North West Coastal Highway. The borefield is expected to supply up to 1.5 GL/yr to the mine site.

In general, this aquifer has limited potential for town or horticultural groundwater supplies, as salinities may be higher than accepted levels. There may be some potential for limited abstraction from zones of fresh water immediately around the areas where the Robe and Cane rivers enter the coastal plain. Development in these locations give rise to concerns that long-term abstraction may induce saline intrusion. Less potential exists along the Fortescue River because only a small area of the Yarraloola Conglomerate is found there. In areas away from the major river drainages, very limited potential for town supplies exists.

3.3.3 Lyons Group aquifer

The Lyons Group aquifer is a large confined aquifer composed of Lyons Group sediments distributed over the subsurface of the Onslow coastal plain. The top of the sequence is within 150 m of the surface in the north (Lower Robe River) and about 400 m bgl in the south (Lower Ashburton River). Thickness is generally 500 m or less (Wright 1997), but is reported to be up to 1000 m in places. Where it occurs within 200 m of the surface, it is reported to be approximately 65 m thick.

The small recharge that occurs in the Lyons Group may be through leakage from the overlying sediments. A very low rate of recharge is assumed from reported salinities that range from 6000 to 36 000 mg/L, but are mostly greater than 20 000 mg/L (Skidmore 1996). In general, hydrogeological information on the Lyons Group is very limited.

The potential for town or horticultural water supplies from the Lyons Group is poor due to the high salinity. In addition, the drilling depths required (>150m) preclude the Lyons Group as a useful aquifer.

3.4 Fractured-rock aquifers — granites and greenstones

Fractured-rock aquifers exist within a variety of different basement-rock formations across the Pilbara coast. Groundwater occurs where secondary porosity is developed in fractured and weathered zones or along bedding planes and joints. The rocks contain very little groundwater outside of these zones. Groundwater recharge is rainfall dependent and will only occur directly where fractured, jointed and weathered zones are exposed to rainfall. Recharge will also happen through leakage from overlying sediments and from surface flows directly to areas of secondary porosity. Groundwater flow is largely controlled by local geological structures and weathering.

Archaean greenstones and granites underlie the Port Hedland coastal plain alluvial deposits. In general, the granites and greenstones have less potential for groundwater supply than the alluvial aquifer that overlies them.

Groundwater may occur in the upper weathered zone of granite rocks where secondary porosity is associated with extensive weathering, fractures, joints and quartz veining. In areas where secondary porosity is not developed, granite makes poor aquifers. Greenstone aquifers can be productive where they are brittle (e.g. chert). In both cases, the proximity of drainage lines is a necessary component because river flow is the primary source of recharge. In general, recharge occurs in the upper reaches of drainages and topographically elevated areas. The direction of groundwater flow is controlled by topography.

3.5 Salinity

In general, groundwater becomes more saline away from the source of recharge. The zonation of salinity patterns along the Pilbara coast is shown in figures 5 and 6.

Salinity can also vary vertically where hydraulic conductivity changes vertically. In the De Grey River area, lower-salinity water is typically associated with the most permeable zones within the alluvial aquifer. At this location, salinity is found to increase below the alluvium in the vicinity of the weathered-bedrock aquifer.

In the Yule River area investigated by Davidson (1976), the salinity in the alluvial aquifer's shallow portion was sometimes found to be higher than the salinity at depth. The higher salinity may be due to the flushing down of salt residue at the surface during recharge events, dissolving of salts from oxidation within the capillary fringe or by the concentration of salts due to plant absorption. In the Robe River, Commander (1994b) reported that salinity decreased with depth below the watertable and was probably due to the effects of evapotranspiration.

Periodic sampling around the Robe River (Commander 1994b) indicated that higher salinity readings were measured after river flooding when water levels were high. The sampling also found that salinity decreased with time as the water levels declined. Anecdotal reports from various Pilbara station owners – based on observations of station supply bores located near river channels – point to a similar phenomenon (Commander, Martin & Doherty 2004).

3.6 Recharge

Much of the recharge to alluvial aquifers along the Pilbara coast is by infiltration of river flows. In general, direct rainfall infiltration is only a minor component of the total recharge volume.

The spatial distribution of recharge along river channels is often limited to the area of alluvial gravels. The volume of recharge to the groundwater system is controlled by the frequency, size and duration of surface-water flows. Percolation of recharge water into sediments along the active river channel is rapid.

Very little recharge takes place over extensive clay pans that become flooded during large-flow events, due to their surface soils being rich in clay and inhibiting downward migration of water. Recharge also varies laterally as a result of changing soil horizons – affecting infiltration of floodwater or rainfall penetration.

In general, response to recharge in bores completed in highly transmissive aquifer sections is rapid and shows sharp peaks in hydrographs. Conversely, recharge

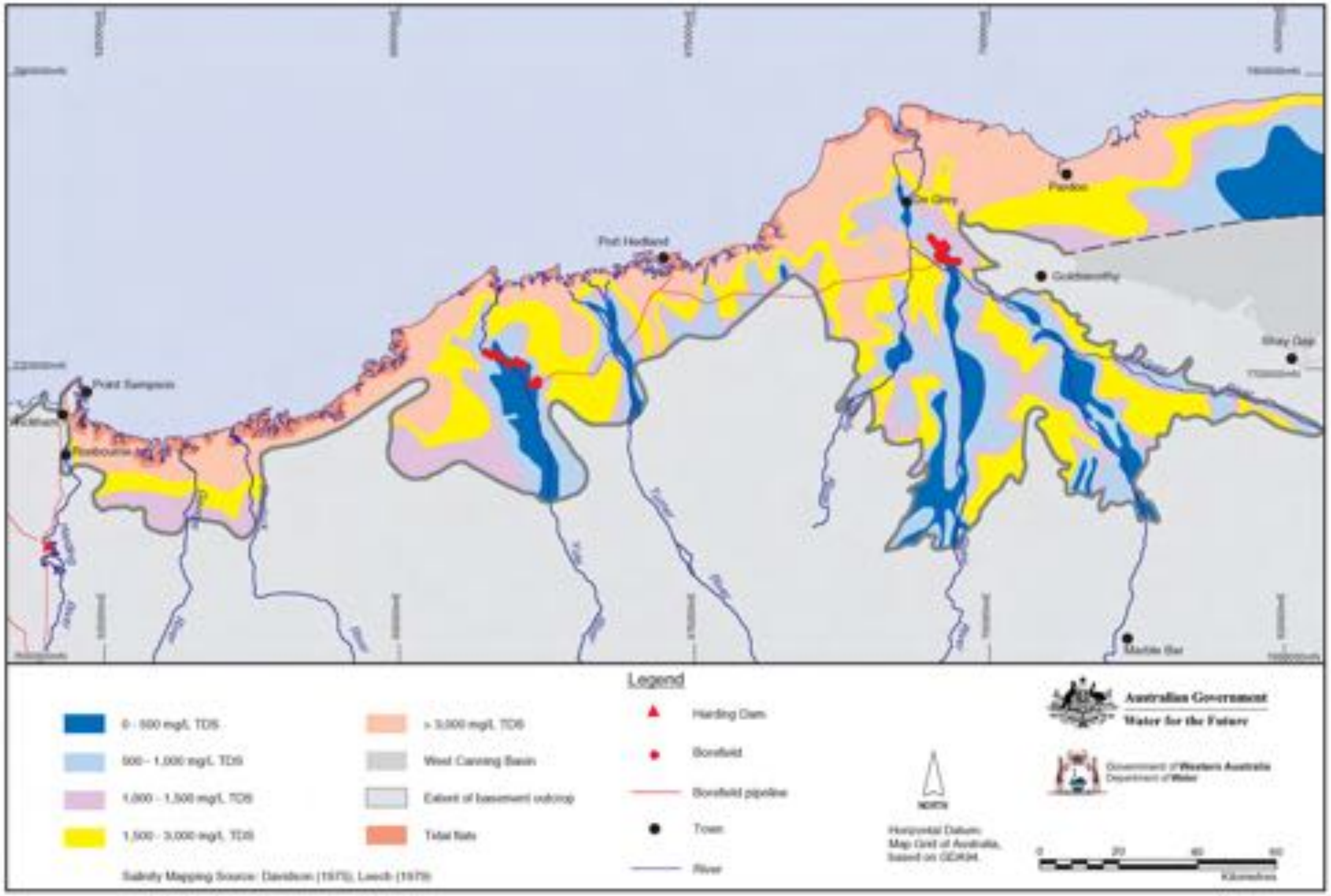


Figure 5: Port Hedland Plain groundwater salinity

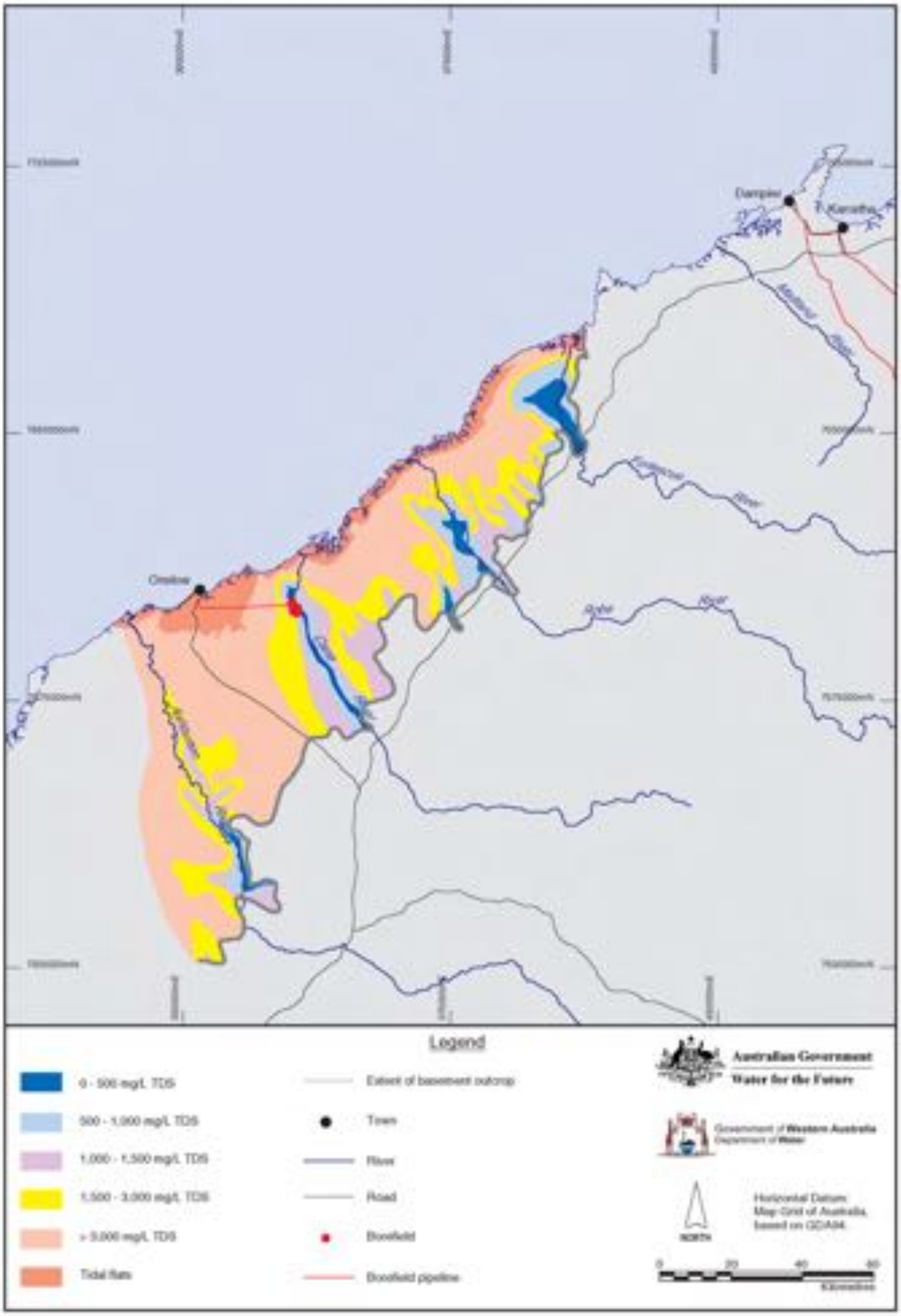


Figure 6: Ashburton Coastal Plain groundwater salinity

response in bores in less transmissive material is much slower and exhibits a flat response in hydrographs. Similar patterns are seen in bores in the vicinity of active river channels. Bores located close to the river channel have a rapid response to recharge and subsequent drainage events. Bores located away from the channel have delayed responses with rises and drops of lower magnitude.

Recharge estimates to alluvial aquifers along river drainages have been based on calculating the volume of aquifer change before and after periods of river flow and applying an estimated specific yield. However, this type of recharge calculation is an underestimate, because it does not take account the volume of water that drains out of and flows through the system.

3.7 Discharge

Discharge from the alluvial aquifer systems along the Pilbara coast can be broken down into three main components:

- the volume of water flowing out of the system
- evaporation from pools as surface expressions of the watertable
- evapotranspiration requirements from ecosystems dependent on groundwater.

Evapotranspiration losses can be very high along riverbanks where vegetation development is dense. Commander (1994b) estimated that transpiration of vegetation downstream of the Robe River aquifer might be approximated as 80 per cent of the pan evaporation rate of 2500 mm/year. However, in many areas of the Pilbara the vegetation along the alluvial channels is sparse. As a result, it may be assumed that evapotranspiration occurs at a relatively low rate in these areas.

3.8 Aquifer parameters

Implied problems with aquifer parameter estimation have been reported in previous Pilbara coast investigations. These included bores that were not fully penetrating, bores that were not sufficiently developed, pumping tests conducted at the incorrect pumping rate and a lack of observation bores. As a result, historic calculations of hydraulic conductivity, transmissivity, storage coefficients and specific yield can be problematic.

In the case of multi-layer (alluvial) aquifer systems, such as the Yule River, pumping-test results may not represent their true transmissivity. Classic pumping-test analysis assumes the aquifer is both isotropic and homogenous. A multi-layer aquifer system does not fit this model and requires analytical techniques beyond the scope of most projects. In such cases, it has been recommended that production bores be drilled through all possible aquifers and screened over the full thickness of the saturated alluvial sediments (Forth 1972). Transmissivity is often the fundamental unknown variable in terms of the regional groundwater-flow systems.

3.9 Potential yields and aquifer allocation

The recharge and therefore potential yield of the alluvial aquifer systems depends on the frequency of river flow and flow duration. Higher groundwater abstraction may be possible following recharge events, whereas reduced storage volumes following extended periods of drought may result in limited abstraction. Allocations from groundwater systems therefore have to account for the periodic nature of recharge events in the Pilbara.

The accepted approach to determine potential aquifer yields is based on calculations of throughflow and/or recharge volume. The potential yield that can be abstracted is an approximation of the increase to storage volume or the volume of water that naturally discharges from the system.

However, determination of allocation limits also has to take into account the cultural, environmental and economic water requirements associated with the aquifer system. The potential yields presented in this study are hydrogeologically based and do not reflect these requirements.

3.10 Reliability of recharge events

River flow is the main component of recharge to the alluvial groundwater systems. Flow data from the Pilbara's major rivers is summarised in Table 4 below.

Table 4. Major river flows in the Pilbara

River	Gauging station number	Catchment area (km^2)	Mean annual rainfall (mm)****	Mean annual flow (GL)	Median annual flow (GL)	CV*
Ashburton	706003	71,387	300	922	534	1.32
Cane	707005	2326	400	88	65	0.8
Robe	707002	7104	500	87	18	1.7
Fortescue**	708002	14,629	450	215	51	1.4
Fortescue***	708003	18,371	400	255	97	1.31
Maitland	709004	1948	375	40	14	2.08
Harding	709001	1058	400	39	23	1.3
Sherlock	709003	4581	400	164	40	1.6
Yule	709005	8427	400	350	136	1.4
Turner	709010	885	400	29	5	1.2
De Grey	710003	50,007	400	1430	1062	1.1
Shaw	710229	6501	400	328	151	1.6
Coongan	710204	3736	400	112	68	1.3
* CV: Coefficient of variation ** Station 708002 at Gregory Gorge *** Station 708003 at Jimbegnyinoo ****Based on mean annual isohyets						

The assigning of supply reliability based on recharge is difficult, because other factors will affect whether one supply is more or less reliable than another. In particular, storage volume and current levels of abstraction are two such factors. Aquifers with greater available storage can support pumping for longer periods than those with smaller volumes. Similarly, a system that is currently being pumped at close to the sustainable yield is at higher risk than a significant resource that is being under-used.

Reliability of supply is more directly related to the volume, duration and frequency of recharge events. Aquifer systems exposed to more frequent flood events – of sufficient volume to cause recharge – are considered more reliable.

Conversely, the frequency of no-flow events will define the potential risk of a groundwater system experiencing drought conditions (drought being defined as an extended period of no flow). Rivers with the shortest periods of no flow are more reliable, while those with the longest periods of no flow are less reliable. The level of risk is implied as being inversely proportional to the reliability.

Time-series data on river flow can be used to estimate the frequency of recharge and duration of no-flow events. It is more valuable to compare components that describe recharge variability – which may imply a general level of reliability.

Table 5 below is an analysis of river-flow data from the gauging stations listed above. It is a simplified attempt to describe recharge variability. The criteria can be described as follows:

- *Recharge events* is defined as the number of flow events during which total flow volume over four consecutive months exceeds the mean annual flow volume.
- *Recharge events per decade of record* is a normalised indication of general frequency of flow events.
- *Drought duration (months)* is the maximum number of consecutive months of no flow. Although not a rigorous definition, it is used for comparative purposes.
- *Low-flow events (years)* is the number of years of total record during which total annual flow was less than 10 per cent of the mean annual flow.
- *No-flow events (years)* is the number of years of total record during which the total annual flow volume was zero.

Table 5 has been sorted against recharge events per decade of record to highlight the river systems with the highest frequency of flow.

A more rigorous attempt to evaluate flood events and the resultant changes in aquifer storage is required. This would lead to a better understanding of reliability of supply. Such an assessment is beyond the scope of this study.

Table 5. Summary of recharge variability

River	Record	Years of record	Mean annual flow (GL)	Recharge events	Recharge events per decade of record	Drought duration (mths)	Low flow events (yrs)	No flow events (yrs)
Turner Pincunah	86–05	20	29	9	4.5	30	7	4
De Grey Coolenar Pool	75–04	30	1430	11	3.7	19	5	1
Yule Jelliabidina Well	73–02	30	350	11	3.7	37	10	3
Fortescue Jimbegnyinoo Pool	69–97	29	255	10	3.4	5	5	0
Maitland Miaree Pool **(5)**	73–04	32	40	11	3.4	34	10	4
Fortescue Gregorys Gorge	69–04	36	209	12	3.3	9	12	0
Cane Toolunga	87–04	18	88	6	3.3	10	1	0
Harding River u/s Cooya Pooya	67–84	18	39	6	3.3	10	6	0
Coongan Marble Bar **(2)**	69–01	33	112	10	3.0	11	4	0
Robe Yarraloola	73–05	33	87	10	3.0	44	12	8
Sherlock Coonanarrina Pool **(4)**	68–87	20	164	6	3.0	30	6	1
Shaw North Pole Mine **(3)**	68–04	37	328	8	2.2	29	9	3
Ashburton Nanutarra **(1)**	72–05	34	922	6	1.8	9	4	0

(1) No proven major groundwater resources associated with the Ashburton River.
(2) The Coongan contributes to flow in the De Grey River.
(3) The Shaw contributes to flow in the De Grey River.
(4) No proven major groundwater resource associated with the Sherlock River.
(5) No proven major groundwater resources associated with the Maitland.

The Department of Water is currently studying the relationships between river flows and recharge events for the Pilbara's major groundwater sources. The objective is to develop a better understanding of the reliability of the various groundwater (and surface water) supply options. The methodology is based on developing an empirical relationship between river-flow volume and the resulting change in aquifer level. With an assumed specific yield and aquifer geometry, the volume of recharge from the flow episode can be estimated. The analysis results in a time series of recharge events tied directly to flows.

It is recommended that additional work be done to further the empirical relationships formulated during this study. The additional work should focus on developing an empirical relationship between the time duration of flow (in days) and the resultant rise in aquifer level. The work would lead to a better understanding of the recharge mechanisms and support future numerical modelling efforts.

3.11 Constraints to development

A major constraint on groundwater development along the Pilbara coast is the potential for increases in groundwater salinity. The intrusion of brackish water into borefields developed near active river channels may occur if overly high pumping rates are maintained. Long periods of no surface-water flow and over-pumping of production bores increase the risk of saline intrusion from surrounding zones of brackish water.

Bores developed away from the river channel can be more susceptible to the intrusion of brackish water than those developed near the active channel and source of recharge. Coastal aquifers in the Pilbara have to be managed very carefully to avoid saline intrusion. Zones susceptible to salinity increases can be defined to enable correct borefield management to minimise or eliminate the possibility of those increases.

4 Existing West Pilbara water supply

4.1 Demand centre

The West Pilbara Water Supply Scheme supplies the towns and port facilities of Karratha, Dampier, Roebourne, Wickham, Point Samson, Cape Lambert and the Burrup Peninsula (Figure 1). The supply is sourced conjunctively from the Harding Dam and the Millstream borefield. When available and of suitable quality, the Harding Dam is used as the primary source. Millstream is used as the supplementary supply when low levels at the dam result in lower water quality and it is taken offline. The Millstream water reserve and the Harding Dam catchment area are proclaimed Public Drinking Water Source Areas (PDWSAs). The Department of Water has prepared drinking water source protection plans for these areas.

4.1.1 Development

The port facilities at Cape Lambert, Dampier and the Burrup Peninsula are the main industry users of scheme water. Although iron ore is the principal heavy industry, large shipments of liquefied natural gas (LNG), salt and condensate also pass through the three major docking facilities.

Pilbara Iron (Rio Tinto) is the largest exporter of iron ore from the port facilities at Cape Lambert and Dampier. In 2005, 130 Mt was shipped from the port facilities; in 2006, this increased to 150 Mt. Total production in 2007 increased to 165 Mt. Iron ore is unloaded, stockpiled, screened, crushed, blended and ultimately shipped from the port facilities. Fresh water is primarily used for dust suppression.

Petrochemical-related industries are focused on the Burrup Peninsula, which is currently undergoing rapid development. In 2007, Burrup Fertilisers P/L opened the world’s largest ammonia plant on the peninsula. The plant uses natural gas as feedstock to produce liquid ammonia for the production of fertiliser and industrial products: annual production capacity is 760 000 tonnes of liquid ammonia. There is also potential for additional fertiliser plants to be developed on the peninsula.

The North West Shelf gas project on the Burrup Peninsula is owned and managed by Woodside Offshore Petroleum. Woodside is in the early stages of expanding its operations. Other development related to the oil and gas industry on the peninsula is associated with Methanex P/L, Pilbara Iron and others.

Dampier Salt (Rio Tinto) operates solar evaporation ponds between Dampier and Karratha, with the salt stockpiled and shipped from Dampier. Dampier Salt is one of the world’s largest exporters of high-quality solar salt.

The Maitland Estate, south-west of Karratha and Dampier, is a centre of commercial and light industry.

4.1.2 Water supply

The Millstream groundwater aquifer and the Harding Dam surface-water reservoir have a combined abstraction licence of 15 GL/yr. Neither source has a separate allocation limit and the scheme is managed as a conjunctive supply. Since the Harding Dam was built in 1985, total abstraction from the scheme has averaged 9 GL/yr, with a maximum take of 11 GL/yr. During that time, the average abstraction from the Harding Dam has been 4 GL/yr with a maximum of 10 GL/yr. The abstraction from the Millstream borefield has averaged 6 GL/yr, with a maximum of 11 GL/yr when the dam was offline for the installation of the microfiltration plant.

In 2004 drought conditions and problems with the microfiltration plant at the Harding Dam resulted in the abstraction of 9 GL from the Millstream aquifer. Those events reinforced the need to revise the Millstream aquifer's sustainable yield. Numerical modelling of the aquifer system through a range of climatic scenarios would support the sustainability estimate.

4.1.3 Water consumption

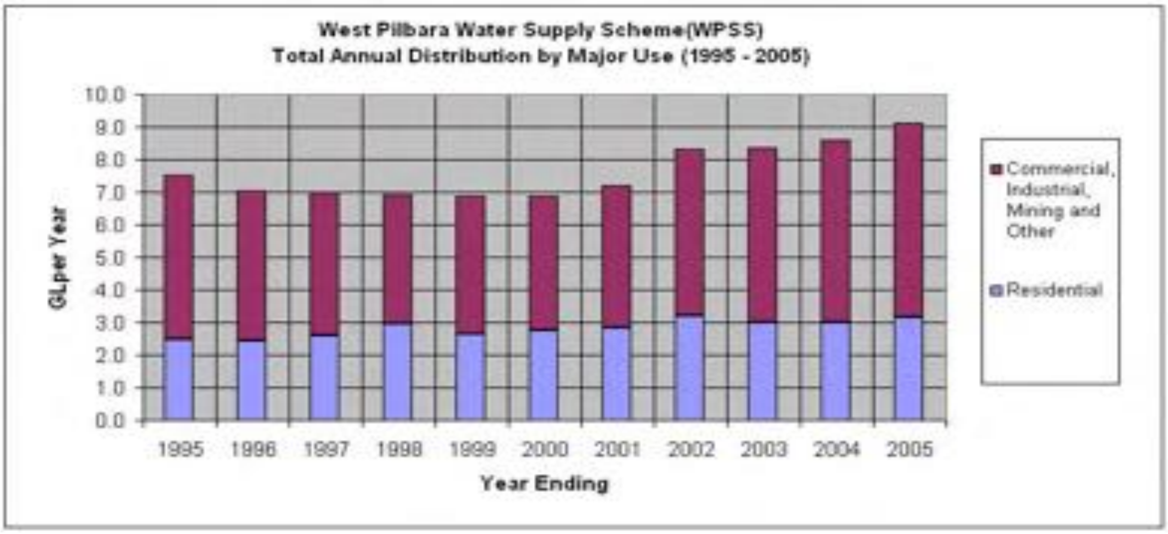
Figure 7 shows the annual distribution from the West Pilbara Water Supply Scheme for the years 1995 to 2005. The average annual consumption from the scheme during this time was about 8.7 GL, with a maximum consumption of 9.1 GL in 2005. During this period, the average efficiency loss from the scheme was less than 10 per cent. This estimate of loss is reasonable considering the accuracy of metering and the system's unmetered users.

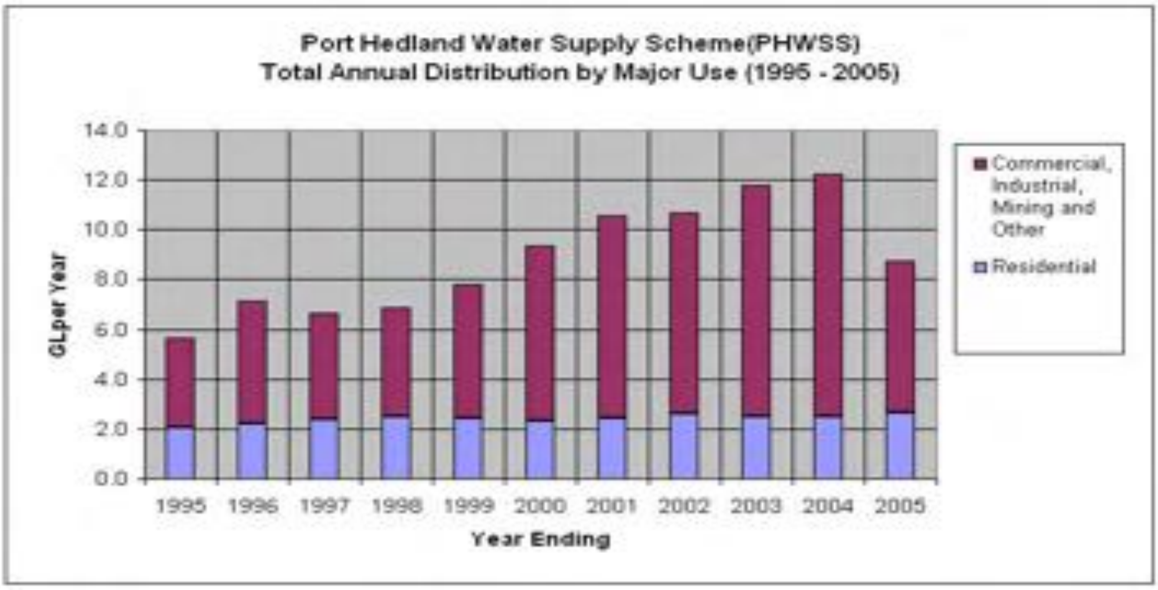
A study by ECS (2007) was commissioned by the Department of Water to report on water use and demand projections. The Water Corporation supplies water to the towns of Dampier, Karratha, Wickham, Roebourne and Cape Lambert for industrial and residential purposes. Water use over an 11-year period to 2006 was broken down into heavy industry, light industry and residential use. The average and maximum annual use for each category is summarised below in Table 6.

Table 6. West Pilbara Water Supply Scheme use (1995–2006)

	Average use (GL)	Maximum annual use during past 11 years (GL)	Average use as % of total
Heavy industry	3.0	3.6	35%
Light industry	1.8	2.3	21%
Residential	3.0	3.2	34%
Other	0.9	Unknown	10%
Total	8.7	9.1	100%

Heavy industry does not have a fixed definition when compared with light industry. In general, heavy industry is considered to be more capital intensive, requiring larger





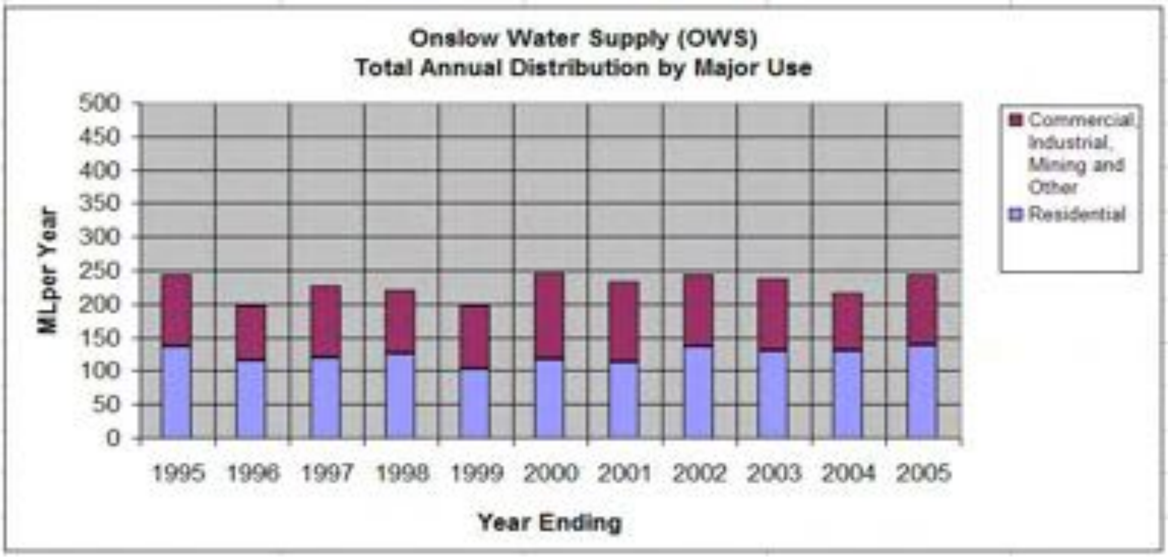


Figure 7: Supple scheme distribution

fixed facilities and having a greater potential environmental impact (ECS 2007). Heavy industry associated with the port facilities includes the downstream processing (dust suppression) of iron ore, LNG plants, salt processing and petrochemical plants. The largest heavy industrial use of scheme water is the downstream processing of iron ore, specifically for dust suppression. The iron ore loading facilities at Cape Lambert and Dampier are owned by Rio Tinto and operated by Pilbara Iron.

The total volume of scheme water used for the downstream processing of iron ore in 2006 was about 3.4 GL (ECS 2007).

Woodside Petroleum operates the LNG plant on the Burrup Peninsula and is not considered to be a large user of scheme water (ECS 2007). Some of the LNG plant's water requirements can be met using condensed water during cooling. Woodside is also planning to develop a new LNG plant adjacent to Burrup Fertilisers.

Salt operations do not require large volumes of fresh water and operational requirements have been estimated at 0.1 GL/yr (ECS 2007).

Burrup Fertilisers' new plant sources its operational water supply from a desalination plant and requires approximately 1.3 GL of fresh water per year (ECS 2007). The desalination plant is separate from the West Pilbara Water Supply Scheme.

Light industry includes services that operate to support heavy industry at the port facilities and the local communities, such as construction, fabrication, transport and retail operations. The volume of light-industry water use is estimated from subtraction of mining requirements and domestic use from the total annual distributed volume.

The current population of the Karratha, Dampier, Roebourne and Wickham areas is about 15 500 people. Annual domestic consumption is about 206 kL/person/year, or about 565 litres/person/day (ECS 2007).

4.1.4 Future water demand

Further downstream (iron ore) projects are planned, along with an expansion of the natural gas and petrochemical industries.

Table 7 below projects the total volumes of iron ore to be shipped from the Cape Lambert and Dampier port facilities from 2007 to 2030 (ECS 2007). Current penetration of the Western Australian iron ore industry into the South Korean, Taiwanese and Japanese market is over 60 per cent of total demand. Exports to China represent just under 40 per cent of that market. The projection scenario below is based on an increase to 50 per cent of the total Chinese market (ECS 2007). It should be noted that these projections were estimated prior to the 2007-2009 financial crisis, which will probably affect the projected tonnages of iron ore shipments out of the Pilbara.

Table 7. Projected West Pilbara iron ore shipments

Year	Cape Lambert (Mtpa)	Dampier (Mtpa)	Total (Mtpa)
2007	55	110	165
2010	80	110	190
2015	100	150	250
2020	125	140	265
2025	150	150	300
2030	170	160	330

The use of water for dust-suppression operations at the ports of Cape Lambert and Dampier is available on the public record (Rio Tinto Iron Ore 2006a). Current estimates of water consumption for dust suppression are 22 L/t at Cape Lambert and 22 L/t at Dampier (ECS 2007). It is expected that current dust-suppression volumes will remain the same at both facilities. Water-use efficiency programs have been factored into the water-use projections. The water-demand projections for downstream processing of iron ore are calculated below in Table 8.

Table 8. Projected West Pilbara water demand for dust suppression

Year	Cape Lambert (GL)	Dampier (GL)	Total (GL)
2007	1.2	2.2	3.4
2010	1.8	2.2	4.0
2015	2.2	3.0	5.2
2020	2.8	2.8	5.6
2025	3.3	3.0	6.3
2030	3.7	3.2	6.9

The Pilbara region's population is expected to increase from 42,900 to 50,200 (17 per cent) by 2031 (Western Australian Planning Commission 2005). Furthermore, the population of the Roebourne Local Government Area (LGA) – comprising the towns of Karratha, Dampier, Roebourne and Wickham – is expected to increase at an even higher rate (27 per cent) than the region overall. This is because of the LGA's role in the booming mining industry. The population growth projection and current residential water use were combined to develop the residential water-demand projection summarised below in Table 9.

The Water Corporation maintains databases of heavy and light industrial water use for the schemes it manages. A review of the data indicates a strong relationship between industrial and commercial use of water and the population trends of the town centres (ECS 2007). This relationship has been used to determine the projected increases in industrial use not associated with iron ore dust suppression (Table 9).

Table 9. Projected West Pilbara water demand for all users

Year	Cape Lambert (GL)	Dampier (GL)	Heavy Industry (GL)	Light Industry (GL)	Resi-dential (GL)	Total (GL)
2007	1.2	2.2	1.8	2.0	3.2	10.4
2010	1.8	2.2	2.0	2.1	3.3	11.4
2015	2.2	3.0	2.0	2.2	3.5	12.9
2020	2.8	2.8	2.0	2.3	3.6	13.5
2025	3.3	3.0	2.0	2.4	3.8	14.5
2030	3.7	3.2	2.0	2.6	4.0	15.5

Since 1985, the West Pilbara Water Supply Scheme has operated at an average rate of 9 GL/yr. The water-demand scenario in Table 9 estimates that an additional 2 GL/yr of water will be required by 2010 to meet demand greater than the historic average use of 9 GL/yr. In 2015, the additional water requirement above the historic average is projected to be about 4 GL/yr. This projection is considered to be conservative in light of current expansion plans that will affect the port facilities.

The projected iron ore shipments shown in Table 7 estimate that the total tonnage shipped from the port facilities in 2015 will be 250 Mtpa. The recent public announcement that Rio Tinto proposes to increase total production to 320 Mtpa by 2012 (Rio Tinto 2006a) implies that the estimates above are conservative.

In November 2005, the Department of Water, the Department of Industry and Resources and the Water Corporation met to discuss the water management and water-availability issues associated with the West Pilbara Water Supply Scheme. During that meeting it was agreed that an additional 5 GL supply needed to be found to meet future water requirements.

The 2015 water demand of 12.9 GL shown in Table 9 may be realised earlier than projected, whereby an additional 4 GL source will be required. Considering the time required to bring a new source online may be up to five years, the development process should begin now.

4.2 Existing groundwater supply

4.2.1 The Millstream aquifer

The Millstream aquifer is located on the Fortescue River approximately 70 km downstream of the crossing of the Tom Price Railway Road and about 110 km south of Karratha (Figure 1). The borefield consists of 12 production bores on the south side of the Fortescue River (Figure 8). It is a composite aquifer system comprising unconsolidated alluvium, conglomerate, calcrete and pisolite variably connected to form a single complex flow system. Although predominantly unconfined, confined conditions are also locally present.

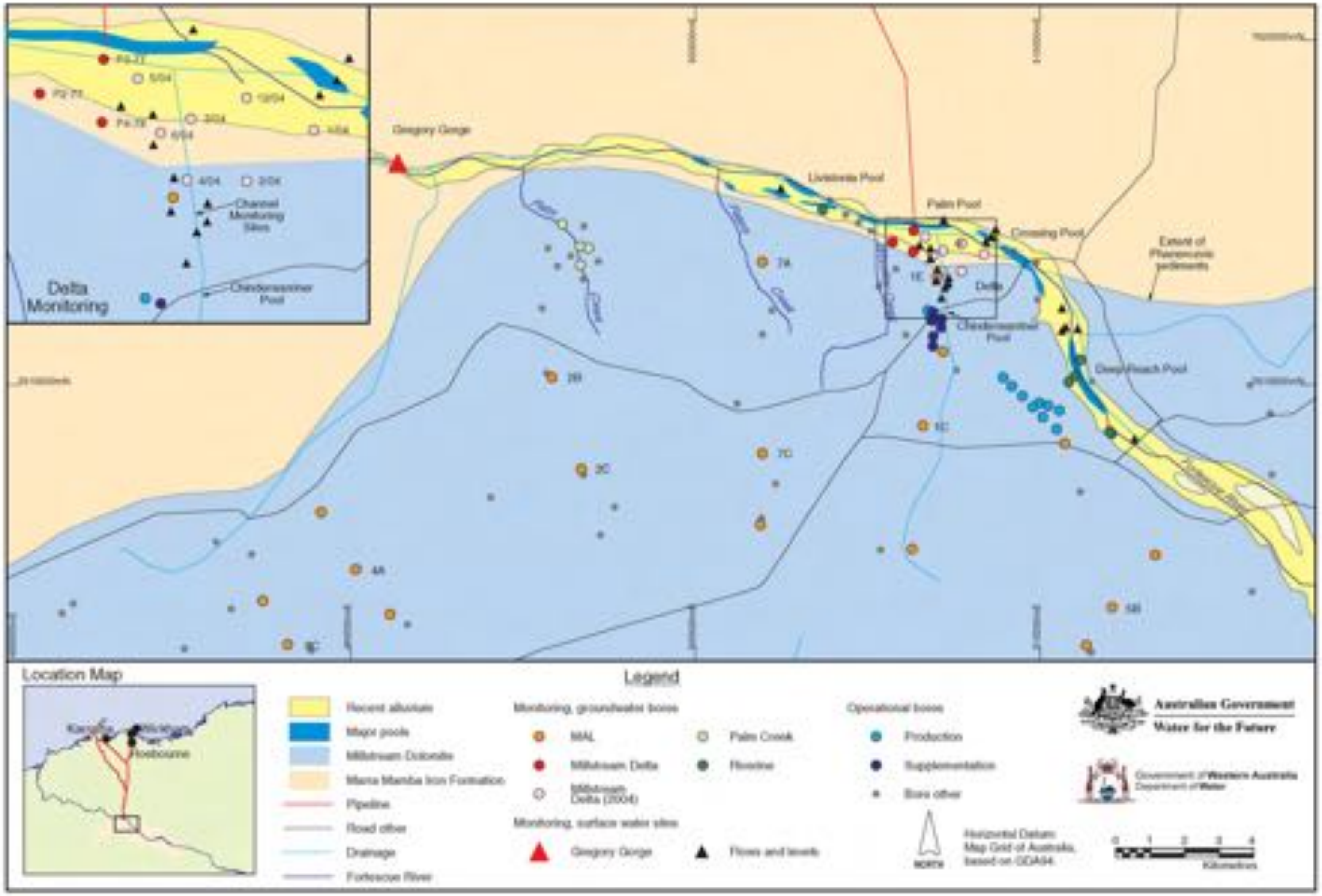


Figure 8: Millstream borefield

The Millstream aquifer was extensively investigated as a source of groundwater for the West Pilbara Water Supply Scheme between 1968 and 1983, and pumping of groundwater began in 1969 to service Karratha, Dampier and Wickham. Numerous pumping tests were conducted on bores between 1968 and 1983, significantly improving knowledge of the aquifer units' hydraulic characteristics. By 1982 approximately 92 GL (average 10 GL/yr) had been abstracted from the aquifer. This resulted in drawdown of the watertable 0.23 m below the average natural mean aquifer level around Millstream and represented a storage depletion of approximately 23 GL. The drawdown of the watertable affected local springs and spring-fed vegetation, and supplementary water was required to maintain local groundwater-dependent ecosystems.

In 1985, abstraction from the Millstream aquifer was reduced after completion of the Harding Dam, which now provides most of the West Pilbara scheme's water. From 1986 to 2006 its annual abstraction was reduced to approximately 6 GL/yr and is now primarily used to supplement the supply from Harding Dam. Due to significant recharge events and reduced pumping, groundwater levels are managed at the average natural mean aquifer level.

The sensitivity of local ecosystems to watertable drawdown during times of limited recharge has resulted in a strong emphasis on sustainable pumping and aquifer management. Due to reconfiguration of the current borefield, numerical modelling has been used to assess potential impacts on groundwater levels.

Geology

The western Fortescue River valley is a sequence of alluvial, colluvial and lacustrine sediments of Cretaceous to recent age (Barnett & Commander 1986). Sediments were deposited into a broad valley cut into the underlying Proterozoic basement, which follows the strike of the less-resistant Wittenoom Dolomite. The northern half of the valley is underlain by the Marra Mamba Iron Formation and the southern half by the Wittenoom Dolomite: both formations dip to the south. The axis of the valley roughly follows the contact between these two formations and the Cainozoic and Mesozoic sediments lie unconformably on the Proterozoic basement rock. A stratigraphic column based on the work of Barnett and Commander (1986) is shown in Table 10.

Figure 9 shows the geology of the Phanerozoic sediments overlying the Proterozoic basement rocks. Figures 10 and 11 are schematic cross-sections across and along the Fortescue River valley showing the relationship between the Phanerozoic sediments and the underlying Proterozoic basement rocks.

