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

Feasibility of managed aquifer recharge using drainage water

A supporting document for the Murray drainage and water management plan

Looking after all our water needs

Water*Science*
technical series

Report no. WST 38
June 2011

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Cover photograph: Looking west to the towards the Peel Inlet with the Murray River and Ravenswood development in the foreground, October 2010 (photo: Andrew Watson, Department of Water).

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Foreword

Ensuring that we have adequate water supplies to meet the demands of Western Australia's growing population is the highest priority for the Department of Water. One source we are investigating is stormwater harvesting from our urban catchments, combined with managed aquifer recharge, so that winter runoff can be stored to balance our seasonal demands.

Managed aquifer recharge will make stormwater an asset for communities, as it has the potential to supply industry, public open spaces, sporting fields and private gardens. It can also reduce the cost of managing the impact of stormwater on sensitive waterways such as estuaries, and increase water security through drought-proofing.

The recently released Murray Drainage and Water Management Plan offered a unique opportunity to explore the potential for stormwater harvesting and managed aquifer recharge pre-development. This report has realised that opportunity, and it has created a platform that brings together much of the information required for the successful implementation of managed aquifer recharge. It has also identified the knowledge gaps that the Department of Water and proponents of managed aquifer recharge schemes need to address in order to ensure the full potential for stormwater harvesting is realised.

The Department of Water acknowledges the support of the National Water Commission (through the Raising National Water Standards Program). This project is part of a larger investment by the National Water Commission, which intends to reduce the risk of investing in managed aquifer recharge by supporting the preparation of feasibility studies.

I am pleased to commend this report to you and look forward to seeing the implementation of managed aquifer recharge schemes in Western Australia.

Maree De Lacey

Director General
Department of Water

Contents

Figures

Tables

Charts

Summary

In the context of increasing demand for water, climate variability and the current low rainfall being experienced in south-western Australia, the need to develop alternative water supplies has become critical. Stormwater harvesting and storage via managed aquifer recharge (MAR) has great potential in Perth, with its significant sandy aquifers already supplying water to the city.

The *Australian guidelines for water recycling* offer a framework for assessing the risks involved in MAR, and how those risks can be mitigated to ensure schemes are sustainable into the future. The Department of Water encourages MAR scheme proponents to use the guidelines to formulate proposals as outlined in our recently released *Draft approval framework for the use of non-drinking water in Western Australia*. Unfortunately the guidelines are often perceived as complex or onerous and, as such, we believe it is important to give examples of how to apply them.

This study aims to help proponents develop proposals for MAR of harvested stormwater in the *Murray drainage and water management plan* area. It is unique in that it assesses the feasibility of MAR at the pre-planning stage of development, and covers a large area being considered for development (~84 km^2). The study addresses Stage 1 of the national MAR guidelines assessment process using existing data, assesses the availability of stormwater and the storage capacity of local aquifers (focusing on the confined aquifers), and discusses the viability and degree of difficulty of a conceptual MAR scheme.

In addition, we advise on the further requirements of Stage 2 of the guidelines and give direction on how to address remaining regulatory requirements.

In the much of the Murray plan area, current demand for alternative water supplies, namely groundwater, already exceeds or is close to exceeding the supply potential of the aquifers under natural recharge conditions. Development is forecast to increase this demand by up to 24 GL by 2031.

Based on this desktop assessment, in broad terms it appears that stormwater, particularly that which is collected through subsurface drainage systems, offers significant potential for harvesting and MAR. Catchment modelling has estimated (under a range of scenarios) that between 12 and 23 GL of subsoil drainage water would be available for harvesting.

There is an opportunity to integrate MAR into future urban and industrial developments for providing a safe, reliable and energy-efficient alternative water supply. This study illustrates that the most suitable aquifer for MAR in the region is the Cattamarra – based on its hydrogeology, quality of groundwater and environmental values. Conservative estimates of the aquifer's storativity indicate that between 20 and 100 GL of storage is available within the whole study area if its potentiometric heads are restored to 1984 levels. MAR offers an opportunity to manage drainage water in the region so it becomes an asset, rather than a liability.