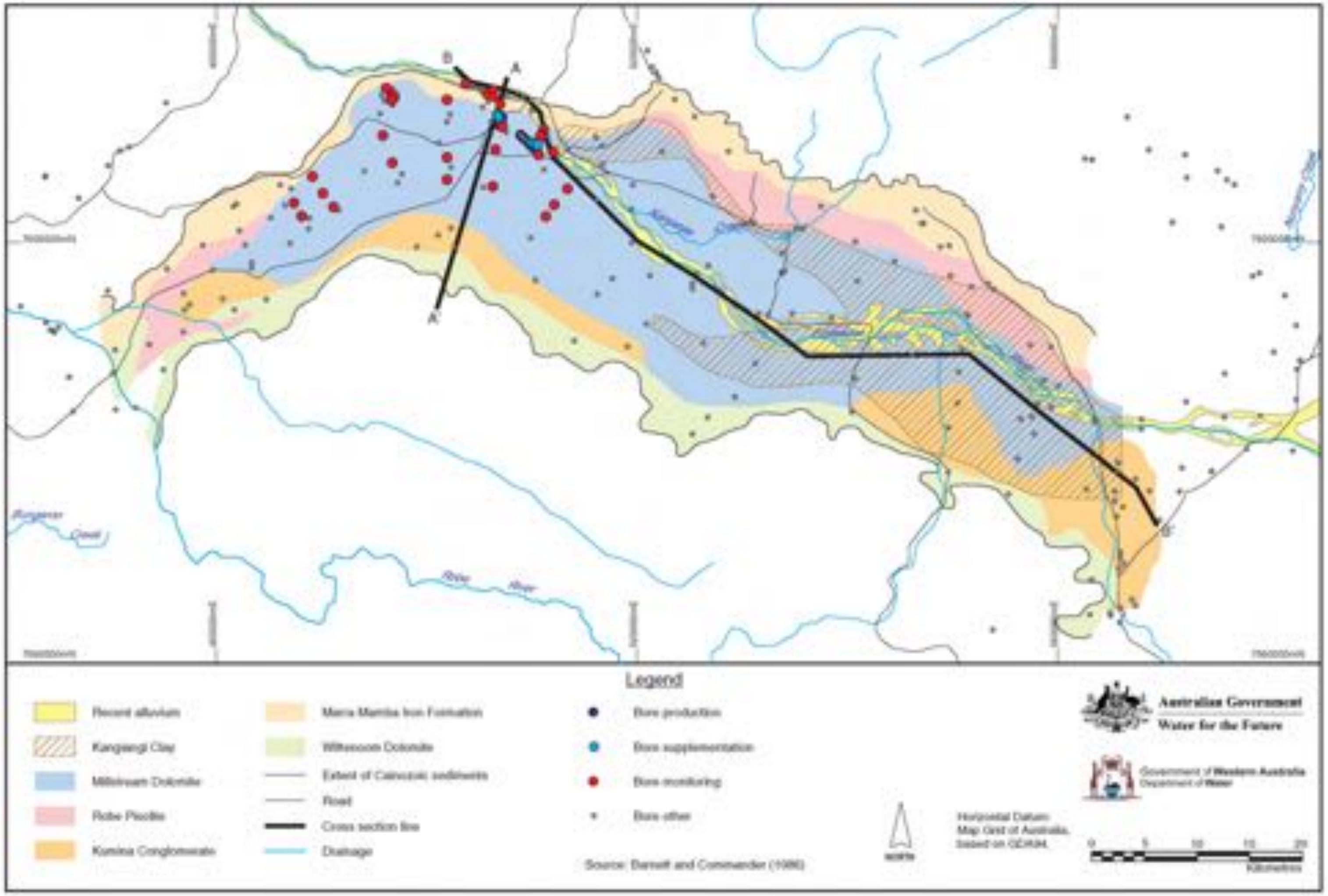


Figure 9: Millstream aquifer

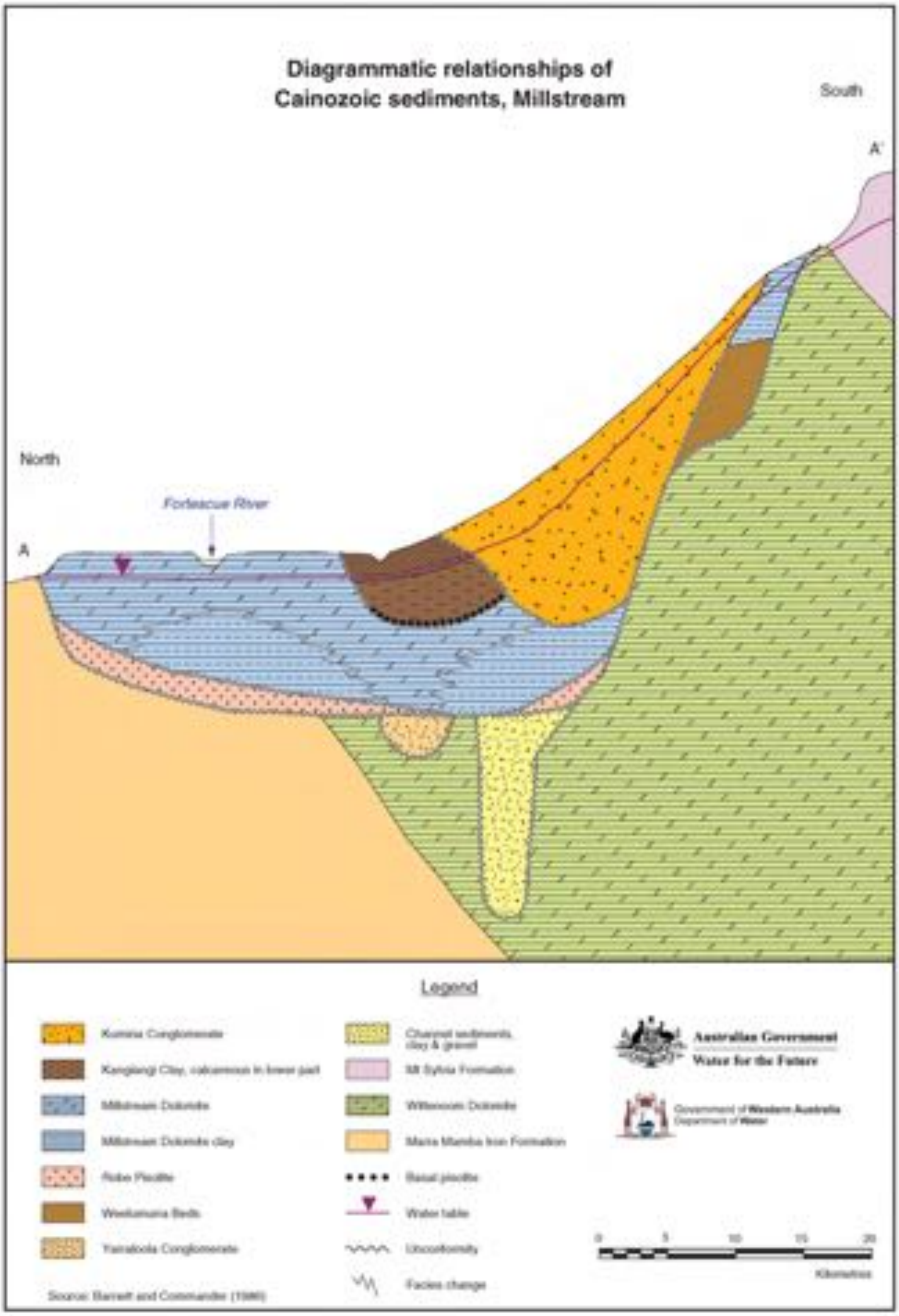


Figure 10: Millstream cross-section, across drainage

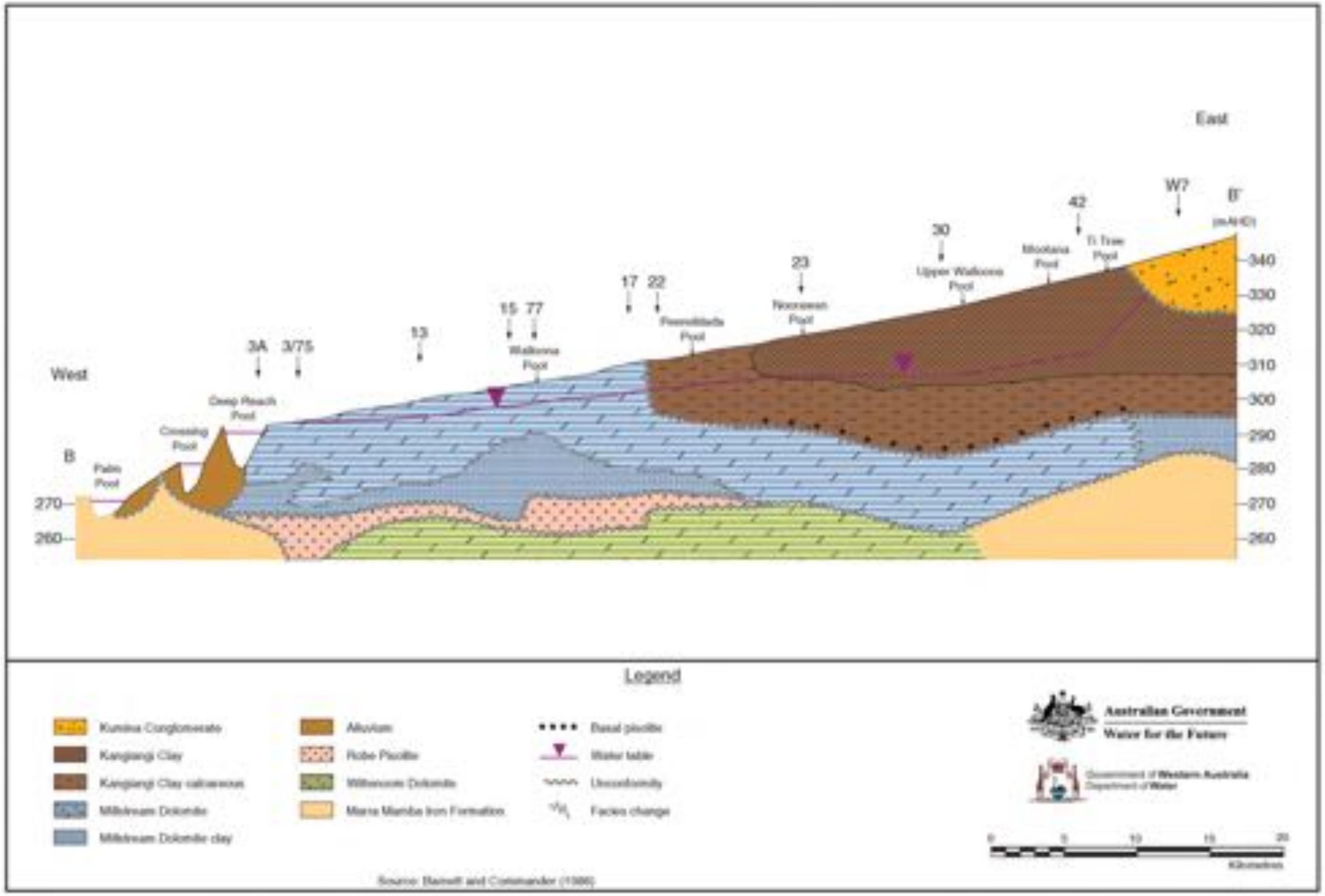


Figure 11: Millstream cross-section, along drainage

Table 10. Stratigraphic summary of the Millstream area

Age	Stratigraphic unit	Maximum recorded thickness (m)	Lithology/remarks
Late Pleistocene – Holocene	Alluvium	15	Alluvium present along water courses
	Calcareous Silt	5	Grey calcareous silt and tufa
	Residual Clay	3	Overlies Millstream Dolomite
	Alluvium	3	Unconsolidated alluvial fan deposits
	Colluvium	5	Colluvium
Middle Tertiary – Pleistocene	Kumina Conglomerate	90	Boulder, cobble, gravel and sand in clay matrix. Ferruginous at base.
	Kangiangi Clay	47	Indurated bedded silty clay, minor sand and gravel
	Millstream Dolomite	50	Dolomitic calcrete with layers of silcrete, clay and gravel
Early – Middle Tertiary	Weelumurra Beds	34	Dark grey pyritic shale
	Robe Pisolite	33	Massive and pisolitic ironstone with clayey layers
Tertiary or Cretaceous	Undifferentiated	75	Conglomerate and clay
Early Cretaceous	Yarraloola Conglomerate	36	Fluviatile conglomerate
Proterozoic	Hamersley Group		
	Wittenoom Dolomite	150	Grey calcitic crystalline dolomite
	Marra Mamba Iron Formation	20	Interbedded shale and chert, minor banded iron formation (BIF)
	Fortescue Group		
	Roy Hill Shale Member	35	Black carbonaceous shale, locally pyritic with marcasite

Precambrian

The Roy Hill Shale Member is the uppermost formation of the Fortescue Group (Jeerinah Formation) and crops out beyond the northern edge of the Fortescue plain. It is 30 to 40 m thick and comprises black carbonaceous shale with nodules of pyrite and marcasite and narrow calcite bands. Where weathered, it is white to variegated with goethite replacing iron sulphides.

The Marra Mamba Iron Formation crops out along the northern edge of the Fortescue Plain and forms the bedrock to Cainozoic deposits beneath the northern part of the plain. In this area it is about 20 m thick, consisting of interbedded shale, chert and minor banded iron formation (BIF). It is conformably overlain by the Wittenoom Dolomite Formation.

The Wittenoom Dolomite is about 150 m thick and forms the bedrock to the Cretaceous and Cainozoic deposits below the southern part of the Fortescue Plain. It crops out at the foot of the Hamersley Range. The lowermost West Angela Member comprises shale, minor BIF and chert. This is overlain by the Paraburdoo Member, which is a blue-grey crystalline dolomite with minor calcite veining, and is locally karstic. The Bee Gorge Member overlies the Paraburdoo Member dolomite and comprises dolomite and calcareous shale.

Cretaceous

The Yarraloola Conglomerate is a fluviatile conglomerate consisting of pebbles of chert, quartzite, jasper and quartz of possibly Early Cretaceous age. It unconformably overlies the Wittenoom Dolomite and is overlain by the Robe Pisolite. Its distribution is incompletely known and appears to be confined to narrow channels in the erosional surface of the underlying Proterozoic rocks. This occurrence is similar to that of the Yarraloola Conglomerate found at the Lower Robe River.

Tertiary

The Robe Pisolite is an Early to Middle Tertiary massive and pisolitic ironstone with layers of clay and shale. It occurs discontinuously at the base of the Millstream dolomite and below the Kangiangi Clay.

The Weelumurra Beds are comprised of Early Tertiary-aged dark grey pyritic shale, sometimes seen as grey to brown clay in borehole samples.

The Millstream Dolomite is a Middle to Late Tertiary calcrete and calcareous dolomite with layers of silcrete, clay and gravel. The dolomite is up to 46 m thick and is typically vuggy with cavities of up to 0.5 m high: it is cavernous in some places with sinkhole development at the surface.

Quaternary

The Kangiangi Clay is possibly Late Tertiary to Pleistocene in age and consists of indurated well-bedded silty clay with sand and gravel beds. It unconformably overlies the Millstream Dolomite and the Robe Pisolite and is overlain by (and possibly inter-fingers with) the Kumina Conglomerate.

The Kumina Conglomerate consists of boulders, cobbles and gravel in a matrix of silty clay. It is an alluvial fan deposit developed over a long period of time that extends to the present. It is currently being eroded by Kumina Creek. The Kumina Conglomerate occupies the southern edge of the valley and forms the piedmont slope to the Hamersley Range.

A thin mantle of recent unconsolidated sediments covers much of the Cainozoic formations. These are typically colluvium and sheetwash deposits on both flanks of the valley associated with present drainage.

Hydrogeology

The main aquifer units in the Millstream aquifer system are the calcrete of the Millstream Dolomite, Kumina Conglomerate, Robe Pisolite and the weathered portion of the Wittenoom Dolomite. The aquifers are interconnected as a single complex flow system, which is generally unconfined with confining conditions locally present. Proterozoic bedrock is considered to be a hydraulic boundary system (Barnett & Commander 1986).

Millstream Dolomite

The Millstream Dolomite is the most extensive and highly productive aquifer unit, extending over most of the western Fortescue valley. It is absent in the Robe River area (due to erosion) and along the north-eastern margin of the valley. Secondary porosity is well developed in the dolomite, calcrete and silcrete facies with cavities particularly well developed around the watertable. A clay facies is present along the valley's southern flank and in the Weelumurra area. The greatest saturated thickness of the Millstream Dolomite occurs in the centre of the valley where it approaches 33 m. The aquifer is unconfined for the most part, with only limited confining conditions occurring at the eastern end of the valley where it is overlain by the Kangiangi Clay. Bore yields are generally high and range up to 5500 kL/day (Barnett & Commander 1986).

Kumina Conglomerate

The Kumina Conglomerate comprises poorly sorted gravels with interbedded clay. It occurs as alluvial fan deposits along the southern side of the valley and extends across the entire valley around Weelumurra Creek. A significant saturated thickness of the aquifer occurs in the Kumina Creek/Robe River and Caliwingina Creek/Weelumurra Creek areas, where it is about 40 m. The aquifer is unconfined and in some places comprises a thin, perched aquifer where it overlies the Kangiangi Clay.

Robe Pisolite

The Robe Pisolite occurs as a discontinuous layer at the base of the Millstream Dolomite and in places below the Kangiangi Clay. It also crops out in the Robe River area. The aquifer consists of vuggy pisolitic ironstone interbedded with clay and has a maximum saturated thickness of approximately 18 m. Around the Robe River area the aquifer is unconfined, but for the most part it occurs beneath the dolomite aquifer or is confined by the Kangiangi Clay. The hydraulic gradient implies a lower transmissivity than the adjacent Millstream Dolomite, but bore yields of as much as 1700 kL/day have been reported (Barnett & Commander 1986).

Yarraloola Conglomerate and undifferentiated channel deposits

The distribution of the Yarraloola Conglomerate and other channel deposits is poorly known, and limited to narrow paleo-erosional features beneath the Robe Pisolite and Millstream Dolomite. Their lithologies vary from pebble gravels to clays and limited testing has indicated they are locally productive with borehole yields up to 1600 kL/day.

Precambrian basement

The bedrock underlying the Cainozoic sediments consists of shale, dolomite and banded iron formation. Limited investigations indicate that the basement transmissivity is lower than the overlying formations, although locally, borehole yields can be as high as 1300 kL/day (Barnett & Commander 1986). The top of the Wittenoom Dolomite Formation can often have cavities up to 0.5 m thick, with very high transmissivity in these zones.

Aquifer testing and hydraulic parameters

Numerous pumping tests were carried out on the Millstream aquifer between 1968 and 1983, with the majority concentrated on the highly productive Millstream Dolomite. Estimates of hydraulic parameters are hampered by the highly transmissive nature of the aquifer, in that drawdowns are low to negligible, even at discharges in excess of 5500 kL/day (Balleau 1973). Reliable estimates of specific yield were made on five cored holes in 1975 using a combination of downhole stereoscopic photography and laboratory analysis (Barnett et al. 1976). Attempts at measuring transmissivity have been less successful: packer testing of discrete intervals in the dolomite (as small as 0.3 m) could not induce pressure-head changes at the maximum pump capacity of 720 kL/day due to very high transmissivity. Consequently, there is only a relative observation that the dolomite is very highly transmissive (Barnett & Commander 1986). Locally the hydraulic conductivity shows widespread lateral and vertical variation, due to the irregular development of the voids and cavities forming the conduit system – as is typical of karstic aquifers.

The transmissivity of the Kumina Conglomerate was found to be generally low due to clay content and poor sorting, but reports of high-yielding bores intersecting the unit emerged during the construction of the Tom Price to Dampier railway. Bore yields range up to 600 kL/day.

The Robe Pisolite has a lower transmissivity with respect to the Millstream Dolomite, – as indicated by the hydraulic gradient across it – but is locally very transmissive. Bore yields as high as 1700 kL/day are reported. Hydraulic parameters for the Millstream aquifer units determined by Barnett and Commander (1986) are summarised below.

Table 11. Hydraulic parameters of the Millstream aquifer units

Aquifer	**No. of bores tested**	**Maximum yield (kL/day)**	**Transmissivity (m^2/day)**
Alluvium (a)	4	53	14 – 110
Kumina Conglomerate (a)	1	80	6
Kumina Conglomerate (b)	7	653	7 – 110
Millstream Dolomite (c)	30	5500	Low – very high
Millstream Dolomite (d)	2	600	12 – 2200
Robe Pisolite	3	1708	210 – 5000
Yarraloola Conglomerate	2	1610	45 – 1400
Wittenoom Dolomite	6	1310	0.5 – 100
Marra Mamba Iron Fm.	3	195	5.5 – 540

(a) Robe River area

(b) Weelumurra

(c) Including Balleau (1973) and Davidson (1969)

(d) Confined

River flows and aquifer recharge

Recharge is predominantly from infiltration of river water directly into the calcrete during flow events, with minor recharge from creeks flowing from piedmont slopes flanking the plains and directly from rainfall. The gauging station on the Fortescue River at Gregorys Gorge is suitably placed to provide measurements of the magnitude and duration of river flow crossing over the Millstream aquifer system. Figure 12 shows the hydrographs of river-flow volumes and measurements of mean aquifer level (MAL).

The average monthly flow at Gregorys Gorge is highly variable and flooding events are infrequent. Statistically the largest flow event recorded was Cyclone Joan in 1975 (a 1-in-70-year event). This event saw large flows through the Millstream aquifer, but there was negligible rainfall – indicating that the large rise in MAL was associated with the flow event. Although the largest flow events tend to be associated with cyclones, prolonged seasonal rainfall between November and April can also contribute significantly to above-average river flows.

Barnett and Commander (1986) calculated the volume of recharge resulting from Cyclone Joan from rising water levels, using a specific yield of 0.15. The river flood recharge event represented an increase in storage of 49 GL, as compared with an estimated discharge of 15 GL. Although the magnitude of flow during Cyclone Joan is the highest on record, it does not represent the most significant recharge event when considered in terms of rises in MAL. Duration of flow also appears to be a significant factor, as illustrated by rises in MAL during particularly wet years when closely spaced cyclonic events have resulted in above-average river flows being maintained for up to four months. The largest apparent rise in MAL occurred between January and March 2006 when higher-than-average river flows were maintained due to

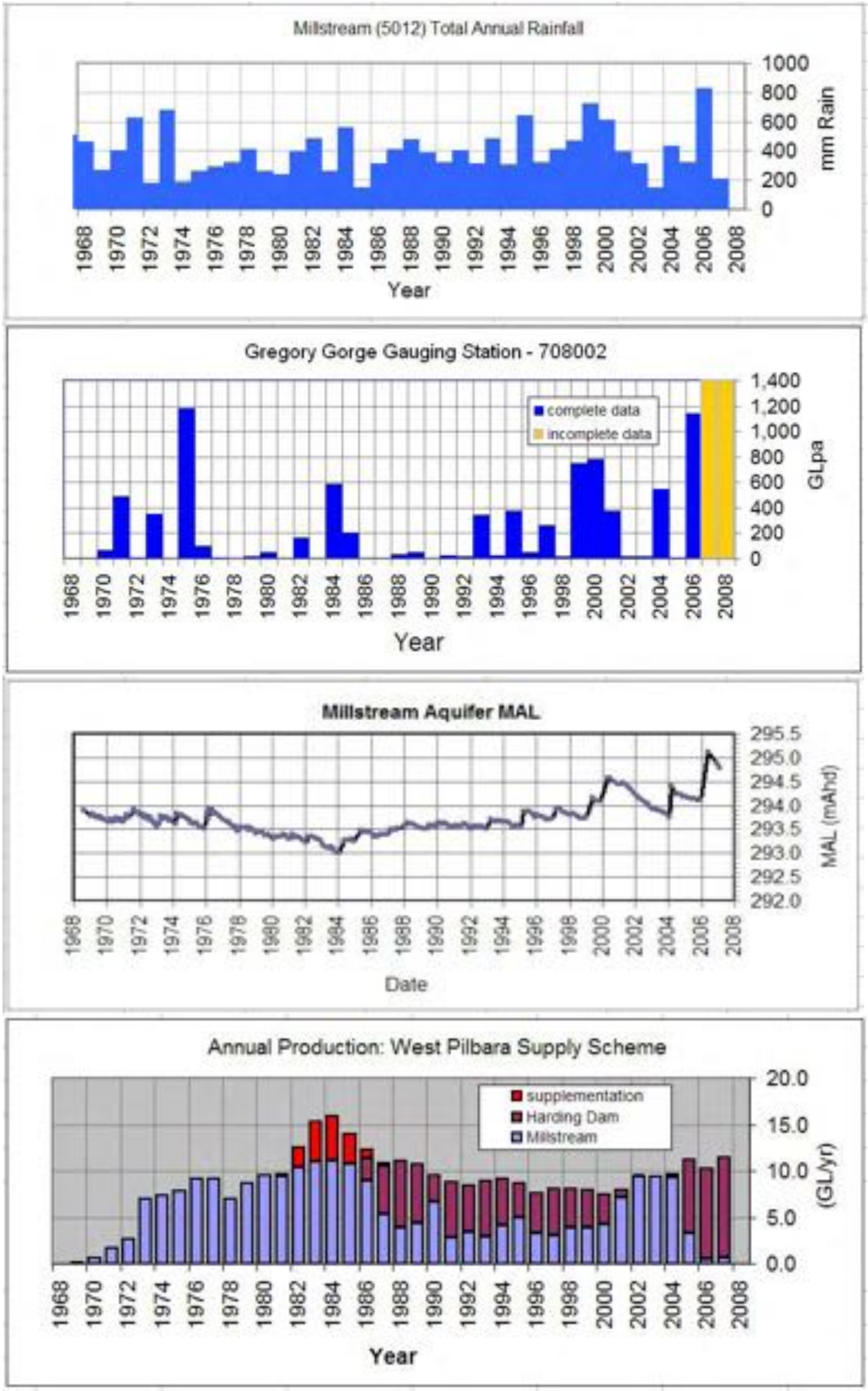


Figure 12: Millstream hydrographs and borefield production

cyclones Clare (January) and Glenda (March). Significant recharge events in recent times also include the period from December 1999 to April 2000, when three cyclones – John (December), Steve (March) and Rosita (April) – resulted in a prolonged period of elevated river flow.

A second source of recharge is to the valley flanks along streams draining the Hamersley and Chichester ranges, and directly from rainfall. It is difficult to separate the effects of rainfall and runoff recharge. As a result, both are considered together.

Commander (1996) estimated the combined runoff/rainfall recharge of five different catchment areas. The calculations were based on a chloride ion balance between rainfall and groundwater. The results of the analysis are tabulated below. This method does not take into account the loss of chloride by surface runoff: the estimates are only of maximum recharge.

Table 12. Rainfall/runoff recharge estimates

Area	**Chloride content (mg/L)**	**Area (km^2)**	**Recharge (GL)**
Hamersley Range – Mount Flora	110	740	2.6
Hamersley Range – Mount Pyrton	Not given	400	1.4
* Caliwingina Creek	50	990	7.7
** Weelumurra Creek	26	1120	6
Chichester Range	Not given	990	***Less than Hamersley Range

* Caliwingina Creek has a perched aquifer in the Kumina Conglomerate and an extensive area of low salinity in the dolomite aquifer.”

** Weelumurra catchment is similar to Caliwingina, except that there is no underlying dolomite aquifer.

*** Because lower-gradient defined channels flow over less permeable material, and groundwater salinity is much higher, lower calculated recharge is the result.

Storage

Total storage estimates for the Cainozoic sediments are reported to be 1700 GL, based on a specific yield of 0.1 for the saturated thickness. From the storage volume of 1700 GL, 1400 GL has salinity of less than 1000 mg/L (Barnett & Commander 1986). Table 13 below shows the storage estimates made by Barnett and Commander (1986) for the aquifer units within the Millstream aquifer.

Table 13. Storage estimates for the Millstream aquifer units

Aquifer	Salinity (mg/L)	Area (km^2)	Storage per km^2	Storage (GL)
Millstream Dolomite (unconfined)	<1000	250	1.5	375
Millstream Dolomite (unconfined)	>1000	200	1.5	300
Millstream Dolomite (confined)	<1000	450	1.5	675
Millstream Dolomite (confined)	>1000	50	1.5	75
Robe Pisolite	<1000	150	1.0	150
Kumina Conglomerate (Weelamurra)	>1000	120	1.0	120
Kumina Conglomerate (Weelamurra)	>1000	60	1.0	60

Aquifer discharge

Aquifer discharge is predominantly to the river, smaller creeks and springs and pools where the Fortescue River cuts into the underlying dolomite, allowing discharge to the watercourse. Deep Reach Pool is the main discharge point with the annual discharge estimated by Barnett and Commander (1986) to be 10.3 GL. Approximately 0.7 GL/yr of spring flow is also required to account for evaporation from Deep Reach Pool. Estimates of evapotranspiration for surface-water bodies, wetland areas and vegetation range from 550 to 3700 mm/year (Welker Environmental Consultancy 1998).

Minor discharges include Chinderwarriner Pool (3.8 GL/yr), Woodley Creek, Palm Springs and Peter Creek, which all support groundwater-dependent ecosystems. There is also a small discharge to the Fortescue and Robe rivers through alluvium and fractured bedrock.

Barnett and Commander (1986) estimated the total annual discharge to be 14.8 GL/yr. Discharge estimates modelled by the Water Corporation in 2005 determined a relationship between discharge and MAL, with an estimated discharge of 8.56 GL/yr for a MAL of 293.1 mAHD, increasing to 70.4 GL/yr at a MAL of 294.6 mAHD.

Water quality

Figure 13 shows the baseline isohalines reported by Barnett and Commander (1986). Salinity variations reflect the recharge and discharge mechanisms operating in the aquifer system. Groundwater salinity is lower along the valley flanks and attributed to peripheral recharge, while salinity is greatest in the centre of the valley (1000 to 1500 mg/L). The higher salinity is probably the result of a combination of evapotranspiration and brackish recharge during flood events.

The lowest salinity in the Kumina Conglomerate and Millstream Dolomite is close to the Caliwingina and Weelumurra creeks (300 to 400 mg/L), where the units are overlain by the Kangiangi Clay. Discharge is low and recharge occurs by rainfall

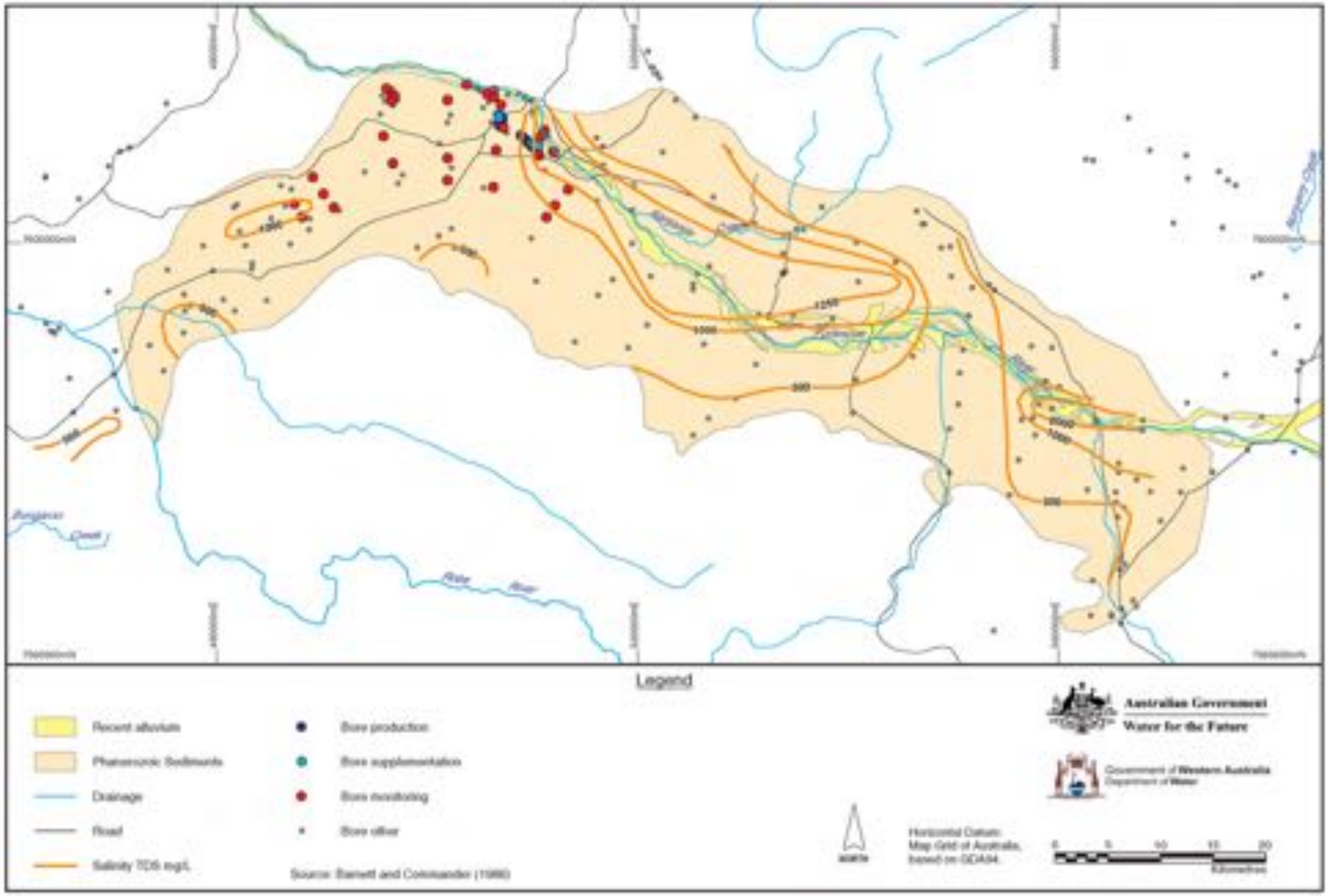


Figure 13: Millstream groundwater salinity in Cainozoic aquifers

filtering around the edge of the clays, through the Robe Pisolite and into the underlying dolomite.

Millstream borefield

The Millstream borefield consists of 12 production bores located on the south side of the Fortescue River. Ten production bores are in use and two have been decommissioned.

Production bore depths range from 23.2 to 36.2 m below top of casing (mbtoc) and the screened lengths range from 8.3 to 13.9 m over the most productive horizons of the aquifer. Table 14 provides a construction summary of the Millstream production bores.

Table 14. Millstream production bores construction summary

Production bore no.	Depth (mbtoc)	Screened interval (mbtoc)	Recommended pumping rate (kL/day)
PB1	24.8	9.1–22.0	17,743
PB2	20.9	5.9–18.1	17,774
PB3	28.3	16.5–24.8	17,698
PB4	23.2	9.1–20.5	8980
PB5	23.2	9.4–21.3	8879
PB6	23.8	11.2–21.1	8838
PB7	33.3	21.3–32.7	8911
PB8	32.5	20.3–31.7	8887
PB9	36.2	22.0–33.1	8923
PB10	31.9	15.2–29.1	8809
*PB11	24.8	11.9–22.3	8694
*PB12	26	13.8–22.8	8561

* Decommissioned

The borefield is located within several kilometres of Deep Reach Pool, Crossing Pool, Chinderwarriner Pool and the Millstream Homestead (Figure 8). Bores PB11 and PB12 were decommissioned due to increased salinity, but are still monitored for salinity and groundwater levels.

Historic production from the Millstream borefield has ranged from a minimum of 1 GL/yr to a maximum of 11 GL/yr between 1978 and 2006. Total pumping during 1983–84 was actually 15.9 GL due to the additional pumping of 4.9 GL from supplementation bores (Water Corporation 1997). The average production from 1978 to 2006 is 6 GL/yr. The highest production was from 1982 to 1985 when production averaged 10.8 GL/yr. Abstraction volumes from Millstream were reduced following completion of the Harding Dam in 1986. Figure 12 shows the annual production from the West Pilbara Water Supply Scheme, and includes the contributions from both the

Millstream aquifer and the Harding Dam. The additional abstraction from supplementation bores is also shown for the periods when sustained pumping at Millstream increased the decline of aquifer water levels.

Monitoring

Both the Department of Water and the Water Corporation monitor the Millstream aquifer using a range of hydrogeological and hydrological parameters. The current monitoring of the aquifer and borefield is summarised in Table 15 and includes groundwater levels, pumping volumes and chemical parameters. Table 16 summarises the environmental monitoring of water levels, creek flows and pool levels.

Table 15. Borefield monitoring network

Monitoring frequency	Water levels	Pumping volumes	Conductivity and pH	Major ions	By
Production bores					
PB1, PB2, PB3B, PB4A, PB5A, PB6, PB7, PB8, PB9, PB10	Monthly	Monthly	Monthly (when operating)	Annual	WC
Decommissioned bores					
PB11, PB12	Bi-monthly		Annual	No	WC
Supplementary bores					
Deep Reach DR1(1/84), DR2(2/84), DR3(3/84)	Monthly	Monthly	Monthly (when operating)	No	WC
Chinderwarriner CP1(1A), CP2(2/81), CP3(11/81)	N/A		Annual		WC
MAL 8 & 7A monitoring bores (current)					
1C, 1E, 2B, 2C, 4A, 5B, 7C, 8C, 7A	Bi-monthly	N/A	Annual	No	WC
MAL 19 monitoring bores (previous)					
1B, 1D, 3A, 4B, 4C, 5A, 5C, 7A, 7D, 8B	Monthly and annual readings from 1968 to 2002				n/a

Table 16. Hydrological monitoring program

Monitoring point	Monitoring suites and frequency	By
Millstream delta bores		
P3/77, P4/78, P2/77	Bi-monthly groundwater levels and physical chemistry	WC
Palm Creek bores		
Palm Creek: P2, P4, P5, P8	Bi-monthly groundwater levels and physical chemistry	WC
Riverine area bores		
P9/77, P9/78, P7/78, P8/77	Bi-monthly groundwater levels	WC
Millstream Pool levels and Delta flows		
Chinderwarriner Pool	Monthly outflow rates, pool levels and physical chemistry	WC
Delta channels 1, 2, 3, 4, 5, 6a and 6b	Fortnightly flow distances/volume into Fortescue River	DoW
Additional channels	Monthly physical chemistry	WC
Riverine area pool levels and channel flows		
Crossing Pool	Monthly outflow rates and pool level	WC
Deep Reach Pool	Monthly pool level	WC
Palm Pool	Monthly pool level	DoW
Livistonia Pool	Monthly pool level	DoW
Gregorys Gorge	Continuous flow, observed inflow rate	DoW
Creek flows		
Peters Creek	Monthly flow estimates	WC
Woodley Creek	Monthly flow estimates	WC
Palm Creek	Monthly flow estimates	WC
WC depot meteorological		
WC depot	Daily rainfall and pan evaporation	WC

The Water Corporation does most of the monitoring, while the Department of Water measures selected pool levels and discharges and monitors gross vegetation distribution, vegetation dynamics and significant environmental areas.

Management criteria

Abstraction from the Millstream aquifer is managed by monitoring the mean aquifer level (MAL) to ensure that set water-level-decline criteria are not exceeded. Surface-water features are managed on the basis of pool water levels and measured discharge flows. Outflow guidelines are specified for Chinderwarriner Pool and Crossing Pool and are designed to ensure that sufficient water flow occurs between Deep Reach Pool and Gregorys Gorge to maintain riparian vegetation health. Supplementation bores have been installed for the Deep Reach and Chinderwarriner pools to be used when natural surface-water flows fall below set Environmental Water Provisions EWP limits. Cease-to-pump levels have also been set for Chinderwarriner, Crossing and Deep Reach pools. The Department of Water is currently reviewing the operating strategy that sets the management criteria for the aquifer.

Groundwater levels

Figure 14 shows the isopotentials reported by Barnett and Commander (1986). The groundwater gradient trends from the south and south-east towards the north and more or less follows the direction of the river.

Aquifer levels are assessed using the mean aquifer level (MAL), which is the average water level of nine priority monitoring wells (MAL 8 and 7a monitoring bores) observed on a bi-monthly basis. Figure 12 shows the changes in MAL since the Millstream borefield came online in 1968. As trends seen in non-priority monitoring bores are also reflected in the MAL, it is considered an appropriate representation of changes in groundwater levels in the aquifer due to recharge, drainage and abstraction.

The major control to the changes in water level is recharge, which is predominantly from river flow from episodic cyclonic events. The flow events result in sharp rises in water levels and can be directly correlated to flow hydrographs from Gregorys Gorge. Rainfall recharge is more difficult to correlate to the water-level hydrograph and is a less significant component of recharge. Drainage from the aquifer is represented by the gradual recession curve that follows each recharge event. High pumping during the times of drought in 1983–84 has caused water levels to drop to historic lows.

The water levels from 1969 to 1978 vary between 293.5 and 293.4 mAHD. During this time, significant river-flow events were occurring every other year. Production from the borefield between 1973 and 1977 averaged about 8 GL/yr and during this time aquifer levels did not drop markedly. It should be noted that lowering of the MAL below 293.4 might have an adverse impact on the environment.

The hydrograph shows a gradual drop from 293.9 mAHD in early 1976 to a historic low of 293.0 mAHD in January 1984. This correlates with a seven-year period between 1976 and the end of 1983 when river flows did not occur or were well below the annual mean. Production during this time averaged about 8 GL/yr, but increased to 11 GL/yr (15.9 GL with supplementation) in 1983–84. The period of greatest supplementation was during 1983–84 when the total abstraction from the aquifer was 15.9 GL/yr. This also coincided with the period of lowest aquifer levels, which indicates that supplementation pumping is not without its problems.

The drop in water levels from early 1976 to 1984 is clearly a combination of very low river-flow recharge and pumping. The increased rate of drawdown during 1983–84 is due to the increase in total abstraction from 10 GL/yr in 1982 to 15.9 GL in 1983–84. Rates of decline between 1978 and 1981 were about 0.25 m over a four-year period, or about 0.06 m/year. Pumping during that time was below 10 GL/yr. Increasing the pumping rate in 1983–84 caused rates of decline of about 0.4 m over two years, or about 0.2 m/year. It can be concluded that pumping rates of 15 GL/yr during periods of drought result in an increased rate of decline.

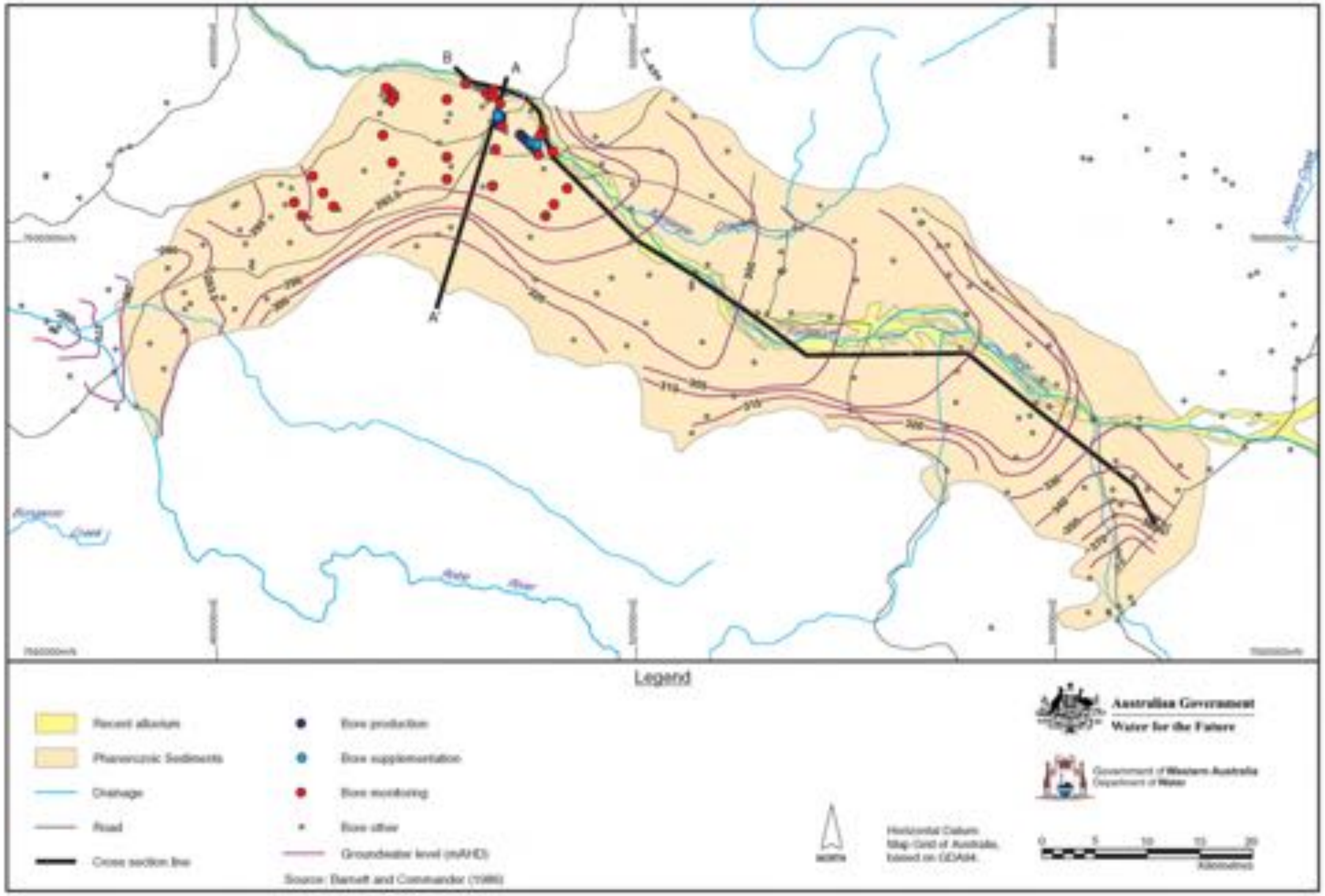


Figure 14: Millstream water levels in the Cainozoic aquifers

The Harding Dam was brought online in August 1985. Production from Millstream for the water year ending in 1986 was reduced to just under 10 GL/yr, including supplementation. From 1987 to 1992, production from Millstream averaged about 4 GL/yr. That period also coincides with a six-year period of extremely low river flows. The MAL from 1987 to the end of 1992, however, was relatively stable. This would indicate that pumping rates of about 4 GL during times of infrequent river flow results in stability of the MAL.

The period from 1992 to 1998 showed river-flow events of greater than the mean annual flow volume occurring about every other year. During that time, pumping from the Millstream was kept at an average of about 4 GL. As a result of the periodic recharge events and the low pumping, water levels in the Millstream gradually rose to those seen in the early to mid 1970s. It appears that during times of periodic recharge, pumping at rates of 4 GL/yr results in an increase in aquifer storage. At pumping rates of about 8 GL/yr under similar circumstances (e.g. 1973–77), it appears that storage remains the same and the MAL is stable.

Major recharge events from large river flows occurred in 1999, 2000 and 2001 as a result of periodic cyclones. The MAL reached an all-time high of 294.56 in 2000 following Cyclone Rosita. During the first two years of that period, production was kept at about 4 GL/yr. In 2001, production rose to 7 GL/yr. Because the Harding Dam was offline, pumping at Millstream averaged about 9 GL/yr for three years from 2002 to 2004. Although there were significant recharge events before 2002, there were no river-flow events in 2002 and 2003. During the two-year period of minimal recharge and pumping at 9 GL/yr, water levels dropped significantly at a rate of about 0.25 m/year. It should be noted that the aquifer was draining from a large increase in storage and that the rapid dropping of water levels to between 293.5 and 294.0 was a result of the aquifer stabilising after a significant recharge event. Between December 2003 and February 2004, supplementation pumping to Chinderwarriner Pool was necessary due to outflows approaching the minimum flow criteria. It appears that drought events of only two years in duration and pumping rates of 9 GL/yr may result in dramatic drops in water levels and that spring discharges may approach minimum criteria.

Following cyclone events in early 2004 and again in early 2006, the MAL has again been elevated to record high values in excess of 295.0. Since the microfiltration plant at the Harding Dam came online in 2004, abstraction from Millstream has been reduced to less than 1 GL/yr in 2006 and 2007. The MAL shows a very steep rate of decline following the 2006 recharge event as the aquifer system drained naturally.

Aquifer supplementation

Between 1981 and 1984, supplementation bores were drilled to provide a source of water for springs affected by drawdown of the watertable.

The falling Millstream MAL during the first half of the 1980s led to the need to use supplementation bores from 1981 to 1987. The largest supplementation volumes were abstracted from 1983 to 1986, with a peak level of approximately 4.9 GL/yr abstracted in the water year 1983–84. During that year, total pumping from both production bores and supplementation bores was 15.9 GL.

Water levels in the Millstream aquifer rose as a result of the recharge event associated with Cyclone Chloe in 1984. In addition to rising groundwater levels, the Harding Dam came online in August 1985. Subsequently, production from the Millstream aquifer was reduced in the 1985–86 water year. Supplementation pumping was also reduced from 1985 to 1987 and was not necessary following the 1986–87 water year.

From December 2003 to February 2004, a small amount of supplementation pumping was required, but has not been needed after that date. Since the recharge events caused by cyclones Clare and Glenda in early 2006, pumping from the Millstream aquifer has been below 3.5 GL/yr.

Modelling results

A numerical model was developed for the Millstream aquifer (URS 2007) to assess the effects of borefield abstraction on water levels and discharges. Currently the model is being updated following a review of the model (CyMod Systems 2007).

Restrictions to resource development

Barnett and Commander (1986) reported that the groundwater salinity in the Millstream aquifer is higher in areas upstream of the current borefield: the Water Corporation has confirmed this during bi-annual reporting. Development of a borefield in this location would require a use to be found for higher-salinity water.

A restriction on such a scenario would be the chloride content in water accessed from the new location. Approximately one third of the water supply used at the port facilities is for heavy industry, which is predominantly related to dust suppression of iron ore. High-chloride water is undesirable for the wetting of ore due to complications with blast furnace linings at the receiving smelter facilities. As a result, higher-chloride water would not be appropriate for iron ore processing.

A second restriction would be the need to construct a second pipeline to keep the brackish water separate from the fresh water piped from the Harding Dam. The cost effectiveness of this scenario would need to be thoroughly assessed before any development went ahead.

Further work

The current Millstream aquifer model should be revised based on limitations identified in the modelling report and in light of deficiencies highlighted by an independent technical review. A major improvement would stem from topographic surveys of river stage elevations, which would improve control over aquifer drain cells in the numerical model.

To aid knowledge of the recharge mechanism, it is recommended that two stream-flow gauging sites be installed on the Fortescue River. One should be placed upstream of the borefield where the calcrete is at the surface. The other should be placed further upstream where the Kangiangi Clay forms a confining layer over the calcrete aquifer. The gauging will provide more accurate estimates of flood volume and duration. The gauging sites should be supplemented with the installation of at least three monitoring bores at the edge of the river channel in the calcrete. The gauging data and the groundwater aquifer data adjacent to the river will allow for a better understanding of the surface-water and groundwater interactions.

The model should also assess the aquifer response and potential impacts/benefits to augmenting the current borefield. Various development scenarios should also be investigated to determine trigger values for various climatic and abstraction scenarios. The value in developing a surface-water model, such as MIKE11, should be reviewed to determine if such a project would improve the groundwater model.

There is a need to understand the salinity of recharge water following flood events. The conceptualisation of this phenomenon could be tested with solute transport modelling to generate the high-salinity zone around the river channel. The change in salinity is not easily explained with the current conceptual hydrogeology.

It is also recommended that the current groundwater-monitoring network be reviewed and expanded as necessary.

Mapping of watertable contours is required, especially across the river where intermittent and permanent pools exist. Good control over watertable contours is required to increase understanding of aquifer water levels and the reliance of local vegetation on groundwater.

4.3 Potential groundwater supplies

4.3.1 Lower Fortescue River alluvium

The Lower Fortescue alluvial aquifer lies along the lower reaches of the Fortescue River on the Ashburton plain approximately 100 km south-west of Karratha (Figure 2). The water-bearing alluvial sequence was deposited in an alluvial fan environment during Quaternary progradation of the Fortescue River outwards from the coastal scarp, and comprises significant gravel horizons favourable for groundwater abstraction.

Initial groundwater exploration and aquifer testing was carried out in 1965 to support a potential iron ore processing facility at Cape Preston (Bradberry Associates 1965). The work included 15 exploration bores (of which six were test pumped) and identified an extensive shallow gravel aquifer, however the resource was not developed at that time. In 1972 two petroleum exploration wells (Mardie West 1 and Coonga 1) were drilled in the area, targeting the underlying Tertiary and Cretaceous sequences. Later work on the Lower Fortescue River alluvium included salinity distribution mapping (Davidson 1975a), which identified low-salinity groundwater coincident with the major gravel aquifer. A seismic survey was later conducted to determine the thickness of the saturated profile (Nowak 1979). Additional seismic lines were also run during 1984 (Kevi 1984).

In a review of supply options for the West Pilbara, the Lower Fortescue area was evaluated as a potential borefield site by Dames and Moore (1979). The hydrogeology has also been briefly described by Allen (1988) as part of a broader review of groundwater in the Carnarvon Basin.

The main body of work on the Fortescue River alluvium stems from Geological Survey of Western Australia (GSWA) groundwater-exploration programs undertaken between 1983 and 1985 (Commander 1989, 1994). A total of 36 exploration bores and three test-production bores (Figure 15) were drilled and constructed, and five aquifer tests were conducted – each comprising step and constant rate tests.

Geology

The Lower Fortescue River area overlies an area of basement known as the Peedamullah Shelf (Hocking et al. 1987) in the northern part of the Carnarvon Basin. The Peedamullah shelf comprises a sequence of gently northwest-dipping Cretaceous strata up to 90 m thick unconformably overlying Precambrian basement rocks correlated with the Hamersley Basin. Cretaceous sequences are unconformably overlain by Tertiary sediments, which are themselves unconformably overlain by up to 30 m of Quaternary alluvial sediments associated with the Fortescue River. The local stratigraphy is summarised below in Table 17.

Table 17. Stratigraphy of the Lower Fortescue River area

Age	Formation	*Thickness (m)	Lithology
Quaternary	Alluvium	30	Clay, gravel, calcrete close to the watertable
Unconformity			
Tertiary (Miocene)	Trealla Limestone	17	Limestone, clay, marl
Unconformity			
Cretaceous	Muderong Shale	0	Shale
	Yarraloola Conglomerate	23	Conglomerate
Unconformity			
Precambrian	Mt. Bruce Supergroup		Basalt, chert

* Note: maximum thickness intersected during drilling

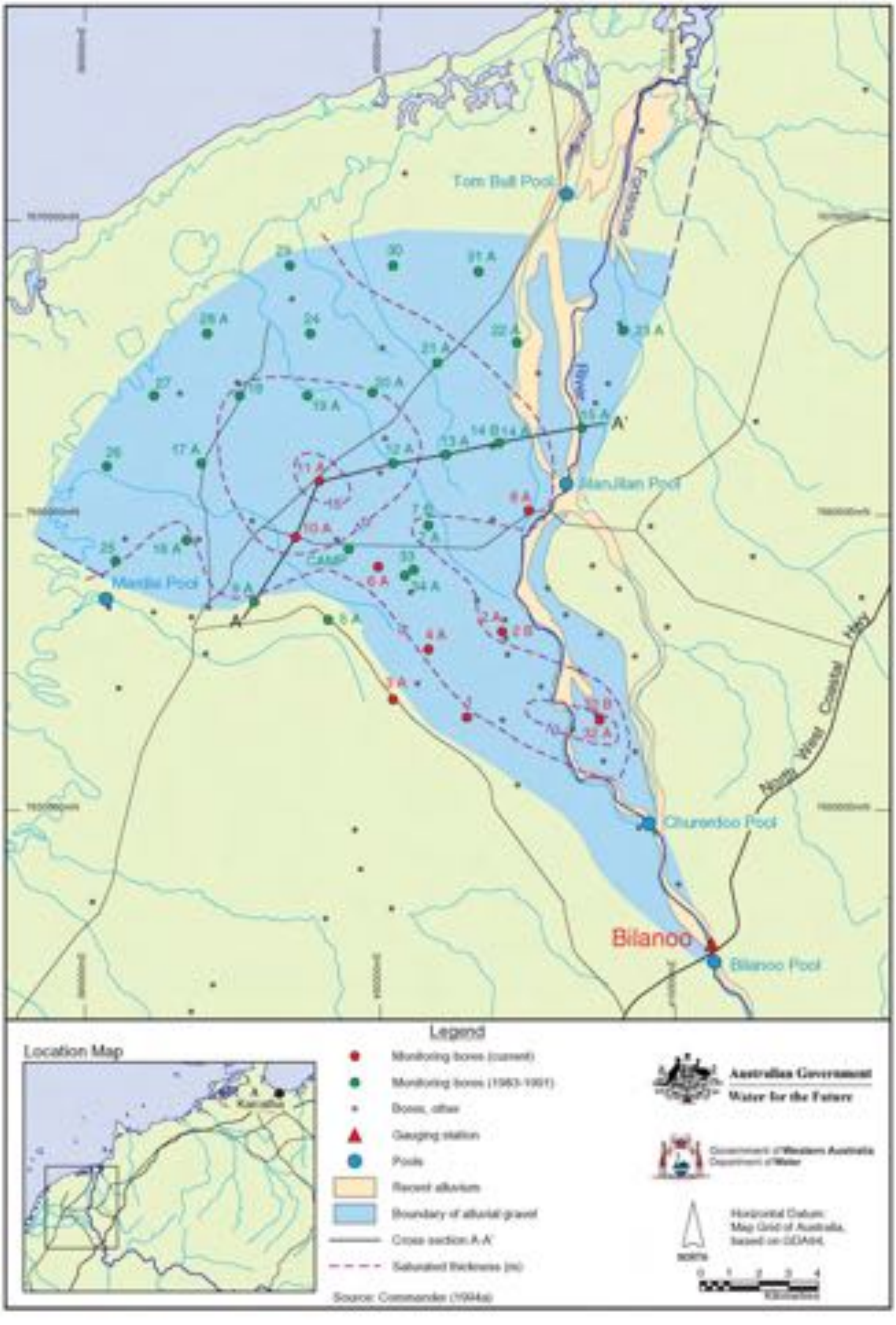


Figure 15: Lower Fortescue River

Precambrian

Precambrian basement rocks of the Mount Bruce Supergroup crop out on the hills either side of the upper reaches of the Lower Fortescue River (near the North West Coastal Highway) and in small outliers between the Mardie and Balmoral homesteads. The basement is also intersected in some deeper exploration bores. Rock types include basalt (correlated with the Maddina Basalt), cherts (correlated with Brockman Iron Formation) and ferruginous shale.

Cretaceous

The Early Cretaceous Yarraloola Conglomerate unconformably overlies and infills incised valleys in the Precambrian basement. It crops out in places adjacent to the Precambrian bedrock along outliers located north of the Balmoral Homestead. It was intersected in three wells during the GSWA exploration program and consists of angular to rounded pebble gravel (mainly derived from Mount Bruce Supergroup) with minor beds of sand and clay formed as stream deposits in a fluvial environment. At other locations on the Peedamullah Shelf, it grades laterally into the Nanutarra Formation and the Birdrong Sandstone (Commander 1994a).

The Early Cretaceous Muderong Shale unconformably overlies the Precambrian basement and comprises grey-green siltstone with a basal greensand (Mardie Greensand Member). As the groundwater exploration bores were generally stopped in the Trealla Limestone, the Muderong Shale was only intersected in the petroleum exploration bores at depths of 74 m (Coonga 1) and 93 m (Mardie West 1).

Tertiary

The Middle Miocene Trealla Limestone unconformably overlies the Yarraloola Conglomerate or Muderong Shale. It consists of interbedded clay, marl and fine gained limestone, and typically forms the lower confining beds of the Lower Fortescue River alluvial sequence.

Quaternary

Quaternary alluvial deposits are up to 30 m thick and form part of an alluvial fan associated with the discharge of the Fortescue River onto the Ashburton plain. The alluvium unconformably overlies Precambrian, Cretaceous and Tertiary rocks, deposited on the pre-existing erosional surface. Figure 16 shows a contoured representation of the base of the Quaternary alluvial sequence (mAHD), and Figure 17 is a cross-section through the Lower Fortescue area.

The present surface is dominated by clayey over-bank deposits with gravel beds in drainage channels and in subsurface paleochannels. The gravel consists of rounded pebbles up to 100 mm in diameter of basalt, chert, tuff, jaspilite and minor quartz, derived from the surrounding Precambrian basement. These are partially cemented adjacent to semi-permanent river pools. Over-bank deposits comprise dense red to yellow ferruginous clays and pink to white silty and sandy clays. The gravel deposits

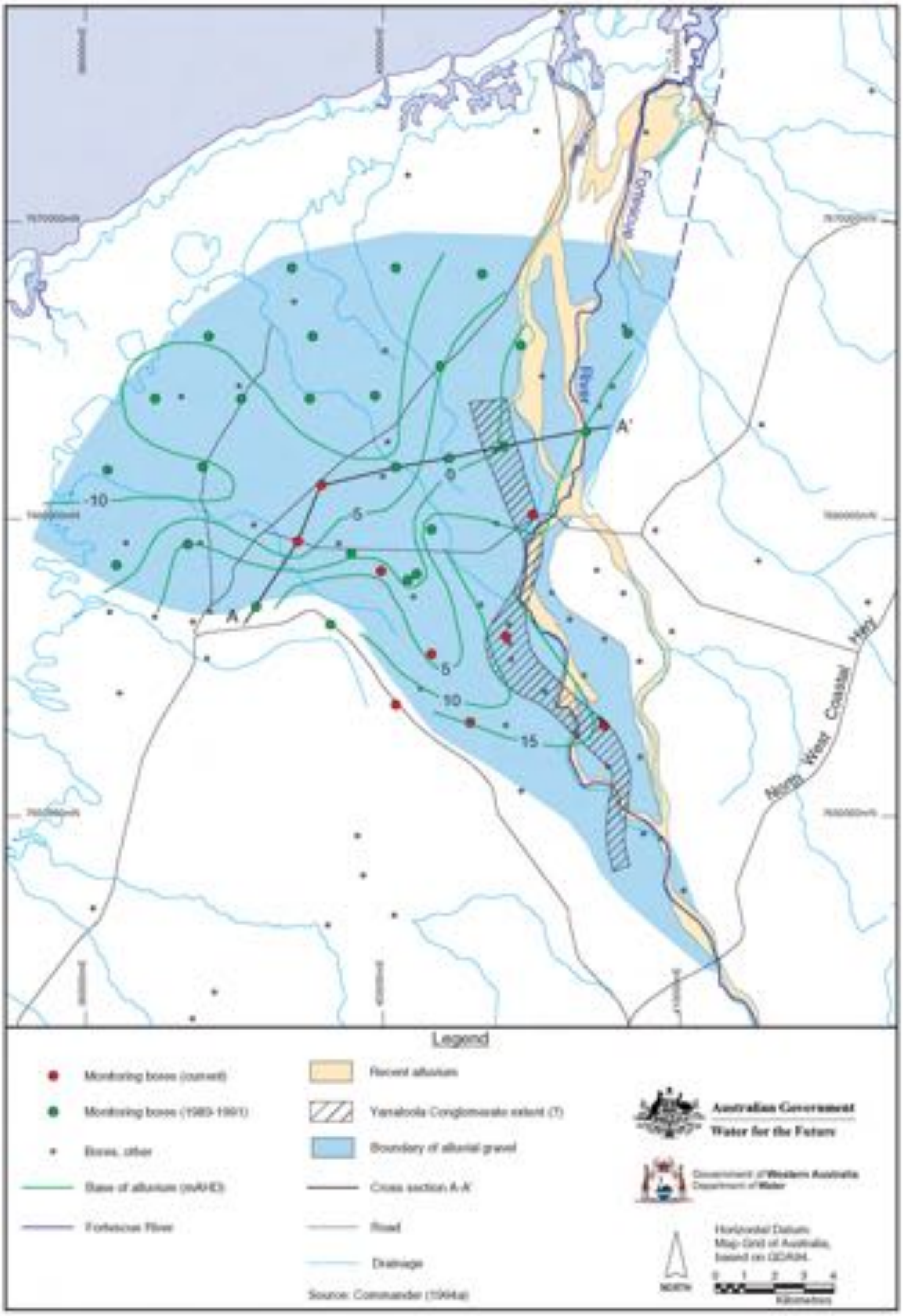


Figure 16: Lower Fortescue River base of alluvium

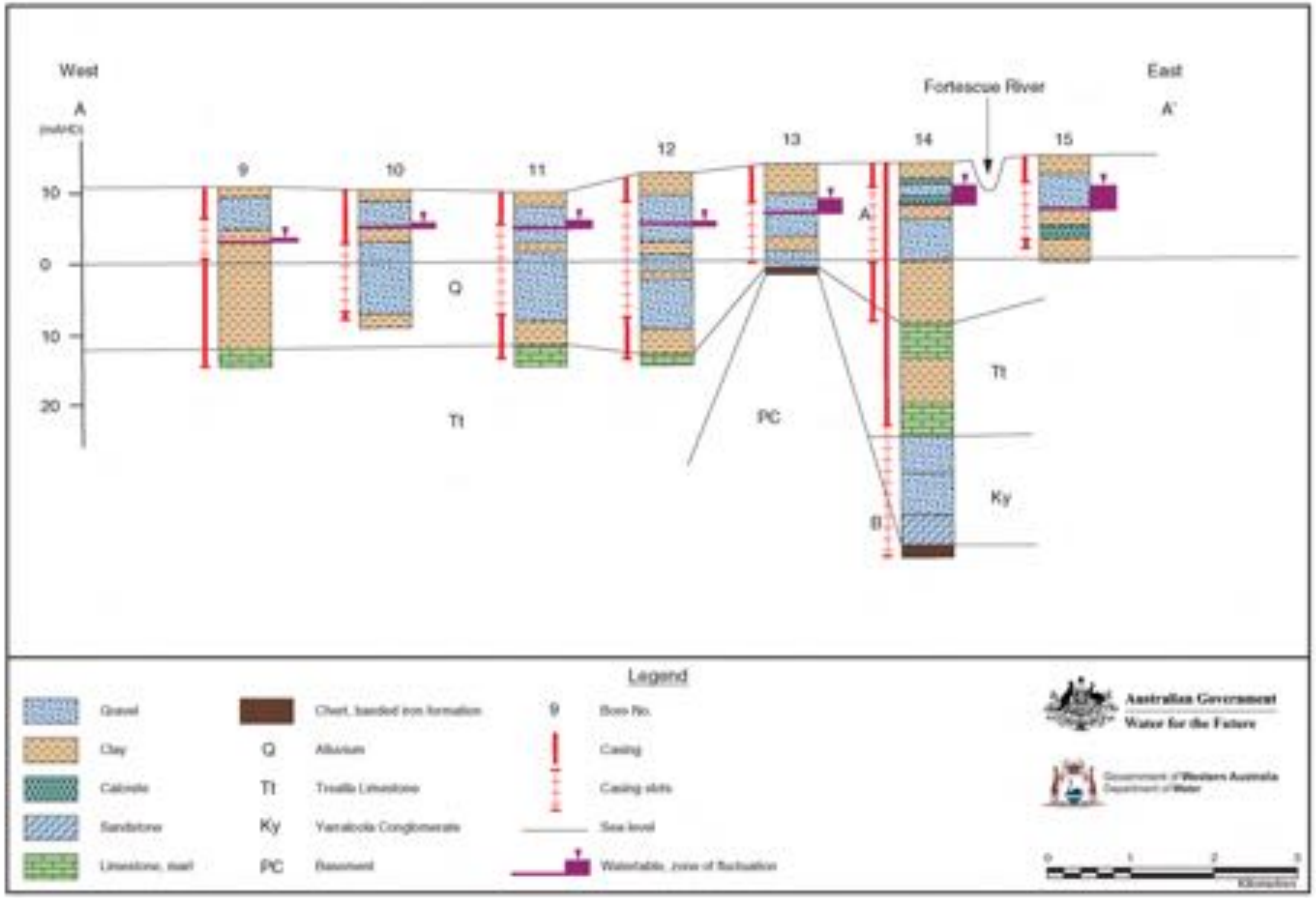


Figure 17: Lower Fortescue River cross-section A-A’

thin outwards from the main drainage channels into predominantly clayey sequences that are locally ferruginous and silicified. Calcrete is locally formed in a close zone of watertable fluctuation, typically at depths between 4 and 12 m below the surface.

Hydrogeology

The Lower Fortescue River alluvial aquifer extends over the alluvial fan deposit to the west of the present-day Fortescue River. It is defined by highly transmissive gravel beds deposited through the central area of the alluvial fan with a saturated thickness up to 15 m and an aerial extent of approximately 200 km^2 (Commander 1994a). Figure 15 shows the extent and thickness of the saturated gravel aquifer. The aquifer grades laterally into the floodplain into clay and silt deposits of much lower transmissivities.

The gravel deposits coincide with a fresh water lobe, typically less than 1000 mg/L TDS, which grades outwards into saline groundwater near the coastal interface and margins of the alluvial fan. The low salinity is a result of recharge from periodic river flow.

Yarraloola Conglomerate aquifer

The Yarraloola Conglomerate is present in a narrow channel that coincides approximately with the current position of the Lower Fortescue River. In general, the Yarraloola Conglomerate fills erosional features in the Precambrian basement rock. The distribution is incompletely known and appears to be confined to narrow channels in the erosional surface of the underlying Proterozoic rocks. This occurrence is similar to that of the Yarraloola Conglomerate found in the Robe River and in the Fortescue River at Millstream. At the Lower Fortescue River, the Yarraloola Conglomerate aquifer is confined by up to 30 m of Trealla Limestone.

Aquifer testing and hydraulic parameters

In addition to step-rate tests, constant-rate pumping tests of eight hours duration were conducted on three bores during the GSWA investigation of the Lower Fortescue River alluvial aquifer. Limitations of pump and casing size resulted in relatively low discharge rates of 230 to 590 kL/day, with drawdown in observation bores (20 m from pumping bore) less than 0.5 m. Pumping tests of Cliffs No. 2B by Bradberry and Associates (1965) at a pumping rate of 1690 kL/day resulted in a drawdown of 0.5 m.

Drawdown data from the GSWA testing was interpreted using delayed yield non-equilibrium type curves. Estimations of transmissivity ranged between 380 and 1760 m^2/day in the alluvial aquifer.

A specific yield of 0.3 was assumed from samples of river gravel, however a specific yield of 0.1 was assumed to be more realistic as the gravel has a proportion of clay in the matrix.

Groundwater levels

The watertable in the Fortescue River alluvium is generally between 5 and 12 m below ground level and is subject to seasonal and annual fluctuations of as much as 6 m close to the river. Figure 18 shows the watertable contours (Commander 1994a), which drop 23 m over a distance of 20 km from the bedrock outcrops to the tidal flats. Anecdotal evidence indicates that a mesquite infestation caused water levels to lower by 2 m. The mesquite's subsequent removal caused water levels to recover (by 2 m).

River flows

The Fortescue River's flow has been measured since 1968 at Jimbegnyinoo Pool, which is located 4.5 km upstream of the North West Coastal Highway. The hydrograph of total annual flow at Jimbegnyinoo Pool (708003) is also shown in Figure 19. The mean annual flow at Jimbegnyinoo Pool is 255 GL (1969–97).

During the station's 29 years of operation, there were 10 years during which the volume of flow over a four-month period exceeded the mean annual volume of 255 GL. Historic flow associated with cyclone (and rain) events indicates that flows will often persist for several months following the flood peaks. River-flow events of greater magnitude than the annual mean occurred in approximately one out of every three years.

River flow has been recorded at the Jimbegnyinoo Pool station every year for 29 years. Although the record indicates that the river flows every year, there were five years during which the maximum-recorded annual flow was less than 10 per cent of the mean annual flow. This indicates that in about one out of every six years, the total annual flow to the Lower Fortescue River alluvial aquifer system is very low. The longest number of consecutive months during which no flow was recorded at Jimbegnyinoo Pool is five months (Table 5). This estimate of drought duration based months of no-flow events is the lowest of the major river catchments in the Pilbara.

Recharge to the alluvial aquifer

Recharge to the Lower Fortescue River alluvial aquifer results from direct infiltration through the riverbed during periods of stream flow. The volume of recharge is controlled by the duration of flow, frequency of flow, depth of flow and the available storage of the aquifer. Following the flow event resulting from Cyclone Chloe in February 1984, recharge was estimated by calculating the volumetric change in the saturated aquifer between March and July of 1984. A specific yield of 0.1 was assumed for the alluvial gravels and the change of water levels was determined from hydrographs. The recharge during the flood event caused by Cyclone Chloe was estimated to be 22.7 GL (Commander 1994a).

Recharge to the Yarraloola Conglomerate

Recharge into the Yarraloola Conglomerate is from downward leakage from the overlying alluvium where sections of the Trealla Limestone have been eroded away.

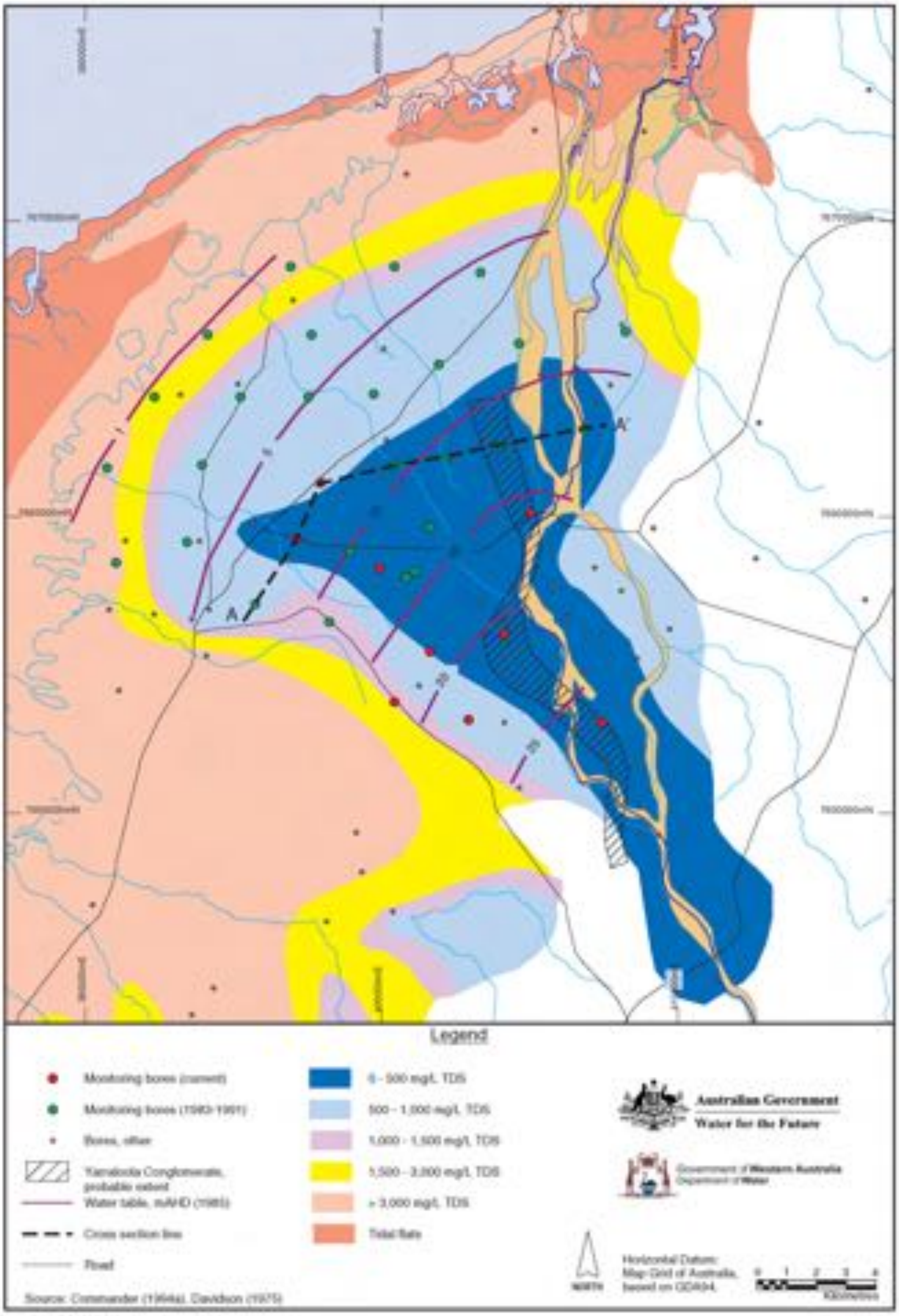


Figure 18: Lower Fortescue River groundwater levels and salinity

Figure 19: Lower Fortescue River – hydrographs

No recharge estimates are available for the Yarraloola Conglomerate from previous investigations.

Storage — alluvial aquifer

The volume of storage in the Lower Fortescue River alluvial aquifer can be estimated by applying an assumed specific yield to the volume of saturated thickness. Commander (1994a) defined the aerial extent of different thickness intervals as determined from drilling, and applied a specific yield value of 0.1. The total volume of storage in November 1985 was estimated to be 126 GL.

Storage — Yarraloola Conglomerate

Storage coefficients could not be determined for the Yarraloola Conglomerate. As a result, an estimate of total storage could not be made. Until further analysis of the aquifer parameters can be made, it can be assumed that the volume of storage in the conglomerate is significantly less than that of the alluvial aquifer.

Throughflow

Groundwater flow through the Lower Fortescue River alluvium generally trends away from the river towards the north-west. During periods of stream flow there is mounding of groundwater beneath the river bed, which results in temporary reversal of the local hydraulic gradient towards the east: this returns to a westerly flow on cessation of the river flow.

Throughflow in the Lower Fortescue River alluvium was estimated by using a range of hydraulic conductivities consistent with those calculated from aquifer pumping tests. Adopted hydraulic conductivity values ranged from 50 to 200 m/day, with the estimated annual throughflow across a section of the alluvial gravel ranging between 2.3 and 9.2 GL/yr. The storage depletion during a 12-month period between 1985 and 1986 was estimated to be 11 GL/yr, assuming a specific yield of 0.1 (Commander 1994a). Considering the results were formulated during a period of no stream flow, the higher value of hydraulic conductivity of 200 m/d may be more realistic. Accordingly, the upper estimate of 9.2 GL/yr may be more representative of the throughflow of the alluvial gravel.

Discharge

Discharge from the alluvial gravel aquifer is by a combination of evapotranspiration from phreatophytic vegetation in the north-west of the area and evaporation from the bare tidal flats. Evapotranspiration by the mesquite is considerable and the effect on the watertable has already been mentioned with respect to water-level changes. A study of mesquite in an area of Arizona where the watertable is 5 m deep (similar to the north-west of the study area) found the evapotranspiration rates approached the summer pan-evaporation rate of 80 per cent pan evaporation – an area of only 5.5 km^2 is required to account for an estimated annual discharge of 11 GL (Commander 1994a). Before the advent of mesquite, it is likely that most of the groundwater discharge was to the bare tidal flats, with the groundwater flow taking place over a saltwater interface. The information above is based on observations from the 1950s (pers. comm. DP Commander, November 2007).

Commander (1994a) calculated the discharge as depletion in storage volume in the alluvium during a period of low river flow when the groundwater levels declined. A specific yield of 0.1 was used and the change in groundwater levels between 12 November 1985 and 26 November 1986 were measured. The total depletion in storage volume was calculated to be 11 GL and can be equated to the average annual discharge from the aquifer. The value of specific yield of 0.1 was considered to be conservative and thus the above value is a minimum estimate of discharge.

Water quality

Fresh groundwater in the Lower Fortescue River alluvium is distributed in a lobe coinciding with the distribution of the main aquifer gravel: it extends north-west onto the tidal flats from the main river channel (Figure 19). Salinity measurements in the central part of the aquifer are less than 500 mg/L TDS. The salinity rises to more than 1000 mg/L on the edges of the alluvial aquifer, due to the lower-transmissivity sediments limiting freshwater recharge during periods of river flow. Near the saltwater interface along the coastal edge of the tidal flats, salinity measurements are more than 2000 mg/L.

Results described in Commander (1994) show that with increasing salinity there is a progressive increase in sodium chloride at the expense of calcium and bicarbonate. The development of calcrete around the zone of watertable fluctuation suggests that the calcium and bicarbonate are removed by precipitation. The groundwater ranges from slightly hard to very hard.

Salinity for the Yarraloola Conglomerate was reported to range from 454 to 492 mg/L TDS. The ionic composition is similar to that of the overlying alluvial aquifer.

Ecosystem

Large areas around the Lower Fortescue River are degraded by dense mesquite and buffel grass and to a lesser extent, date palms (Kendrick & Van Leeuwen, pers. comm. 2006). In general, the vegetation is in declining, fair condition (May & McKenzie 2002). More detailed site-specific vegetation community descriptions for the Lower Fortescue River area are contained in HGM (2000). The permanent pools of the Fortescue River are in declining, fair condition and recovery requires significant management intervention (May & McKenzie 2002).

In the Lower Fortescue River area, subregionally significant wetlands are associated with permanent and semi-permanent pools (Figure 15) such as Jilan Jilan Pool, Tom Bull Pool, Mardie Pool and Chuerdoo Pool (Masini 1988; May & McKenzie 2002; Geoscience Australia 2003; Semeniuk 2000).

The Jilan Jilan Pool is located on the Robe River, approximately 2 km from the Balmoral Homestead site. This pool may be affected by any development of the alluvial aquifer; thus a review of the potential impacts is recommended.

Tom Bull Pool is located on the western channel of the Lower Robe River, 10 km downstream of the Balmoral Homestead and directly downstream of the area mapped by Commander (1994a) as having salinity of less than 1000 mg/L. Effects of development closer to the old homestead site should be assessed.

Mardie Pool is located 11 km west of the Lower Fortescue River where the flood plain meets the salt flats. Impacts from development along the Fortescue River would be unlikely.

Chuerdoo Pool is located on the Fortescue River, but is about 2 km upstream of the alluvial aquifer. This pool is unlikely to be affected.

Other pools such as Bilanoo Pool, Jimbegnyinoo Pool and Bullinnarwa Pool are upstream of the alluvial aquifer system and any development of the alluvial aquifer below the highway would have minimal to no impact.

Resource development

Commander (1994a) recommended the most suitable area to develop the alluvial aquifer (as well as the strip of the Yarraloola Conglomerate) was close to the present river where recharge occurs from river flows. Bore yields of up to 900 kL/day have been demonstrated by pumping tests.

The yield of the aquifer is limited by the frequency and amount of recharge from flow events on the Fortescue River. Based on estimates of recharge (11 GL) and throughflow (9.2 GL), the potential yield of the aquifer is estimated to be about 10 GL/yr (Commander 1994a). This is an estimate of the volume of water that could be extracted from the alluvial aquifer in the Lower Fortescue River.

Potential increases in the aquifer infiltration capacity could be achieved through lowering of the watertable near the river to create a larger storage capacity for immediate use when river flows begin. Slowing down the river flow (barrage structures) and increasing the area available for direct infiltration would also allow the storage capacity of normally unsaturated gravel away from the river to be used.

An estimate of sustainable yield has not been determined according to current definitions. The economic, social and environmental values of this area need to be defined. The sustainable yield can then be estimated after considering the ecological water requirements.

Development potential — Yarraloola Conglomerate

Potential yield estimates from the strip of Yarraloola Conglomerate at the Lower Fortescue River are not available. Considering the low transmissivities and narrow nature of the Yarraloola Conglomerate, it can be assumed that the potential for long-term yields would be limited.

Restrictions to resource development

Development of this site as a supplementary supply to the West Pilbara Water Supply scheme is affected by competition between several mining companies. The recent sale of mining leases in this area has resulted in a concentrated interest in obtaining licences to extract from the Lower Fortescue and current groundwater exploration activities are underway to secure a groundwater licence for mining purposes. It is anticipated that the total requirement will be more than 16 GL/yr. The current level of knowledge about the yield potential of the Lower Fortescue aquifer (Commander 1994a) and environmental water provisions suggests it is unlikely that the Lower Fortescue will be able to deliver the volume of water required. To adequately meet future water requirements for development, any future water-supply considerations should include desalination as a supplementary supply source.

Any future allocation from this resource will require the ecological water requirements to be identified.

Issues with the infestation of mesquite will need to be addressed when developing this resource. Commander (1994a) reported that the mesquite may adversely impact on groundwater levels through evapotranspiration. The full impact of mesquite in regard to site access, ecosystem hierarchy and possible effects on water levels will need to be investigated.

Further work

The current investigation and assessment work that the mining companies are undertaking should be reviewed.

Current information on the alluvial aquifer system should be used to develop a numerical groundwater model. The model would facilitate the estimates of ecological water requirements, potential effects of future development scenarios and the sustainable yield of the aquifer system.

Access to current monitoring sites needs to be improved and the monitoring network reviewed and expanded as required. It would also be an advantage to install automatic water-level loggers into existing monitoring bores to capture the periodic (and rapid) recharge events to support future modelling endeavours.

Mapping of watertable contours is required, especially across the river where intermittent and permanent pools exist. Good control over watertable contours is required to increase understanding of aquifer water levels and the reliance of local vegetation on groundwater.

4.3.2 Fractured bedrock aquifers, Upper Harding River

Three main areas of fractured bedrock and alluvial sediments were investigated in the Harding River and Upper Maitland River catchments. The Water Corporation commissioned the investigation of three areas: the Sholl shear zone, the East Harding alluvium (Area A1) and Area KT (Rockwater 2006). The areas of investigation are shown in Figure 20. The following summary is based on that work.

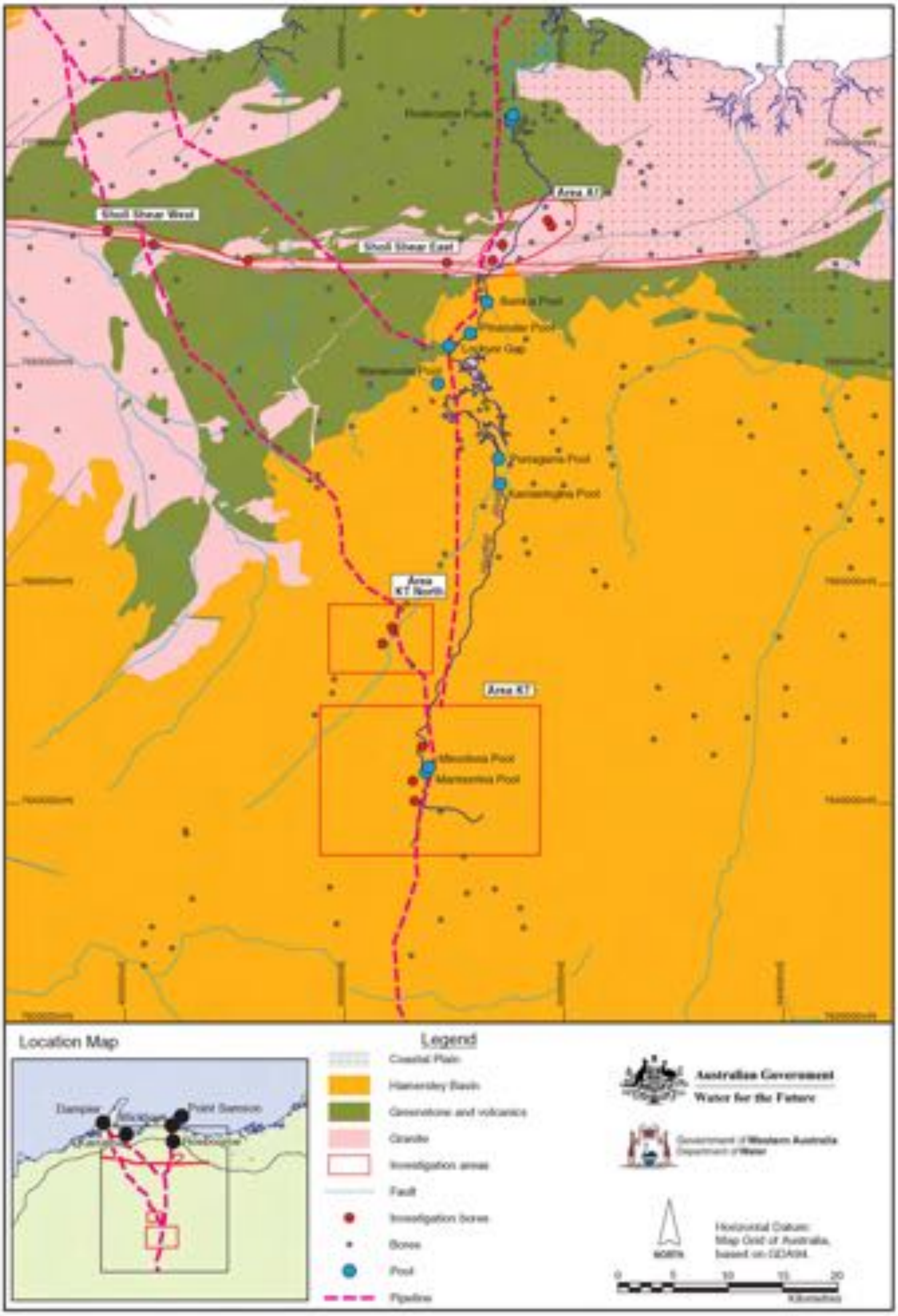


Figure 20: Harding River Area fractured bedrock investigation

It was reported that a total potential supply of 6 GL/yr might be available if all three areas were fully developed. To confirm that possibility, an extensive exploratory drilling and testing program would be required.

Geology/hydrogeology

The Sholl shear zone

The Sholl shear zone is a regional-scale tectonic contact that has been reactivated during multiple tectonic events in a predominantly strike-slip regime. It trends east-west and cuts greenstone, as well as minor granite, volcanic and sedimentary basement rocks. Permeability has been increased as a result of strong fracturing, and there are several creeks crossing the area that provide a source of recharge.

Exploration drilling identified fracturing in the upper 25 to 30 m of the shear zone and airlift yields ranged from 140 to 430 kL/day. It was proposed that construction of production bores at these sites might produce yields ranging from 500 to 1200 kL/day. Groundwater salinities in the shear zone ranged from 650 to 2800 mg/L (Rockwater 2006).

It was estimated that a total of 3 GL/yr of fresh groundwater might be available along the full length of the shear zone (Rockwater 2006).

Area KT and KT North

Area KT and KT North are in the Chichester Range, with the underlying geology comprised of volcanic rocks, volcanogenic sediments and dolomite. The area is highly jointed and fractured. Exploration drilling targeted areas that were close to river channels (where potential recharge was likely) and areas where the concentration of jointing was high (storage and transmissivity). Exploratory bores at Area KT were drilled near the Harding River channel, and bores at KT North were drilled near Western Creek, a tributary of the Harding River.

Airlift yields from bores drilled in Area KT ranged from 120 to 360 kL/day, and the water was fresh with 490 to 650 mg/L TDS (by electrical conductivity). Airlift yields from bores drilled in KT North ranged from 100 to 350 kL/day. Water quality was fresh and ranged from 410 to 420 mg/L TDS. It was estimated that construction of production bores could produce yields ranging from 300 to 1200 kL/day (Rockwater 2006).

It was estimated that a total of 1 GL could be developed from four bores located on Area KT and KT North (Rockwater 2006).

<u>East Harding alluvium area A1</u>

The investigation area covers the Harding River and the East Harding River where alluvial sediments overlie fresh and weathered granite bedrock. Calcrete occurrence and the possibility of paleochannels were targeted during the investigation. Downstream of the investigation site, the alluvial aquifer adjacent to the Harding River had been developed as a supply for Roebourne until 1986. At that site, the groundwater salinity was generally less than 1000 mg/L TDS. Salinities in the borefield were reported to increase with increased drawdown during years of low stream flow and recharge.

No paleochannels were found during the drilling investigation and the maximum depth to bedrock was 19.5 m. Saturated alluvium was found to range from 4.2 to 8.3 m thick. Airlift yields ranged from 5 to 40 kL/day from exploration bores completed with a 50 mm casing. Projections of potential yields from production bores could not be made. Salinities ranged from 790 to 1500 mg/L TDS.

It was proposed that this site might be developed to produce a total supply of 2 GL/yr. This depended on drilling of 24 exploration bores to develop six production bores at yields of 500 kL/day for each GL of water supply. This implies that a total of 48 exploration bores and 12 production bores will need to be drilled to develop a total of 2 GL of water (Rockwater 2006).

Resource development

The resources have not been investigated since the Rockwater (2006) study. At present there are no indications that the area will be explored further. The advantage of developing this option is that the sites are located along existing supply lines (Figure 20). The disadvantage is that the reported results are based on limited drilling and a significant amount of follow-up drilling and testing is required to prove the estimated yields. Until the required work is completed, the reported potential yields are unreliable.

Ecosystems

Wetlands of subregional significance in the Harding River area are associated with permanent to semi-permanent pools such as Bamba Pool, Pinanular Pool, Wananoolar Pool, Lockyer Gap, Purragurra Pool, Karrawingina Pool, Roebourne pools, Marmurrina Pool, Minnorinna Pool and other unnamed pools (Masini 1988; May & McKenzie 2002; Semeniuk 2000; Streamtec 1998).

Bamba Pool, Pinanular Pool, Wananoolar Pool and Lockyer Gap are located upstream of the Sholl shear zone and Area A1 investigation sites. It is unlikely that development of groundwater sites located downstream of the pools will affect them.

Purragurra Pool and Karrawingina Pool are located upstream of the Harding Dam Reservoir footprint and 25 km downstream of the Area KT and KT North investigation areas. It is also unlikely that development at the investigation sites will affect the pools.

The two pools at Roebourne are located approximately 12 km downstream of Area A1 and potential impacts from development are considered minimal.

The only wetlands found during the desktop survey within a reasonable distance of an investigation site are Marmurrina Pool and Minnorinna Pool. The two pools are near the exploration bores drilled in Area KT. If development of this site goes ahead, the potential impacts on these pools will have to be assessed.

Limitations to resource development

The potential effects of abstraction on pools and vegetation will need to be thoroughly investigated before development of the KT area can proceed.

Accessibility to proposed investigation sites in areas KT and KT North may restrict the development of a borefield in this area.

Further work

Further drilling is required to confirm the viability of the supply and potential supply estimates of Rockwater (2006). The recommended drilling program is extensive and the total expense will have to be reviewed. It may be determined that the work required to prove a supply of 6 GL in this area is not cost-effective.

4.3.3 Maitland River

The Maitland River crosses the North West Coastal Highway approximately 30 km west of Karratha (Figure 2). The associated alluvium has been identified as a groundwater resource of relatively low potential.

Hydrogeology

The groundwater resources in the Maitland River catchment are predominantly from alluvial gravels that overlie Archaean basement rocks (Figure 21). Many of the station bores are completed in shallow aquifers where individual bore yields are about 100 kL/day (Davidson 1975). Alluvial thickness varies considerably in the catchment and thicker sections are associated with buried paleochannels where gravels have filled erosional features in the basement rock. It is possible that the alluvial sediments may be up to 30 m thick (Davidson 1996). The extent of the active alluvial channels in the Maitland River area is also shown in Figure 21. Groundwater also occurs in fractured bedrock consisting of banded iron formations or basic volcanic rocks where river flow provides a source of recharge (Davidson 1975). Limited information is available on bore yields or recharge in this area.

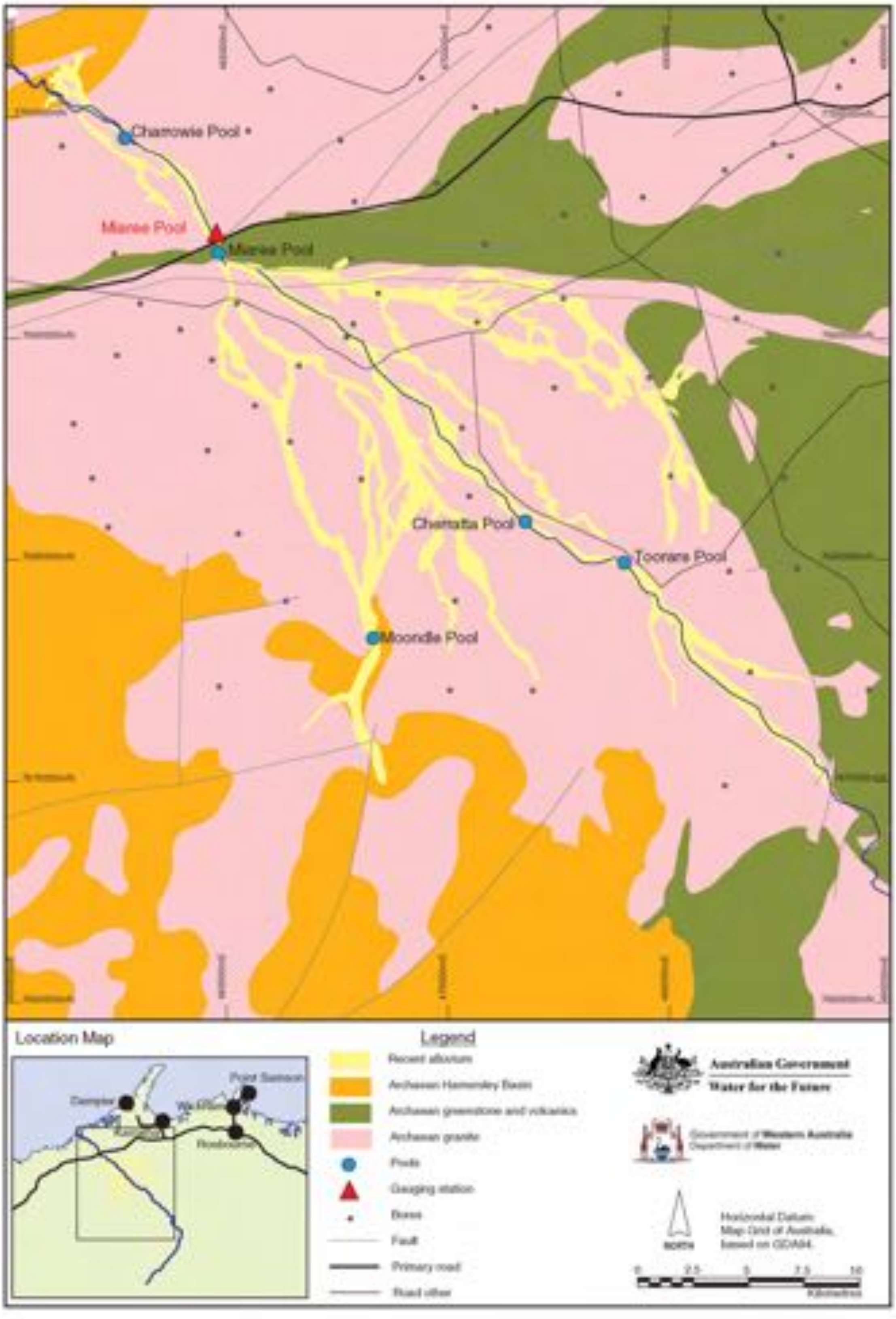


Figure 21: Maitland River Area

Resource development

The portion of the Maitland River most suitable for investigation extends 15 km from Miaree Pool to around the Cherratta Well (Davidson 1996). The Water Corporation has proposed to investigate the area to assess the resource potential.

Ecosystems

Vegetation with varying degrees of dependence on groundwater occurs throughout the area. The subregionally significant wetlands are associated with permanent and semi-permanent pools such as Moondle Pool, Charrowie Pool, Miaree Pool, Cherratta Pool, Toorare Pool and other unnamed pools (Geoscience Australia, 2003).

Charrowie Pool is located 5 km downstream of Miaree Pool and the highway. The Charrowie Pool, Miaree Pool, Cherratta Pool and Toorare Pool are located along the Maitland River. The Moondle Pool is about 9 km away from the Maitland River channel. As any development in the area will need to be near the source of recharge (the Maitland River), it is unlikely that Moondle Pool will be affected.

Limitations to resource development

The river supports the culturally significant Miaree Pool. Other areas may also have Aboriginal cultural significance, which needs to be assessed before any investigation work.

Further work

Investigation and assessment work is warranted for the Maitland River area. The work program should consist of a desktop study, review of available hydrogeologic information, inventory of existing bores, field surveys, monitoring, sampling and reporting.

The investigation work should focus on the alluvial sediments that extend from Miaree Pool in the north-west to Cherratta Well in the south-east. The area includes a 25 km stretch of the Maitland River and captures the lower tributaries of Four Mile, Corringer and Barrawanga creeks.

Geophysics could be used to delineate possible paleodrainages beneath the river alluvium. Appropriate methods would be transient electromagnetic (TEM) and SIROTEM. Five electromagnetic traverses of approximately 3 km in length would be sufficient to delineate buried paleochannels. A drilling program would be effective in evaluating alluvial aquifer thickness adjacent to the Maitland River. The geophysical surveys would help place the exploration bores. The drilling program should also focus on areas where secondary porosity may be present as fracturing in the basement rock that underlies the alluvium.

4.3.4 George River alluvium

The George River crosses the North West Coastal Highway approximately 70 km east of Karratha (Figure 2). The groundwater potential of the associated alluvial sediments and calcrete in the mid-George and Sherlock rivers was identified during early reporting by Balleau (1974).

Previous groundwater reviews assumed river alluvial thicknesses in the George River were greater than those of the Harding, thus making this area a better prospect. However, drilling data in the area is limited and the existing information indicates the alluvium may be thin, which would limit storage and yield potential. Although a potential yield of about 1 GL/yr was estimated from the alluvial sediments, previous reviews recommended that additional investigations verify the groundwater potential in this area.

Hydrogeology

The Lower George River catchment is underlain by Proterozoic-aged granites and the volcanic rocks of the Pilbara craton. In the upper catchment the basement rocks consist of sedimentary and volcanic rocks of the Fortescue Group. The distribution of the basement rock geology is shown in Figure 22. Balleau (1974) also reported on the existence of calcrete in the Upper George River catchment. The Upper George River also has the Cliff Springs Formation and the Lyre Creek Agglomerate, both of which had unknown potential yields as of 1974. It should be noted that the Upper George River has more alluvial sediments than the Upper Harding River and in comparison may be a better prospect.

Sadler and Parker (1974) also reported on areas of the George River where calcrete was absent. No drilling information was available for those areas in 1974, but it was reported that that the chances were small of a groundwater resource with adequate storage being available. It is assumed that the alluvium is thin, but this remains untested. The active alluvial channel deposits are shown as recent alluvium in Figure 22. Considering the size of the catchment, the actual thickness of the alluvium in the Upper George River area should be investigated.

The most important aquifer in the George River drainage is the alluvial gravels, which is the primary source of station supplies. When underlain by basalts, the top 5 m of the rocks is the best prospect for investigation. Drilling to deeper depths is unlikely to achieve improved yields. Shales and slates provide added potential, as they may be fractured and sheared at depth. Maximum yield is about 150 kL/day from the area’s deep weathered and fractured volcanic rocks, approximately 300 kL/day from the fractured sedimentary rocks and about 500 kL/day from the deep alluvial channels (Davidson, 1975).