1 Introduction

This study's primary objective is to broadly appraise the feasibility of MAR in the *Murray drainage and waterway management plan* area (DoW 2010c), focusing on the confined aquifers. While Perth's water supply has rapidly expanded to take advantage of the confined aquifers, aquifer management has mostly been limited to extraction management. Increasingly, water managers are realising that to further raise extraction rates from fully allocated aquifers, mechanisms to enhance recharge will also be required.

MAR offers an opportunity for water to be stored in a suitable aquifer when surplus is available, and for it to be recovered from the same aquifer when it is needed (Pyne 1995). Recent studies have shown that most rainfall onto the high-watertable areas of the Murray region is lost to evaporation, or runs off to the sea over winter when demand is low (Hall et al. 2010a). A portion of the flow is required to meet environmental flow requirements. In urban areas it is not unusual to have lower evaporative losses, as well as additional runoff via drains into rivers and estuaries (which carries urban pollutants such as nutrients that negatively affect waterway health). Treating this pollution is an issue, as is the lost opportunity to use this valuable water resource.

Adequate storage is critical to improving the water balance by reducing wastage of this resource and helping Perth to achieve sustainable water management. Currently, Perth's water supply largely depends on the integrated water supply scheme (IWSS), with water being sourced from a combination of dams, borefields and desalination plants. Based on modelled climate scenarios it is likely that future streamflow will decrease and a diminishing amount will be available from dams (DoW 2010c). As a result, groundwater and desalination plants will come under more pressure to maintain and increase supplies for an expanding population. By 2030 it is expected Perth's population will increase from 1.6 to 2.2 million (WAPC 2009). In the Peel region, if current per capita demand continues the expanding population will require up to a further 38 GL/yr of water through the IWSS and alternative water supplies compared with the current level of use (DoW 2009c). This is an increase of nearly 50 percent over current demand.

MAR enables water managers to enhance aquifer recharge rates and raise depleted aquifer hydraulic heads, thus allowing more water to be stored in winter and be made available in summer for supply. In the past MAR has encountered some geotechnical, treatment, cost and social perception issues, yet these have largely been resolved through new technological processes and education (Pyne 1995).

This study encompasses the area investigated as part of the *Murray hydrological studies* (Hall et al. 2010a; 2010b; 2010c), in particular those regions being considered for future urban development in the *Southern metropolitan and Peel sub-regional structure plan* (WAPC 2009) (an area of approximately 84 km^2). These hydrological studies highlighted that the proposed development regions were located in areas highly constrained by watertables at or near the surface in most winters. Modelling of subsurface drainage scenarios for the proposed development regions identified that between 12 and 23 GL of drainage water would require management overall, with it potentially being available for re-use (Hall et al. 2010c). The technical hydrological studies supported the *Murray drainage and water management plan* (DWMP) (DoW 2010c). The DWMP encourages management outcomes that ensure the efficient use of drainage water while at the same time maintaining the region's natural water balance and improving water quality. Under the *Better urban water management* guidelines, a DWMP should also investigate synergies for the management of stormwater, groundwater and wastewater for alternative fit-for-purpose water supply, and assess and begin feasibility assessments (WAPC 2008). This report has been written to support the Murray DWMP by providing the relevant technical advice associated with the 'toolbox' of solutions under Key Principle 3 of the plan: 'Ensure the efficient use and re-use of water resources'.

This study aims to promote the incorporation of MAR into the region's urban planning framework, and illustrate that MAR is an attractive and feasible option for its water management.

1.1 Study area

The study area shown in Figure 1.1 is located on the Swan Coastal Plain, where there is relatively flat terrain, extensive winter waterlogging, wetlands of significance, and the risk of riverine flooding (Hall et al. 2010a). The study area extends east to the Darling Fault, west to the Indian Ocean and Peel-Harvey estuary, and north and south to the approximate boundary of Dirk Brook and Caris Drain respectively.

1.2 Scope of work

This study's primary objective is to broadly appraise the feasibility of MAR for the region's stormwater, focusing on the confined aquifers. The potential development subareas shown in Figure 1.1 are derived from WAPC (2009). These areas are located in an environment highly constrained by water, particularly due to the close interaction between the watertable and the ground surface, riverine flooding, issues associated with water quality, and excess nutrients affecting the Ramsar-listed Peel-Harvey estuarine system (DoW 2010c; Hall et al. 2010a; Kelsey et al. 2010).