Salinity varies greatly over the area and ranges from 400 mg/L to 3500 mg/L. Areas of fresh water represent more dynamic groundwater and surface-water interactions where volumes of recharge approximate the volume of discharge. Areas of higher

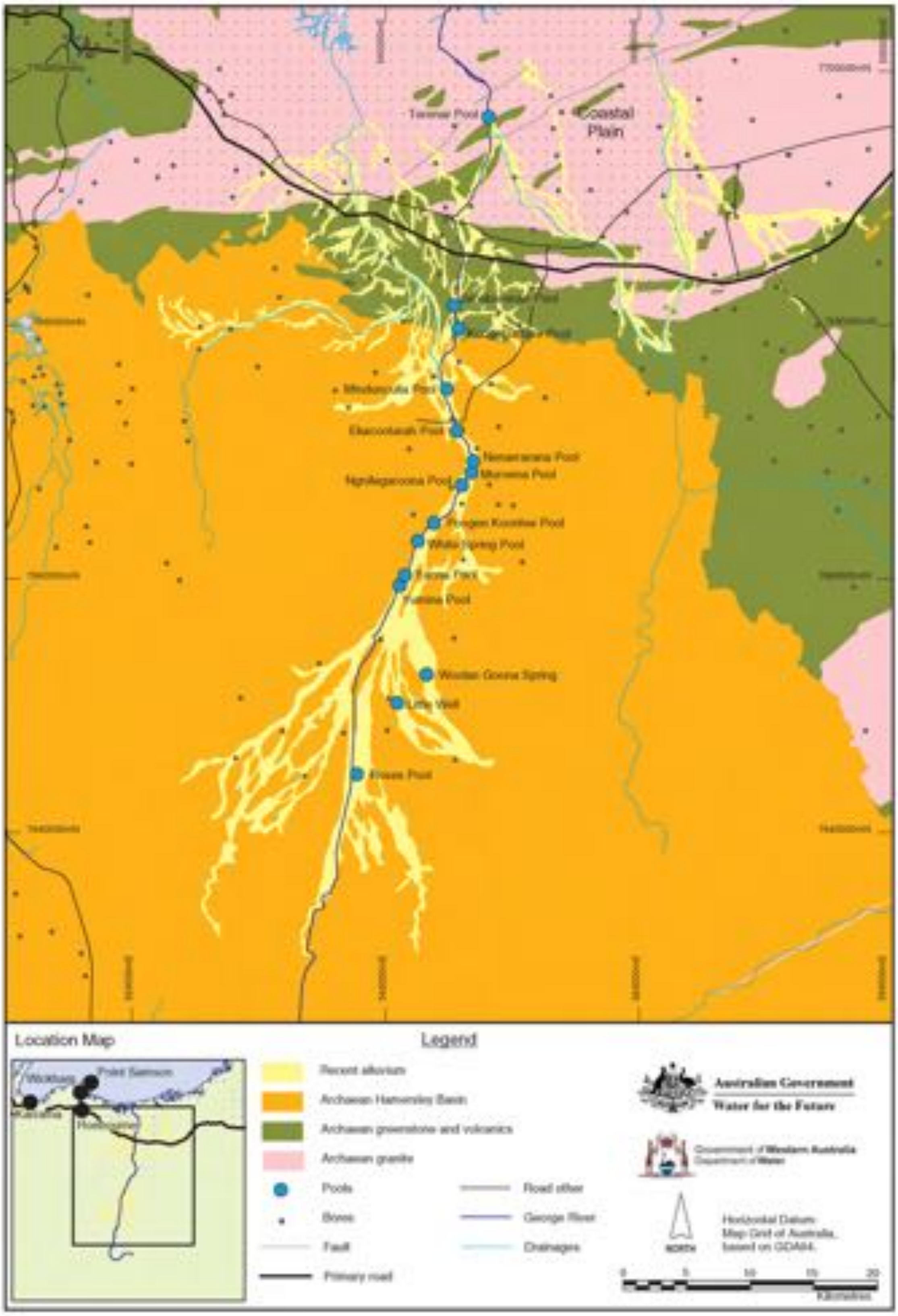


Figure 22: George River Area

salinity are representative of low permeability aquifers where groundwater is held in storage for a longer period and rates of evapotranspiration are high (Davidson, 1975).

The mid-George and Sherlock rivers in the coastal area have a thin alluvial cover over tuffs and other basement rock (Sadler & Parker, 1974). Sadler and Parker (1974) estimated the total storage in the mid-George and Sherlock river areas as being small, with the extractable storage also being small. The potential yield from both areas was estimated to be 1 to 2 GL/yr.

Restrictions to source development

At this time, there have been no reports on the cultural, environmental and social issues associated with this area.

Further work

The George River alluvium needs further investigation and assessment to determine the thickness and extent of alluvial sediments. Geophysical surveys and exploratory work should be undertaken to test alluvium thickness and lateral extent in this area.

5 Existing Port Hedland water supply

5.1 Demand centre

Port Hedland is located about 1660 km north of Perth and about 180 km east of Karratha (Figure 1). The Port Hedland Water Supply Scheme services Nelson Point, Finucane Island, Port Hedland and South Hedland, and draws water from borefields on the Yule and the De Grey rivers. The Yule River borefield is located 40 km west of Port Hedland and the De Grey River borefield is located 75 km to the east. The Water Corporation is licensed to take a total of 13.5 GL/yr from both borefields. The Yule River water reserve and De Grey River water reserve are proclaimed Public Drinking Water Source Areas. The Department of Water has prepared drinking water source protection plans for these areas.

5.1.1 Development

The main areas associated with development are the six districts of Port Hedland: West End, Cooke Point, Pretty Pool, Redbank, Wedgefield and South Hedland. Wedgefield and Redbank are mixed-use industrial areas; the Boodarie industrial estate is located away from the main districts.

At the port facilities, the dominant heavy industry is the shipment of iron ore, which totalled 115 Mt in 2007 (BHP Billiton 2007). BHP Billiton Iron Ore ships from the facilities at Nelson Point and Finucane Island. FMG is the second competing iron ore producer in the area and began shipping from its Cloudbreak mine in 2008. Rio Tinto is developing the Hope Downs mine and will be the third major producer shipping iron ore from the port facilities.

The port authority also operates bulk-loading facilities that handle a range of minerals including salt, manganese, chromite and copper concentrate. A number of small iron ore companies are looking to export through the port using the new bulk-handling facility currently under development.

5.1.2 Water supply

The Yule River borefield has a groundwater licence for abstraction of 6.5 GL/yr. Production from the borefield between 1995 and 2005 averaged about 3.5 GL/yr; maximum annual production during this period was about 5 GL/yr. Pumping trials to test the sustainability of the aquifer at abstraction rates of 8.5 GL/yr have been proposed by the Water Corporation.

The Namagoorie borefield on the De Grey River has an abstraction licence of 7 GL/yr. Production from the borefield between 1995 and 2005 averaged about 4 GL/yr; maximum annual production during this period was less than 6.5 GL/yr.

The sustainable yields of the Yule River and Namagoorie borefields need to be revised to determine ecological water requirements and develop environmental water provisions. The hydrogeological assessment of each site is part of the proposed work program managed by the Department of Water in partnership with the Water Corporation.

5.1.3 Water consumption

Figure 7 shows annual consumption from the Port Hedland Water Supply Scheme for 1995 to 2005. The average distribution to Port Hedland during that time was 10.9 GL/yr; the annual distribution ranged from a minimum of about 6 GL/yr to a maximum of about 11.9 GL/yr. The maximum distribution of 11.9 GL was recorded in 2003–04 before the BHP Boodarie iron plant was shut down in May 2004. Distribution in 2004–05 subsequently decreased to 9 GL/yr. Unaccounted-for supply-scheme water between 2001 and 2005 was nine to seven per cent, which is below the target set by the Water Corporation of 15 per cent.

Table 18 below summarises the main users of the Port Hedland Water Supply Scheme (ECS 2007). The dominant heavy industry is the processing and shipping of iron ore.

Table 18. Port Hedland Water Supply Scheme use (1995–2006)

	Average use (GL/yr)	**Maximum annual use during the past 11 years (GL/yr)**	**Average use as % of total**
Heavy industry	4.4	5.8	40%
Light industry	2.1	3.5	19%
Residential	2.5	2.6	23%
Other	1.9	Unknown	18%
Total	10.9	11.9	100%

5.1.4 Future water demand

Future water demand at Port Hedland will be driven BHP Billiton's expansion plans, Rio Tinto's development of Hope Downs (Lang Hancock Railway), and increased production at FMG's Cloud Break.

BHP Billiton has approved a major expansion in capacity through the Rapid Growth Project 4, whereby production is proposed to increase to 155 Mtpa by the first half of 2010 (BHP Billiton 2007). BHP has also announced its plans to expand iron ore production to 200 Mtpa by 2011 through the Rapid Growth Project 5. The Rapid Growth Project 6 will lift production to more than 240 Mtpa by 2012 (*The Australian* 2008). Future, long-range contracts to meet iron ore demand may be met by increasing total iron ore production to 300 Mtpa by 2015 (marketwatch 2008).

In 2009 Rio Tinto plans to ship iron ore from the Hope Downs project stage-one development. Initial production of 15 Mtpa will increase to 25 Mtpa during the stage-two development (Rio Tinto 2006).

FMG began shipping iron ore from the Cloudbreak mine in May 2008. Initial production is scheduled to be 55 Mtpa (ABC news 2008). An aggressive expansion plan is looking to increase in production to 100 Mtpa by 2010 (FMG 2008).

Projected iron ore shipments from the Port Hedland facilities to 2030 are shown below in Table 19. The projection assumes that the aggressive expansion targets announced by the major iron ore producers will be realised.

Table 19. Projected Port Hedland iron ore shipments

Year	BHP Billiton (Mtpa)	Fortescue (Mtpa)	Rio Tinto (Mtpa)	Total (Mtpa)
2007	115	0	0	115
2010	155	100	25	280
2015	300	100	25	425
2020	300	100	25	425
2025	300	100	25	425
2030	300	100	25	425

The downstream processing of iron ore accounts for approximately 40 per cent of water use at the port (Table 18). An increase in the volume of ore handled per year will result in a commensurate increase in water demand. Efficiency targets for water used in dust suppression at Port Hedland will decrease current use from 43 L/t to 30 L/t by 2020 (ECS 2007). Table 20 below summarises the maximum hypothetical increase in water use for dust suppression at Port Hedland. It should be noted that water requirements may vary from one producer to another and that the actual water source may not be from the current scheme. The table below projects a worst-case scenario: assuming multiple users consistently need to suppress dust and that the water needs to be sourced from the supply scheme.

Table 20. Projected Port Hedland water demand for dust suppression

Year	Total (Mtpa)	Port Hedland (L/t)	Total water use for dust suppression (GL)
2007	115	43	4.9
2010	280	39	10.9
2015	425	34	14.5
2020	425	30	12.8
2025	425	30	12.8
2030	425	30	12.8

Of all the Pilbara shires, the Port Hedland Local Government Area has the highest anticipated rate of population growth. The population is projected to increase by about 30 per cent (with associated residential water use) in the next 25 years (ECS 2007).

The Water Corporation has monitored light-industrial water use for the Port Hedland Water Supply Scheme. The data indicates a strong relationship between industrial/commercial use and population (ECS 2007). This relationship has been applied to light industrial/commercial water-use projections. Heavy-industry water use unrelated to the mining industry is low when compared with the requirements of iron ore processing. Table 21 below shows the total projected volume of water demand at Port Hedland to 2030.

Table 21. Projected Port Hedland water demand for all users

Year	Total water use for dust suppression (GL)	Heavy Industry (GL)	Light Industry (GL)	Residential (GL)	Total (GL)
2007	4.9	0.065	2.3	2.8	10.1
2010	10.9	0.065	2.4	2.9	16.3
2015	14.5	0.065	2.6	3.0	20.1
2020	12.8	0.065	2.7	3.2	18.7
2025	12.8	0.065	2.9	3.4	19.1
2030	12.8	0.065	3.0	3.6	19.4

Current demand of about 10 GL/yr is met by the existing supply scheme. Development projections in tables 20 and 21 indicate that annual demand may increase to 16.3 GL by 2010. If the expansion plans of the major iron ore producers are realised, the water requirements at the port facilities may exceed the current scheme allocation of 13.5 GL. To meet future water demand, the projections imply a requirement to bring additional supplies online to supplement the current scheme.

5.2 Existing groundwater supply

5.2.1 The Lower Yule River

The Lower Yule River flows in a northerly direction and crosses the North West Coastal Highway approximately 40 km west of Port Hedland. The current borefield operates in conjunction with the Namagoorie (De Grey) borefield to form the Port Hedland Water Supply Scheme (Figure 2). The borefield comprises 10 production bores and is located approximately 8 km downstream of the highway crossing. The borefield extends for approximately 20 km along the east side of the riverbed (Figure 23). The current licensed allocation is 6.5 GL/yr.

Following the initial work of Whincup (1967) and Forth (1972), Davidson (1976) fully assessed the Yule River alluvium and estimated the development potential of the following three areas (also shown in Figure 23):

- Area AB, which was considered to be the most appropriate area for borefield extension at the time
- Area EF located downstream of Area AB
- Area CD located south of the Yule River.

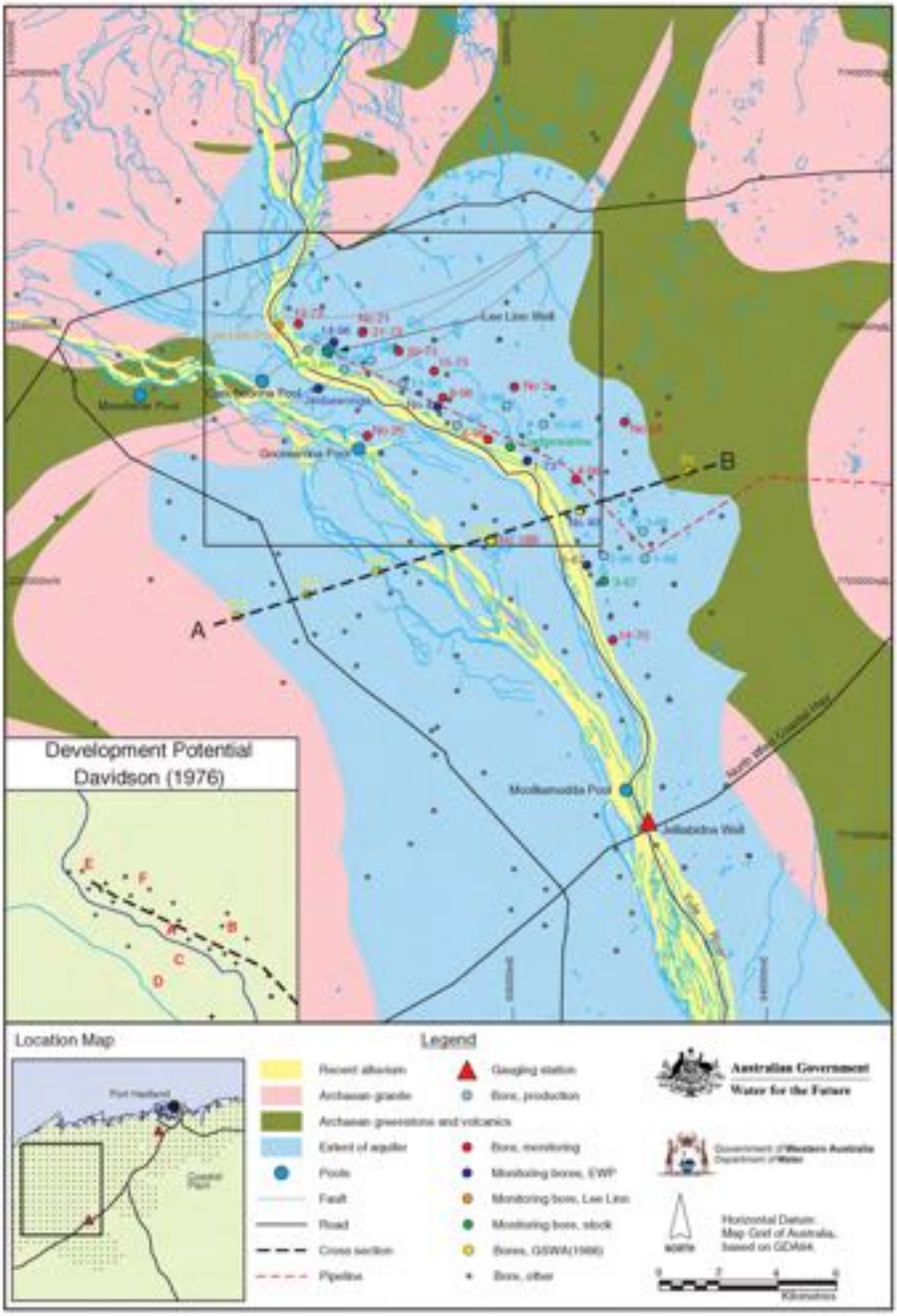


Figure 23: Yule River borefield

Woodward Clyde (1996) reported that the Yule River alluvial aquifer's total potential yield could be doubled by expanding the existing borefield upstream (south) of the current location; however, the thickness and extent of the alluvial sediments to the south of the current borefield are poorly understood. Further investigations are required to adequately assess the groundwater potential in this area.

Geology

The geology of the Lower Yule River consists of recent alluvium overlying Archaean granite-greenstone basement rocks. A broad alluvial trough eroded into the basement has been identified with an axis that trends north-west and coincides roughly with the present course of the Yule River (Figure 24). Within the trough structure there are two areas where a slight deepening has been identified: one on the north side of the Yule River that coincides with the present spread of the Yule River borefield and another located south of the Yule River. The coarsest sediments in the alluvial trough are most likely concentrated in these two areas. Figure 25 shows a cross-section through the Yule River alluvium.

The alluvium consists of sequences of clay, silt, sand and gravel with minor occurrences of calcrete. The alluvium ranges in thickness from 17 m in the south to more than 70 m in the north.

Archaean

The Archaean basement rock unconformably underlies the alluvial sediments and consists of granite and greenstones. The greenstones typically consist of gneiss, quartzite, schist, siltstone and chert. A weathered profile is variably developed at the top of the Archaean basement rock throughout the area. Calcrete has been reported to occur within the weathered profile above the granite basement rock (Whincup 1967; Davidson 1976).

Tertiary and Quaternary

The alluvium consists of layers of clay, silt, sand and gravel and varies in thickness from 27 to 50 m (Davidson 1976). In some parts of the borefield, it can be separated into three different zones: the upper alluvium, the middle bed of silty clay below the watertable, and the lower alluvium. Calcrete is present near the watertable, but is discontinuous and patchy and is also associated with the weathered top of the granite basement rocks.

Due to the lateral inhomogeneity of the sediments, lithologic correlation can be difficult, but the sediments generally become less silty upstream. The thickest portion of the alluvial sediments is on the north side of the Yule River near the western end of the current borefield.

Investigative drilling identified the occurrence of a 'laterised surface' in the north-eastern part of the area (Whincup 1967). The laterite is located at the top of the

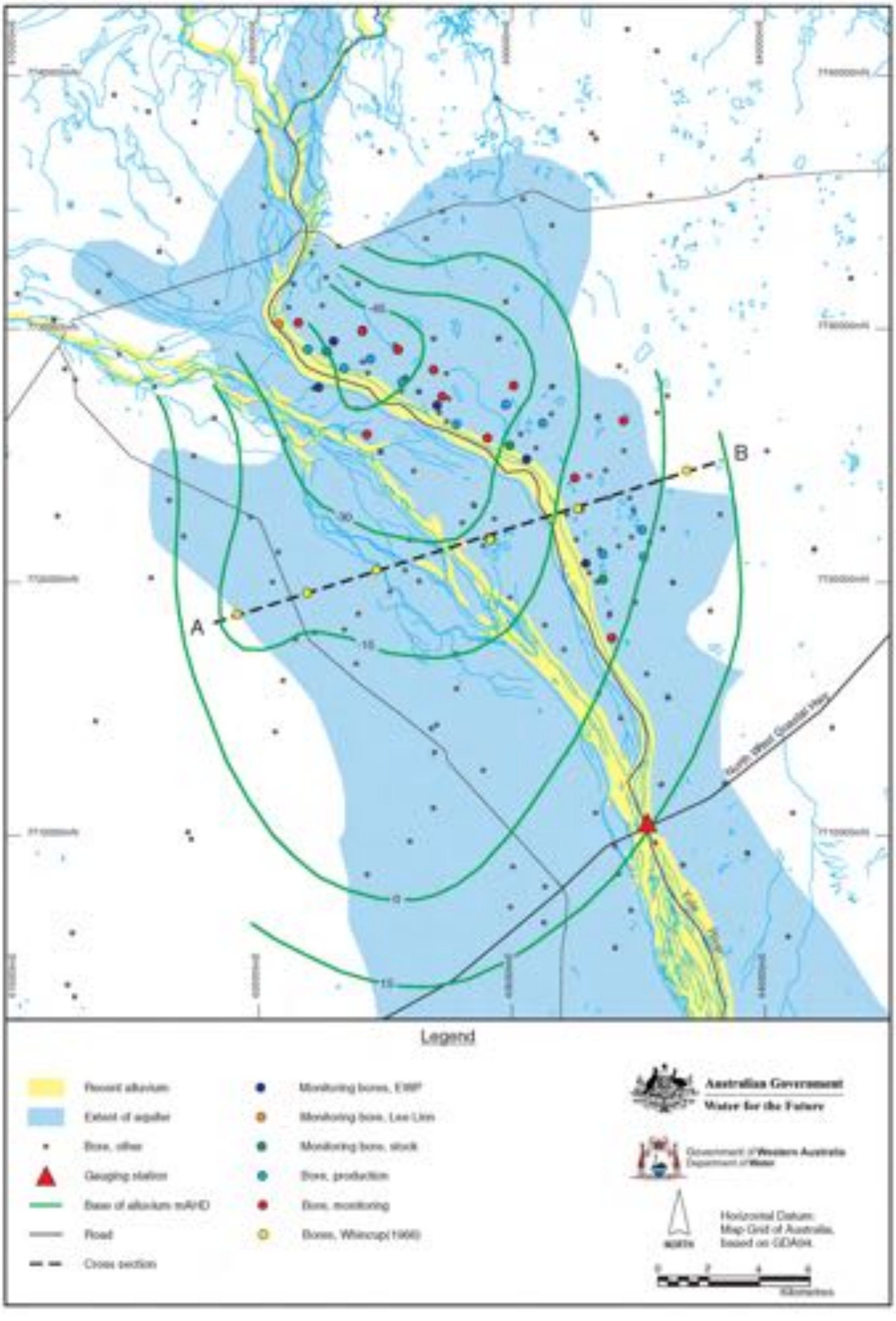


Figure 24: Yule River base of alluvium

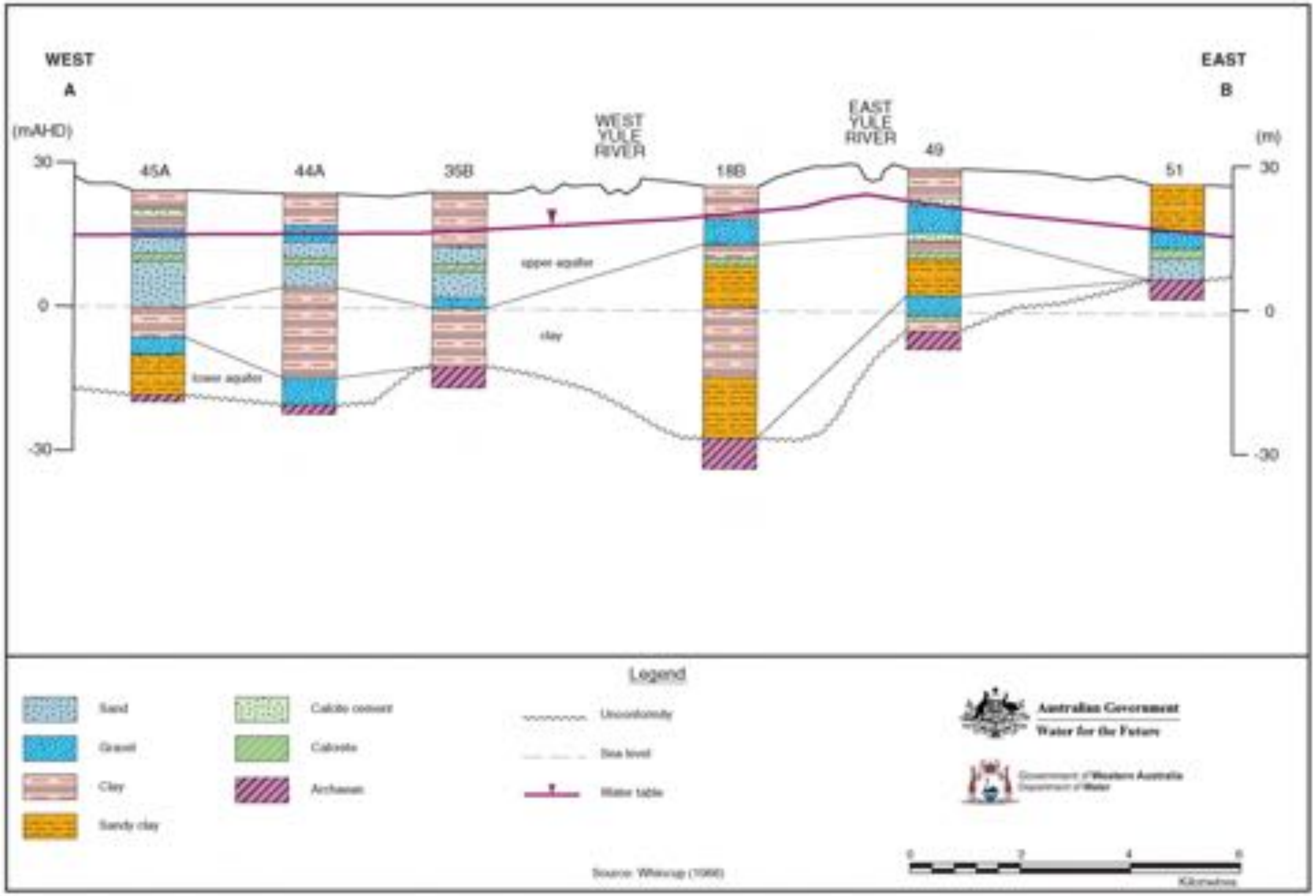


Figure 25: Yule River cross-section A-B

weathered bedrock surface and may be contemporaneous with the development of Tertiary-aged pisolites reported in the Robe and Lower Fortescue rivers.

Hydrogeology

Groundwater exploration in the Yule River area has been extensive, with the initial study by Whincup (1967) comprising 58 shallow auger holes and 32 percussion holes, with pumping test carried out in most of the constructed percussion holes Forth (1972) undertook additional pumping tests to refine the hydraulic parameters of the initial testing. During 1973, 22 additional bores were drilled on the east side of the Yule River, all of which were test pumped (Davidson 1976).

The main aquifers in the Yule River area are associated with the alluvial sediments. Discontinuous occurrences of calcrete around the watertable are not considered to be aquifers. Where calcrete has developed in the upper weathering horizon of the granite, a bedrock aquifer may be locally present and appreciable volumes of water can also be found from fractures and joints.

Aquifers

The unconfined upper sand aquifer extends to depths of 9 to 18 m over most of the area and consists of sandy gravel with calcrete developed around the watertable. About 3 m of silty sand and gravel are at (or below) the watertable. Beneath the upper sand aquifer there are silt and clay beds at depths of 18 to 33 m that can locally act as an aquitard. Beneath the silt and clay beds is the lower aquifer that consists of sand and gravel layers with minor silt and clay. The lower sand aquifer is present at depths of 33 to 55 m (Forth 1972) and may be confined or unconfined depending on the thickness of the overlying silt/clay layer.

In the vicinity of the active river channel, the aquifers may be hydraulically connected to recent river gravels. Bores have been screened in a wide variety of depths and generally indicate good hydraulic continuity throughout the aquifer system.

For throughflow and storage calculations, the aquifer system is considered to be unconfined.

Aquifer testing and hydraulic parameters

Aquifer properties vary greatly and previous attempts to estimate aquifer parameters have been problematic. From most pumping bores, the transmissivities calculated during early investigation and assessment programs were invalid (Davidson 1976). Most of the pump testing was carried out without the control of an observation bore, which resulted in estimates of transmissivity that were too low. Forth (1972) estimated an aquifer transmissivity of 155 m^2/day based on flow-net analysis. Later work by Davidson (1976) reported a transmissivity of 550 m^2/day, based on a single pump test that was considered to be reliable. A storage coefficient of 2.0 E-4 was estimated, confirming that the portion of aquifer tested was confined for the duration of the test. The test may not have been of sufficiently long duration to see delayed-yield effects.

Whincup (1967) and Forth (1972) estimated a storage coefficient for the aquifer system of 0.02. This value may appear too high for confined conditions and too low for unconfined conditions. Considering that the Lower Yule River aquifer ranges from unconfined to confined conditions, an estimated storage coefficient of 0.02 may be appropriate.

Davidson (1976) recommended that additional pumping tests be completed to improve the current estimates of transmissivity, and thus the aquifer yield.

River flows and aquifer recharge

The Yule River is approximately 217 km long and has a catchment area of 12 000 km^2. Jellebidina Well gauging station is located on the Yule River at the North West Coastal Highway crossing and approximately 10 km upstream of the borefield (Figure 23).

The gauging station's records extend from 1973 to the present, showing a long-term mean annual flow (1973–2002) of 350 GL. During that time, there were 11 years during which the volume of flow over a four-month period exceeded the mean annual volume of 350 GL. The Lower Yule River alluvium receives significant recharge events in approximately one out of every three years.

The longest number of consecutive months in which no flow was recorded at Jellebidina Well gauging station has been 37 months. Over the 30-year record, there has been a total of seven years in which zero flow was measured at Jellebidina Well station. This indicates that for about one out of every four years, there was no flow in the Yule River. There were 10 years in which the maximum-recorded annual flow was less than 10 per cent of the mean annual flow. This indicates that during one out of every three years, the total annual recharge to the Lower Yule River alluvial aquifer is very low.

Direct rainfall recharge does occur, but to a very limited extent and only during large rainfall events. Recharge is predominantly from river flow. Percolation through the alluvial gravels along the active river channel is rapid. Very little recharge takes place over the clay pans, which become flooded during large flow events and inhibit downward migration of water.

Whincup (1967) estimated an annual recharge of 14.6 GL from river flow based on water-level rise and a specific yield of 0.02. Forth (1972) made a similar calculation over a slightly different spatial distribution of recharge to estimate an annual recharge of 13.4 GL.

Groundwater levels

Figure 26 shows the potentiometric surface determined by Davidson (1976), which represents the baseline watertable. The potentiometric surface indicates that aquifers on the north-east side of the present river channel are recharged directly by the river. The aquifers to the south-west of the river are recharged primarily by groundwater throughflow, rather than by direct river recharge.

Storage

Forth (1972) calculated the volume of fresh water with a salinity of less than 1000 mg/L to be 574 GL. The storage calculation was based on a specific yield of 0.15 over the average saturated thickness of 10 m. Only a small proportion of fresh water in storage could be withdrawn if water-quality standards were to be maintained over the long term. Although estimates of annual recharge ranged from 13.4 to 14.6 GL, Forth (1972) estimated that a volume of 9.1 GL could be safely pumped without causing the intrusion of brackish water.

Throughflow

Early calculations of throughflow by Forth (1972) were underestimated because of the use of transmissivities that were too low. Later calculations by Davidson (1976) resulted in higher throughflow due to a higher estimate of transmissivity.

Groundwater throughflow was calculated for the proposed (1976) borefield expansion, near Area AB on Figure 23. Area AB is located along the north side of the Yule River between the spread of bores that comprise the current (2007) borefield configuration. The throughflow beneath this area was calculated to be about 4 GL/yr.

Throughflow was also calculated for the borefield in production in 1976, located at the upstream end of the current (2007) borefield configuration. Throughflow for the 1976 borefield was estimated to be about 3 GL/yr. It was noted that at the time of the throughflow calculation, the borefield production level was about 4.6 GL/yr.

Throughflow calculations were also made for two other areas of investigation: areas EF and CD. Area EF is located immediately upstream of the western end of the current borefield and the throughflow calculation for this area is about 0.4 GL/yr (Davidson 1976). Area CD is located on the south side of the Yule River and across from the current (2007) borefield. The throughflow for this area is calculated to be about 0.02 GL/yr.

Total throughflow for the entire aquifer area was estimated to be about 7.4 GL/yr. Davidson (1976) reported that the potential yield determinations based on throughflow were realistic, providing recharge occurred annually and that bores were sufficiently spaced to intercept the maximum volume of throughflow.

Discharge

Discharge is predominantly by throughflow to the north – away from the Yule River – or from evapotranspiration (ET) along the river. ET losses are very high along

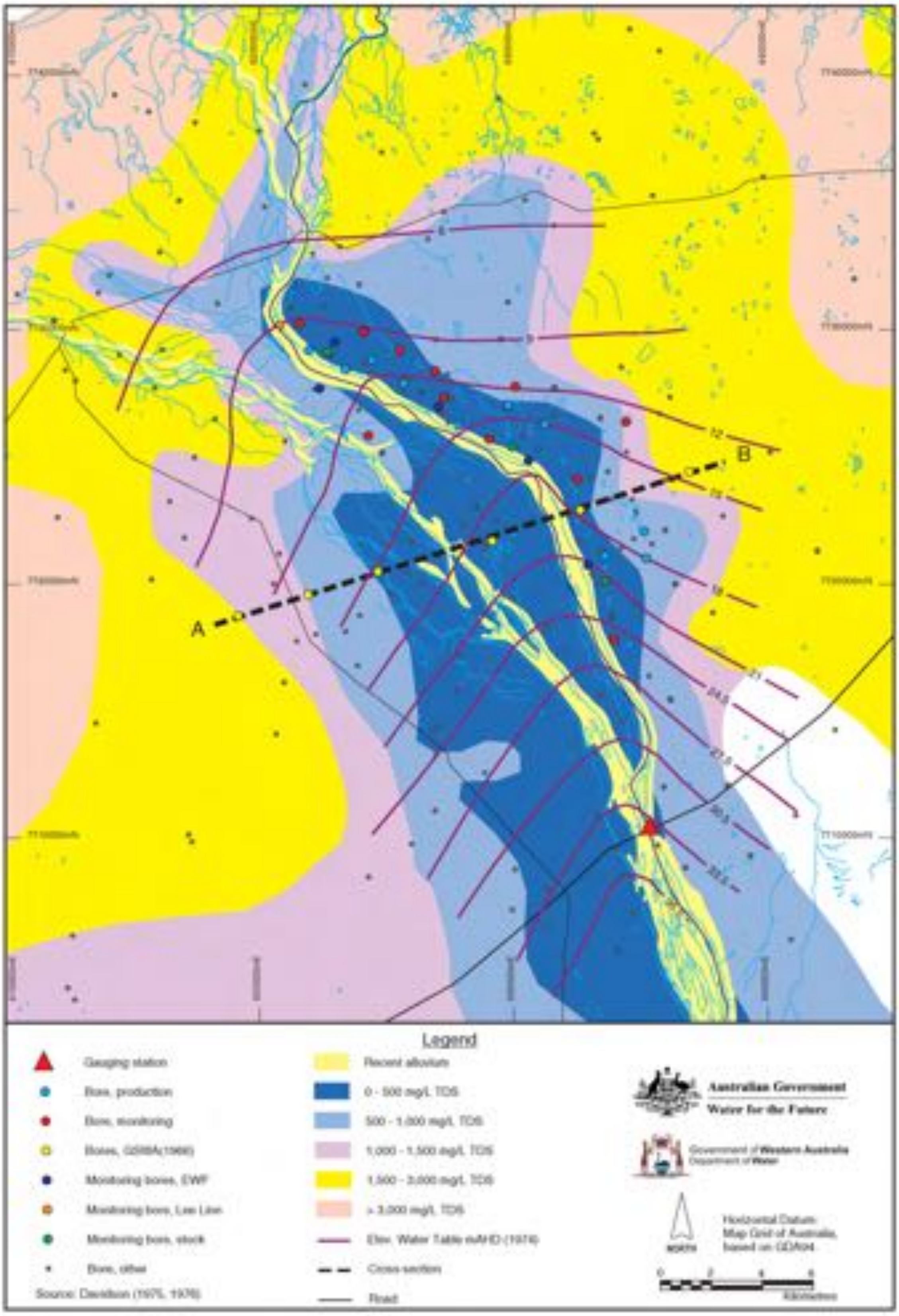


Figure 26: Yule River water table and salinity

riverbanks where vegetation development is dense. Annual water-level recession and the application of an assumed specific yield of 0.1 resulted in an ET estimate of 0.2 GL/km of aquifer (Water Corporation 2003). The ET of groundwater from the borefield area was estimated to be 3.6 GL/yr and about 5.4 GL/yr between the borefield and the highway. The ET from the area to the west of the borefield was estimated to be 8 GL/yr over a 100 km^2 area.

Water quality

Mapping of alluvial salinity along the Port Hedland coast was completed by Davidson (1975) and is shown in Figure 26. Although the salinity will shift in position from the variable effects of recharge, the data from 1974 provides a good indication of the extent and general trend of water quality along the Yule River. The isohalines show that the salinity is lowest near the active river channel and increases with distance away from the river. Variations also occur with depth, with salinity in the shallow portion of the alluvial aquifer relatively high, and then decreasing with depth. Higher salinity may be due to the flushing down of salt residue at the surface during recharge events, dissolving of salts from oxidation within the capillary fringe or by the concentration of salts due to plant absorption (Davidson 1976). A similar occurrence of higher-salinity water in shallow portions of the aquifer also occurs in the De Grey River alluvium (Davidson 1976).

Throughout the area assessed by Davidson (1976) the water is suitable for stock supply, with domestic supplies limited to the areas near the active river channels and sources of recharge.

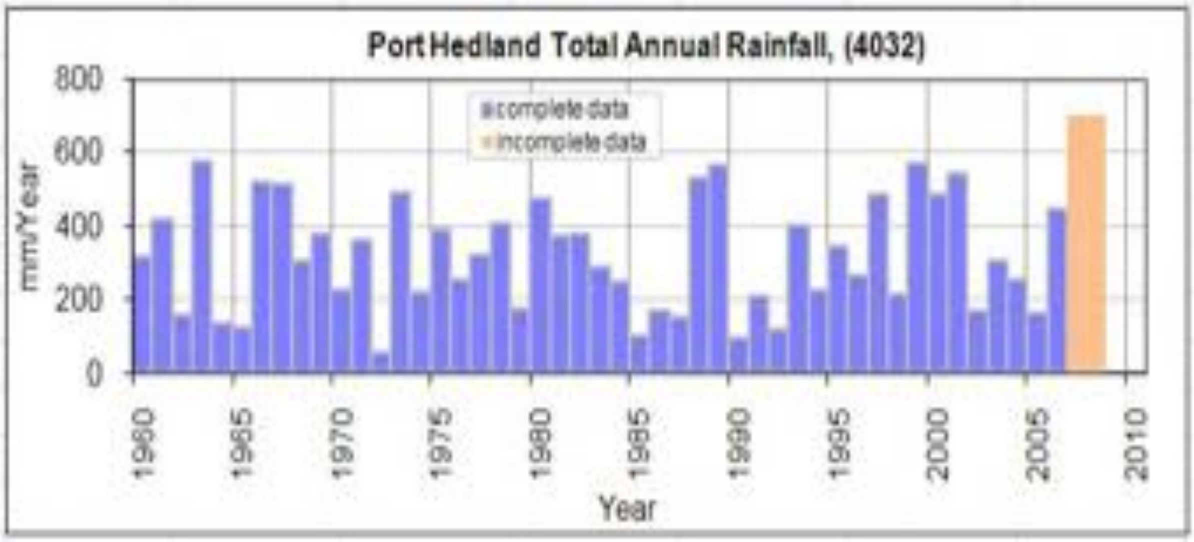
Current borefield

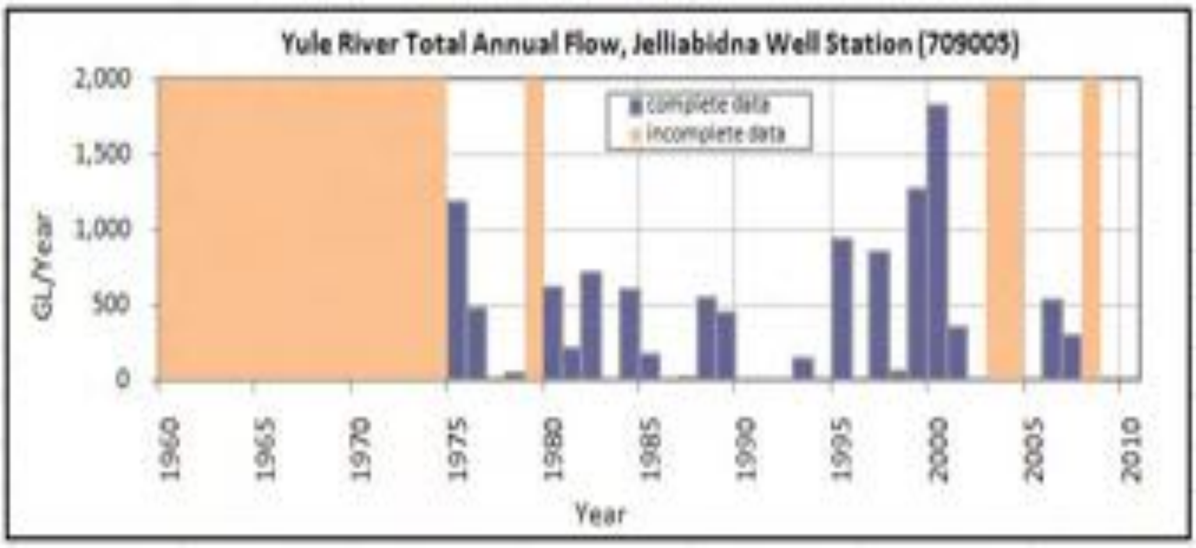
The Yule River borefield was commissioned in 1967 to supply water to Port Hedland in conjunction with the existing Public Works Department borefield on the Turner River. After a borefield on the De Grey River was commissioned in 1979, the Turner River borefield was closed. Port Hedland is currently supplied by the Yule River and De Grey River borefields.

The Yule River borefield consists of 10 production bores and 22 monitoring bores (Figure 23). The monitoring bores comprise 13 aquifer performance bores, six environmental-water-provision bores and three stock bores. Water levels are also measured in Lee Linn Pool (Water Corporation 2007a).

The Yule River borefield has a licensed allocation of 6.5 GL/yr. The Department of Water and the Water Corporation have together undertaken a monitoring program and pumping trial to assess the sustainability of a higher allocation of 8.5 GL/yr.

Production from the Yule River borefield is shown in Figure 27. Abstraction since 2000 has ranged from 3.6 to 6.4 GL/yr with an average of 4.8 GL/yr.





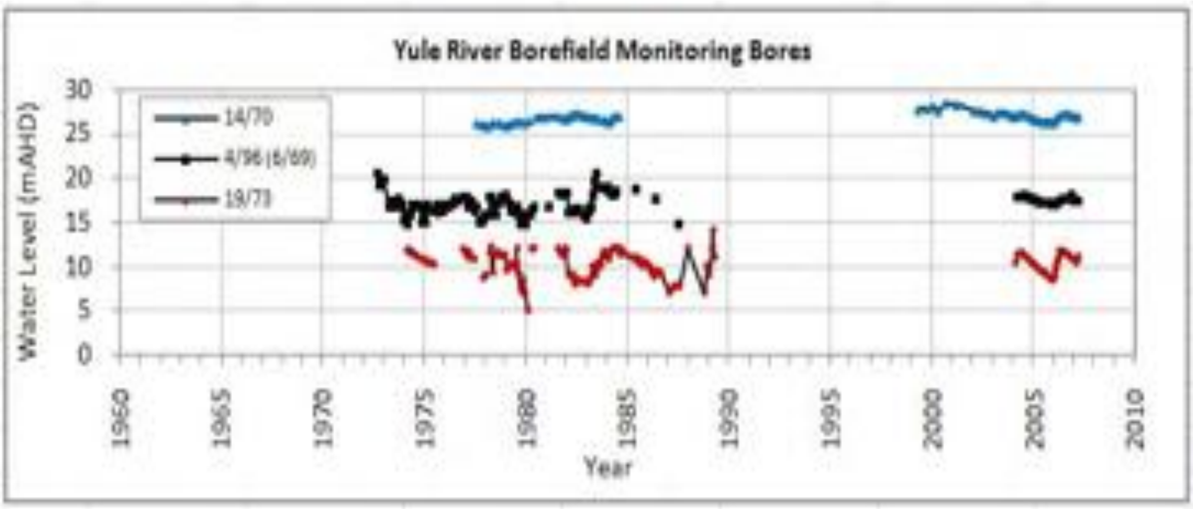


Figure 27: Yule River hydrographs and borefield production

Borefield water levels

General observation

Hydrographs of monitoring bores located in the southern, central and northern portions of the borefield are plotted on Figure 27. Water levels are generally above the seasonal historic low water level in the monitoring bores. Across the borefield, there is a greater overall drawdown to the north than to the south.

Recent recharge events

A 14-month drought occurred before the December 2005 recharge event, which is shown in the hydrograph for bore 19/73. Subsequent recharge events that can be observed in the monitoring record occurred in January to April 2006 and again in January to April 2007.

Production-bore water levels

Water levels in production bores in the northern portion of the borefield have generally dropped from 3.5 to 6.5 m between 2001 and 2007. Some of the bores in the north are located close to the river and thus experience a broader range of water-level fluctuation due to recharge events. Regardless, there appears to be an overall pumping imprint on water levels located in the northern portion of the borefield. The overall abstraction from the borefield is greater in the northern section than in the south. The water levels in production bores to the south have generally dropped about 1.0 to 1.5 m between 2001 and 2007.

Monitoring-bore water levels (aquifer-performance bores)

Monitoring bores have generally shown drops of about 0.5 to 1 m over the entire borefield from 2001 to 2007. As much as a 3 m drop in water levels is observed in monitoring bores located close to the river over short intervals, as seen in the hydrograph of bore 19/73. Water levels in bore 19/73 dropped about 3 m from January 2004 to just before the January 2006 recharge event. Nearby Lee Linn Pool showed an identical amount of fluctuation during this time, which indicates good hydraulic continuity between bore 19/73 and Lee Linn Pool. In contrast, production bore 16/96 showed as much as 6 m of drawdown between January 2004 and March 2006. The pumping effects from production bore 16/96 are not observed as cumulative drawdown in monitoring bore 19/73 and Lee Linn Pool.

Management criteria

An interim approach to determine ecological water requirements and environmental water provisions (EWP) has been developed based on water levels in the EWP-criteria bores. The interim ecological water requirement of 0.25 m below minimum recorded historic water levels has been adopted as the interim EWP, which is expressed as an absolute minimum water-level criterion in selected EWP-criteria bores (Water Corporation 2007a).

Management actions have been developed for instances when water levels approach and reach criteria levels.

Trigger levels were reached between 2001 and 2007 in bores 14/96 and Jimbawonga Well. The breaches occurred between April 2005 and January 2006 following a period of drought. The resulting actions were an increase in monitoring intensity in both water level and ecological monitoring sites. Water levels in both bores rose above trigger values following the recharge events of January 2006.

Water quality

Salinity in all production bores in 2006–07 is generally stable and has ranged from 200 to 515 mg/L (Water Corporation 2007a).

Ecosystems

The subregionally significant wetlands in the Lower Yule River area are associated with permanent and semi-permanent pools, such as Meedanar Pool, Carloboorina Pool, Moolkamudda Pool, Bookan Pool, Goorearrina Pool, Lee Linn Pool, 16/96 Pool, Northwest Hwy Pool and other unnamed pools (Maunsell 2003; Geoscience Australia 2003).

Free-standing water is found at two locations (Maunsell 2003, HGM 1998). The Lee Linn Pool is located at the northern extreme of the borefield. The other pool is a large unnamed pool adjacent to the North West Coastal Highway and is outside the current borefield area. There are concerns about potential impacts on Lee Linn Pool, which is of cultural and environmental significance.

Whincup (1967) reported that salinity levels in Lee Linn Pool remained low (150–200 ppm), while other pools experienced significant increases in salinity due to evaporation effects. It was concluded that such low salinity levels were a result of Lee Linn Pool being fed from the alluvial aquifer.

Resource development

Early development of the Yule River alluvium was focused on the upstream portion of the current borefield – on the north-east side of the river (Figure 23). In 1976 the area was referred to as the ‘east-side aquifers’, which included the area under production in 1976 and the proposed areas of expansion downstream of that area.

In 1976, the level of production from the original borefield was 350 000 kL/month (4.5 GL/yr). At the time, the development of 4.5 GL/yr from that portion of the borefield was considered to be over the ‘safe yield’ (Davidson 1976).

Davidson (1976) recommended three areas as most suitable for expansion of the original borefield: areas AB, CD and EF. Areas AB and EF, as well as the 1976 borefield, lie within the approximate boundary of the current (2007) borefield. Area CD is located across the Yule River and to the south of the current borefield, and would require additional drilling and pump testing to estimate throughflow and potential yield. Additional supplies may be located upstream of the current borefield, but this is currently untested.

Davidson (1976) reported that the 'safe yield' of the alluvial aquifer system in the Lower Yule River was 7.4 GL/yr, which is based on throughflow calculations and assumes that pumping will be spread over the entire area. This volume could be extracted for up to one year following a river recharge event.

Davidson (1976) reported that up to 9.1 GL/yr could be pumped from the 'east-side aquifers' and that this level of production could be sustained for six to 10 years without river flow. However, there were concerns about brackish water migrating from the east towards the production area of the time. It was concluded that 9.1 GL/yr would be the upper limit of production from the current borefield – if salinity increases were the single issue. This evaluation did not take into account potential effects on pools or ecosystems that may depend on groundwater.

Downstream expansion of the 1976 borefield was recommended because it would have no influence on water levels in the existing borefield.

Restrictions to development

A restriction to development is the potential for brackish-water intrusion because of a lack of recharge and over-pumping of the borefield.

Expansion of the borefield to the south (upstream) may be limited by potential effects on existing pools and the thinning of alluvial gravels. A survey of the area would be required to assess the presence of culturally or environmentally significant sites.

Further work

Adequate pump testing and aquifer parameter analysis is recommended for the southern side of the Yule River (Area CD), across from the current borefield. Previous calculations for transmissivity in this area are inaccurate and resulted in a low estimate of throughflow.

Exploration drilling and testing is required upstream of the current borefield to assess the alluvium thickness and potential for expansion. The drilling could be preceded by geophysical surveys (TDEM) to delineate zones of fresh and brackish water and to help determine where to locate exploratory bores. Davidson (1975) mapped a broad zone of fresh water (TDS <1000 mg/L) to approximately 20 km downstream of the North West Coastal Highway and Jelliabidina Well gauging station.

Mapping of watertable contours is required, especially near the river. Good control over watertable contours is required for dependable estimates of gradient and aquifer throughflow – and thus potential yield.

A groundwater model would strengthen knowledge of river recharge mechanisms within the aquifer system. The model would also enable assessment of the impacts on local groundwater levels due to pumping.

The borefield should be pumped at the full licensed amount of 8.5 GL/yr while monitoring water levels and vegetation. Testing would support refinement of the ecological water requirements and the borefield's ability to sustain the full licensed allocation. A numerical groundwater model that the Water Corporation is currently developing will support such a trial. Work related to the evaluation of the borefield will be conducted as a cooperative effort between the Department of Water and the Water Corporation.

An increase in supply would ultimately be associated with an upgrade of the current infrastructure and pumping capabilities. The viability of such an extension and how it would fit into the planning framework of the Water Corporation would need to be thoroughly reviewed.

5.2.2 The Lower De Grey River

The Lower De Grey River area is located approximately 70 km east of Port Hedland (Figure 1). The current borefield forms part of the Port Hedland Water Supply Scheme in conjunction with the Yule River Borefield.

The Geological Survey of Western Australia (GSWA) investigated the area's alluvial sediments between 1969 and 1972 as a potential groundwater supply to service Port Hedland (Davidson 1974). Investigations comprised a bore census of existing bores, exploration drilling, geophysics and test pumping.

The Lower De Grey River area consists of dissected highlands, extensive gravel plains and wide alluvial flats leading westward onto a narrow coastal plain – with a small desert area that extends onto the south-western edge of the Canning Basin. Dissected highlands are made up of Precambrian basement rocks with minor exposures of Mesozoic sediments, and rise abruptly from the plain with associated scree slopes.

The four main drainages are the De Grey, Strelley, Shaw and Coongan rivers, which flow to the north-west over wide, sand-covered plains underlain by granitic bedrock. The rivers flow intermittently, are sometimes very wide and braided, and have permanent to semi-permanent pools. Pools on the De Grey riverbed indicate it is scoured below the watertable. The only other major drainage is Pardoo Creek, which is located to the north of the De Grey River and flows intermittently to the north over the western part of the Canning Basin.

The Namagoorie borefield was commissioned in 1979 and is located on the east side of the De Grey River near the crossing of the North West Coastal Highway (Figure 28). The borefield comprises 11 production bores constructed in the alluvial sediments adjacent to the river.

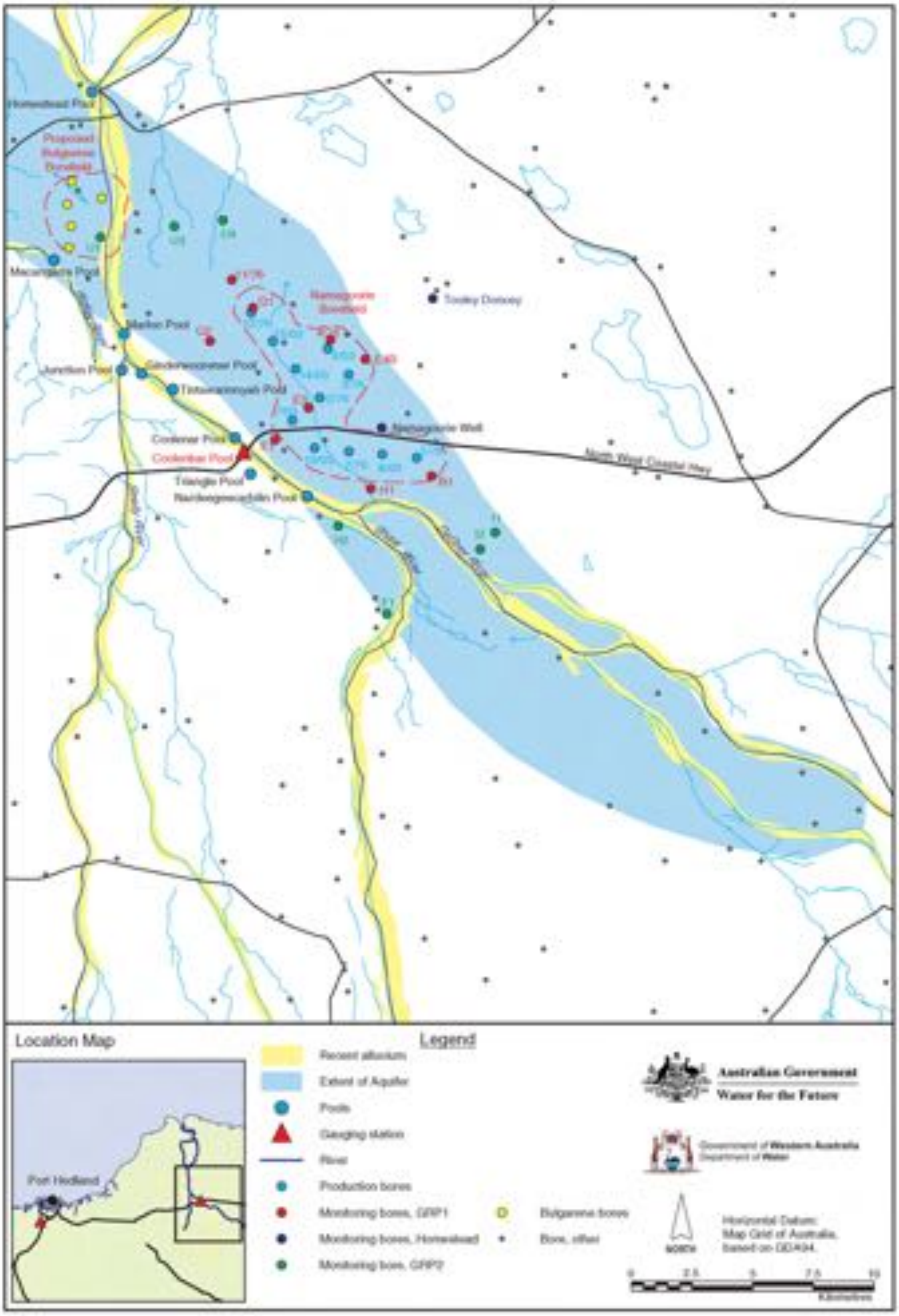


Figure 28: De Grey River borefield

The proposed Bulgarene borefield is located approximately 12 km downstream of the Namagoorie borefield on the west side of the De Grey River. The bores constructed in 1995 are not operational. The Water Corporation is continuing to investigate the feasibility of integrating the borefield into the Port Hedland Water Supply Scheme.

Geology

The De Grey River area comprises Tertiary to Quaternary alluvial sequences deposited in current and ancient channel structures, unconformably overlying Archaean and Mesozoic basement rocks.

Archaean

The basement rocks in the area assessed by Davidson (1974) consist of Archaean granite and greenstone rocks of the Pilbara craton. The granites and greenstones are intruded by numerous quartz veins and minor dolerite dykes. The sheared contact between the granites and greenstones has been preferentially weathered, with the current drainage channel of the De Grey River roughly following the trend of the contact.

Mesozoic

The Archaean rocks are discontinuously overlain by Mesozoic sediments, which may be part of the West Canning Basin (Davidson 1974). The grey, sandy shales could be part of the Early Cretaceous Broome Sandstone.

Cainozoic

Discontinuous patches of pisolite and calcrete of Tertiary age occur in the area. Calcrete has formed in two instances: at the watertable or at the top of the weathered zone of the granite basement rocks.

The alluvium in the Lower De Grey River area ranges in thickness from a few metres to about 75 m, with an average thickness of about 50 m (Davidson 1974). Figure 29 shows the base elevation contours of the alluvium in the vicinity of the De Grey River borefield. In the vicinity of the Strelley and Shaw rivers, the alluvium can be separated into an upper and lower zone of sedimentation that is lithologically distinct. The distinction is stronger in the Strelley River compared with the Shaw River. Table 22 summarises the stratigraphy in the De Grey River area, adapted from Davidson (1974).

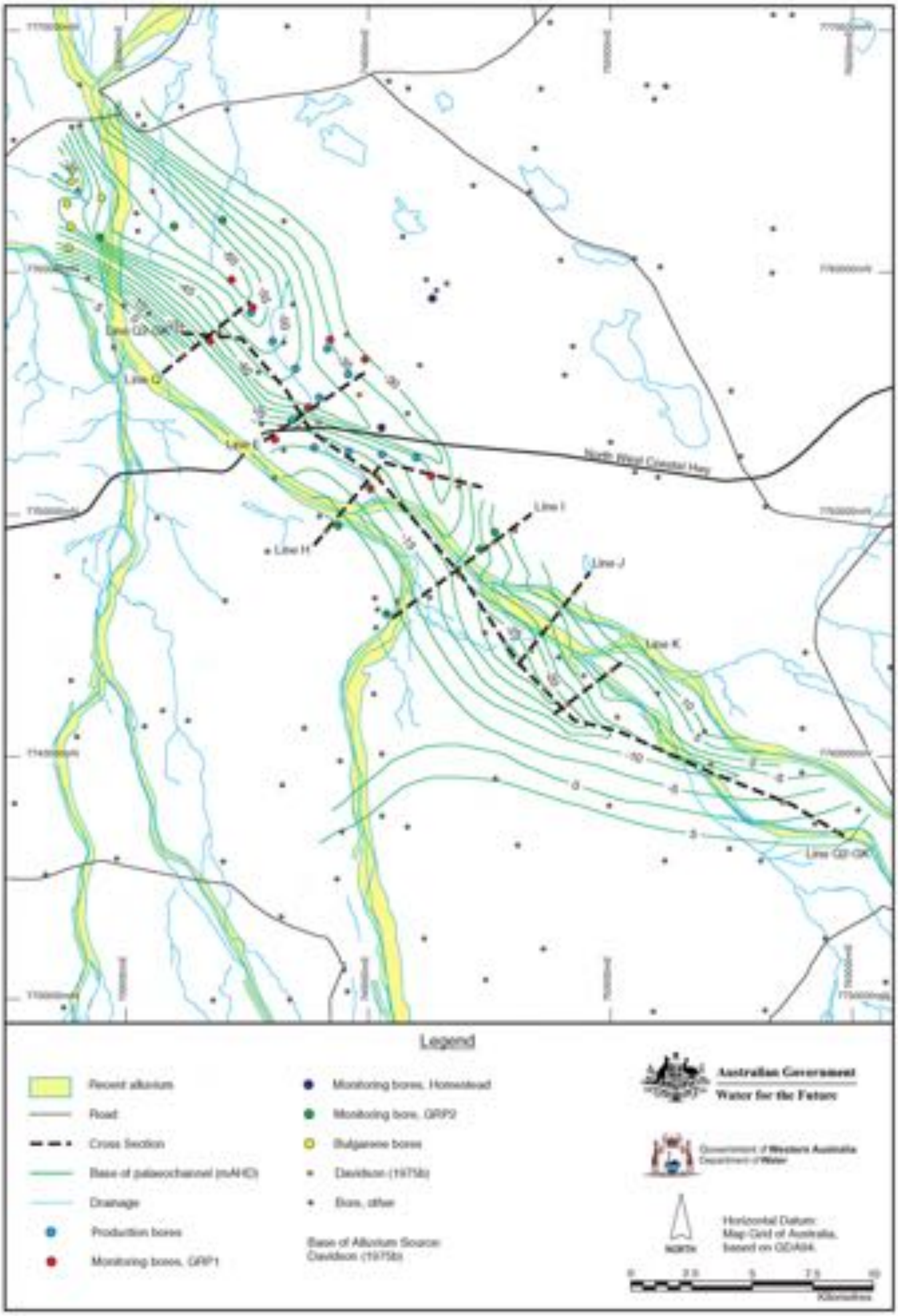


Figure 29: De Grey River base of alluvium

Table 22. Stratigraphic units of the Lower De Grey River area

Era	Period	Rock unit	Lithology
Cainozoic	Quaternary	Alluvium	Alluvial clay, silt, sand, gravel and conglomerate
	Tertiary	Paleochannel	Alluvium, pisolite and calcrete
Mesozoic	Early Cretaceous	Broome	Sandstone, shale and claystone
Unconformity			
Archaean		Greenstone	Metasediments and volcanic rocks
		Granite	Granite and intrusive rocks

The lithologic distinction within the alluvial sediments is arbitrary and there is typically good hydraulic connection between the palaeochannel alluvium and the recent alluvium. In general, the alluvium sourced from the De Grey River and Shaw River drainages can be considered a heterogenous mass of sand, gravel and clay lenses (Davidson 1974). Figure 30 shows cross-sections through portions of the De Grey River alluvium in the vicinity of the current borefield.

A paleochannel occurs adjacent to the present-day De Grey River drainage. The current borefield is located on the northerly portion of the paleochannel, to the east of the present river channel. The palaeochannel represents the original course of the De Grey River before it migrated to the present location and is shown in Figure 29 as a depression in the Proterozoic bedrock surface.

Hydrogeology

The hydrogeology of the Lower De Grey River near the North West Coastal Highway crossing was described in detail by Davidson (1974). Forty-nine exploration drill holes into the alluvium and underlying weathered bedrock formed the basis of the investigation. Geophysical surveys, test pumping, hydrochemical analysis, palaeontologic studies and aquifer parameter estimation were also undertaken during the course of the work.

Aquifers

The only productive aquifer in the Lower De Grey River area is the alluvial sediments, which appear capable of yields suitable for a major supply. Discontinuous occurrences of calcrete form minor aquifers, which are suitable for stock and domestic supply only. However, if the calcrete horizon is present at the top of the weathered granite basement rock, it may be considered an additional source of water to the overlying alluvium. The Mesozoic sediments were found to be rich in clay and silt and were very low yielding. Archaean volcanics and greenstones have low potential and only moderate yields. Archaean granite may have a weathered horizon that is water bearing and may be locally productive in wells screened in conjunction

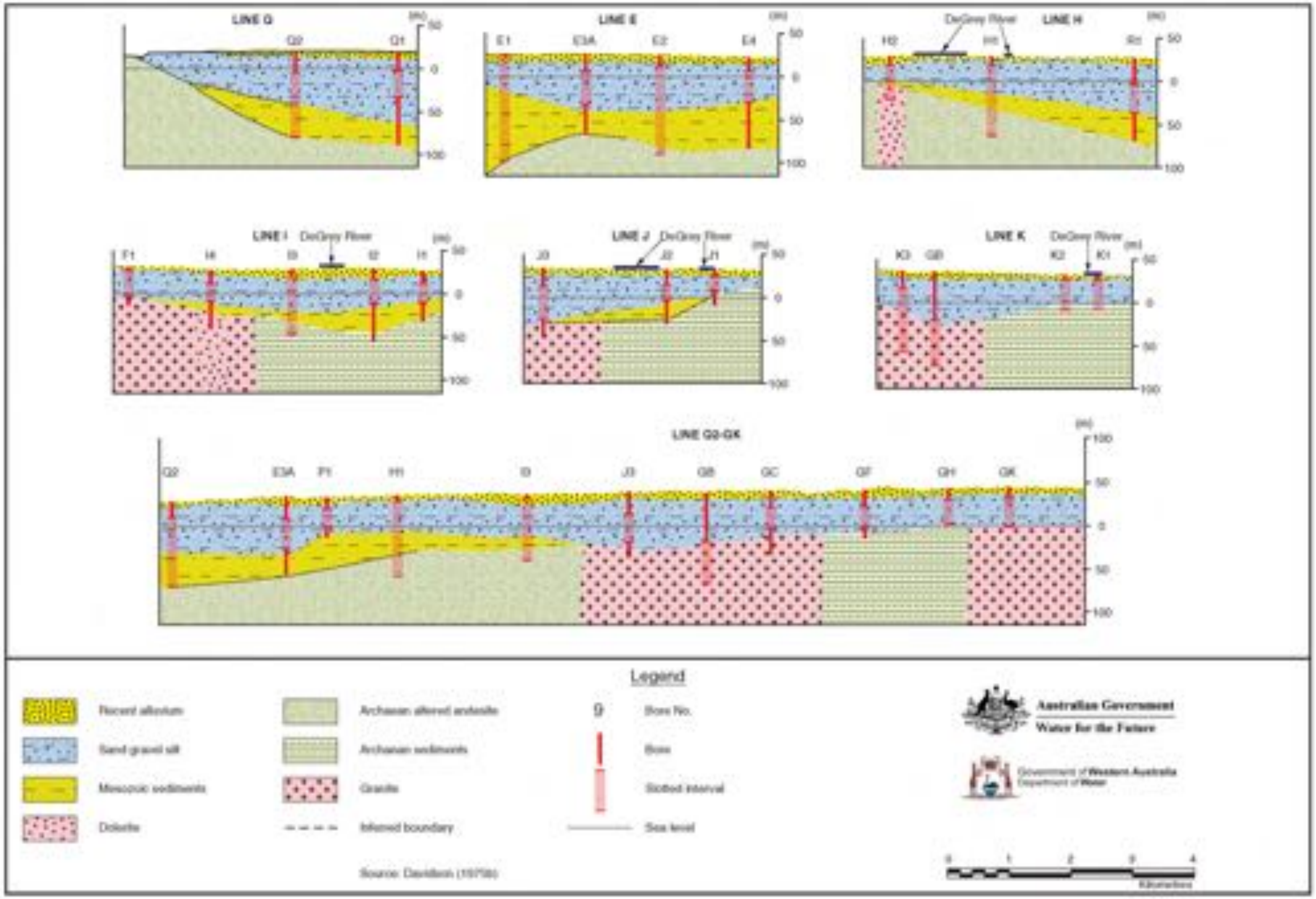


Figure 30: De Grey River cross-sections

with the overlying alluvium. If the weathered horizon is not present, the granite is unimportant as an aquifer.

Alluvial aquifer

The alluvial aquifer in the De Grey River is a heterogeneous mass of sand, gravel and clay lenses with a maximum thickness of about 75 m and an average thickness of 50 m. The most productive portion of the alluvial sediments lies along the palaeochannel, as shown on Figure 29.

Sediments of the Strelley and Shaw rivers can be divided into an upper alluvium and a lower palaeochannel zone. In general, the upper aquifer is comprised of sand and gravel, whereas the lower paleochannel aquifer consists of sand with occasional gravel, clay and silt. In the Strelley and Shaw rivers, there is a layer of silty clay that forms a confining layer between the two aquifers. As a result, the upper aquifer is generally an unconfined aquifer, whereas the lower aquifer is generally under confining conditions.

In the De Grey River drainage, the lithologic distinction between an upper and lower aquifer is more arbitrary and the confining layer of silty clay is absent. Drilling and pump testing has indicated that the lower paleochannel aquifer in the De Grey is better developed than the lower palaeochannel aquifers in the Strelley and Shaw rivers (Davidson 1974). No such distinction has been made for the upper aquifer zone. The alluvial sediments in the De Grey River area exhibit both unconfined and confined conditions throughout the aquifer system, depending on the homogeneity of the alluvial stratification.

Aquifer testing and hydraulic parameters

During GSWA investigations into the De Grey River alluvium, 24 bores were test pumped to determine hydraulic parameters. Most bores were pumped without observation bores and many bores were only partially penetrating. Combined with the heterogeneous nature of the alluvial aquifer, this resulted in highly variable responses that included confined and unconfined, leaky artesian, delayed yield and boundary/barrier effects. Estimates of transmissivity range from 58 to 1400 m^2/day with an average transmissivity of 560 m^2/day (Davidson 1974). Test pumping indicated it was reasonable to expect bore yields from the alluvial gravels to be as high as 2000 kL/day.

A storage coefficient could not be calculated because of the lack of observation bores. Davidson (1974) estimated a reasonable storage coefficient for the heterogeneous alluvial aquifer would be between 0.1 and 0.0005. A storage coefficient of 0.1 was assumed for all subsequent recharge and storage calculations.

River flows and aquifer recharge

Flows in the Lower De Grey River area are recorded at the Coolenar Pool gauging station (701003). The site is located at the crossing of the North West Coastal

Highway and is adjacent to the Namagoorie borefield. The Coolenar Pool gauging station record extends from 1969 to the present with a long-term mean annual flow (1975–2004) of 1430 GL. During that time, there were 11 years in which the volume of flow over a four-month period exceeded the mean annual volume of 1430 GL. The Lower De Grey River alluvium receives river-flow events in excess of the mean annual volume in approximately one out of every three years.

The longest number of consecutive months during which no flow was recorded at Coolenar Pool has been 19 months. During the 30-year record, there has been measurable flow at the Coolenar Pool station for all but one year. Although the record indicates the river flowed in 29 out of 30 years, there were five years in which the maximum-recorded annual flow was less than 10 per cent of the mean annual flow. This indicates that during one out of every six years, the total annual flow to the Lower De Grey River alluvial aquifer is very low. The annual flow record (Figure 32) indicates that the low-flow sequence can occur over a run of years (e.g. 1990–93).

Davidson (1974) reported that approximately 70 mm of rain over the dry catchment is required before the De Grey River will flow. Once wet, less than 24 mm is required for flow to occur.

Recharge to the alluvium occurs predominantly through river flooding and to a much lesser extent, direct infiltration of rainfall. Hydrographs indicate an average 1 m rise in the watertable each year. By using a storage coefficient of 0.1 for the unconfined superficial aquifer, the total recharge for the 170km^2 area is 17 GL/yr (Davidson 1974).

In general, recharge response in bores completed in sections of the aquifer that are highly transmissive is rapid, and shows sharp peaks in hydrographs. Conversely, recharge response in bores in less transmissive material is slower, and exhibits a flat response in hydrographs.

Discharge

Transpiration loss along the river is very high and is the largest contributor to discharge from the aquifer system: it has been estimated at 50 per cent of pan evaporation (Davidson 1974). Applying a transpiration of 1.25 m over an area of 11 km^2 resulted in an estimated transpiration volume from the alluvial aquifer of 13.75 GL/yr.

Pool evaporation was estimated from a pan evaporation rate of 2.5 m/yr. Over an estimated pool area of 0.25 km^2, the total pool evaporation was 0.63 GL/yr. Evaporation and transpiration losses from the alluvium upstream of the confluence of the Shaw River are substantial.

Storage

Davidson (1974) estimated the storage volume along a 25 km stretch of the De Grey River, extending from the north end of the borefield to approximately 10 km upstream of the Shaw River confluence. The area roughly coincides with the deepest portions of the palaeochannel shown on Figure 29. The area was divided into three subareas (A,B,C): A and C with salinity less than 1000 mg/L and B with salinity greater than 1000 mg/L (Figure 31). A storage coefficient of 0.1 was assumed. The total groundwater storage at minimum water levels was estimated to be 65 GL, of which 38 GL was fresh and 27 GL was brackish. If the annual recharge of 17 GL was included, the total water storage would be 82 GL.

Throughflow

The primary mechanism of recharge is river flow. Throughflow calculations were made from flow-net analysis for the buried palaeochannel to the north of the current De Grey River channel and downstream of the confluence of the Shaw River. This is also the vicinity of the current Namagoorie borefield. The throughflow was estimated to be 5900 kL/day or 2.2 GL/yr (Davidson 1974).

Groundwater quality

Consistent with other alluvial aquifers in the Pilbara coastal area, salinity increased with distance away from the active river channel because of decreasing recharge. The best water quality is close to the present river channels. In the case of the De Grey River, fresh water is available away from the active river channel due to the presence of the transmissive buried palaeochannel.

In the area of the De Grey River that includes the confluence of the Shaw and Strelley rivers, a wide range of salinities exist. Throughout the area, water suitable for stock is readily available, and about half the area has fresh water suitable for public supply. Upstream of the junction with the Coongan River, water quality is poor.

Fresh groundwater is associated with the confluence of the Shaw River and extends into the palaeochannel on the north side of the De Grey River. The Shaw and Coongan rivers are the main contributors of the best quality water as recharge to the De Grey River alluvial aquifer. Groundwater salinity based on regional mapping by Davidson (1975) is shown in Figure 31.

Namagoorie (De Grey) borefield

The Namagoorie borefield is located 75 km to the east of Port Hedland on the east side of the De Grey River (Figure 28). The borefield was commissioned in 1979 as a supplementary supply to the Port Hedland Water Supply Scheme. At that time, the scheme consisted of the Yule River and Turner River borefields. Shortly after the Namagoorie borefield was commissioned, the Turner River borefield was closed.

The borefield has 11 production bores and 18 monitoring bores. The monitoring bores comprise nine Group 1 bores, seven Group 2 bores and two homestead bores (Figure 28). The Namagoorie borefield has an abstraction licence for 7 GL/yr.

Production from the Namagoorie borefield is shown in Figure 32. Abstraction since 2000 has ranged from 4.36 to 7.1 GL/yr with an average of 6.1 GL/yr.

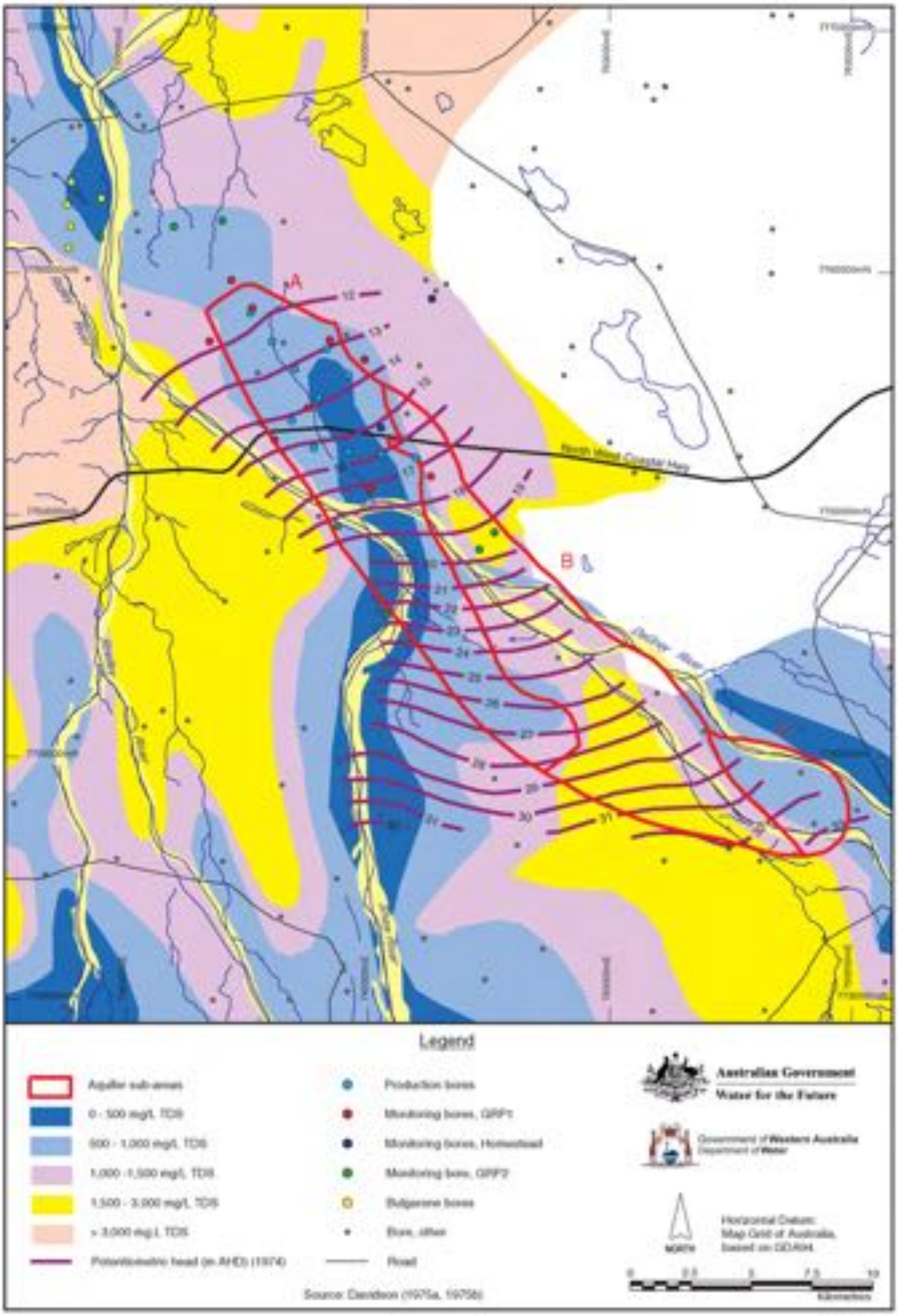


Figure 31: De Grey River salinity

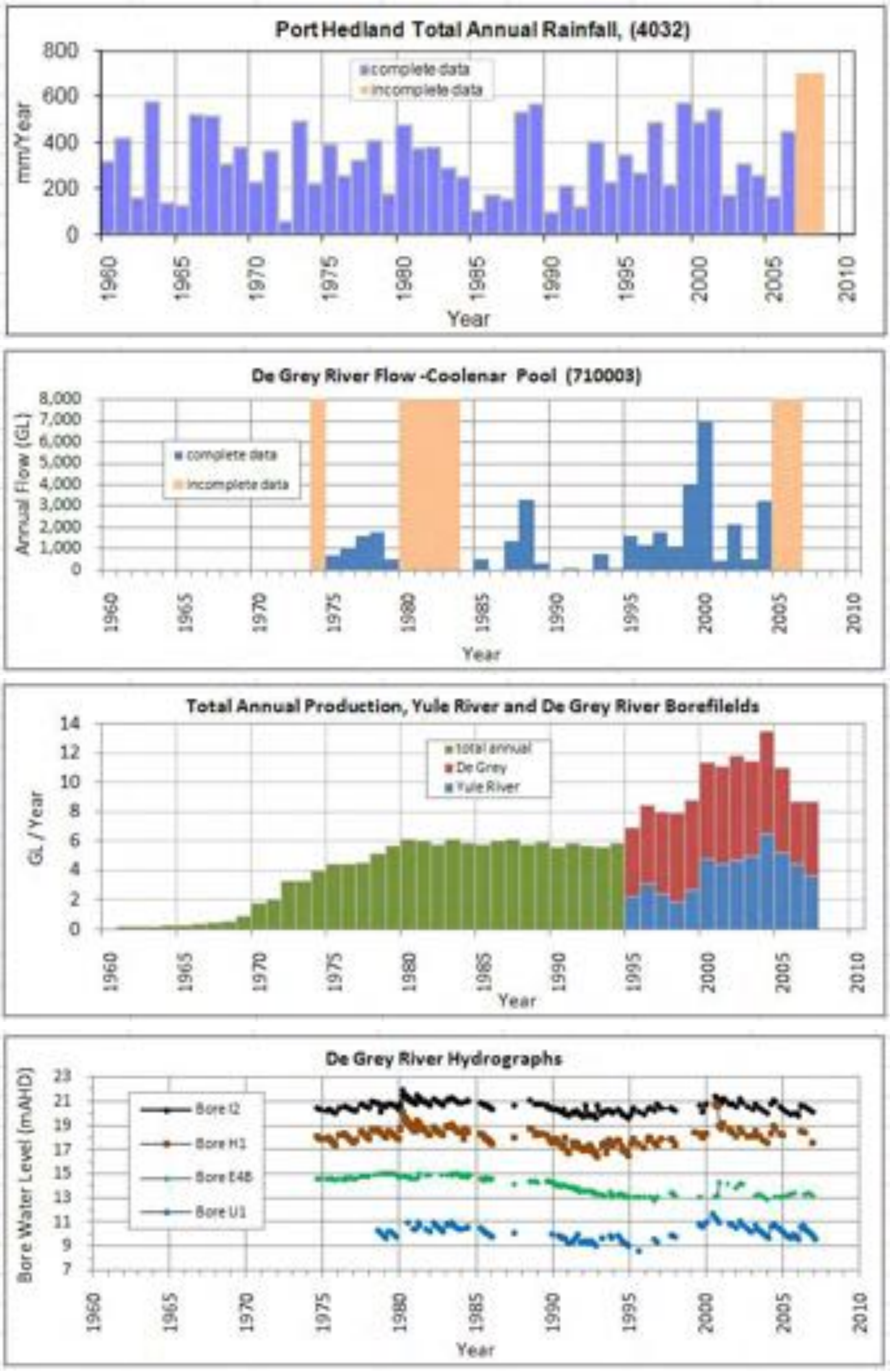


Figure 32: De Grey River hydrographs and borefield production

Namagoorie (De Grey) borefield water levels

Hydrographs for monitoring bores I2, H1, E1 and U1 are shown in Figure 32. The bores are located close to the active river channel and show the sharp annual fluctuations in water levels associated with periodic recharge events and subsequent drainage. Over the long term, the bores follow the climatic trends associated with periods of increased or decreased frequency of flooding.

From 1985 to 1992, the bores show a general lowering in water levels due to a period of low-flow events, as shown in the record from Coolenar Pool. From 1995 to 2000, the frequency of river recharge events was more consistent and water levels subsequently rose. Intermittent low-flow events between 1995 and 2005 resulted in the gradual lowering of water levels. Water levels have stabilised since early 2006 as a result of cyclone-related river flows. In general, all the observation bores indicate the aquifer water levels have generally remained stable from 2006 to the present. Water levels in almost all production bores have remained above recorded minimum historic rest water levels during the past few years.

Namagoorie (De Grey) borefield water quality

Salinity in all production bores in 2006–07 is generally stable and has ranged from 585 to 1000 mg/L (Water Corporation 2007a). Production bores generally show decreases in salinity when abstraction has been significantly reduced at different times of the year.

Ecosystems

The three main groundwater-dependent ecosystems in the De Grey River area are riverine ecosystems (pools), riparian ecosystems and aquifer ecosystems. The groundwater-dependent elements in the riverine ecosystems are aquatic macrophytes, macroinvertebrates, icthyofauna and vertebrate terrestrial fauna. In riparian ecosystems, the dependent elements include large deep-rooted vegetation such as eucalypts and melaleucas. Groundwater-dependant elements in the aquifer ecosystems are associated with stygofauna – if found to be present (Maunsell Australia 2003).

The De Grey River is listed as a wetland of national significance in the *Directory of Important Wetlands* (May & McKenzie 2002). The area is a significant refuge for biodiversity (Morton et al. 1995).

Subregionally significant wetlands are associated with the permanent and semi-permanent pools along the De Grey River, such as Nardeegeecarbilin Pool, Triangle Pool, Coolenar Pool, Tintawarmnyah Pool, Ginderwoorener Pool, Junction Pool, Marloo Pool and other unnamed pools (Geoscience Australia 2003). The wetlands are in declining, fair condition where recovery requires significant management intervention.

Biological surveys of the De Grey River in the vicinity of the Namagoorie and Bulgarene borefields were conducted by Halpern Glick Maunsell (1998). They provide additional detail on the description and distribution of vegetation communities, as well as terrestrial and aquatic faunal assemblages. The De Grey River vegetation is in rapidly declining, fair condition where recovery requires significant management intervention (May & McKenzie 2002).

The Water Corporation recently conducted additional investigations into the aquifer's ecology and its relationship with other ecosystems to help prepare environmental assessment documentation for the proposed Bulgarene borefield.

Resource development

The De Grey River alluvial channel is the only practical aquifer with development potential in the De Grey River area, including the confluence of the Shaw and Strelley rivers. The Shaw River alluvium is not appropriate for development due to low potential bore yields. The Strelley River alluvium is also not a potential development source due to low yields and high salinity (Figure 31). Underlying Archaean bedrock has little or no production potential.

The early work of Davidson (1974) identified three possible areas for development. Two areas are located upstream of the confluence of the Shaw River. The first area lies along line Q (Figure 29), which coincides with the north-west extension of the current borefield. The second site extends from line E to the south-east end of the current borefield. These sites were recommended due to the thicker section of paleochannel sediments and the potential sources for recharge from both the De Grey River and Shaw River drainages.

A third site was described along a 14 km stretch of the De Grey River between lines H and K, downstream of the current borefield and the confluence of the Shaw River (Figure 29). It was noted that pumping at this location – in the vicinity of the riverbank – could possibly lower the watertable associated with the occurrence of vegetation communities and nearby pools.

Davidson (1974) recommended that expansion to the north of line Q might be possible, pending the results of exploratory drilling. Subsequent drilling investigations in this area have resulted in a fresh water resource being identified beneath the proposed Bulgarene borefield (Figure 31).

Restrictions to development

There are concerns that high abstraction rates could lead to dewatering of the alluvial system and increase the potential for saline intrusion from surrounding zones of brackish water. Environmental impacts from development of the Bulgarene borefield need to be assessed.

Further work

Mapping of watertable contours is required, especially across the river where intermittent and permanent pools exist. Good control over watertable contours is required to increase understanding of aquifer water levels and the reliance of local vegetation on groundwater.

A groundwater model would strengthen knowledge of river recharge mechanisms within the aquifer system. The model would also enable assessment of the impacts on local groundwater levels due to pumping. The model would also develop a better understanding of the recharge mechanisms.

The installation of permanent automatic loggers in current monitoring bores would assist with future modelling endeavours.

5.3 Potential groundwater supplies

5.3.1 Proposed Bulgarene borefield

The Bulgarene borefield consists of four test bores located 12 km downstream of the current Namagoorie Borefield (Figure 28). The borefield is currently being assessed to develop a better understanding of the relationship between groundwater abstraction and possible impacts on local pools of cultural importance.

The new borefield may have the potential to increase the Port Hedland supply scheme by 3 to 6 GL/yr. The final allocation from the Bulgarene borefield and the licenced volume will depend on the outcome of ongoing hydrogeological and environmental assessments. The Water Corporation has conducted a range of investigations and studies to assess the potential environmental impacts of the borefield’s development. The work completed by February 2005 was discussed during a meeting in 2005 between the (then) Department of Environment, Environmental Protection Authority Services Unit, Water Corporation and the consultants. The work program summarised below is based on the information presented at the meeting.

Early work

<u>Investigative drilling</u>

Investigative drilling in 1996 resulted in the construction of four test bores along the west bank of the De Grey River (Figure 28). If approved, the first stage of borefield development will be the conversion of the test bores to production bores by installing pumping equipment and supporting infrastructure.

<u>Baseline environmental survey and monitoring</u>

From 1996 to 1998 preliminary surveys were conducted on groundwater-dependent ecosystems, river pool ecosystems, riverine vegetation and terrestrial fauna. The work consisted of water-level monitoring and photo-point monitoring of pools along the De Grey River, such as Bulgarene Pool and Homestead Pool (Figure 28). The preliminary studies also included the monitoring of tree stress and aquifer water levels.

Recent studies

Groundwater modelling

The modelling of the De Grey River aquifer was completed (Worley 2005) to further the understanding of the groundwater system. The key objectives were to:

- validate the understanding of the aquifer system and the conceptual hydrogeology
- develop a groundwater model calibrated with existing monitoring data
- improve the understanding of the resource in relation to the frequency and duration of both river recharge events and periods of drought
- evaluate the sustainability of the proposed Bulgarene Borefield under different pumping and climatic scenarios.

Aquatic ecosystems

This study was completed (National Centre for the Tropical Wetland Research 2005) to further the existing ecological knowledge, assess the current ecological status and to define the conservation significance of the study area. The key objectives were to:

- determine the aquatic ecological and habitat values of the Lower De Grey River pool ecosystems
- assess the sensitivity of the river pool ecosystems to changed hydrological conditions
- assess the impact of the proposed groundwater abstraction on the pools and the river pool system
- place the outcomes in a local, catchment and regional context
- develop a groundwater model calibrated with existing monitoring data.

Terrestrial and riverine fauna/flora

These studies were completed for the riverine pools, riverine forests and savannah steps (Strategen 2005; Outback Ecology 2005). They assessed the sensitivity of Bulgarene Borefield area's fauna and flora, looking at:

- changes in the water regimes of pools on the De Grey and Ridley rivers, specifically in regard to frequency and duration of drying
- changes in the condition, composition and extent of the riverine vegetation
- potential impacts on groundwater-dependent vegetation due to pumping from the Bulgarene borefield
- the sensitivity of groundwater-dependent vegetation along the De Grey River to changes in the groundwater regime.

Cultural and social setting

The Pilbara Native Title Service completed a cultural values study in consultation with Ngarla representatives and the Ngarla working group. The key objectives of the study were to:

- identify areas of Aboriginal heritage along the De Grey River, such as pools and burial sites (Figure 28).
- define the relationship between groundwater and Native Title rights and Aboriginal social values.

Further work

The work program culminated in the Water Corporation preparing a draft environmental scoping document in 2005. At present, the borefield is being assessed for its supply capability.

5.3.2 West Canning Basin

The West Canning Basin is an area of approximately 3500 km^2 that was subject to an extensive groundwater exploration program during the 1970s (Leech 1974, 1979). It represents only a small part of the Canning Basin, which is the largest sedimentary basin in Western Australia covering an onshore area of 430 000 km^2. The geology of the wider basin is well understood as a result of deep oil-exploration bores, and the groundwater resources of the entire basin are considered substantial (Laws 1990).

The West Canning Basin area investigated during the 1970s is located about 100 km east of Port Hedland and about 30 km east of the De Grey River's Namagoorie borefield. A potential groundwater source was identified with a total estimated yield of fresh water as high as 50 GL/yr (Leech 1979). This source is considered to be a prime target for expansion of the Port Hedland Water Supply Scheme.

A drilling, rehabilitation and decommissioning program was carried out by the then Department of Environment in 2005. The bores drilled during this program and those drilled previously (Leech 1979) are shown in Figure 33.

The West Canning Basin overlaps onto the Pilbara craton and is a low-lying flat plain; it generally lacks dissection by rivers, except for the ephemeral creeks in the upper reaches of the De Grey River and Pardoo Creek drainages. The coastal parts of the basin are generally used as pastoral land, with the inland areas predominantly unused Crown Land.

The program detailed by Leech (1979) comprised geophysics, exploration drilling, bore construction, aquifer testing, petrological/palynological investigations and porosity testing. Drilling included a deep exploration hole to 696 m. A multi-layer aquifer system was identified with both confined and unconfined aquifers, with the water being predominantly fresh to locally brackish.

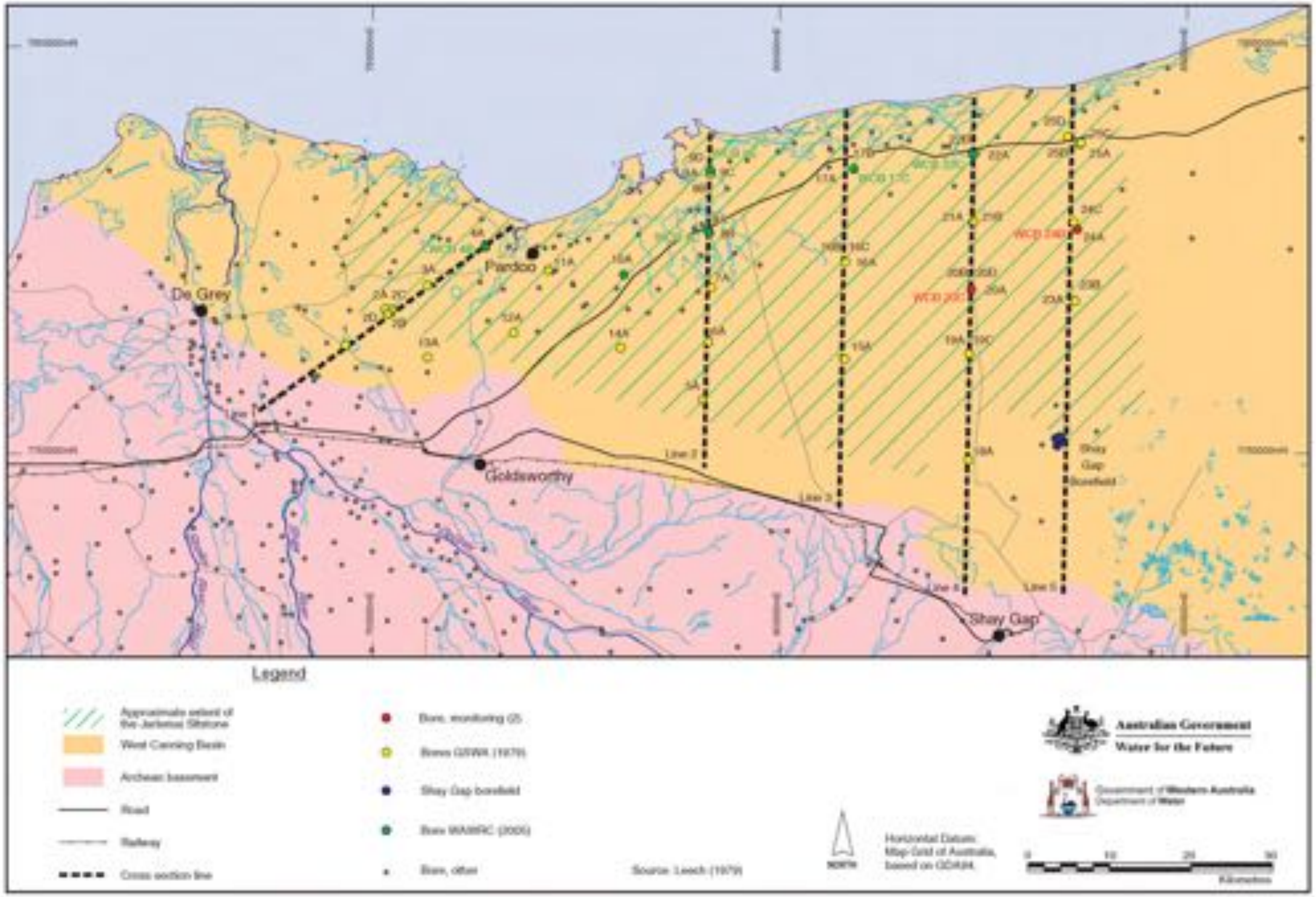


Figure 33: West Canning Basin location

Geology

The Canning Basin is a sequence of Cretaceous, Jurassic, and Permian sediments deposited in two north-west trending elongate sub-basins unconformably overlying an Archaean and Proterozoic basement. The western part of the basin overlies the Anketell Shelf, which has up to 696 m of sediments. The stratigraphy of the basin and its underlying basement geology are shown in Figure 34. The major stratigraphic units of the West Canning Basin within the study area are shown below in Table 23.

Table 23. The stratigraphic units of the West Canning Basin

Era	Period	Rock unit	Lithology
Cainozoic	Quaternary		Alluvium, tidal flat deposits, calcarenite, calcrete and laterite
	Quaternary	Bossut Formation	Calcarenite
	Tertiary		Calcrete, laterite
Mesozoic	Cretaceous	Prada Sandstone	Mudstone with fine siltstone lenses
		Unconformity	
Mesozoic	Cretaceous	Broome Sandstone	Sandstone with rare siltstone
	Jurassic	Jarlemai Siltstone	Siltstone, claystone and rare sandstone
		Wallal Sandstone	Sandstone with rare siltstone and grave interbeds
		Unnamed formation	Claystone with rare lignite
Unconformity			
Palaeozoic	Permian	Dora Shale	Siltstone and claystone
		Grant Formation	Siltstone, claystone and sandstone
Unconformity			
Archaean		Muccan Batholith	Granite
		Gorge Creek Group	Metasediments and volcanic rocks

<u>Archaean to Proterozoic</u>

Archaean rocks of the Pilbara craton crop out along the southern boundary of the West Canning Basin. They are predominantly Archaean granites associated with the Muccan Batholith, which intrude low-grade metamorphosed sediments and volcanic rocks of the George Creek Group including shales, banded iron, quartzite, amphibiolites and schists. Rocks of the George Creek Group crop out at the south-western edge of the basin and underlie the sedimentary sequences in the western part of the basin only. The remaining (majority) of the basin is underlain by a granite basement.