MAR offers an opportunity to manage drainage water in this region so it becomes an asset rather than a liability. Appropriate investigations at an early stage of planning will help this opportunity be realised.

This study was conducted within the context of the *Australian guidelines for water recycling: managing health and environmental risks, Phase 2: managed aquifer recharge* (MAR guidelines) (NRMMC-EPHC-NHMRC 2009a). The guidelines provide principles and a framework for safe implementation of recycled water schemes. They can be used to assess the viability, difficultly, benefits and risks in establishing a viable MAR scheme. Figure 1.2 outlines the four major stages of a MAR scheme investigation. This study closely followed the steps involved in a Stage 1 investigation (desktop study and entry-level assessment). The three modules of the guidelines that are directly applicable in this case are:

- *Australian guidelines for water recycling* – Phase 1
- *Stormwater harvesting and reuse* – Phase 2
- *Managed aquifer recharge* – Phase 2.

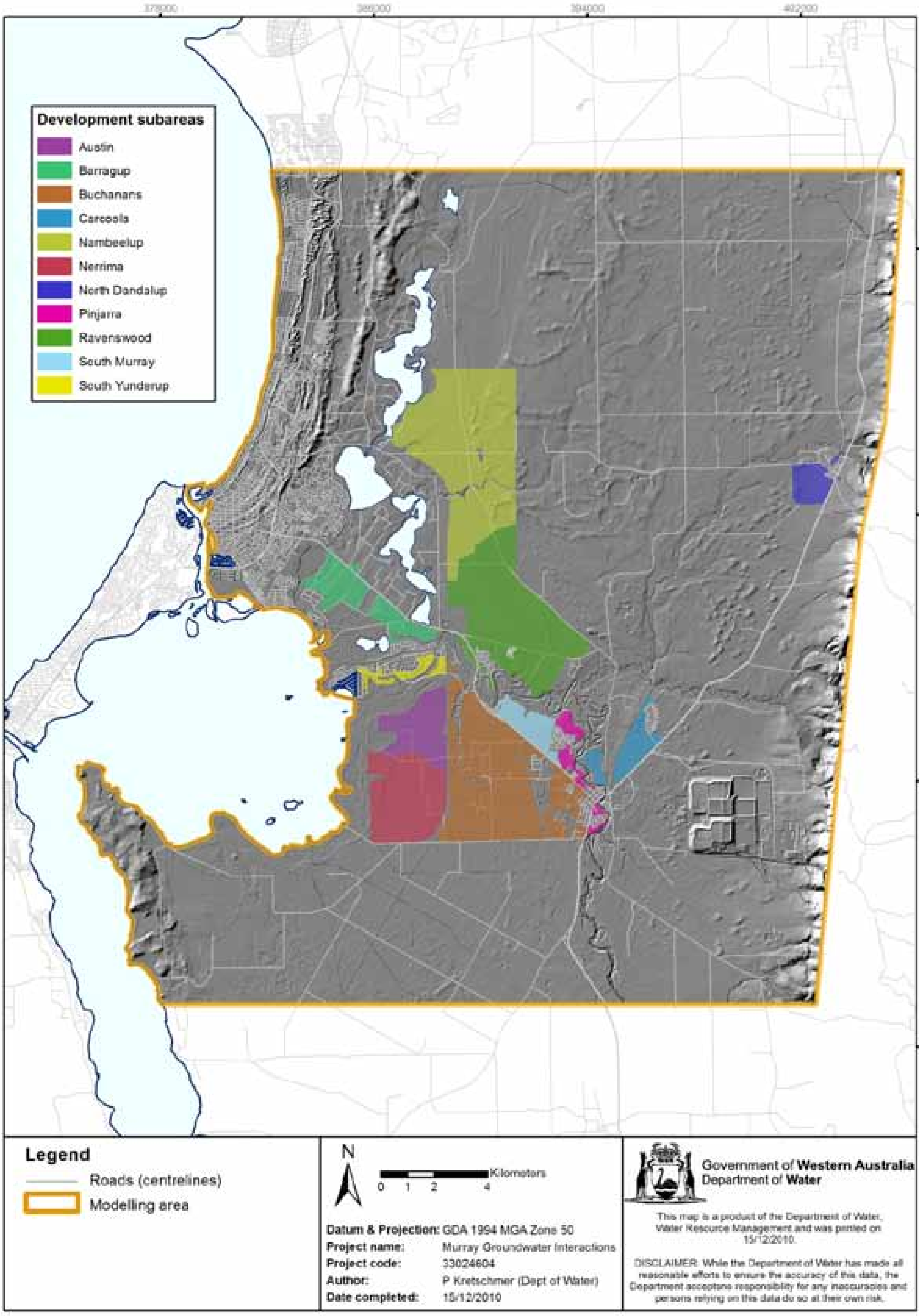


Figure 1.1 The Murray MAR study area and proposed development regions from WAPC (2009)

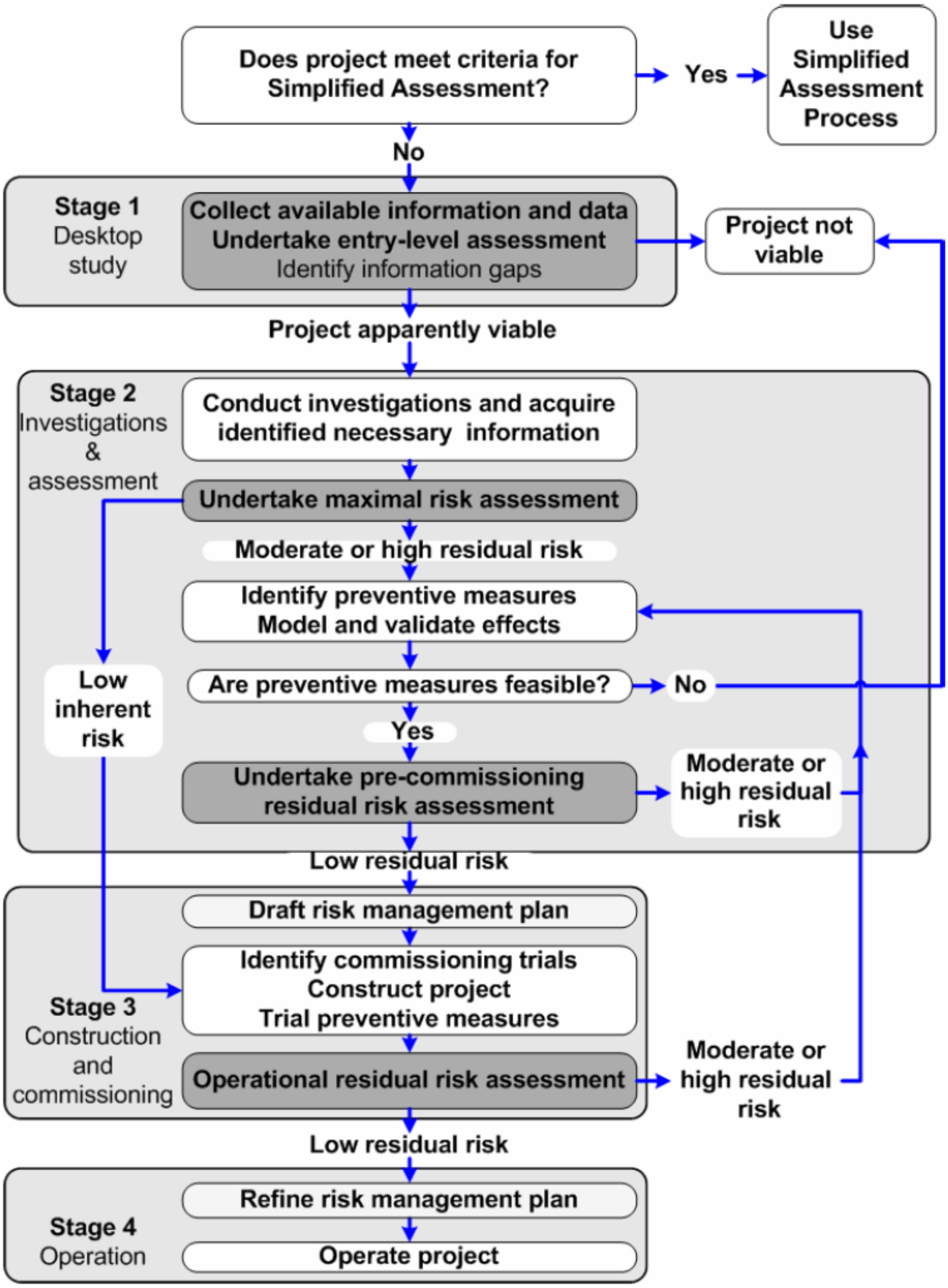


Figure 1.2 Stages of investigation for a managed aquifer recharge project (source: NRMMC 2009)

1.3 Report structure

This report is structured as follows:

Chapter 1 gives a general overview and introduction to the study area and the national guidelines framework for MAR.

Chapter 2 outlines current knowledge of the region's geology and hydrogeology, and summarises aquifer and stormwater water quality.

Chapter 3 demonstrates how the guidelines should be followed, including:

- a conceptual diagram of a generic stormwater aquifer storage and recovery scheme
- a broad entry-level assessment for both viability and degree of difficulty for each of the development areas
- guidance on subsequent Stage 2 investigations that proponents need to undertake to gain approvals for commissioning of trials
- further requirements to complete validation monitoring and a risk management plan to meet the Western Australian MAR regulatory approvals process

Chapter 4 provides a discussion, conclusions and recommendations based on the information gathered.

2 Review of available information

2.1 Regional geology

The study area is located within the Perth Basin, a north-trending sediment-filled trough extending approximately 1000 km along the south-western margin of the Australian continent. Rifting of the continental plates and deposition of sediments began in the early Permian along the Darling Fault, culminating in the separation of Greater India from Gondwana by the Early Cretaceous. Post break-up tectonic activity abated and the Perth Basin subsided. Sediment deposition has continued episodically though to the present day in progradational shallow water and fluvial environments (Davidson 1995; Pennington Scott 2009). In this study the main formations of interest from earliest to latest are the Jurassic Cattamarra Coal Measures, and the Cretaceous Gage Sandstone, South Perth Shale and Leederville Formation. The stratigraphic sequence is provided in Table 2.1 and is illustrated in four cross-sections.