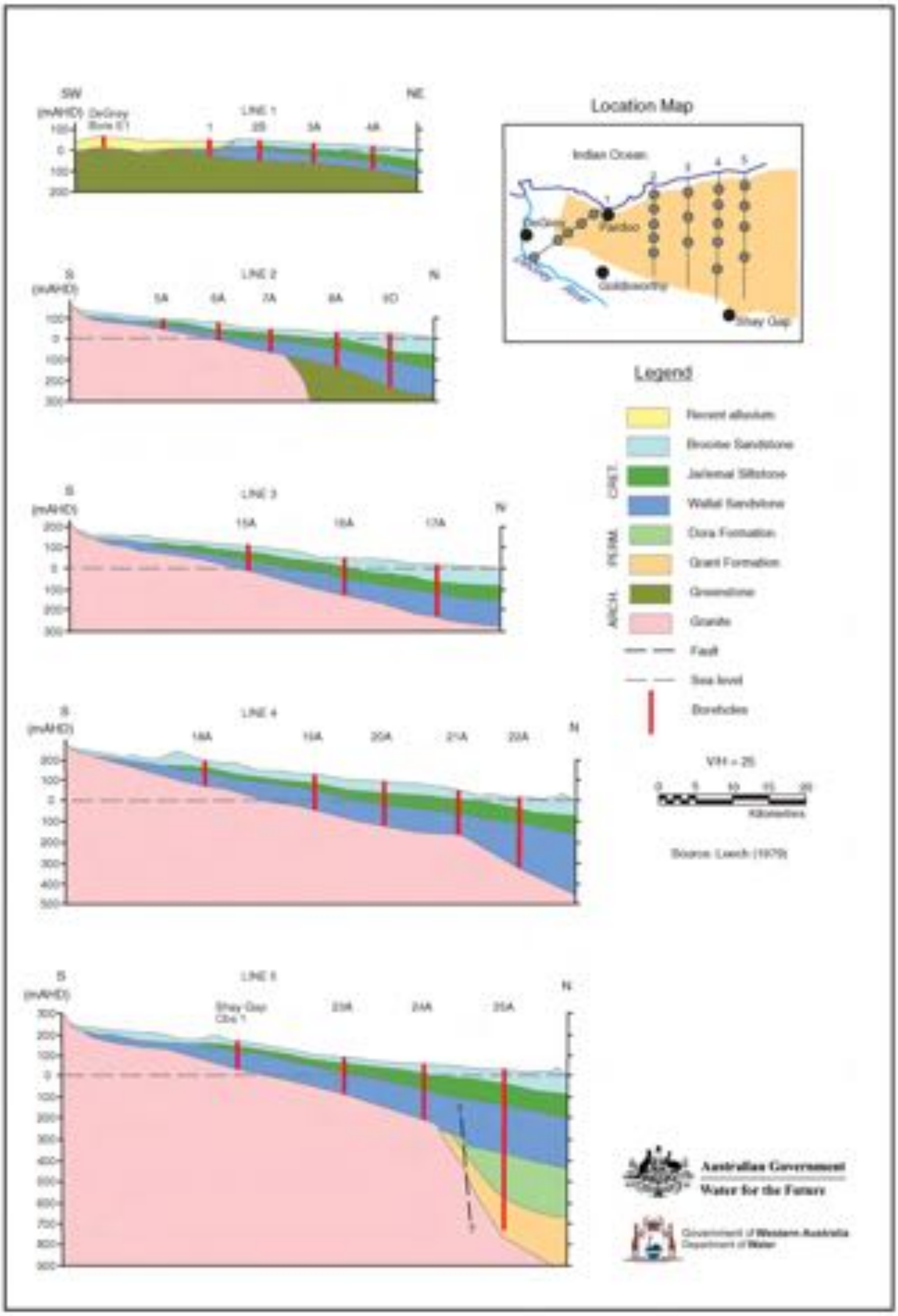


Figure 34: West Canning Basin geological cross-sections

Palaeozoic

Unconformably overlying the Archaean basement rocks are the Permian Grant Formation and Dora Shale. These units were only intersected by previous drilling in the north-eastern part of the study area approximately 10 km south of the coast. The Grant Formation was intersected at a depth of 565 m and the Dora Shale at a depth of 341 m. Geophysical logging indicated the water in the Grant Formation in this area was salty and thus the Dora Shale was not considered to be a potential source of groundwater (Leech 1979).

Mesozoic

Four Mesozoic units overlying the Palaeozoic rocks have been identified in the West Canning Basin: an unnamed Jurassic formation, the Wallal Sandstone, the Jarlemai Siltstone, and the overlying Cretaceous Broome Sandstone. As the Palaeozoic rocks are almost completely absent in much of the area, the Mesozoic rocks lie unconformably on the Archaean-aged basement rocks.

The unnamed formation is only found locally near the coast in the north-central part of the West Canning Basin. It unconformably overlies the Archaean basement and forms an impermeable base (where present) to the Wallal Sandstone aquifer.

The Wallal Sandstone is present in the subsurface over most of the area and has a maximum reported thickness of 218 m (Leech 1979). Through most of the area, it lies unconformably over the Archaean basement. Along the southern edge of the West Canning Basin, the Wallal Sandstone may be absent within 3 to 10 km of the margins of the basin. In which case, the overlying Broome Sandstone lies directly on Archaean or Proterozoic basement rock.

The Jarlemai Siltstone unconformably overlies the Wallal Sandstone (Leech 1979). It occurs only in the subsurface and has a reported maximum thickness of 95 m. The Jarlemai Siltstone is missing along the southern portion of the West Canning Basin. As a result, the Wallal Sandstone may be in direct contact with the overlying Broome Sandstone.

The Cretaceous Broome Sandstone is exposed throughout the area and forms isolated mesas. Leech (1979) reported that the Broome Sandstone rests unconformably over Jarlemai Siltstone throughout most of the area, but overlies the Wallal Sandstone along the southern margin of the basin where the Jarlemai Siltstone is absent. More recent evaluations of bore logs and rehabilitation drilling on existing bores indicate that the lithologic distinction between the Broome Sandstone and underlying Wallal Sandstone is difficult. Uncertainty exists as to whether the sandstone present along the southern margin of the West Canning Basin is the Broome Sandstone or the underlying Wallal Formation (Michelson 2005).

Tertiary to Quaternary

Mesozoic sediments of the Canning Basin are covered by discontinuous occurrences of Tertiary laterite and calcrete. The laterite has a maximum thickness of 5 m and crops out near Pardoo Creek, along the flanks of paleodrainages and to the east of Shay Gap (Leech 1979).

The Quaternary sediments consist of the Bossut Formation (a coastal limestone cropping out at Cape Keraudren), numerous tidal flats, sand dunes and river alluvium.

General hydrogeology

The understanding hydrogeology of the West Canning Basin is based on exploration and assessment work completed in 1977 (Leech 1979).

The West Canning Basin is a multi-layer aquifer system with the main aquifer units being the Wallal and Broome sandstones. The Wallal Sandstone is predominantly confined and separated from the overlying unconfined Broome Sandstone by the Jarlemai Siltstone. In the southernmost parts of the basin, the Jarlemai Siltstone is absent and the Wallal Sandstone is directly overlain by the Broome Sandstone where it is considered unconfined. Groundwater flow direction in each aquifer is different where the confining Jarlemai Siltstone is present.

The Tertiary and Quaternary sediments are not considered to be significant aquifers in this area and may contain only small groundwater storages. These formations are probably in hydraulic connectivity with the underlying Broome Sandstone.

The Broome Sandstone is unconfined and recharge is from direct infiltration of rainfall or indirectly from the overlying Tertiary or Quaternary sediments. The Wallal Sandstone is confined by the overlying Jarlemai Siltstone and is recharged by rainfall in limited areas where the Jarlemai Siltstone is not present.

The Wallal Sandstone has a greater volume of water and generally better water quality than the Broome Sandstone aquifer.

Wallal Sandstone aquifer

The Wallal Sandstone aquifer has a maximum intersected thickness of 218 m (Leech 1979) and consists of fine- to coarse-grained poorly consolidated sandstone. Figure 35 shows the contoured thickness of the Wallal Sandstone. The aquifer has large artesian flows, particularly in the northern parts of the basin, and positive heads in excess of 30 m above ground level have been measured (Leech 1979).

Aquifer testing and hydraulic parameters

Bore discharges during testing ranged from 614 to 3030 kL/day. Pumping test analysis indicated that the aquifer showed a steady-state response after one to three minutes of pumping.

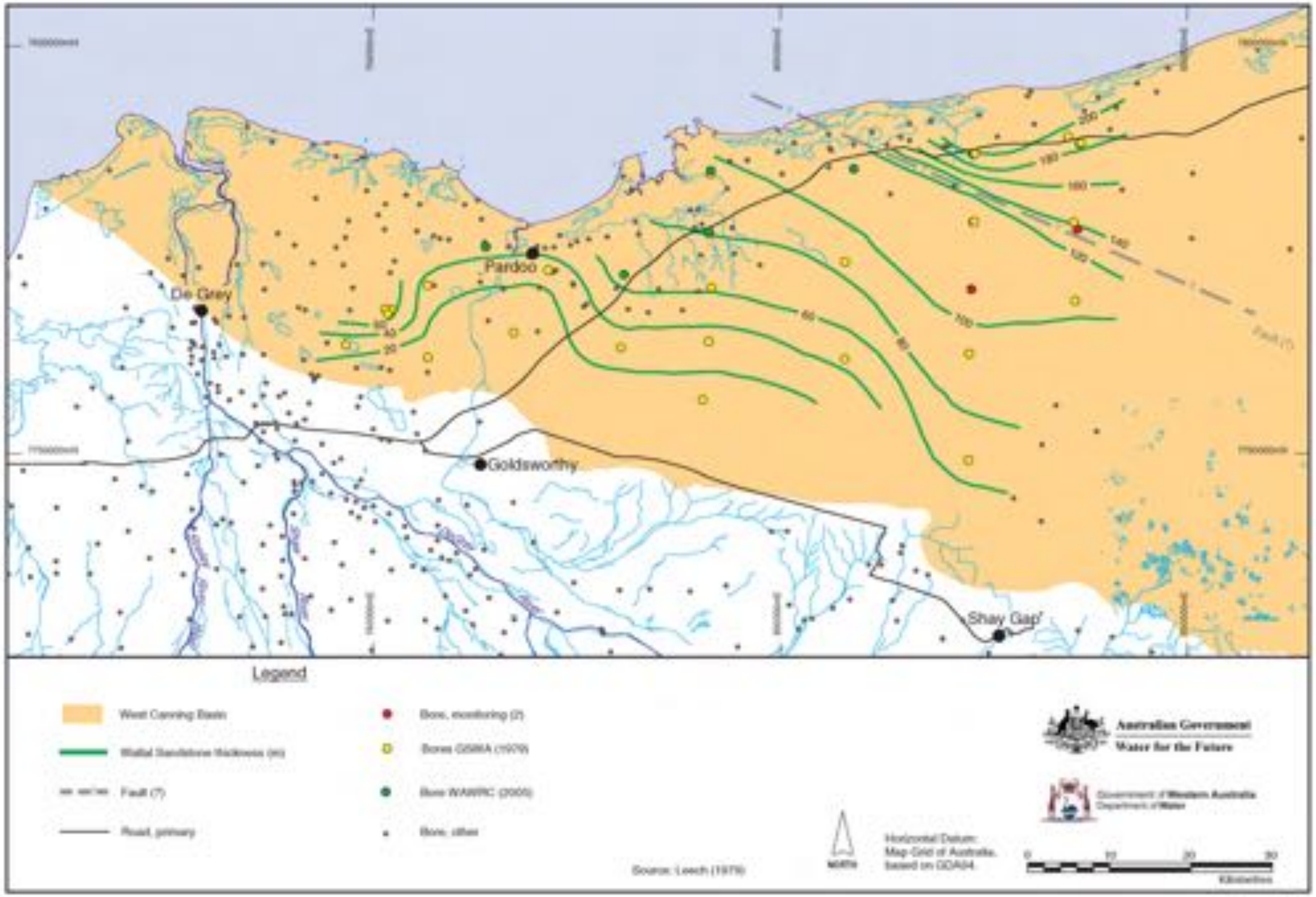


Figure 35: West Canning Basin Wallal Sandstone thickness

Transmissivities for screened aquifer intervals ranged from 10 to 2490 m^2/day with an average of 340 m^2/day. A storage coefficient of 2.0 E-4 was calculated from test pumping, which was in good agreement with the storage coefficient of 3.3 E-4 derived from barometric efficiency calculations. A specific yield of 0.28 was calculated from laboratory porosity analysis of drilling samples. An average hydraulic conductivity of 30 m/day was estimated from pump-test analysis, which was in close agreement with conductivity of 26.1 m/day that was estimated from flow-net analysis (Leech 1979).

Groundwater levels

Monitoring bore WCB-20C is completed in the confined portion of the Wallal Sandstone. The surface elevation is 78.1 mAHD and it has a screened interval from 169 to 187 m bgl. Figure 36 shows hydrographs of water levels measured in the Wallal Sandstone from 1978 to present. An increase has occurred since 2000, which is associated with a rise in water levels in the overlying Broome Sandstone. Overall, the water levels in bore WCB-20C have risen about 1 m during the 30-year monitoring period.

Recharge

Recharge to the Wallal Sandstone occurs from direct rainfall along the southern margin of the West Canning Basin where the Jarlemai Siltstone is absent. Monitoring of rainfall and bore water levels during early investigations (Leech 1979) indicated that rainfall events from cyclone Karen and Leo had no recharge response in the aquifer. The only fluctuations in groundwater levels during rainfall events were due to changes in barometric pressure or tidal effects.

Leech (1979) assessed the aquifer response to recharge through storage-to-flow ratio analysis. The ratio of storage in an upstream portion of the aquifer to the volume of flow moving through that section can be expressed in years. Work on the effects of groundwater storage and flow on water balances by Chapman (1963) indicated that a storage-to-flow ratio of greater than 50 years was representative of steady-state conditions. Leech (1979) estimated storage-to-flow ratio of 330 years, which implies that the Wallal Sandstone aquifer may be in a steady-state condition. This is consistent with pump-test analysis and with recorded water levels during cyclone episodes – in that short-term recharge events have no impact on water levels in the confined portion of the aquifer.

Storage

The storage of the Wallal Sandstone aquifer was calculated to be 54 900 GL from estimates of the total aquifer volume of 196 000 GL and a specific yield of 0.28 (Leech 1979).

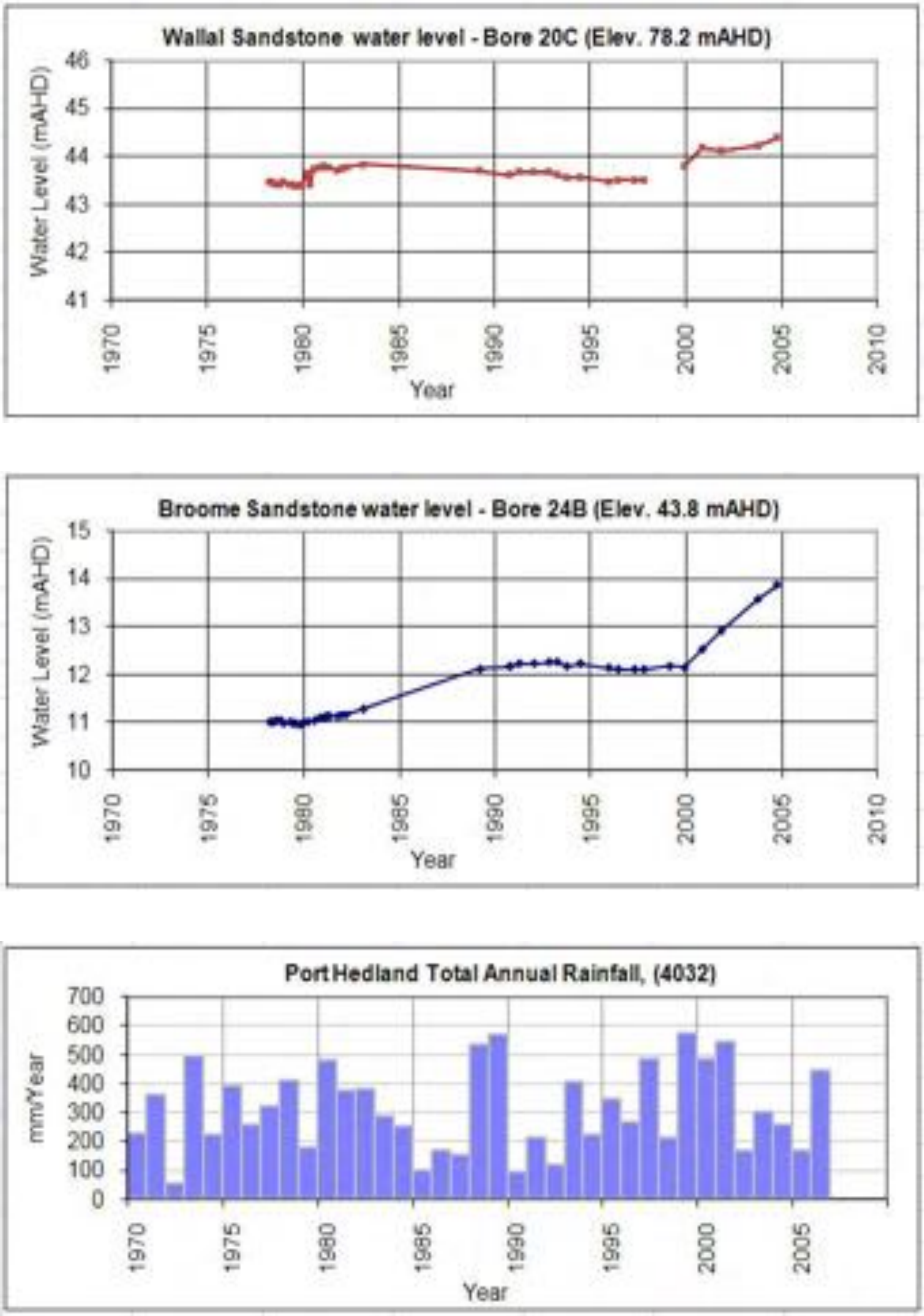


Figure 36: West Canning Basin hydrographs

Throughflow

Groundwater flow in the Wallal Sandstone aquifer in the West Canning Basin is mostly to the west, but in the eastern portion it is to the north-west, as can be seen in the potentiometric surface mapped in Figure 37. By comparison, the overlying unconfined Broome Sandstone aquifer flows mostly to the north. A flow-net analysis of the confined Wallal aquifer was constructed by Leech (1979) based on potentiometric contours.

A throughflow analysis was conducted using transmissivities calculated from the product of aquifer thickness and mean hydraulic conductivity derived from aquifer tests (20 m/day). Throughflow was calculated to be about 21 GL/yr (Leech 1979), which is an indication of the potential yield of the aquifer. The flow-net construction used by Leech (1979) was truncated just to the west of Pardoo Station.

Plotting of isohalines indicates that approximately two thirds of the flow-net area has salinities of less than 500 mg/L. The volume of extractable throughflow that is most suitable for domestic purposes was estimated by Leech (1979) to be 14 GL/yr.

Discharge

Discharge from the Wallal Sandstone is predominantly offshore. Leech (1979) reported three springs that were likely to receive water sourced from the Wallal Sandstone aquifer: Mayadee Spring, which is located near the North West Coastal Highway approximately 20 km east of Pardoo Station; Banningarra Spring, which is located approximately 15 km north-east of Pardoo and 3 km inland from Mount Blaze; and Mound Spring, which is located near Pardoo Creek.

The springs result from leakage from the underlying Wallal Sandstone through the Jarlemai Siltstone. Leech (1979) reported that the water quality of the springs was similar to samples from the confined portion of the Wallal Sandstone, but differed from the chemical components of the unconfined aquifer.

Discharge also occurs at the nationally significant wetlands associated with the mound springs of the Mandora Marsh (Lake Walyarta). The springs are located about 100 km north-east of the study area, but are still within the Canning Basin. The marshes are also part of the Ramsar-listed Eighty Mile Beach site and are a significant refuge for biodiversity (Morton et al. 1995).

As well as the springs, the area also has soaks and a series of clay pans unlikely to be connected with groundwater. The springs and soaks are similar in occurrence to those found at Pardoo – in that they may be surface expressions of the confined Wallal aquifer. If sourced from the Wallal aquifer, the discharges would occur through permeable paths in the Jarlemai Siltstone that allow groundwater to reach the surface. Hydrochemical analysis from the confined Wallal Sandstone, the unconfined Broome Sandstone and from the springs at both locations is required to assess this theory.

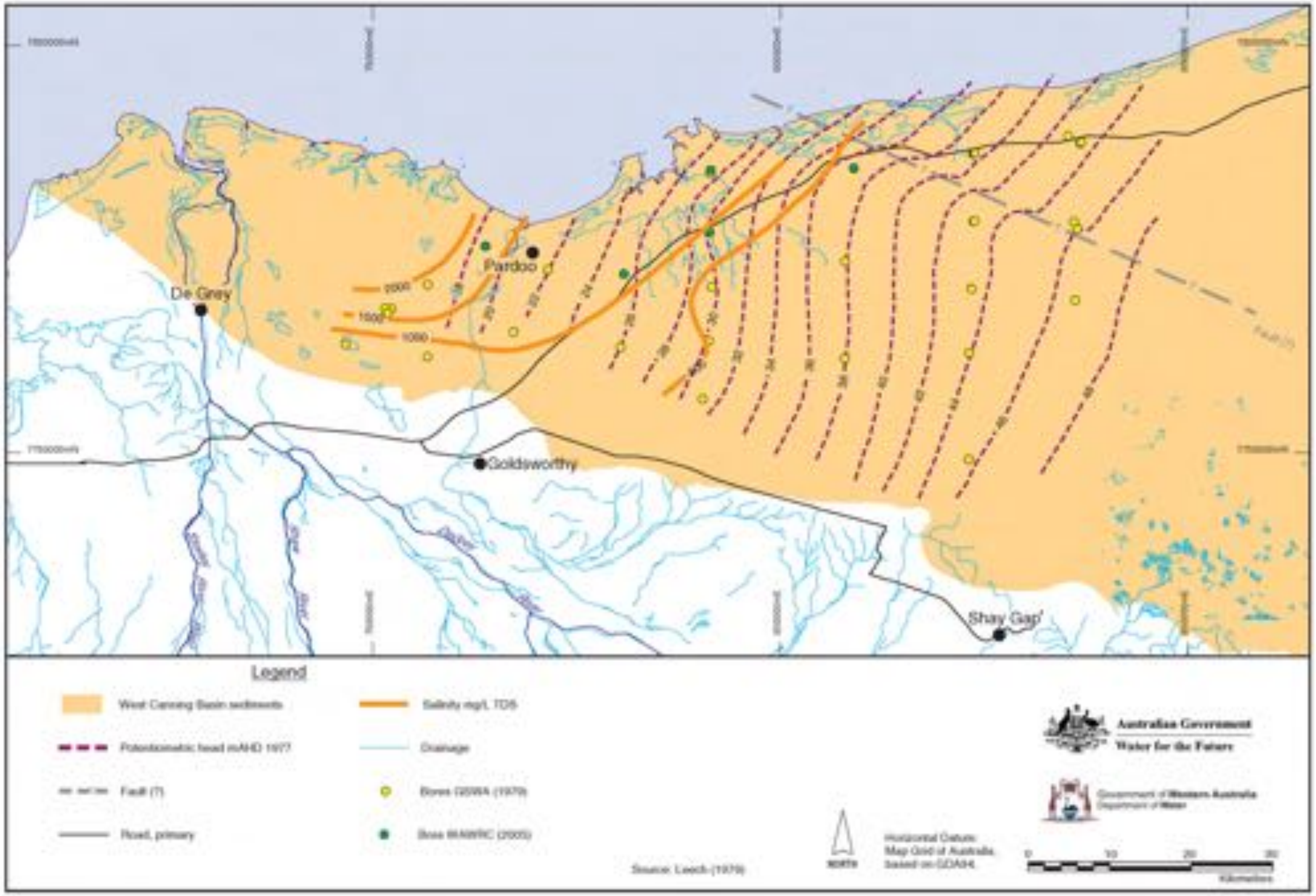


Figure 37: West Canning Basin Wallal aquifer potentiometric surface and salinity

Groundwater quality

Groundwater salinity in the area to the west ranges from 1000 to 10 000 mg/L; however, the controls on salinity variation are not well known (Leech 1979). To the east of Pardoo, salinities are generally between 500 and 1000 mg/L. The isohalines for the Wallal Sandstone have also been plotted in Figure 37.

The major anions and cations of the groundwater from the Wallal Sandstone have two distinct chemical compositions. Water sampling from bores in the western part of the West Canning Basin reflects a greater distance from the source of recharge. Sampling of bores to the east reflects a less distant source of recharge. The chemical composition of groundwater from the Wallal Sandstone in the east is not dissimilar to that of the overlying Broome Sandstone. In general, the chloride content in the Wallal Sandstone increases down gradient (to the west and north) as water flows away from the source of recharge.

Groundwater salinity in the eastern portion is less than 500 mg/L and is for domestic supplies. Where the salinity is less than 500 mg/L, it is also suitable for agriculture as the Sodium Absorption Ratio (SAR) and the salinity hazard are low. Leech (1979) reported high nitrate concentrations of 23 to 25 mg/L occurring in the vicinity of Shay Gap Borefield. This could have been the result of bore construction and/or local contamination from other nearby land uses. Regardless, 50 mg/L NO^3 is the limit for potable water supply, according to the *Australian Drinking Water Guidelines (ADWG)*.

Groundwater quality deteriorates in a westerly direction: salinity is greater than 500 mg/L, the water becomes hard and the levels of calcium, sodium and chloride may exceed acceptable *ADWG* limits. Water quality in the west may not be appropriate for agriculture, but may be suitable for industrial purposes.

Wallal aquifer development

Throughflow analysis has indicated that a total extractable volume of 21 GL/yr may be possible from the Wallal Sandstone aquifer. The area to the east has salinity of less than 500 mg/L, whereas in the west the salinity increases. Of the 21 GL/yr throughflow volume, about 14 GL/yr may be suitable for domestic or agricultural purposes. The remaining 7 GL/yr from the western portion of the area is only suitable for industrial purposes.

Shay Gap borefield (Figure 33) was in use during Leech’s investigation (1979). The total annual abstraction was about 1.2 GL/yr from the Wallal Sandstone aquifer. The borefield had been in operation since 1972 and at the time of Leech’s report, had experienced less than 2 m of decline in the potentiometric surface.

Restrictions to resource development

Development of the Wallal Sandstone aquifer may be restricted by the economics of borefield construction and the cost of operating bore pumps with large operating lifts.

Salt-water intrusion from the north is not necessarily a restriction to developing the Wallal Sandstone along the coast. Given the high potentiometric head, the salt-water interface should be located offshore.

Broome Sandstone aquifer

In the western portion of the Canning Basin, the Broome Sandstone has a maximum thickness of about 71 m and is the only unconfined aquifer in the sedimentary sequence. The aquifer consists of a fine- to coarse-grained moderately sorted sandstone, with rare thin bands of shale and siltstone. It has a saturated thickness ranging from about 20 to 56 m, with an average of 20 m. It unconformably overlies the Jarlemai Siltstone over most of the West Canning Basin area, but lies directly on Wallal Sandstone in the southern part of the basin. The elevations of the base of the Broome Sandstone are shown in Figure 38.

Hydraulic testing and aquifer parameters

Bore discharges during testing ranged from 29 to 735 kL/day. Transmissivities determined from pumping bores ranged from 138 to 854 m^2/day and averaged 325 m^2/day (Leech 1979): no value for the specific yield of the Broome Sandstone could be determined as monitoring bores were not installed.

Groundwater Levels

Figure 39 shows the interpreted water table elevations in the unconfined portions of the West Canning Basin from data collected in 1977. Groundwater levels in the unconfined aquifer indicate that the direction of groundwater flow is from south to north.

Bore WCB-24B was completed in the Broome Sandstone with a screened interval from 34 to 40 m bgl. The hydrographs of the water levels from 1978 to present were included in Figure 36. Changes in water level are directly attributed to rainfall recharge. The mean annual rainfall in Port Hedland is 308mm. Port Hedland is located 100 kilometres to the east of the monitoring bore and only general correlation between the two sites can be made. Increases in water levels can be broadly attributed to higher rainfall in the late 1980’s and from 2000 to present. Water levels have risen approximately 3 metres since monitoring began in 1978.

Recharge

Recharge to the Broome Sandstone is by direct infiltration of rainfall. Water level monitoring from 1975 to 1977 recorded the recharge events of cyclone Karren and Leo during March of 1977, which resulted in total rainfall of 159mm. The records indicate that the delay time between the rainfall event and the rise in water level was about 3 months. Smaller rainfall events during the 2 year recording history had no effect on the water table.

Leech (1979) calculated recharge by applying an assumed porosity of 0.3 to the increased aquifer volume resulting from cyclonic rainfall events. The recharge was

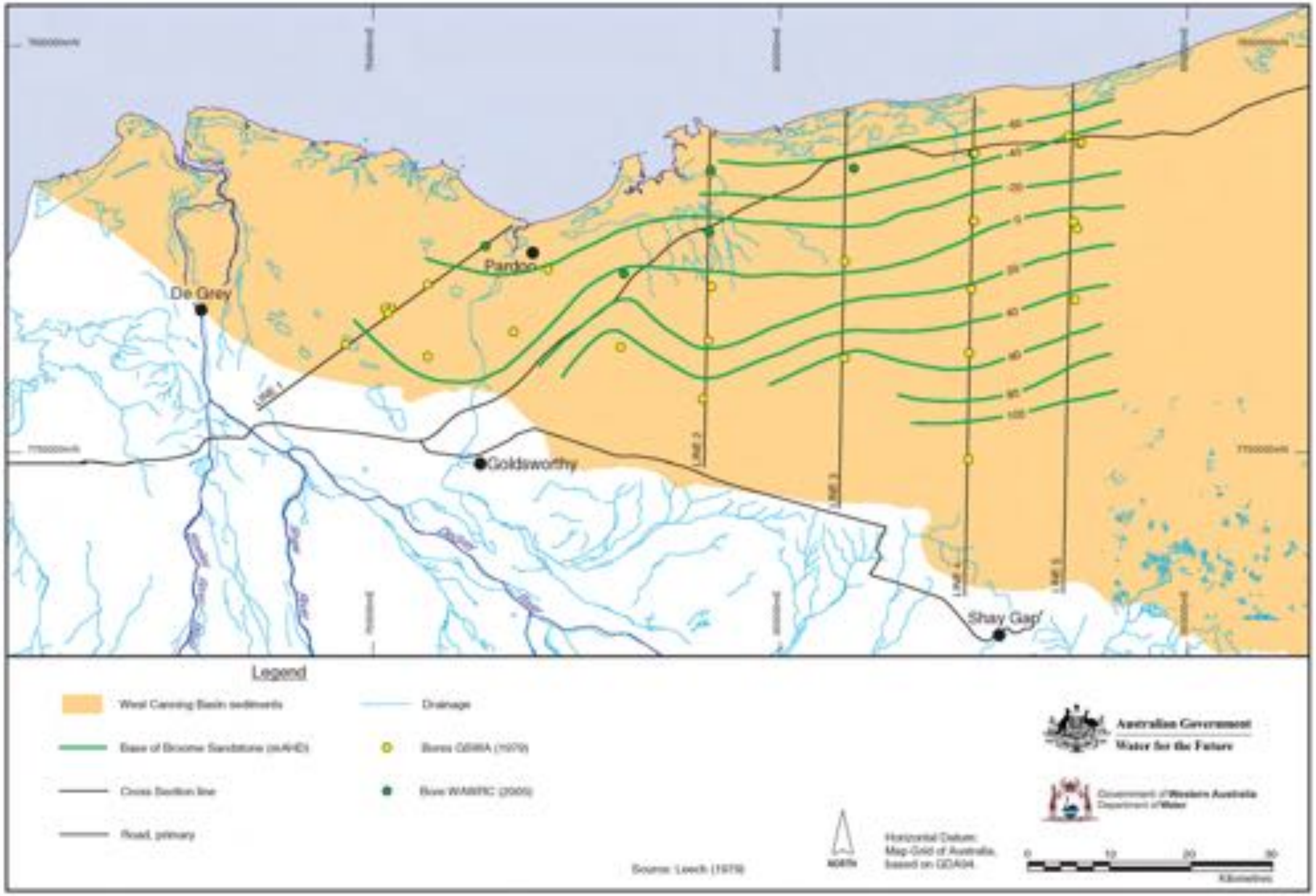


Figure 38: West Canning Basin base of Broome Sandstone

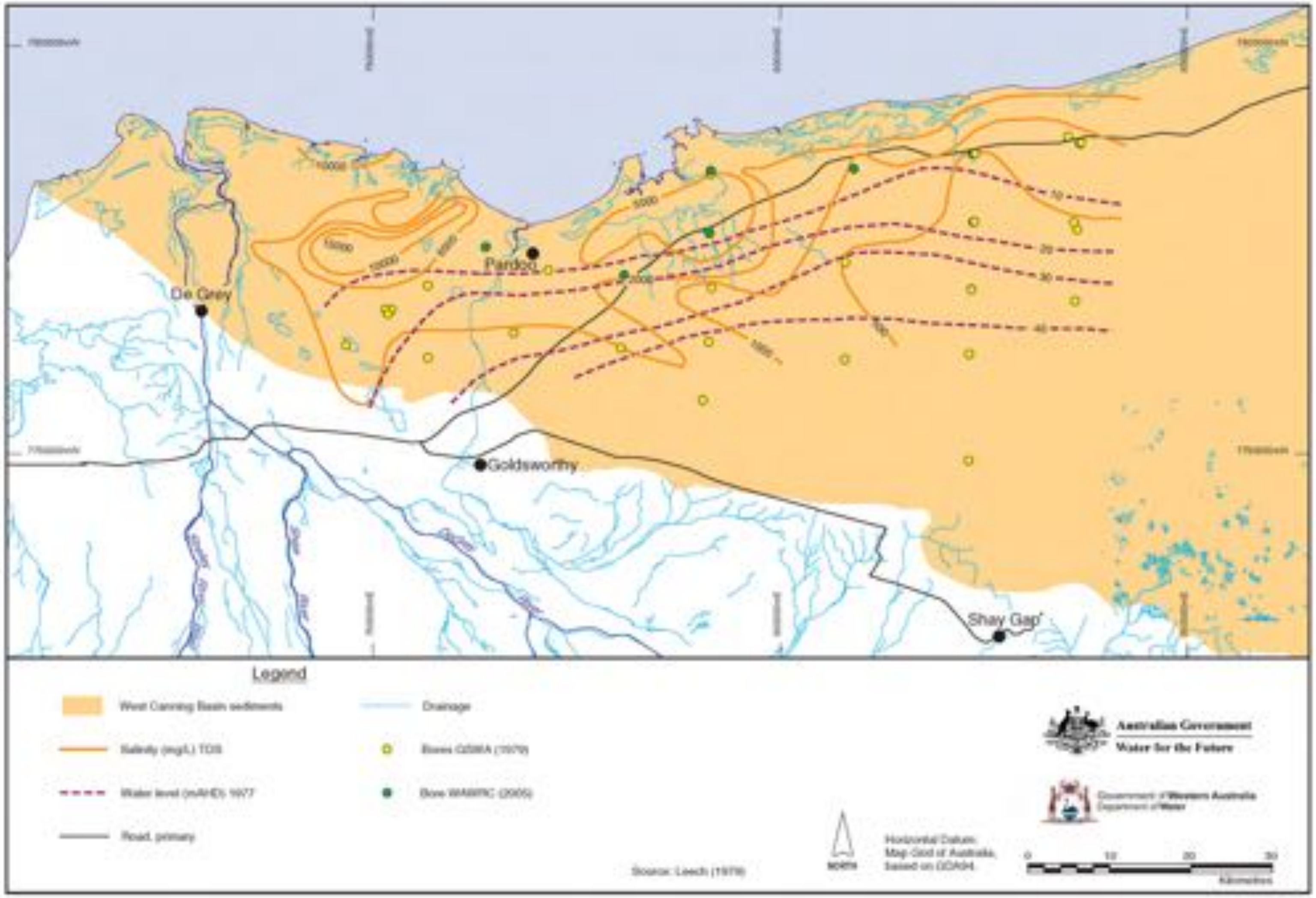


Figure 39: West Canning Basin salinity and water table in the unconfined aquifers

estimated to be about 6% of total annual rainfall. As this estimate was based on an intense rainfall event, it was assumed that it may be relatively high.

Leech (1979) assumed an “effective area” of the Broome sandstone with a saturated thickness of 20 metres to be about 1,575 km^2 in extent. Skidmore (1996) applied a conservative recharge rate of 3%, an annual rainfall of 250mm over an area of 1,575 km^2 to report an estimated recharge rate of 18 GL/yr. Salinity isohalines developed by Leech (1979) and also shown in figure 39 indicate that the proportion of the “effective area” with salinity less than 1,000 mg/L is approximately a third of the aquifer area. It is assumed that the volume of recharge in the area where potable water can be extracted is about 6 GL/yr.

Storage

Leech (1979) estimated a specific yield of 0.1 for the Broome Sandstone, which was considered to be low. This was applied to the “effective area” of 1,575 km^2 and an average saturated yield of 20 metres to estimate total aquifer storage of 3,200 GL. As the portion of water with a salinity of less than 1,000 mg/L is a third of the “effective area”, it is estimated that the volume of fresh water in storage in the area from which groundwater can be extracted is about 1,100 GL.

Throughflow

Throughflow was estimated across the 10 m water table elevation contour shown by Leech (1979). An average hydraulic conductivity of 7.5 m/day was assumed from pump testing and an average gradient of .0025 was estimated. The saturated thickness across the 10 m water table contour was estimated to be 29.3 m. Throughflow in the Broome sandstone was calculated to be 20 GL/yr. Leech (1979) noted that only about a third of this throughflow had a salinity of less than 1,000 mg/L total dissolved solids. As a result, the volume of throughflow with fresh water is estimated to be 7 GL/yr.

Discharge

Over most of the West Canning Basin, groundwater movement in the Broome Sandstone is to the north towards the coast where it discharges into the Indian Ocean. A much smaller volume of discharge may be intercepted along the coast by phreatophytes (normally eucalypts) when present (Leech 1979). In the western-most portion of the WCB, discharge is to the south and south west into the De Grey alluvium.

Groundwater Quality

Salinities in the eastern portion of the WCB are less than 1,000 mg/L. To the west, salinities rise to more than 5,000 mg/L along the coast to the east and west of Pardoo (Figure 39). Analysis of cations and anions of the Broome Sandstone water indicate that it is generally suitable for domestic purposes where the TDS is less than 1,000 mg/L. The ADWG limit the maximum nitrate content to 50mg/L for potable supplies. The elevated nitrate levels in some bores (up to 52 mg/L) give rise to water treatment requirements if the Broome Sandstone is used for domestic purposes. The nitrate may be naturally occurring in the Broome Sandstone and not necessarily a result of land use. Sodium absorption ratio analysis of water samples indicates that the water has a medium to high salinity hazard. This would indicate that the water from the Broome Sandstone is probably not suitable for irrigation (Leech 1979).

Broome Sandstone Aquifer Development

The Broome Sandstone Aquifer has a total estimated groundwater resource of 18 GL/yr in the West Canninig Basin. The eastern part of the aquifer is suitable for domestic purposes and the volume of fresh water has been estimated to be 6 GL/yr. A method of denitrification may be required to reduce nitrate levels to make the water suitable for human consumption. The western part of the basin is only suitable for industrial purposes due to high salinity. The volume of brackish water has been estimated to be 12 GL/yr.

Water from the western portion of the West Canning Basin may not be suitable for agriculture as the salinity hazard can be high. If the eastern portion of the WCB is developed, both the Broome and the underlying Wallal sandstone aquifers should be developed to allow for mixing of the waters to increase the development potential.

At present, there is no licensed abstraction from the Broome or Wallal Sandstone aquifers in the West Canning Basin. Current groundwater use is from shallow bores constructed for monitoring or stock purposes. There is currently an interest in exploiting this resource by mining companies with operations along the southern edge of the basin.

Restrictions to source development

The potential for impact to ecologically sensitive areas are of a lesser degree than the potential impacts associated with groundwater development of an alluvial aquifer system. The extent of potential environmental impacts will need to be assessed prior to any future development.

Further Work

A work program which includes the development of a numerical groundwater model is recommended. The program should also include carbon 14 and Chlorine 36 sampling to improve the understanding of recharge processes. Down hole geophysical logging may be required to better define lithological differences between the Broome Sandstone and the underlying Wallal Sandstone. Water chemistry testing is necessary to map salinity changes both vertically and laterally in the aquifers. The current monitoring program should be reviewed and expanded.

The work program should also include ecological investigations of those springs which are sourced from aquifers in the West Canning Basin. The mound springs near Pardoo should be assessed as part of the numerical modelling project. The Ramsar listed Mandora Marshes are located to the East of the study area. An understanding of the source of the springs at this location should be assessed if development were to expand in that direction.

5.3.3 Turner River

The Turner River flows in a northerly direction and crosses the North West Coastal Highway approximately 27 km west of Port Hedland (Figure 2). The Turner River Borefield was constructed and operated by the Public Works Department between 1969 and 1980. The borefield was located approximately 6 km downstream of the North West Coastal Highway (Figure 40). It was previously used to augment the Port Hedland Water Supply scheme before being replaced by the Yule River Borefield. The fresh portion of the Turner River has an estimated sustainable yield of less than 1 GL/yr (Farbridge 1966). The Turner River water reserve is a proclaimed Public Drinking Water Source Area because of the pre-existing Public Works Department borefield. The Department of Water has not developed a drinking water source protection plan for this source.

Geology

<u>Archaean</u>

The basement rock consists of Archaean granites and greenstones of the Pilbara Craton that are overlain by more recent alluvial sediments. The basement rock has a weathered horizon that may be from 5 to 30 m thick when present and often has secondary calcrete development.

<u>Quaternary</u>

The Quaternary to recent alluvium lies unconformably on the Archaean bedrock surface and has a maximum thickness of 43 m. The lithology consists of clay and sand with minor gravel. Calcrete occurrence is common and typically found near the watertable. The strata contain a high percentage of clay and silt fractions and have few intervals of clean sands or gravels. The upper 12 to 16 m of the alluvium typically consists of a layer of clayey sand or sandy clay, below which the alluvium has a igher percentage of sand and gravel layers. The alluvium fills a short, northerly trending valley that coincides with the present location of the East and West Turner rivers (Figure 41). The thickest sections of alluvium have been identified in this valley. Figure 42 shows cross-sections at two locations in the Turner River alluvium.

Hydrogeology

Two aquifers in the Turner River area were assessed by Farbridge (1966): the alluvial sediments and the weathered bedrock.

Water-bearing sections in the alluvium of 6 to 7 m thick were found below 30 to 40 m of clayey sand, which forms a confining layer. Calcrete development is also associated with the water-bearing zone at the base of the alluvium. Correlation between boreholes in the alluvium was difficult because of the lithologic variability of the alluvial sediments. The heterogeneity also led to complications with pumping-test analysis and the estimation of aquifer parameters. Bore yields from the lower alluvium aquifer were reported to range from 110 to 330 kL/day. The most productive

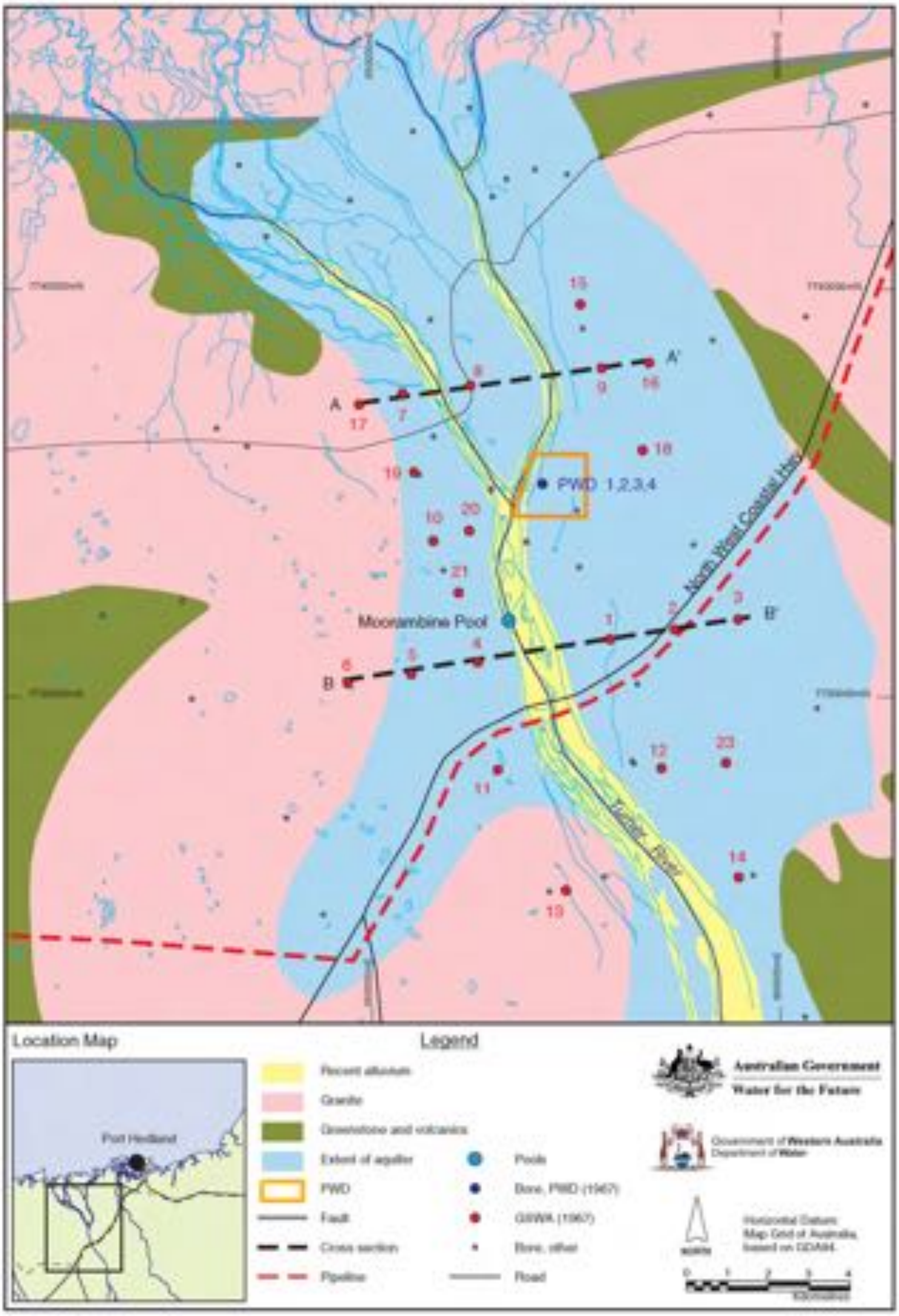


Figure 40: Lower Turner River bores

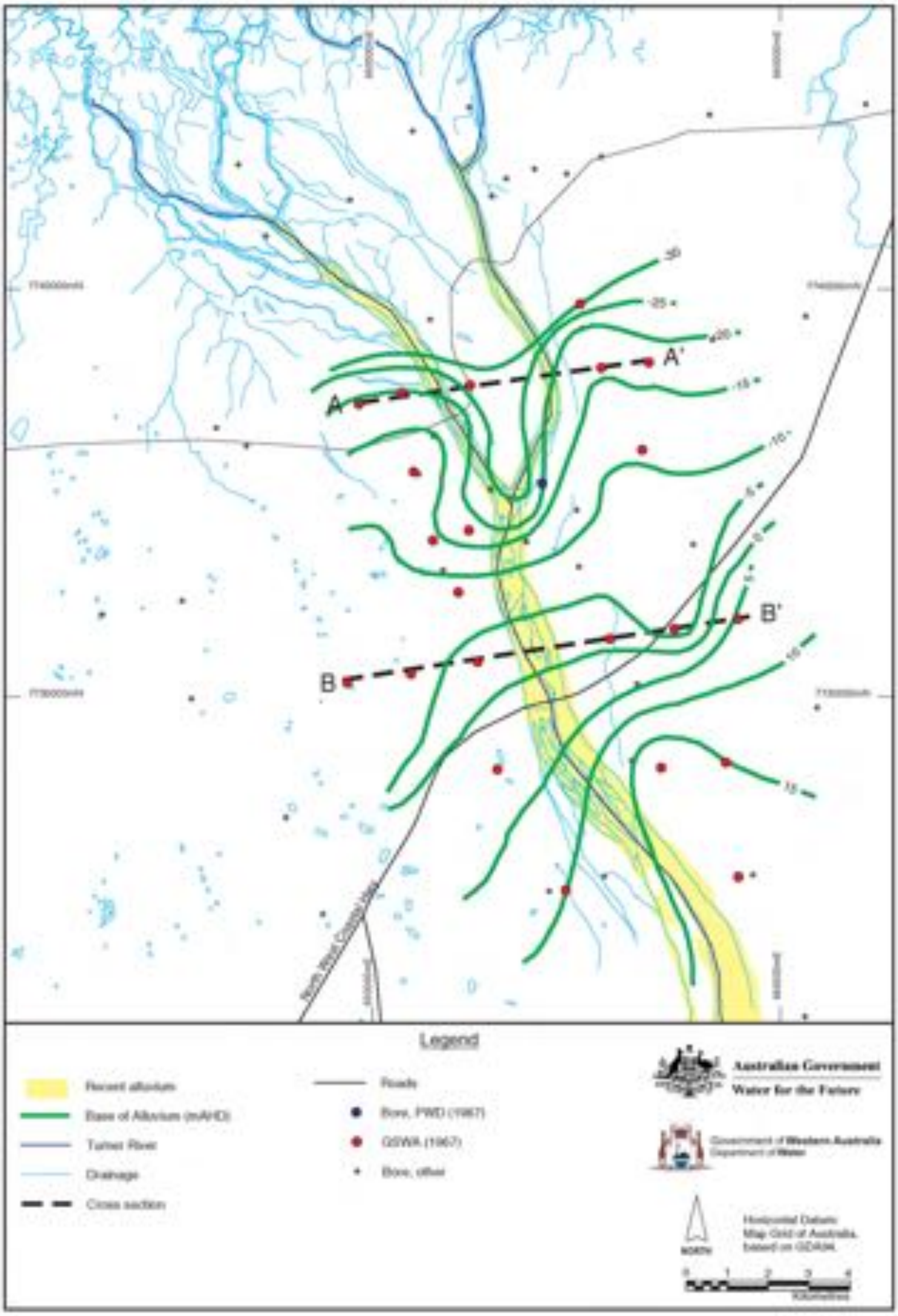


Figure 41: Turner River base of alluvium

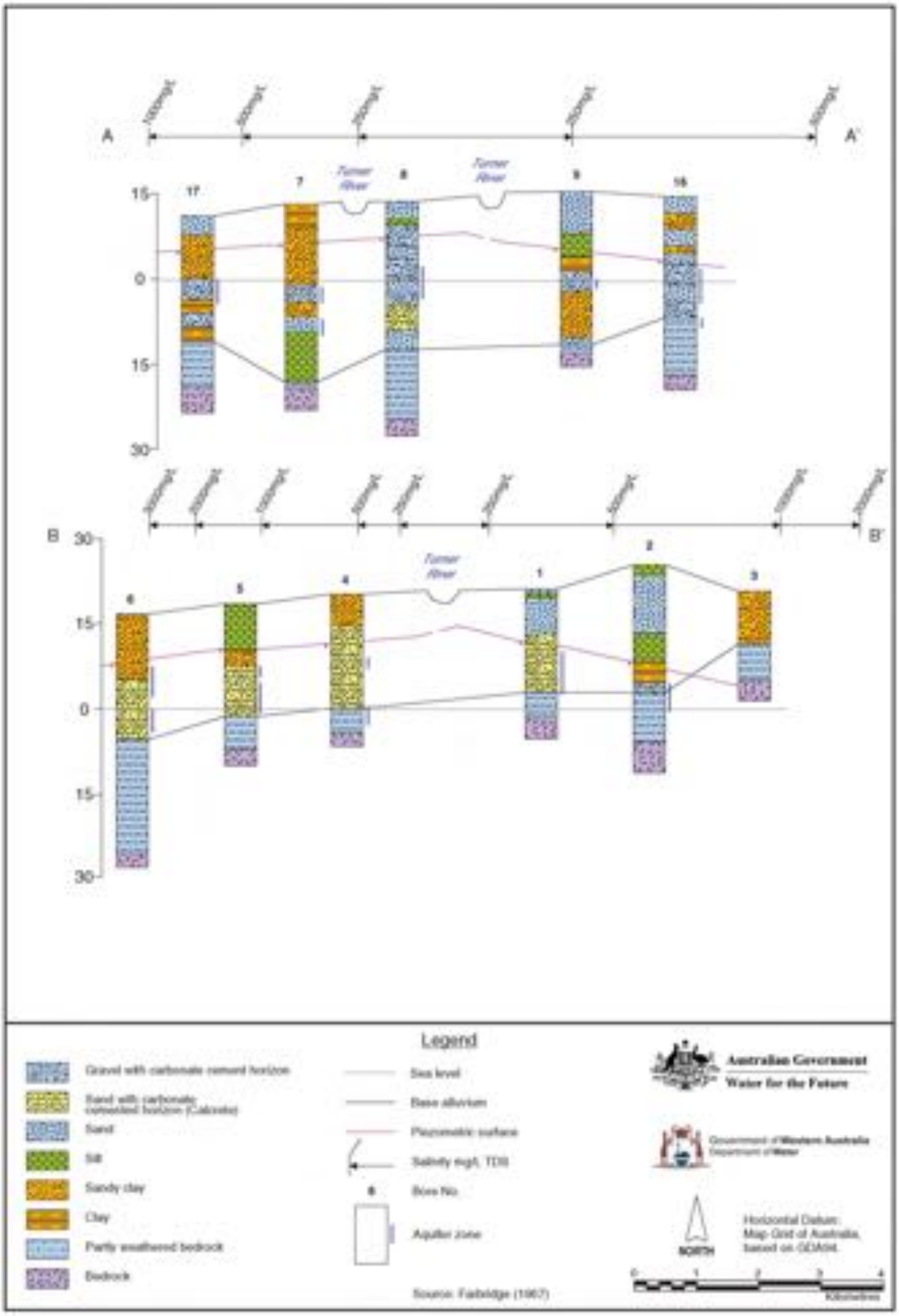


Figure 42: Turner River Area cross sections A and B

zones in the alluvial aquifer were associated with gravel and the occurrence of calcrete.

The cross-sections AA and BB in Figure 42 show the aquifer zones and screened intervals. Of the 10 bores in the cross-sections, eight are screened in the lower alluvial aquifer, one is screened in the weathered bedrock aquifer, and one is screened in both the alluvium and the weathered bedrock.

The weathered bedrock aquifer also has secondary calcrete development. A bore completed in the weathered bedrock had pumping yields of 650 kL/day. Water quality sampling has indicated that the weathered bedrock aquifer and the alluvial aquifer are hydraulically connected.

Aquifer parameters

A transmissivity for the alluvial aquifer of 30 m^2/day was estimated from pumping results (Farbridge 1966). This is a very low transmissivity when compared with an estimate of 560 m^2/day for the De Grey River alluvium (Davidson 1974) and 550 m^2/day for the Yule River alluvial aquifer (Davidson 1976). Test pumping resulted in an estimate of hydraulic conductivity in the alluvial aquifer of 4 m^2/day. A storage coefficient of 0.02 was estimated based on the reduction in known storage volume compared with the volume of water lost due to pumpage and throughflow.

Groundwater levels

Potentiometric contours from November 1965 are shown in Figure 43. The contours show the movement of fresh water in a north, north-east and north-west direction that coincides with active recharge zones along the east and west branches of the Turner River. At present, the monitoring record in the Lower Turner River area is limited to the study by Farbridge (1967).

Farbridge (1967) showed a cone of depression that formed around the Public Works Department production bores. The centre of the cone has a drawdown of about 20 feet (6 m). The lateral extent of the cone of depression shows a drawdown of 10 feet (3 m) at a distance of 0.25 miles (400 m) from the pumping bore. The report states that production on the Turner River from the old Public Works Department borefield was 200 000 gallons per day, or about 27 ML per month. This estimate represents a continuous pumping rate of 10.5 litres/second for a single bore, or 5 litres/second/ bore for two bores. The extensive drawdown cone is consistent with the low transmissivities of 30 m^2/day. It is apparent that any future development in the alluvial aquifer in this area should be assessed for potential bore interference and drawdown impacts.

River flow and aquifer recharge

The Pincunah gauging station is the closest to the study area and is located about 90 km upstream of the North West Coastal Highway crossing. The gauging station record extends from 1986 to the present and has a long-term mean annual flow

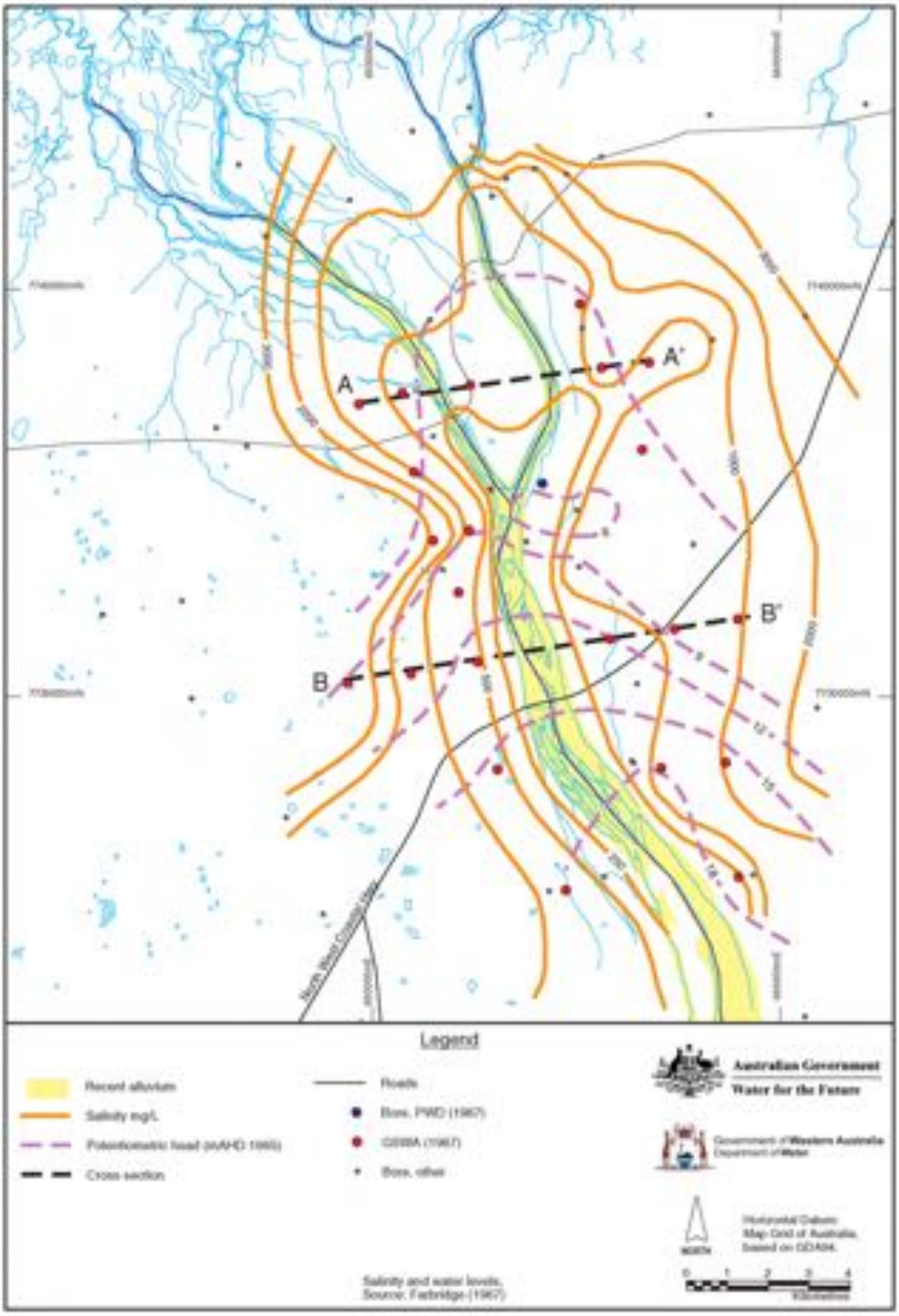


Figure 43: Turner River potentiometric surface and salinity

(1986–2005) of 29 GL. During the 20-year record, there were nine years in which the volume of flow over a four-month period exceeded the mean annual volume of 29 GL. If river-flow events of greater magnitude than the annual mean are considered to be significant recharge events, then the Lower Turner River alluvium receives significant recharge in approximately one out of every two years.

The longest number of consecutive months during which no flow was recorded at Pincunah gauging station has been 30 months. Over the 20-year record, there has been a total of four years in which zero flow was measured. This may indicate that in one out of every five years, there is no flow in the Turner River. There were seven years in which the maximum-recorded annual flow was less than 10 per cent of the mean annual flow. This indicates that during one out of every three years, the total annual flow to the Lower Turner River alluvial aquifer is very low.

Farbridge (1966) estimated recharge of 0.7 GL/yr based on rising water levels and a storage coefficient of 0.02. It was estimated that this volume of water could be extracted from the aquifer over a three-year period before the next recharge event.

Discharge

Farbridge (1966) estimated discharge of 0.3 GL/yr from falling aquifer levels and a storage coefficient of 0.02. Groundwater abstraction over the same period of time was estimated to be 0.2 GL/yr. The total discharge from the system was 0.5 GL/yr, which does not include an estimate of evapotranspiration.

Throughflow

Farbridge (1967) estimated a throughflow of 0.1 GL/yr from a hydraulic conductivity of 4 m/day and a saturated aquifer thickness of 9 m.

Groundwater quality

A high-salinity zone exists in the shallow alluvium as a result of salts leaching from the unsaturated zone during fluctuations in the watertable. This is consistent with shallow salinity occurrence in the Yule River and De Grey River alluvium. Isohalines developed from water quality sampling in 1965 are shown in Figure 43. The isohalines show an elongated section of quality fresh water that suggests recharge from the active river channel.

Ecosystems

The subregionally significant wetlands in the Lower Turner River area are associated with permanent and semi-permanent pools, such as the Moorambine Pool and other unnamed pools (Geoscience Australia 2003).

Resource development

Farbridge (1966) calculated an aquifer recharge of 0.7 GL/yr. This volume was considered to be aquifer system’s potential yield that could be safely withdrawn over a three-year period. It was estimated that recharge events occurred once every three years. Production in 1967 was about 0.3 GL/yr and it was concluded that production could not be increased because of a potential risk of high salinity. It was also noted that such a risk could be reduced by increasing the distance between bores – but that option has not been investigated.

The Turner River alluvium might have the potential to be used as a brackish ‘fit for purpose’ water supply. One option that requires further assessment might be to use the brackish water as a supply source for desalination.

Further work

Existing information on the alluvial aquifer’s geology and hydrogeology should be compiled to develop a geological model. The development of a geological model would help to calculate fresh versus brackish water volumes.

It is recommended that drilling investigations be conducted to determine the characteristics and extent of the alluvial aquifer system. Exploration drilling is required to investigate the aquifer’s thickness, particularly upstream of the original borefield site. The drilling program should also include test pumping.

The investigation work should also include surface geophysical surveys, down-hole geophysical logging, water chemistry testing, elevation surveys and monitoring.

Another option, before investigative drilling and test pumping, would be to use time (or frequency) domain electromagnetic (TDEM) methods to delineate zones of fresh and brackish water. The geophysics could be calibrated from sampling the old Public Works Department bores, if present. The TDEM survey could also be run with a gravity survey to give estimates of alluvial thickness. The information would help develop the geological model and guide any future drilling investigations.

The investigative work should be supported with comprehensive reporting that identifies gaps in current knowledge and defines the potential for developing a wellfield along the Turner River.

It is also recommended that automatic loggers be installed in suitable Public Works Department bores to support any future modelling endeavour. At present, there are no bores with a time series of water-level measurements in the Lower Turner River area. Until water levels are collected, the calibration of a numerical groundwater model is problematic.

A gauging station should be established upstream of the North West Coastal Highway. The current gauging station located at Pincunah is 90 km upstream of the Lower Turner River alluvial aquifer system. Future correlation of stream flow at Pincunah to any new monitoring record in the Lower Turner River area would be tenuous.

6 Existing Onslow water supply

6.1 Demand centre

The town of Onslow is located on the Pilbara coast approximately 1400 km north of Perth and approximately 200 km south-west of Karratha. Onslow is a regional support centre for the offshore oil and gas industries. Other industries are tourism, pastoralism, fishing and salt mining. In 2007 the population was 594 (ECS 2007). Water for the Onslow Water supply Scheme is supplied from the Water Corporation borefield on the Cane River, located approximately 30 km east of the town (Figure 1).

6.1.1 Development

Current industrial development at Onslow is limited to a light industry facility at Beadon Creek (2 km east of the town centre) and a solar salt project located south-west of the town. Beadon Creek is also a small port facility that provides support for the offshore oil industry and the local fishing industry. The Onslow Salt Project is located 10 km south of the town and began harvesting salt in 2001.

The Department of Industry and Resources commissioned Worley Parsons to study the potential effects of the expansion of the Onslow Strategic Industrial Area (SIA). Worley Parsons (2005) reported that BHP Billiton intended to complete pre-feasibility studies for an onshore liquefied natural gas (LNG) plant and export facilities south of the Onslow town site. The plant will be supplied initially by the Scarborough gas field approximately 280 km north-west of Onslow.

Potential new development would be related to the expansion of support facilities for the oil and gas industries and downstream processing. Downstream processing industries may be developed from opportunities created by the BHP Billiton LNG processing plant.

6.1.2 Water supply

The current groundwater licence issued to the Water Corporation is for an allocation of 0.350 GL/yr from the Cane River borefield. Maximum annual production from the borefield for the past 20 years has been about 0.340 GL, although the average annual production during this time has been about 0.270 GL.

6.1.3 Water consumption

Figure 7 shows annual consumption from the Onslow groundwater supply for the years 1995–2005. The average consumption from the scheme during this time was about 0.230 GL/yr. Commercial, industrial, mining and other uses make up about 46 per cent of the distribution, while residential supplies account for about 54 per cent.

From 1994–98, the average loss due to inefficiency was approximately 20 per cent. Loss from the supply scheme from 1995–2005 was estimated to be about 15 per cent. It is assumed that losses can be explained by inaccurate metres or the difference in calculations made for annual production and annual distribution (Water Corporation 1999).

Onslow's current population is about 594 people: annual domestic consumption is about 200 kL/person/year, or about 548 litres/person/day (ECS 2007).

6.1.4 Future water demand

In 1999, annual abstraction was expected to increase as a result of the solar salt project's construction, domestic growth and tourism development (Water Corporation 1999). The Water Corporation anticipated three per cent growth in Onslow's demand from 2000–05, which equated to a borefield requirement of 0.295 GL/yr. Assuming no large-scale industrial development, it was concluded that the 0.350 GL/yr allocation for the Cane River borefield would be adequate to meet Onslow's water requirements. Consumption levels since 1999 have not increased to the anticipated level and have remained at an average of 0.230 GL/yr.

Increased water demand in Onslow is anticipated with the proposed development of the BHP Billiton LNG project, however its water demands will be met with desalination. If gas processing facilities develop in the Onslow area, there would also be potential for petrochemical and/or fertiliser development.

The light industries in the Onslow Strategic Industrial Area (SIA) may expand as the offshore oil and gas industries continue to develop and a review of the regional port infrastructure development is being carried out by the former Department of Industry and Resources. The report will provide the additional information necessary to refine Onslow's future water requirements.

Current water demand is met by supply from the Cane River Borefield. Additional water requirements in the next few years – associated with the development of the LNG plant – will be met with desalination. There is also the potential for moderate increases in water demand associated with the expansion of the light industry in support of the oil and gas industries, and increased development of the petrochemical industry.

The Onslow groundwater supply is at a low to moderate risk in relation to meeting water requirements in the near future. As the oil and gas industries develop, the risk of being unable to meet demand will increase and a new water supply may need to be developed to satisfy any new demands not met with desalination.

It is recommended that a new groundwater supply of 1 to 3 GL be identified and assessed to meet future demands. If the early stages of investigation and assessment can be completed in the next few years, the supply may be available to meet future demands.

6.2 Existing groundwater supply

6.2.1 The Lower Cane River alluvium

The Cane River is located 30 km east of Onslow and crosses the North West Coastal Highway approximately 60 km inland from its mouth. It drains in a north-west to northerly direction over a gently sloping floodplain to the Indian Ocean.

A borefield was established in 1955 on the north side of the river course, and up until 1988 operated with an annual production of less than 0.25 GL/yr. The borefield was expanded to the southern side of the river during 1988 (Martin 1989) in response to increased water demands from Onslow. Further investigation of the Cane River alluvium was conducted during 1996 and 1997 (Martin 1996; Rockwater 1997; Rockwater 1998). The current borefield comprises 19 production bores and 15 monitoring bores (Figure 44), with a current groundwater licence allocation of 0.35 GL/yr. Average annual abstraction from 1995–2005 was about 0.23 GL/yr.

Although the supply potential in the Cane River area is limited, it is adequate to meet Onslow's current demands. If demand increases, there may be the potential to increase supply by developing alluvial sediments upstream of the current borefield. The option of expanding the current supply on the Cane River is likely to be more cost-effective than developing the Robe River alluvium.

Geology

The Lower Cane River Borefield is underlain by about 25 m of Quaternary alluvium that unconformably overlies the Tertiary Trealla Limestone. Underlying the Tertiary-aged marine sediments are Mesozoic to older marine and non-marine sedimentary rocks of the Carnarvon Basin (Martin 1989).

<u>Mesozoic/Cainozoic</u>

The units underlying the Quaternary alluvial cover are poorly understood, as previous drilling was typically ceased in the Tertiary Trealla Limestone. Deeper drilling would likely intercept Carnarvon Basin sediments. Closer to the North West Coastal Highway, the alluvial sediments are only 1 to 2 m thick and lie unconformably on Cretaceous Birdrong Sandstone and the Nanutarra Formation (Yesertener & Prangley 1996).

<u>Quaternary</u>

The alluvium consists of poorly sorted silt, sand and gravel up to 25 m thick, with lenses of sand and gravel limited to about 5 m thick (Martin, 1989). The limestone may have alternating hard and soft layers and becomes harder with depth. Figure 45 shows cross-sections drawn across and along the Cane River alluvial channel.

Away from the areas of active sedimentation are isolated occurrences of colluvium that are a few metres in depth and consist of silt, sand and clay. The remainder of the area is covered with clay pans and sand dunes.

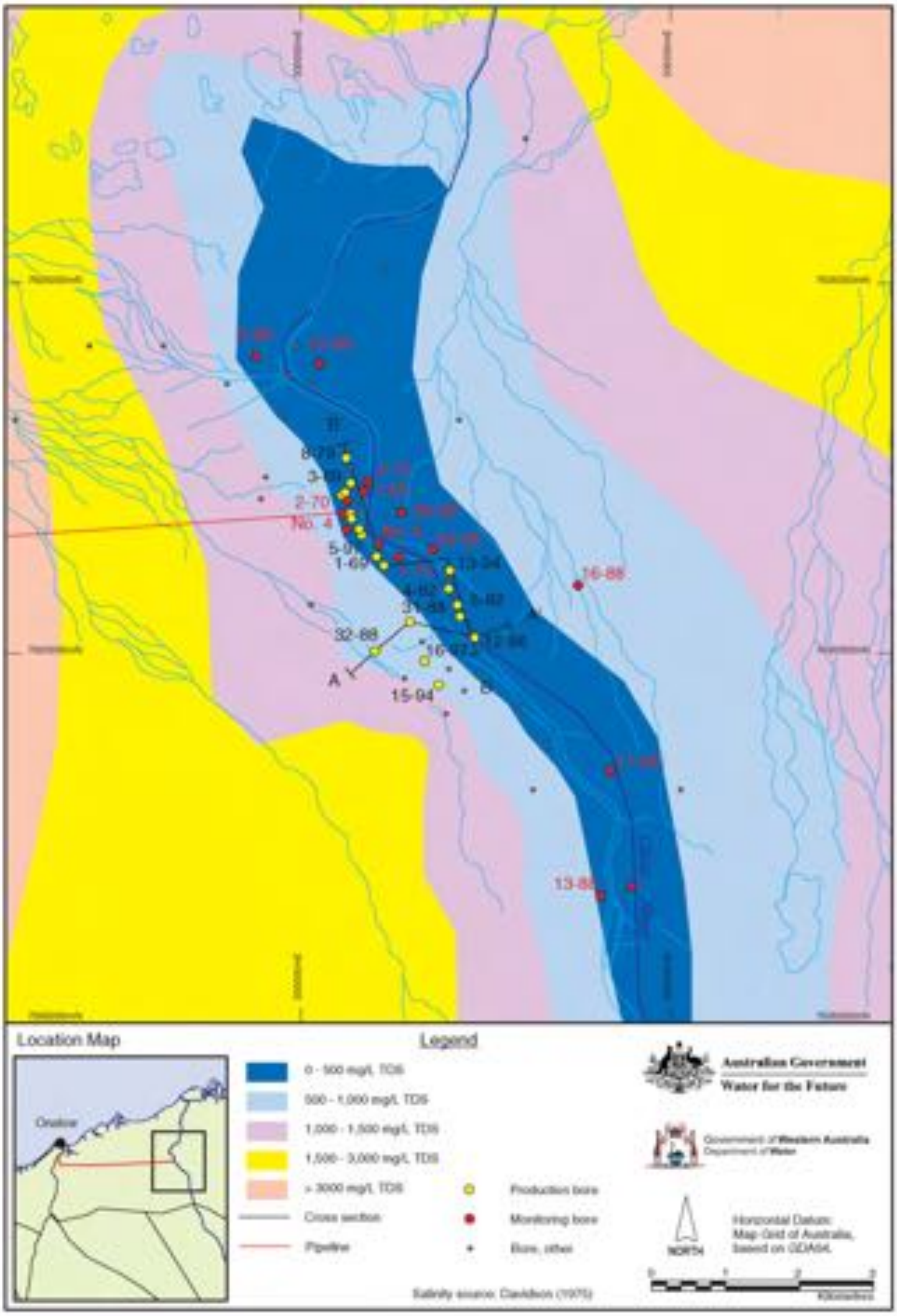


Figure 44: Cane River borefield

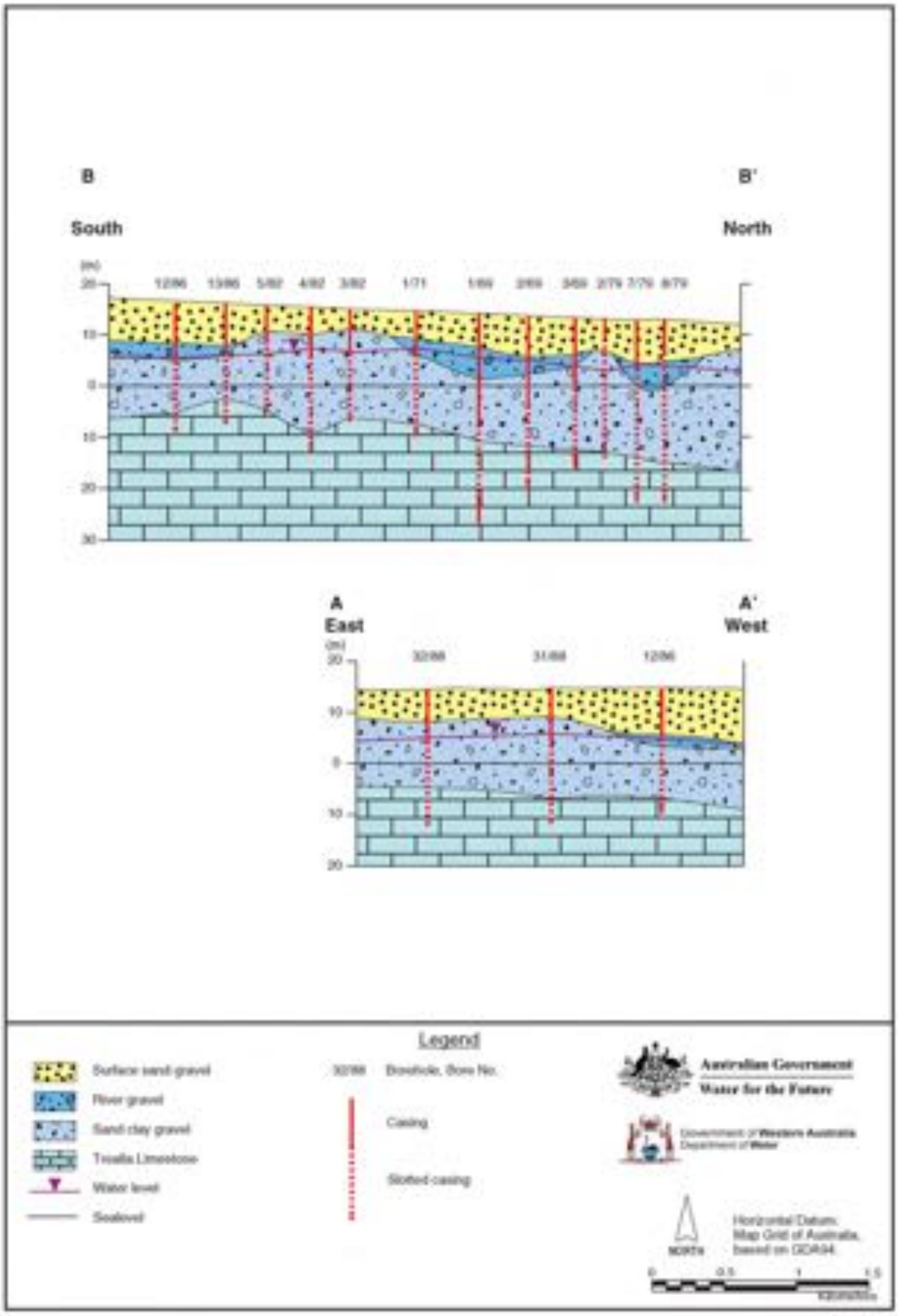


Figure 45: Cane River geological cross-section

Hydrogeology

There are two aquifers present near the current Cane River borefield area: the heterogeneous unconfined aquifer formed by the alluvial sediments, and the underlying Trealla Limestone aquifer. Both aquifers are hydraulically connected.

Aquifers

The transmissive portions of the alluvial aquifer occur as narrow channel deposits sub-parallel to the current river. They have a saturated thickness that ranges from about 7 m in the north to 18 m in the south. The average thickness is about 10 m throughout the area covered by the current borefield. There is generally poor correlation between bore yields, strata and the type of shallow deposit screened (Martin 1989); however, lower yields tend to occur where the sediments are clayey or well cemented. Moderate yields are possible where the sediments alternate between hard and soft layers of sandy alluvium. Yields from investigation bores ranged from trace amounts to 170 kL/day (Martin 1989). Due to the lateral variation in lithology, bore yields may change dramatically with only short distances.

Significant yields are also reported from the contact between the alluvium and the underlying Trealla Limestone. The limestone produces variable yields from bedding-plane partings, fractures and joints. The highest yielding portions of the underlying limestone are associated with alternating hard and soft layers (Martin 1989).

Aquifer testing and hydraulic parameters

No formal pumping tests to determine aquifer parameters are detailed in the Cane River borefield literature. Most reporting for pumping has focused on determining the aquifer's safest yields – in terms of minimising drawdown of the watertable. Yields from bores installed in 1988 were determined through dual-tube airlift measurements obtained during RC drilling and appear to be fairly indicative of expected pumping rates.

Rainfall and river flow

The closest rainfall station (5016) with a complete series of recorded data is located 30 km to the west at the Onslow town site. Onslow's annual rainfall is shown in Figure 46. The complete rainfall record at Onslow began in 1907 and the long-term annual mean is 230 mm. Rainfall records in the Pilbara vary significantly over short distances, which makes it difficult to correlate rainfall to flow in the Cane River. Monthly flow from the Toolunga gauging station and monthly rainfall patterns from Onslow do not have a direct correlation. Instead, annual flows and annual rainfall records do correlate between the two records in a broad sense.

Toolunga gauging station (707005) is located 500 m downstream of the North West Coastal Highway crossing and about 40 km upstream of the Cane River borefield. Annual flow records for the Toolunga gauging station are shown in Figure 46. The gauging station has been operating since 1987. The long-term mean annual flow

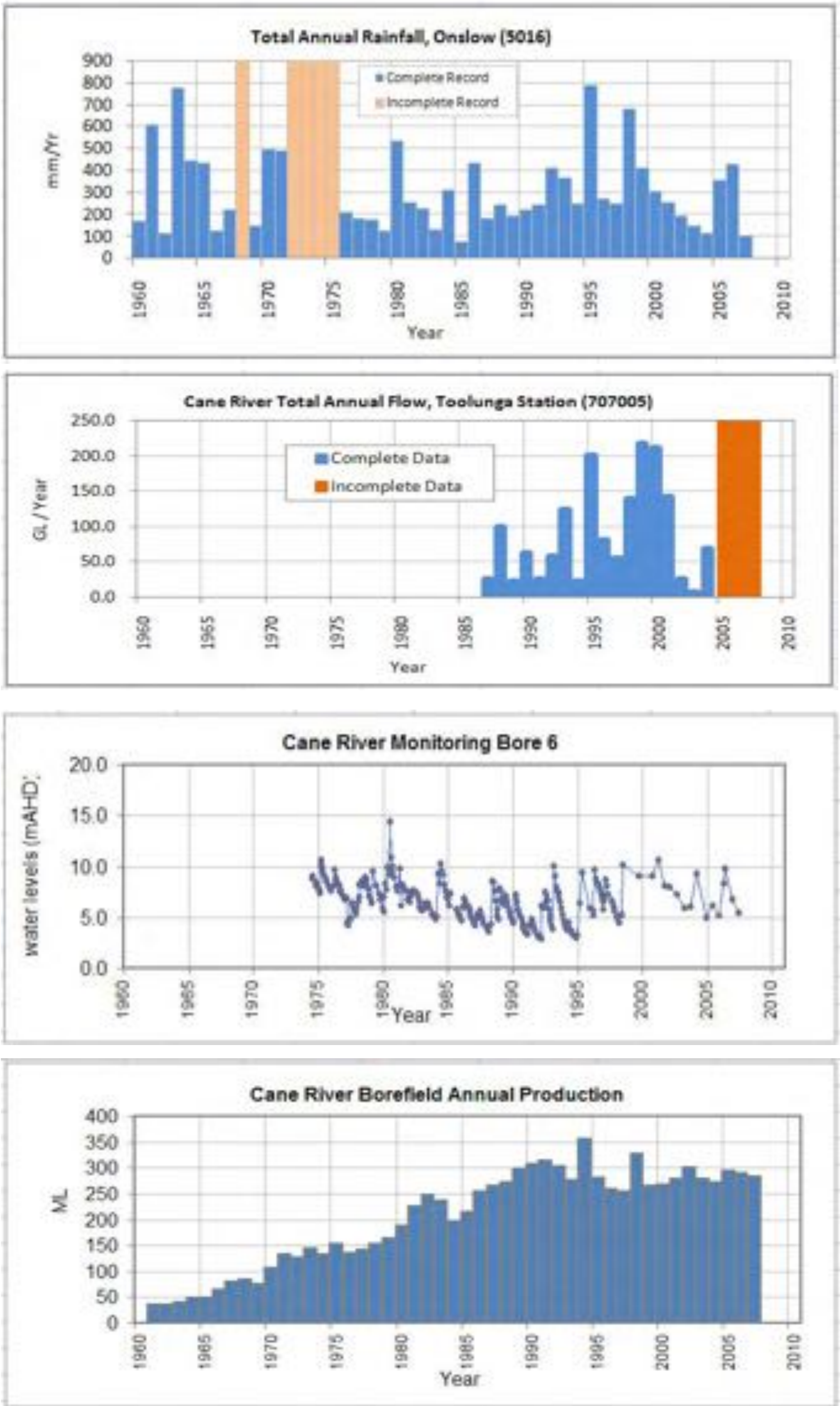


Figure 46: Cane River hydrographs and borefield production

over the 18 years recorded is 88 GL. During that time, there were six years in which the volume of flow over a four-month period exceeded the mean annual volume of 88 GL.

The longest number of consecutive months during which no flow was recorded at the Toolunga gauging station has been 10 months. Over the 18-year period, there were no years in which zero flow was recorded. There was one year in which the maximum-recorded annual flow was less than 10 per cent of the mean annual flow.

Aquifer recharge, discharge and storage

Recharge to the alluvium is predominantly from river flooding. Rainfall recharge occurs to a lesser extent through direct infiltration. The limestone aquifer is recharged by infiltration from the overlying alluvial sediments. Recharge estimates of the Cane River aquifer have not been developed. Estimates of 'available yield' have been made by Tomlinson (1994), which is 0.1 GL/yr/km of the Cane River aquifer.

The main discharges from the aquifer are downstream to the Indian Ocean and to the tidal flats. Abstraction makes a large contribution to discharge and typically accounts for 0.23 GL/yr. Losses to evapotranspiration are variable and probably decrease downstream (to the north) due to increasing depth of the watertable.

Studies of the Cane River alluvium have to date not determined any recharge or storage estimates for the alluvial aquifer or the underlying limestone aquifer.

Borefield

The Cane River borefield was established in 1955 and consists of 19 production bores and 15 monitoring bores (Figure 44). The bores are distributed along the east and west sides of the Cane River over a distance of approximately 3 km. The northern half of the borefield is located on the west side of the river. The southern half of the borefield is distributed along both the west and east sides of the river.

The most recent exploratory drilling was conducted in 1997. The licensed allocation is 0.35 GL/yr for the borefield, which draws from both the Cane River alluvium and Trealla Limestone aquifers. Annual production since 1960 is shown in Figure 46. Production over the past 20 years has averaged 0.28 GL.

Water that is unaccounted for in the reporting period 1999 to 2004 is 15 per cent for three of the last five years. The reason for the 15 per cent loss between the borefield and the distribution points is unknown, but the Water Corporation is investigating.

Monitoring

The current monitoring program includes 19 production bores and 15 monitoring bores, shown in Figure 44. Monitoring of production bores includes water level, abstraction volume, conductivity, temperature and major ion components. Monitoring of observation bores includes water level only.

Management criteria

Tomlinson (1994) estimated the Cane River aquifer's sustainable yield at about 0.3 GL/yr for the wellfield, which traverses a 3 km stretch of the river. The available yield from the Cane River aquifer is about 0.1 GL/yr for each kilometre of river.

The Water Corporation refers to this relationship as the 'guideline safe yield'. It is used to gauge the potential impacts on water levels and salinity that may result from groundwater abstraction. Abstraction is distributed evenly over the borefield to minimise salinity impacts. In most cases, the guideline criterion of limiting abstraction to 0.1 GL per kilometre of river had not been exceeded. There was a 1 km stretch between bores 1/69 and 5/82 where the criterion had been exceeded since 1999. Production bores are periodically taken offline when salinities are found to increase. There have been no observable impacts on water levels or salinity within the borefield that could be attributed to pumping.

Groundwater levels

The groundwater gradient is relatively shallow (1:700) and follows the direction of river flow from south to north. The slope of the land surface is even more shallow (1:1000) and consequently the depth to groundwater ranges from 6 m in the south to 15 m in the north (Martin 1989). Small pools occur in the riverbed and probably represent places where the watertable intersects the surface.

Periods of increased flow volume or frequency in the Cane River correlate to rising or sustained groundwater levels. Periods of increased flow at Toolunga station do have a broad correlation to wetter periods recorded at Onslow. The dominant driver of increases in water levels in the Cane River borefield is river flow.

The rest water levels in pumping and observation bores appear to have dropped gradually from 1990 to 1994. This is due to a low incidence of large river flows as recorded at Toolunga station during this time. From 1990 to 1994, the rainfall record does show annual rainfall is generally lower than the long-term average.

From 1994 to 1999, there seems to be a general rise in rest water levels in pumping and monitoring bores. This can again be attributed to the stream-flow record. The period from 1995 to 1999 shows a general increase in the incidence of large river flows, beginning with Cyclone Bobby in 1995 and Cyclone Vance in 1999. Sharp rises in water levels are clearly seen as a result of the two cyclone events. Rainfall at Onslow during this period is generally higher and approaches the long-term mean. During 1995 and 1999, the annual total rainfall exceeds the mean by more than 200 per cent.

Production-bore rest water levels are generally stable or show a slight amount of decline from 1999 to 2004. Monitoring bores show a similar trend. The water levels during this period were maintained by more frequent river-flow events between 1999 and 2001.

River flows in 2002 and 2003 were very low – a period that also coincides with below-average rainfall at Onslow. The lower incidence of flow events appears to have only a limited impact on rest water levels in production and monitoring bores. Rest water levels appear to be stable, although there is a slight downward trend since 2001. Pumping water levels during this period drop significantly with time and show an increased incidence of bores not pumping. This could be attributed to physical problems with the bores that affect pumping efficiency, such as screen encrustation or bore failure.

Groundwater quality

Salinity trends across the borefield are highly variable. In general, salinity increases can be associated with high river-flow events. Commander, Martin and Doherty (2004) have reported the phenomenon, drawing from a number of similar incidences in the Pilbara and Gascoyne regions. Groundwater and river pool salinities were found to be above the normal recorded levels following large-flow events and/or during exceptionally wet years. This is evident in the Cane River borefield, where salinity peaked in some bores between 1999 and 2001. This period is clearly marked on the Toolunga gauging station record, with Cyclone Vance in 1999 followed by two years of high annual flow volume.

Salinity increases can also be associated with periods of high monthly abstraction. In such cases, pumping is reduced in the affected bores. Increases in salinity have also been reported in bores that are not being pumped.

Not all bores experienced peaks in salinity related to high-flow events or over-pumping. The spatial variation in bore salinity trends cannot be easily explained. The variation may be related to the drawing of water from different aquifer layers, complex fracture networks and variable fracture development.

In general, there does not appear to be a definable progression of salinity rise across the borefield. The encroachment of salinity into the borefield is mitigated by the even distribution of abstraction, as well as by limiting abstraction to the ‘guideline safe yield’ of 0.1 GL/yr for each kilometre of river length.

Chemical analysis indicates that barium, arsenic and iron levels exceed 2004 National Health and Medical Research Council (NHMRC) guidelines in several bores. Composite sampling of raw water indicates that elevated components are mitigated through dilution with compliant bores. Hardness in excess of the guidelines is mitigated through water treatment. Rising salinity trends do not exceed guideline limits. Microbiological sampling has indicated that results are below the guidelines and treatment has proven to be effective. In general, the issues with water quality are managed appropriately and mitigated through standard operational procedures.

Development options

A frequency domain electromagnetic survey was conducted in 1994 and sites identified as having the best potential were drilled during 1997. At that time, investigation bores were drilled along the east and west sides of the Cane River to the south of the current borefield. It was concluded that future expansion of the borefield to the south would be appropriate: it is the only area where the alluvium is thicker and significant pumping capacities may occur on both sides of the river (Martin 1996). The Water Corporation is considering expanding the current borefield to the south (downstream) of the current site.

Favourable results were also obtained from exploration drilling to the east of the current borefield in the sub-parallel alluvial channel. Because this area showed lower salinity, it was considered a potential area for future investigations. To date, no additional investigative drilling has been conducted in this area.

Observation of historic water-level changes under various pumping regimes has indicated that expansion of the borefield to the north is not viable (Martin 1996).

Restrictions to development

Expansion of the current borefield may be restricted by access during the wet season. Flooding isolates the area during large flow events and more than 50 per cent of the area is inaccessible.

Management issues

Historic measurements of water levels and changes in the pumping regime have indicated that uneven distribution of pumping over the borefield may cause declines in water levels. The borefield's future operations should be conducted so that abstraction is spread evenly throughout the borefield to reduce the effects of concentrated areas of pumping. During dry periods, excessive pumping may also result in saline encroachment and would require ongoing monitoring.

Potential contamination is covered in the *Cane River Water Reserve, Water Source Protection Plan* (WRC 1999). The issues related to potential contamination are related to diesel storage, livestock access, herbicide use and fauna trapped in production bore annuli. The Department of Water is currently reviewing the water source protection plan.

Ecosystems

Small pools occur along the bed of the Cane River, approximately 8 km upstream of the current borefield. The pools probably represent incised portions of the river channel that intersect the watertable. There are no reported concerns about ecosystems directly upstream or downstream of the current borefield.

Further work

Drilling investigations are required if the borefield is to be expanded to the south or downstream of the current site. The installation of dedicated loggers in priority bores would increase understanding of the river flow and aquifer recharge mechanisms. Considering the distance between the borefield and the Toolunga gauging station, a method by which river flow could be measured closer to the borefield would support future modelling efforts. The running of time or frequency domain aerial geophysical surveys would improve the mapping of zones of fresh water and brackish water in the aquifer. The survey would also provide improved mapping of the alluvial thickness and thus support future modelling efforts.

6.3 Potential groundwater supplies

6.3.1 Lower Robe River alluvium

The Robe River alluvium is located 80 km east of Onslow and about 60 km north-east of the present Cane River borefield (Figure 2). The alluvial sediments in the study area extend 15 km along the river, downstream of where the North West Coastal Highway crosses the Robe River.

The alluvium was deposited on the Ashburton plain where the Robe River discharges north-west off the scarp near Yarraloola Homestead. The alluvial channel is approximately 15 km in length and varies in width from 3 to 6 km.

BHP undertook the earliest groundwater exploration drilling upstream of the Ashburton plain in 1965 – on discovery of the Robe River channel iron deposits. Alluvium was recognised as a potential source of low salinity groundwater. A significant fresh groundwater occurrence was subsequently recognised during reconnaissance of the Ashburton plain by Davidson (1975), and subsequent drilling confirmed the low salinity and transmissive nature of the sediments north-west of Yarraloola Homestead.

The Geological Survey of Western Australia (GSWA) embarked on the most comprehensive investigation of the Lower Robe River alluvium in 1983 and 1984 (Commander 1988, 1994b). Twenty-four exploration bores were drilled and constructed at 22 sites to delineate the aquifer (Figure 47). Four pumping tests were conducted and the completed bores were geophysically logged.

More recent investigations (2005) have been conducted for mine-site supplies in the Lower Robe River in the vicinity of the homestead.

Geology

The basement rocks comprise the Proterozoic Ashburton Basin, which outcrops in low hills on either side of the Robe River. The Ashburton Basin is overlain by up to 200 m of shallow north-westerly dipping Cretaceous sediments of the Carnarvon Basin. The Carnarvon Basin sediments are overlain by recent alluvium.

The Yarraloola Conglomerate is the basal conglomerate facies of the Birdrong Sandstone, which is the lower of the Carnarvon Basin sediments. The Yarraloola Conglomerate and the Birdrong Sandstone grade laterally into the Nanutarra Formation, which is not present in the Lower Robe River area. The Yarraloola Conglomerate underlies the alluvium, Trealla Limestone and Cretaceous sediments

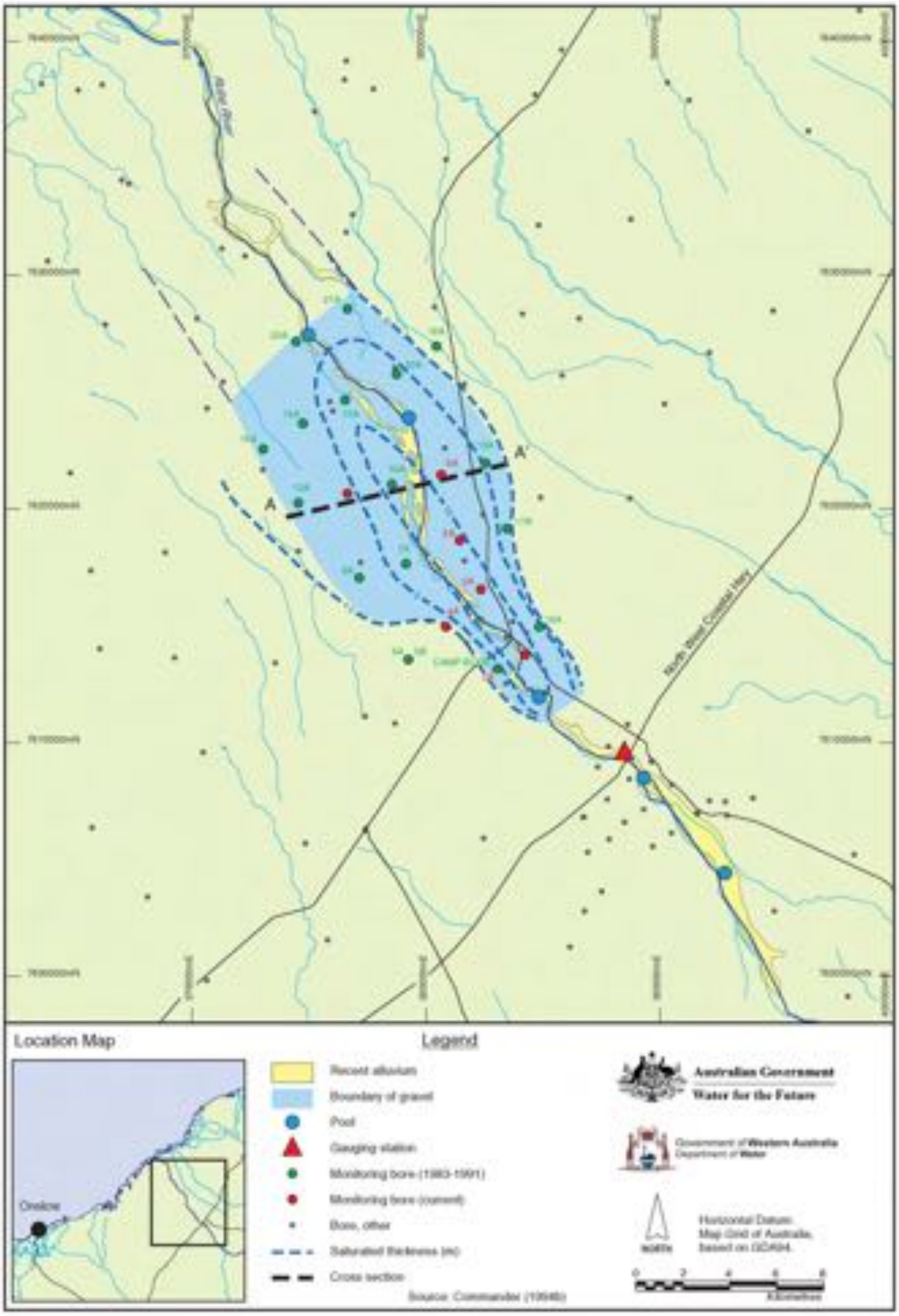


Figure 47: Lower Robe River bores and saturated aquifer thickness

and has an average thickness in this area of 3 to 22 m (Commander 1994b). The Yarraloola Conglomerate can be found in outcrops along the low hills where the Robe River enters the coastal plain.

Overlying the Yarraloola Conglomerate are the clays and siltstone of either the Muderong Shale or possibly the Windalia Radiolarite (Commander 1994b). Up to 8 m of the unit are present in this area.

Unconformably overlying the Muderong Shale is the Cretaceous-aged Toolunga Calcilutite, which is present as clay, claystone or marl.

Unconformably overlying the Cretaceous sediments is the Late Eocene-aged Robe Pisolite, which is found in the subsurface along the present course of the Robe River.

The Trealla Limestone is present beneath the subsurface of the area and ranges in thickness from a maximum of 17 m to about 10 m where it has been eroded away. The limestone unconformably overlies the older Tertiary sediments and is unconformably overlain by the Quaternary to recent-aged alluvial sediments. The limestone is similar in lithology to the Millstream Dolomite in the Upper Fortescue River (Commander 1994b).

Toward the inland area of the Lower Robe River, the Peedamullah shelf sediments are absent and the Cretaceous Carnarvon Basin sediments directly overlie the Proterozoic Ashburton Basin. Quaternary to recent alluvial sediments of up to 30 m thick overlie both the Cretaceous and Proterozoic rocks.

Throughout the floodplain, the alluvial sediments are mainly overbank deposits of clay and silt. Gravels are found in outcrops along the riverbed and occur in the subsurface for up to 3 km away from the river channel, where they are overlain by overbank deposits. The gravel has a maximum thickness of about 15 m in the vicinity of the Yarraloola Homestead. The gravel in general thins laterally away from the river and in a downstream direction, where it ultimately becomes interbedded with clay and silt. Calcrete has also been formed in the alluvial sediments and is typically found close to and at depths of 5 m below the watertable (Commander 1994b). Figure 47 shows the saturated thickness contours of the alluvial gravel aquifer. Figure 48 shows a cross-section through the alluvial aquifer system.

Hydrogeology

The hydrogeology of the Lower Robe River area is based on a report by Commander (1994b). The report was informed by the drilling and pump-testing program completed in 1983 by the GSWA. Numerical modelling was done as part of the Commander (1994b) assessment of the alluvial aquifer.

The major aquifer in the Lower Robe River is the alluvial bed load comprised of tabular banded iron formation cobbles. The Tertiary Trealla Limestone, Cretaceous Carnarvon Basin sediments and Proterozoic bedrock that underlie the alluvial aquifer

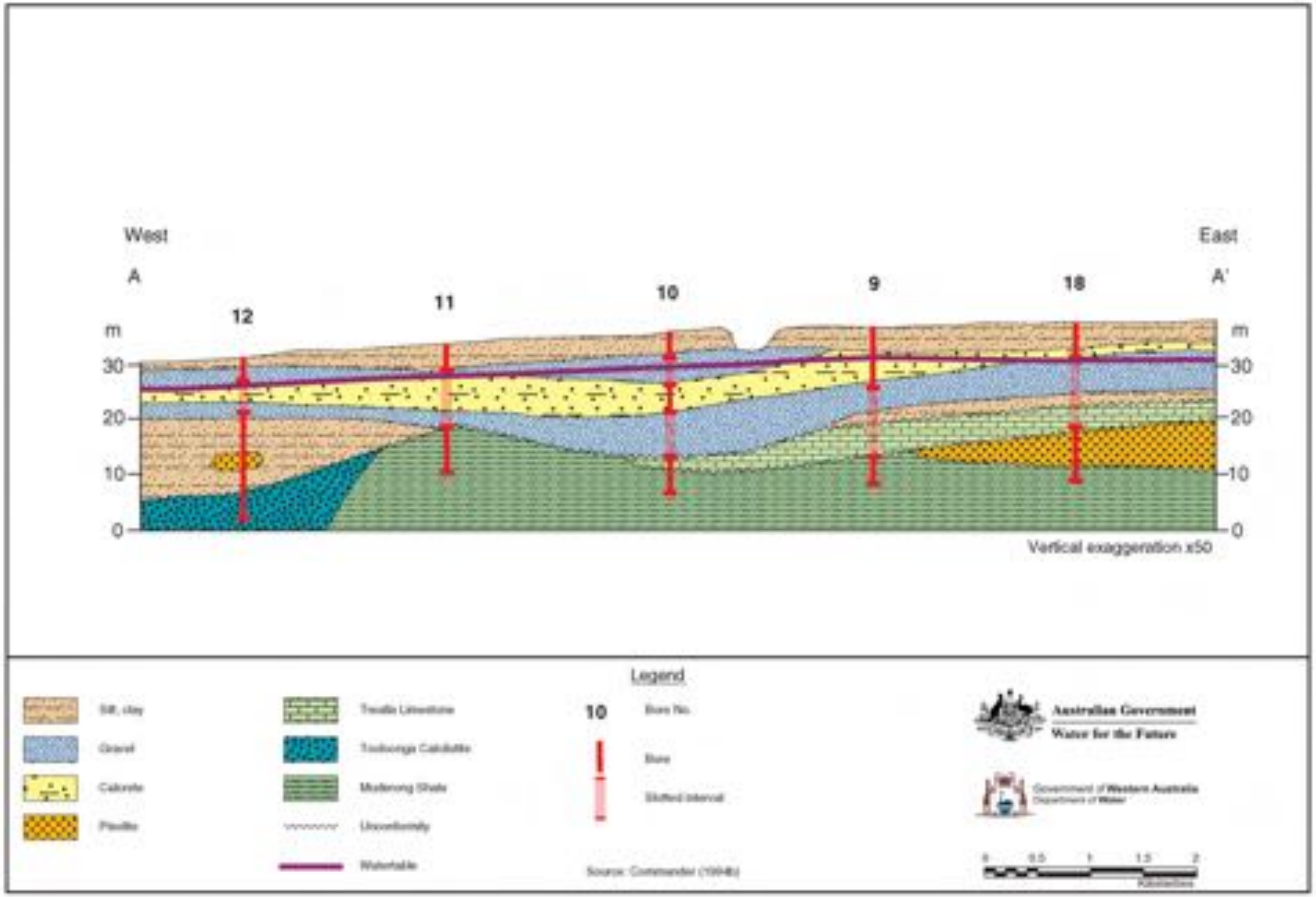


Figure 48: Lower Robe River cross-section A-A’

are relatively impermeable. In this area the Robe Pisolite is considered to have low permeability. Some downward leakage occurs into the Yarraloola Conglomerate from the overlying alluvial aquifer, but it is considered to be low.

Alluvial sediments on the Robe River are approximately 3 to 6 km wide and have a reported maximum thickness of up to 30 m. The alluvium consists of sandy, silty and clayey gravels with thin, interbedded layers of clean gravel. The gravel layers vary greatly in thickness to a maximum of 10 m. Calcrete is also present in the alluvial gravels and typically occurs at or up to 5 m below the watertable (Commander 1994b).

The alluvial sediments lie unconformably over the Trealla Limestone, which is typically a confining bed, but may be considered an aquifer on a local scale when fissures are present. Investigation drilling indicates that the Trealla Limestone is up to 15 m thick (Commander 1994b). Test pumping of a bore completed in the Trealla Limestone resulted in a maximum pumping yield of 980 kL/day and an indicated hydraulic conductivity of 200 m/day (Commander 1994b). The yields and permeability at this site are similar to those in the gravel aquifer in the alluvial sediments. It can be concluded that the Trealla Limestone is generally not an aquifer in this location, but has the potential for high yields in situations where secondary porosity has been developed.

Both the Birdrong Sandstone and the basal gravel unit referred to as the Yarraloola Conglomerate are considered to be an aquifer throughout the Carnarvon Basin. In the Lower Robe River area, however, the Yarraloola Conglomerate encountered in investigative drilling had low permeability and low bore yields where intersected below the alluvial aquifer (Commander 1994b). Salinity measurements were reported to be greater than 2000 mg/L from bores completed in the Yarraloola Conglomerate (Commander 1994b). Any recharge to the Yarraloola Conglomerate and Birdrong Sandstone in this area would be through the Robe River alluvium where the Robe River enters the coastal plain. Considering the low permeability, high salinity and small area of recharge, it is assumed that the recharge to the Yarraloola Conglomerate is very small.

Aquifer testing and hydraulic parameters

Test bores completed in the gravel zones of the alluvial aquifer were pumped at 980 to 1340 kL/day and transmissivities were derived that ranged from 1300 to 4900 m^2/day (Commander 1994b). Hydraulic conductivities were calculated for the gravel layers from test pumping. Conductivities of 150 m/day were estimated for cemented gravels and up to 400 m/day for clean gravels. The modelling of water-level rise versus distance from the river resulted in an estimate of 250 m/day, which agrees broadly with the pump-test results (Commander 1994).

Groundwater levels

The Department of Water currently monitors six bores in the Lower Robe River area. The bores have been monitored annually since 1983. Figure 49 shows hydrographs of bores monitored by the Department of Water.

Bore water levels are generally between 5 and 9 m below ground level and have fluctuated by 3 to 5 m over the 25-year monitoring record. Bores close to the Robe River (1A) can fluctuate by as much as 5 m annually due to recharge events. Even during high recharge events, there may still be as much as several metres of unsaturated alluvial gravel above the high water level.

River flow

Yarraloola gauging station is located where the Robe River crosses the North West Coastal Highway and is immediately upstream of the coastal alluvial aquifer. The gauging station record extends from 1973 to the present with a long-term mean annual flow (1973–2005) of 87 GL. During the 33-year period, there were 10 years in which the volume of flow over a four-month period exceeded the mean annual volume of 87GL.

The longest number of consecutive months during which no flow was recorded at Yarraloola gauging station has been 44 months – the longest duration of any of the Pilbara gauging stations. Over the 33-year record, there have been eight years in which zero flow was measured at Yarraloola gauging station. This indicates that for about one out of every four years, there is no flow in the Robe River at this site. There were 12 years during which the maximum-recorded annual flow was less than 10 per cent of the mean annual flow. This indicates that for one out of every three years, the total annual flow to the Lower Robe River alluvial aquifer is very low.

Recharge

Recharge was estimated by calculating the volume of aquifer storage change before and after the periods of river flow and by applying an estimated specific yield of 0.1. The estimates of recharge did not take into account the volume of throughflow draining out of the system during this time and is thus an underestimate. The estimated volume of recharge from a flood event in 1985 resulted in a recharge estimate of 10 GL. Recharge was also estimated to be 8 GL/yr from numerical modelling, which is in broad agreement with the recharge estimates from water-level rise (Commander 1994b).

Storage

Storage was calculated from the alluvial aquifer's volume and a specific yield of 0.1 was applied. For the Robe River alluvial aquifer, Commander (1994b) estimated the storage with a salinity of less than 1000 mg/L to be 70 GL. Annual change in storage was calculated for three years from 1983 to 1986. During the first year, flood events increased the storage by 16 GL, but over the next two years storage was depleted by

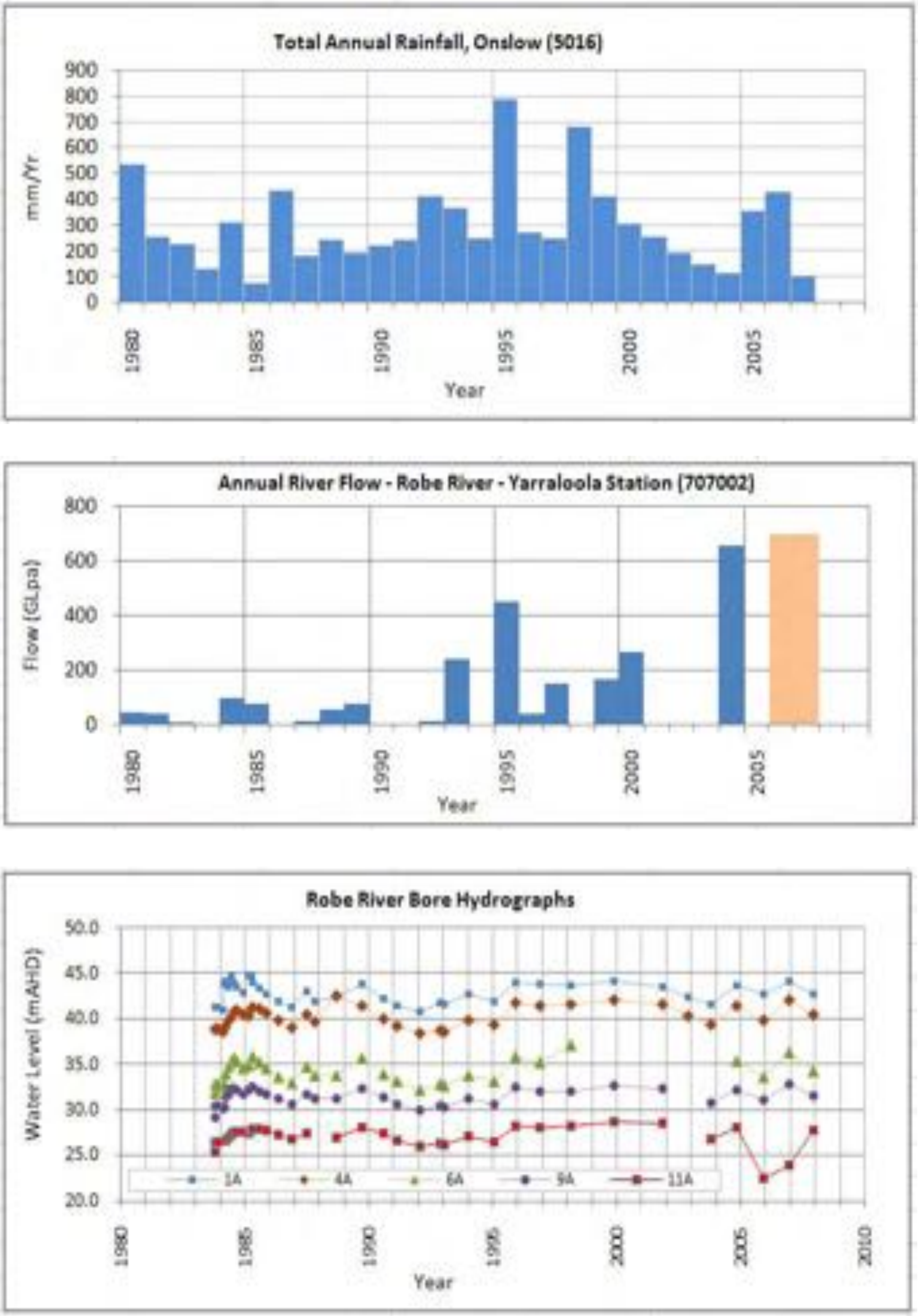


Figure 49: Robe River hydrographs

14 GL. The calculations show the dramatic changes in the alluvial aquifer's storage that flood events as well as subsequent drainage out of the system can cause.

Throughflow

Groundwater flow is approximately parallel to the river. Throughflow was estimated from the watertable configuration in 1984 and was reported to range from 2.9 to 7.6 GL/yr (Commander 1994b). A throughflow of 5 GL/yr was also estimated from numerical modelling, which is in broad agreement with the empirical measurement.

Discharge

Discharge was estimated during a 12-month period (1985–86) when there was no recharge. The annual depletion in storage volume represents the discharge of the system and was estimated to be 12 GL, using a specific yield of 0.1 (Commander 1994b). The calculation represents the total outflow of the system and the loss of water through evapotranspiration.

The coverage of vegetation was estimated to extend over an area approximately 10 km long and 200 m wide. By assuming the transpiration of the vegetation is approximately 80 per cent of the pan evaporation rate, a total transpiration of 4 GL was estimated.

Water quality

Figure 50 shows the isohaline contours reported by Commander (1994b) from data in the mid 1980s. The groundwater salinity measurements in the alluvial gravels ranged from 454 mg/L close to the river and 1280 mg/L away from the river. It was also reported that salinity decreased with depth below the watertable and is probably due to the effects of evapotranspiration.

Ecosystems

There are no subregionally significant wetlands associated with the study area on the Lower Robe River. The ecosystems present in the study area are associated with semi-permanent pools along the river, as shown in Figure 47.

Resource development

The primary aquifer for possible development in the Lower Robe River area is the alluvial aquifer and the Trealla Limestone where secondary porosity occurs. There is sufficient volume and quality of water to supply a town or support local agriculture.

The area most suitable for abstraction is a 2 km strip that extends about 7 km along the Robe River between investigation bores 4A and 10A, shown in Figure 47. The aggregate saturated thickness of the gravel aquifer in this area is 5 m and the salinity ranges from 450 to 700 mg/L. Possible bore yields from the gravel horizons in the alluvium and the fractured portions of the Trealla Limestone may range from 1000 to 1300 kL/day (Commander, 1994b).

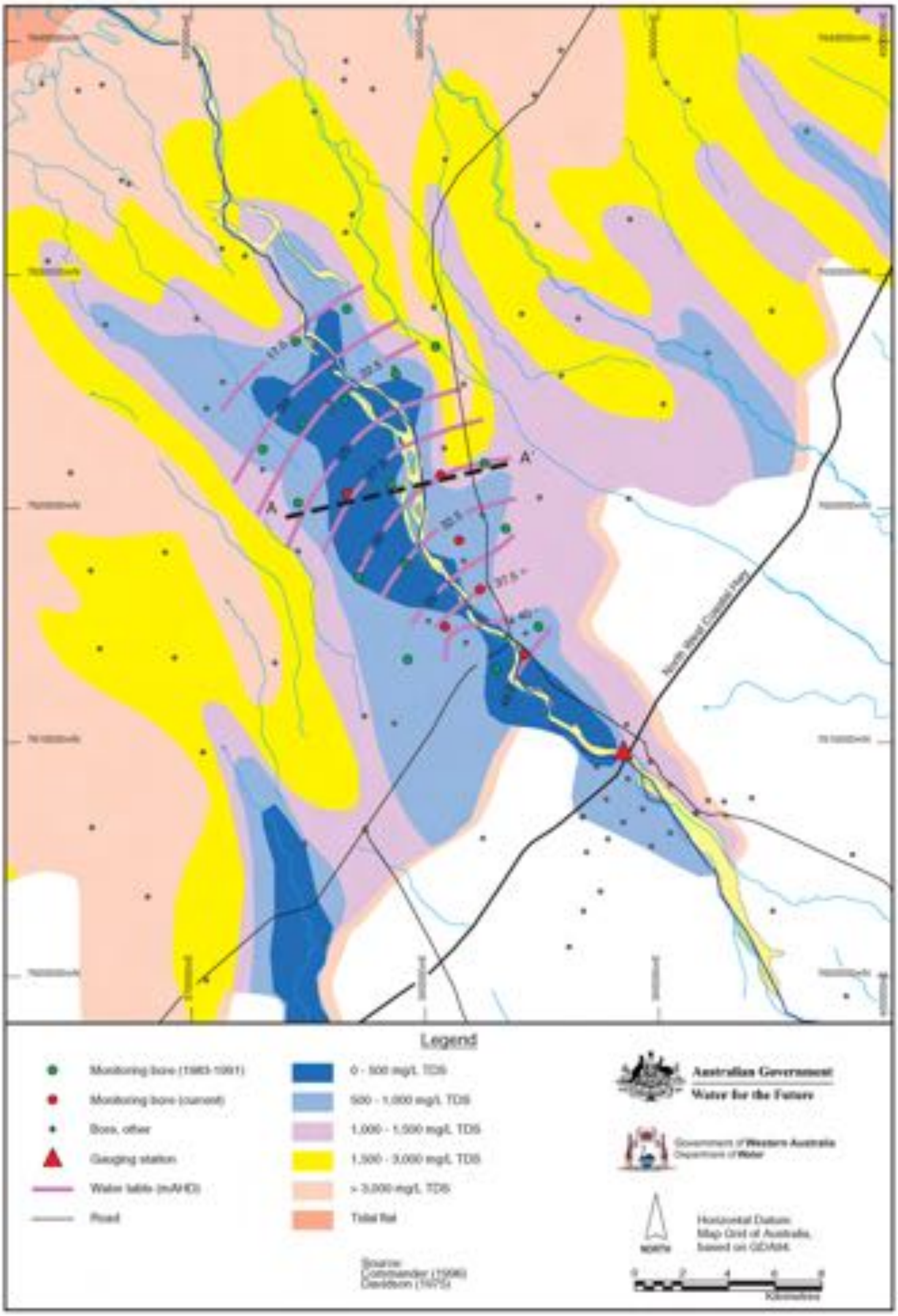


Figure 50: Robe River water levels and salinity

Recharge estimates based on decline in storage during a year with no river flow indicate that a reasonable upper-limit annual abstraction may be 10 GL. Of course this estimate does not consider the cultural, social and ecological water requirements of the area.

Restrictions to development

There are no known Aboriginal sites in the Lower Robe River alluvium (Forrest & Coleman 1996b).

Abstraction from the alluvial aquifer may affect local groundwater-dependent ecosystems or semi-permanent pools, but this has not been verified.

Further work

Sufficient information on the Robe River alluvial aquifer is available to develop a local-scale groundwater model. The model will test the current conceptual hydrogeology of the system that was reported by Commander (1994b). The modelling could also support the determination of ecological water requirements.

Additional drilling will not be required to develop the groundwater model. The reporting on the model should be scoped to bring all existing hydrogeological information up to date. The results of the model would fill information gaps and improve our understanding of the aquifer system. Recommendations could then be made on placement of potential production (test) and monitoring bores.

6.3.2 Upper Cane River — Birdrong Sandstone

Investigative drilling was conducted in the Upper Cane River, approximately 10 km downstream of the North West Coastal Highway and 40 km upstream of the existing Cane River Borefield (Figure 51). The focus of the drilling program was to assess the aquifer potential of the Birdrong Sandstone where it can be recharged by the Cane River (Yesertener & Prangley 1994).

The program comprised seven new exploration bores and conversion of an existing exploration hole to a monitoring bore. Yields were determined by airlifting.

Geology

The investigation area is located on the eastern extension of the Carnarvon Basin. Carnarvon Basin sediments crop out in the vicinity of the study area, along with Proterozoic sedimentary, igneous and metamorphic rocks. The Carnarvon Basin sediments are relatively shallow to the south-east and form a progressively thicker wedge of sediments to the north-west (Yesertener & Prangley 1994).

Proterozoic

The basement rocks intersected by drilling in the Upper Cane River were Proterozoic quartzites of the Mount Minnie Group. These crop out to the east and extend beneath

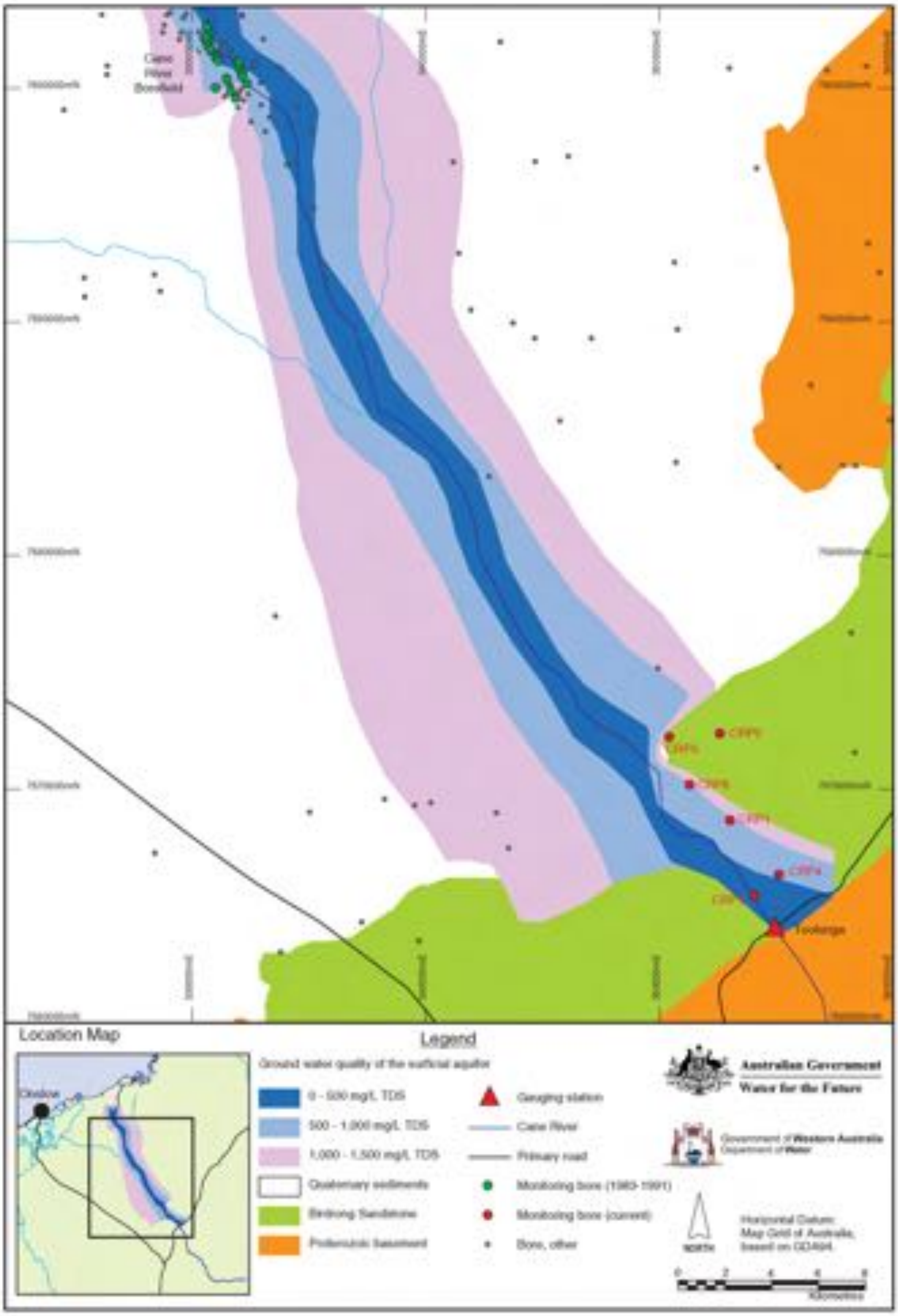


Figure 51: Upper Cane River area

the Carnarvon Basin sediments to the west. The quartzite is unconformably overlain by both the Cretaceous sediments and the Quaternary alluvial sediments.

Cretaceous

The Cretaceous sediments present in the study area are part of the Winning Group and generally thicken towards the west as the Carnarvon Basin deepens. At the base of the Cretaceous sequence, the Birdrong Sandstone grades into the laterally equivalent (but less mature sandstones) of the Nanutarra Formation. At the base of the Birdrong Sandstone, sometimes a basal, sandy, marine unit more commonly referred to as the Yarraloola Conglomerate is present. The Birdrong Sandstone in the study area is about 30 m thick.

The Birdrong Sandstone is overlain by the Muderong Shale and the Windalia Radiolarite, which were found to be indistinguishable during drilling. To simplify this discussion, both units will be referred to as the Muderong Shale. In the 1994 study area, the Muderong Shale had a reported maximum thickness of about 33 m and is overlain by the Gearle Siltstone.

The Carnarvon Basin sediments are overlain by 1 to 5 m of Cainozoic sediments that consist predominantly of alluvium and eolian deposits.

Aquifers

There are two main aquifers in the study area: the Birdrong Sandstone, which includes the basal Yarraloola Conglomerate, and the fractured quartzite basement rock.

Birdrong Sandstone

The Birdrong Sandstone is generally poorly sorted and clayey, and forms an extensive aquifer across the coastal plain confined by the Muderong Shale. At the inland margin of the Carnarvon Basin, the Birdrong Sandstone is unconfined where the overlying Muderong Shale is absent. The saturated thickness is equal to the thickness of the Birdrong Sandstone, which in drilling ranges from 16 to 53 m with an average of 31 m.

Recharge is from the unconfined and outcropping portions of the Birdrong Sandstone. Minor recharge occurs from direct rainfall and most of the recharge is from river flow where the Cane River crosses the outcropping Birdrong Sandstone.

The potentiometric surface of the Birdrong Sandstone aquifer is between 10 and 30 m below ground level and 10 to 20 m above the base of the confining Muderong Shale. Bores completed at the base of the sandstone had reported yields of 26 to 309 kL/day. Where the basal Yarraloola Conglomerate was reported to be present, a bore yield of 180 kL/day was reported.

Flow direction in the Birdrong Sandstone was found to be in a north-east direction and generally away from the source of recharge – the Cane River.

Salinities in the Birdrong Sandstone were reported to range from 890 mg/L near the river to 3450 mg/L at distances of 2.5 km away from the river.

Fractured quartzite aquifer

A second aquifer exists in the strongly weathered upper portion of the underlying quartzite basement rock. The quartzite in the study area is confined and had a maximum reported saturated thickness of 30 m with a potentiometric surface of between 10 and 20 m below ground level and between 12 to 20 m above the water-bearing zone. Recharge to the fractured bedrock is sourced from river flows which then percolate downward through the Nanutarra Formation and into the underlying weathered bedrock surface.

Bore yields from two bores completed in the quartzite ranged from 75 to 184 m^3/day.

Flow direction in the quartzite is similar to that of the overlying Birdrong Sandstone in that it flows away from the river in a north-easterly direction.

Salinities recorded were generally less than that of the Birdrong Sandstone and ranged from 200 mg/L near the river to 570 mg/L at distances of 1.5 km away from the river.

River flow and recharge

The Toolunga gauging station is located upstream of the study area and immediately downstream of the North West Coastal Highway crossing. Flows measured in the Cane River at the Toolunga gauging station have been described in the section on the Lower Cane River.

Resource development

There is only a small fresh-water source available from the Birdrong Sandstone and the fractured quartzite in this area. Groundwater salinities are generally potable near the river, but degrade with distances away from the river due to lack of recharge. Bore yields from the quartzite may generally be higher than those of the sandstone, but the potential for this area to provide adequate support for town supply is limited.

Further work

No additional work is recommended for this area as the investigation work reported by Yesertener and Prangley (1994) was sufficient to identify the potential in this area. The chances of developing a significant supply of potable water are limited.

6.3.3 Lower Ashburton alluvium

The Lower Ashburton River flows in a northerly direction for approximately 150 km over the Onslow coastal floodplain (Figure 52). The river flows beneath the North

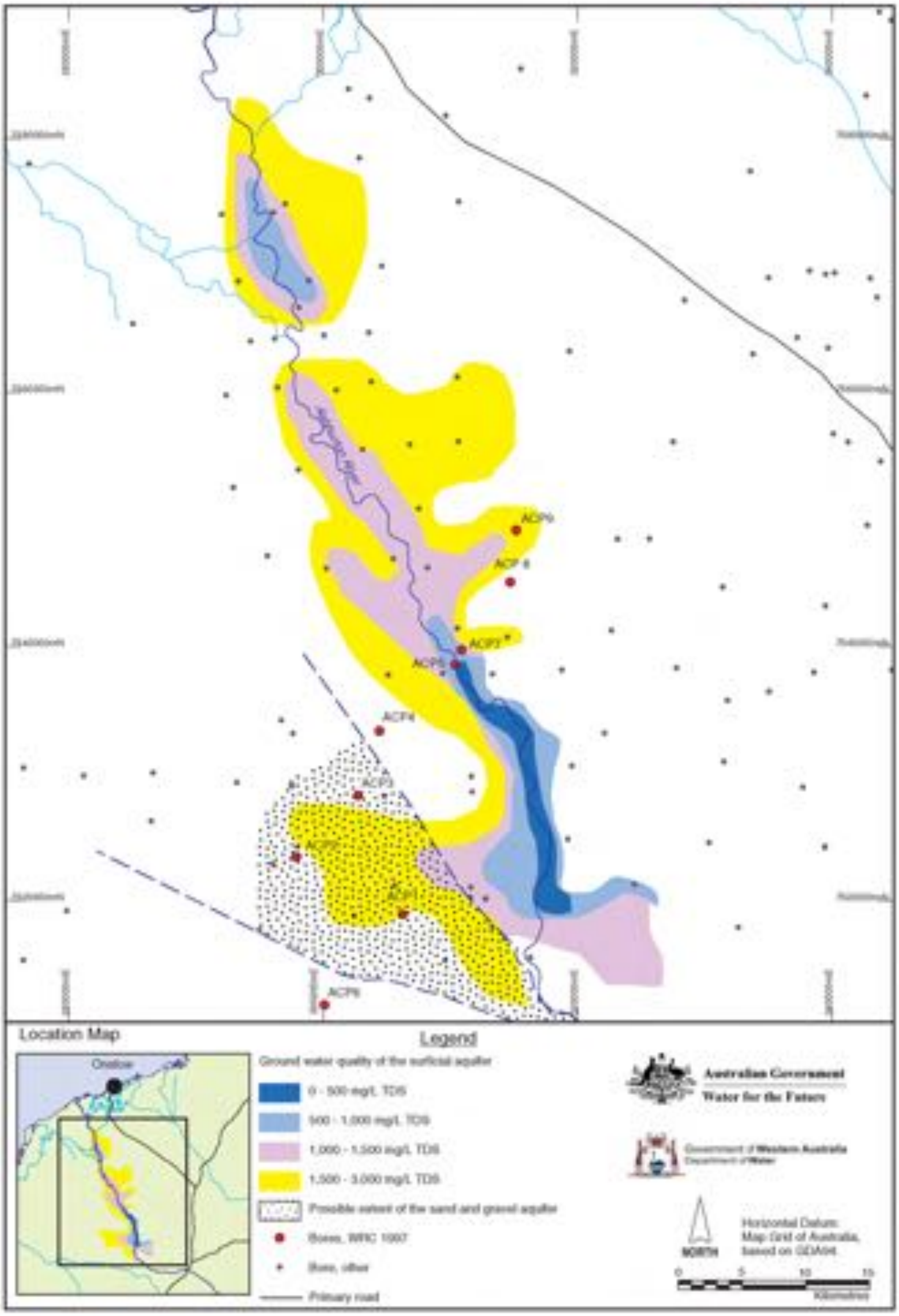


Figure 52: Ashburton River area

West Coastal Highway to the north, where the mouth is about 20 km due west of Onslow.

Numerous bores in the area have been drilled for stock and domestic supplies. A drilling program was conducted by the Water and Rivers Commission (now the Department of Water) to investigate the occurrence of shallow aquifers and low-salinity groundwater associated with the Ashburton River (Yesertener & Prangley, 1997). The investigation consisted of the drilling of nine exploration bores (Figure 52). Aside from the 1997 program, there has been limited systematic groundwater exploration.

Although significant flow volumes are recorded in the Ashburton River, drilling data indicates that not enough alluvial thickness is present to develop a significant groundwater source. There are large supplies of brackish to saline water available from palaeochannels in the south-west portion of the Lower Ashburton River. Figure 52 shows mapping of areas of alluvium with salinities of less than 1000 mg/L (Davidson 1975).

In general, good potential exists for brackish to saline water supplies to stations. Small supplies for domestic use are possible, but only along drainage channels. There is only a very low chance of obtaining significant supplies for towns or agriculture.

Geology

The Lower Ashburton River flows over the Onslow plain, which is covered with Quaternary alluvium. The alluvium is underlain by Tertiary and Cretaceous-aged sediments. Underlying the Cretaceous sediments are Palaeozoic and Proterozoic basement rocks (Figure 52). The stratigraphy of the Lower Ashburton River area is summarised below in Table 24.

Table 24. Stratigraphy of the Lower Ashburton River area

<table>
<tr><th>Age</th><th>Formation</th><th>Lithology</th></tr>
<tr><td>Quaternary</td><td>Alluvium</td><td>Clay, calcrete, sand and gravel</td></tr>
<tr><td colspan="3">----------Unconformity----------</td></tr>
<tr><td>Tertiary</td><td>Trealla Limestone</td><td>Limestone, clay, marl</td></tr>
<tr><td colspan="3">----------Unconformity--------</td></tr>
<tr><td rowspan="4">Cretaceous (Winning Group)</td><td>Gearle Siltstone</td><td>Clay, claystone</td></tr>
<tr><td>Muderong Shale</td><td>Shale</td></tr>
<tr><td>Birdrong Sandstone</td><td>Sandstone</td></tr>
<tr><td>Yarraloola Conglomerate</td><td>Basal conglomerate</td></tr>
<tr><td colspan="3">----------Unconformity----------</td></tr>
<tr><td>Permian</td><td>Lyons Group</td><td>Sandstones</td></tr>
<tr><td colspan="3">----------Unconformity----------</td></tr>
<tr><td>Proterozoic (Gascoyne Group)</td><td>Basement rock</td><td>Granite and metasedimentary</td></tr>
</table>

The Ashburton alluvium is underlain by the Tertiary Trealla Limestone, which is present throughout the area but occurs in isolated patches. The Trealla Limestone was not identified in the bores drilled during the 1997 investigation program. The presence of Tertiary pisolites has not been proven in the Ashburton River drainage.

Underlying the Trealla Limestone are the sediments of the Winning Group, which is the northward extension of the Carnarvon Basin. The Winning Group in this area comprises the Muderong Shale, Gearle Siltstone and underlying Birdrong Sandstone and Yarraloola Conglomerate. The Cretaceous sediments dip to the west and the top of the Birdrong Sandstone is at depths of greater than 200 m over much of the Onslow Plain (Figure 52).

Underlying the Cretaceous sequence is the Permian-aged Lyons Group, which is reported to be at depths greater than 400 m beneath the Ashburton River. The Lyons Formation lies unconformably on Proterozoic basement rock. The Proterozoic basement rock outcrops approximately 10 km east of the 1997 investigation area.

Hydrogeology

The alluvial aquifer along the Ashburton River has limited potential due to limitations in thickness and generally high salinity. The maximum thickness of alluvium in the Ashburton River has been reported to range from 5 to 12 m. A maximum thickness of 37 m has been reported in the south-west of the active river drainage beneath bores ACP1, ACP2 and ACP3 (Yesertener & Prangley 1997) and might represent a buried palaeochannel. The alluvium is the only appropriate target for the development of limited supplies until information about the older sediments becomes available.

The Trealla Limestone, when present, has yields that may generally be less than 100 kL/day and salinities are similar to the overlying alluvium. The information available indicates that the Trealla Limestone has low potential as a groundwater source along the Onslow plain.

The Lyons Formation has no aquifer potential in this area as the depth makes development prohibitive and the water quality is reported to be saline.

River flow

The Nanutarra gauging station is located where the Ashburton River crosses the North West Coastal Highway. The station is upstream of where the Ashburton River flows onto the Onslow plain to form the Lower Ashburton River. The gauging station record extends from 1972 to the present with a long-term mean annual flow (1972–2005) of 922 GL. During the 34-year period, there were six years in which the volume of flow over a four-month period exceeded the mean annual volume of 922 GL. The longest number of consecutive months during which no flow was recorded at Nanutarra gauging station has been nine months. Over the 34-year record, flow has been recorded at the Nanutarra gauging station every year. During the same period, there were four years in which the maximum-recorded annual flow was less than 10 per cent of the mean annual flow. This indicates that during one out of every nine years, the total annual flow to the Lower Ashburton River is very low.

Bore yields

Skidmore (1996) reported regional yields from the Ashburton River alluvium to be poor. Bores were reported to yield a maximum of 131 kL/day, but typically ranged from 15 to 42 kL/day.

Further work

No additional work is recommended. There is not an adequate model to assess the sourcing of fresh water in the Ashburton River alluvium. Developing a source greater than small domestic supplies is problematic. If a cost-effective method of geophysics were available to assess the thickness of alluvial sediments, then an assessment would be warranted. The value of further work in this area should be carefully considered, given the poor results implied by previous investigations and bore records.

7 Conclusions

The Pilbara Coast Water Study is a comprehensive review of the existing water supply schemes, existing groundwater supplies and the potential new supplies that may supplement the schemes. The following general conclusions can be made:

- **Further development** of groundwater resources in the Pilbara coastal region is required to meet projected demand: with the expansion of mining and industry, more water will be required for ore processing and handling. Current water resources are likely to be insufficient to meet long-term demand.
- **Desalination** is an important option because it is independent of climatic variation and is not susceptible to drought. In addition, cheap energy from locally sourced natural gas is available.
- Supplementing existing water-supply schemes by conveying **water from the Kimberley** is not cost-effective when compared with developing groundwater sources and desalination.
- Currently-used groundwater resources have an associated level of uncertainty in regard to **aquifer reliability**. This is primarily due to the infrequency of recharge events.
- **Surface-water** development in the Pilbara is not viable due to complications related to cultural and environmental impacts. The Harding Dam, though currently supplying significant water to the West Pilbara Water Supply Scheme, is subject to these constraints.

The following conclusions relate to existing and potential groundwater options that may support the coastal supply schemes. The yields reported below do not take into account provision for environmental, social and cultural requirements. The allocation of water from all aquifer systems described below will require further work to define sustainable levels of use consistent with sustainability guidelines.

West Pilbara Water Supply Scheme

- The **Lower Fortescue River** alluvium is a well-documented resource with early estimates of potential yield about **10 GL/yr**. A sustainable yield is probably much less than this: further work to assess possible environmental factors will be required.
- **Fractured bedrock** aquifers associated with the Sholl Shear Zone in the vicinity of the upper Harding River have been explored in three locations. Estimates of total potential yield from the three sites range from **3–6 GL/yr**, however significant work is required to prove up the resources.
- Minor groundwater resources associated with the **Maitland River and George River** areas have been identified. The resources are limited and have not been extensively investigated. They may have some potential as supplementary sources and future assessment work is warranted.

- The **Millstream aquifer** system has been extensively investigated through drilling and test pumping, and is used conjunctively with the Harding Dam as the West Pilbara Water Supply Scheme. It has yielded **4 GL/yr** during drought periods without significant falls in aquifer levels. However, yields at about **9 GL/yr** have been problematic, while yields at **14–15 GL/yr** have resulted in significant falls in aquifer levels. Due to the significance and sensitivity of the dependent ecosystems, the aquifer is managed using a number of criteria including mean minimum aquifer levels and rates of decline. When necessary, supplementation to maintain pools and springs is required. A numerical groundwater model has been developed for the aquifer to assess impacts, but this requires further work.

Port Hedland Water Supply Scheme

- The **West Canning Basin** represents a significant groundwater resource. Water quality is variable within both the **Wallal Sandstone aquifer** and the overlying **Broome Sandstone aquifer**. The total groundwater resource from the Wallal Sandstone aquifer is estimated to be 21 GL/yr, of which **14 GL is fresh**. The Broome Sandstone aquifer has a total estimated yield of 18 GL/yr, of which only **6 GL is fresh**. Water from any portion of the West Canning Basin may not be suitable for agriculture as the salinity hazard may be high.
- The **Turner River** alluvium has the potential for only moderate supplies of fresh water (<1 GL), as increases in salinity and drawdown become limiting factors in production. Alternatively, potential exists for the resource to be used as ‘fit-for-purpose’ brackish water supply. One option may be to use the brackish water as a supply source for desalination. This option also requires further assessment.
- The **De Grey River** alluvial aquifer is one of the sources for the Port Hedland Water Supply Scheme. It is currently operating 10 production bores in the **Namagoorie borefield**, which has a licensed abstraction of **7 GL/yr**. At present, environmental approval is being sought to expand production through the commissioning of the **Bulgarene borefield**. The new borefield may potentially increase the scheme supply by **3–6 GL/yr**, although further work is required to adequately assess the sustainable yield and environmental impacts.
- The **Yule River** alluvium is the second source for the Port Hedland Water Supply Scheme and currently operates nine production bores. It has a temporary licence to increase maximum abstraction from **6 GL/yr to 8.5 GL/yr**. A proposed pumping trial and monitoring program will assess the possible effects of the 2 GL increase in abstraction on groundwater-dependent vegetation.

Onslow Water Supply scheme

- The **Lower Cane River** alluvium is the source for the Onslow Water Supply Scheme, and currently 16 production bores are operating with a licensed allocation of **0.35 GL/yr**. There is some heterogeneity within the aquifer and consequently the effects of pumping are variable. Saline encroachment is a potential effect of over-pumping; however, the aquifer is currently meeting Onslow's demands. Expansion of the borefield upstream of the current location may increase the available yield, but this has yet to be verified.
- Recharge estimates on the **Lower Robe River** indicate that a reasonable upper-limit annual abstraction may be **10 GL**. This estimate, of course, does not take into consideration the cultural, social and ecological water requirements of the area.
- River-flow volumes on the **Ashburton River** are considerable, with a long-term annual mean of 922 GL. As yet, significant occurrences of alluvial thickness or secondary porosity in bedrock units are unproven. Assessment work will be necessary to prove up a significant supply for development.

All supply schemes

- Ecosystems with varying degrees of dependency on groundwater occur at all sites reviewed in the study.
- Current estimates of sustainable yield for all sites need to be revised to take into account provisions for environmental, social and cultural requirements. Allocation limits should then be reviewed and adjusted as required.

8 Recommendations

Based on the outcomes of the *Pilbara coast water study,* the following recommendations are made:

- Investigate and assess ways to better define the sustainable yield of the **Lower Fortescue River** alluvial aquifer. The work should include development of a groundwater model to further the understanding of groundwater-dependent ecosystems. The work could be done in partnership with various stakeholders who are actively seeking licensed allocations in this area.
- Use the soon-to-be-completed numerical modelling for the **Millstream aquifer** to reassess the potential yield of the aquifer system and the potential effects of abstraction on local ecosystems. The model should also be used to develop a risk analysis and trigger values associated with varying abstraction regimes over a range of climatic variations. Survey work, construction of new groundwater and surface-water monitoring sites and a review of the current monitoring system is warranted.
- Look at the feasibility of converting the **Millstream aquifer** to a 'fit for purpose' supply. Such as investigation should focus on the economic analysis and cost of using the Millstream aquifer as a non-potable supply and having the Harding Dam reserved for potable supply.
- Conduct a regional review and assessment of all **dewatering sites** associated with mining operations. The review should also focus on the process by which these sites can make the transition from mine dewatering as a private enterprise to a public water supply in support of the major coastal supply schemes.
- Review the work completed on the fractured bedrock aquifers in the **Harding River** catchment. The focus should be an economic analysis of the development options to determine if further work is warranted.
- Investigate and assess the **Maitland River and George River** alluvial aquifers. These sites are considered to be low priority, but are strategically located near existing supply infrastructure. The work should include field investigations to assess alluvial thickness and confirm development potential.
- Perform an environmental review of the Bulgarene borefield on the **De Grey River**.
- Investigate and assess the **West Canning Basin** as the next step toward determining the sustainable yield. It is recommended that a numerical model of the basin be developed based on existing information.
- Investigate and assess the **Lower Turner River** to determine the extent and thickness of the alluvial sediments and to delineate zones of fresh or brackish water. The running of geophysical surveys, such as airborne TDEM, would help to map the extent of the zones of fresh water and brackish water. The information could be applied to the development of geologic models to

quantitatively define the extent of the resource. Investigation drilling is also recommended to define aquifer parameters and to estimate potential yields.

- Investigate and assess the area upstream of the current **Cane River** borefield. The work should focus on determining the extent and thickness of the alluvial sediments and delineating zones of fresh or brackish water. The study will identify appropriate sites for future production bores to supplement the current supply.
- Investigate and assess the **Lower Robe River** alluvial aquifer. The scope of the work would be very similar to that proposed for the Lower Fortescue River and would include development of a groundwater model and hydrogeologic reporting.
- Refrain from further investigating and assessing the **Lower Ashburton River**. The limited potential of the alluvial sediments, Yarraloola Conglomerate and the Birdrong Sandstone do not justify the cost of an additional assessment.
- Conduct additional **environmental investigations** in parallel with the hydrogeological investigations described above. Current knowledge of the links between ecosystems and groundwater is deficient. The combination of hydrogeological investigations and assessment of environmental ecosystems will enhance the regional understanding of ecological water requirements and lead to the development of environmental water provisions.
- Perform a detailed analysis of **river flow hydrographs and aquifer level hydrographs**. The analysis would focus on the relationship between duration of flow events, volume of flow during the event and the resultant changes in groundwater levels. This work could be done as part of future groundwater modelling efforts.
- **Map** watertable contours and salinity in all areas where allocation limits are required. The mapping should support the development of cross-sections across the river where intermittent and permanent pools exist. Accurate **watertable and salinity contours** are required to understand the reliance of local vegetation on groundwater and to determine sustainable allocation limits.
- Undertake additional assessments to further the **recharge estimates** developed by URS. The additional work should focus on developing an empirical relationship between the time duration of flow (in days) and the resultant rise in aquifer level. The work would lead to a better understanding of the recharge mechanisms and support future numerical modelling efforts.
- Carry out a **risk assessment** while developing new sources or expanding existing sources. This will help determine the source's contamination risks and whether it will be suitable as a public drinking water supply. This risk assessment should be guided by the *Australian Drinking Water Guidelines* and consider all land uses within the catchment.

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