Previous geological investigations in the region have been undertaken in localised areas only, with none extending across the entire study area. This study's early intention was to link the previous studies and join the contours of the stratigraphic layers from Davidson (1995) and Pennington Scott (2009), thus creating geological maps to cover the entire study area. The review of these and other published studies revealed there were significant differences in the contours and that linking them was impractical. In places, interpretation of the depth to a particular unit varied by as much as 50 m for a given location. It was therefore decided to review the deep geology (i.e. excluding superficial formations) in the study area and create new maps.

To undertake this component of the investigation, geophysical logs from the area were compiled, scaled and placed in cross-sections to aid interpretation. A literature search was also undertaken to compile existing interpretations and palaeontology reports dating back to the 1960s. These were used and notated on the geophysical logs. Figure 2.1 maps the locations of the geophysical logs used in the interpretation. A more detailed description of the interpretative method is provided in Appendix A.

The new interpretation used a diverse set of geophysical logs from the artesian monitoring network, private bores and the Mandurah series bores discussed in Commander (1975). Information from several bores had not been used in any previous published regional interpretation and proved to be valuable. The final result was a three-dimensional block model of the Cretaceous and Jurassic units that underlie the region (shown in Figure 2.2). In general the new interpretation is consistent with Pennington Scott (2009), however an important result is the reinterpretation of the Rockingham Sand (in the study area) as an equivalent unit to the Wanneroo Member of the Leederville Formation. This interpretation also appears consistent with the type-section of the Rockingham Sand (Passmore 1970). It appears the Rockingham Sand represents an area of the Leederville Formation that is elevated relative to areas of the Leederville east of the Mandurah Fault and south of the Peel Inlet.

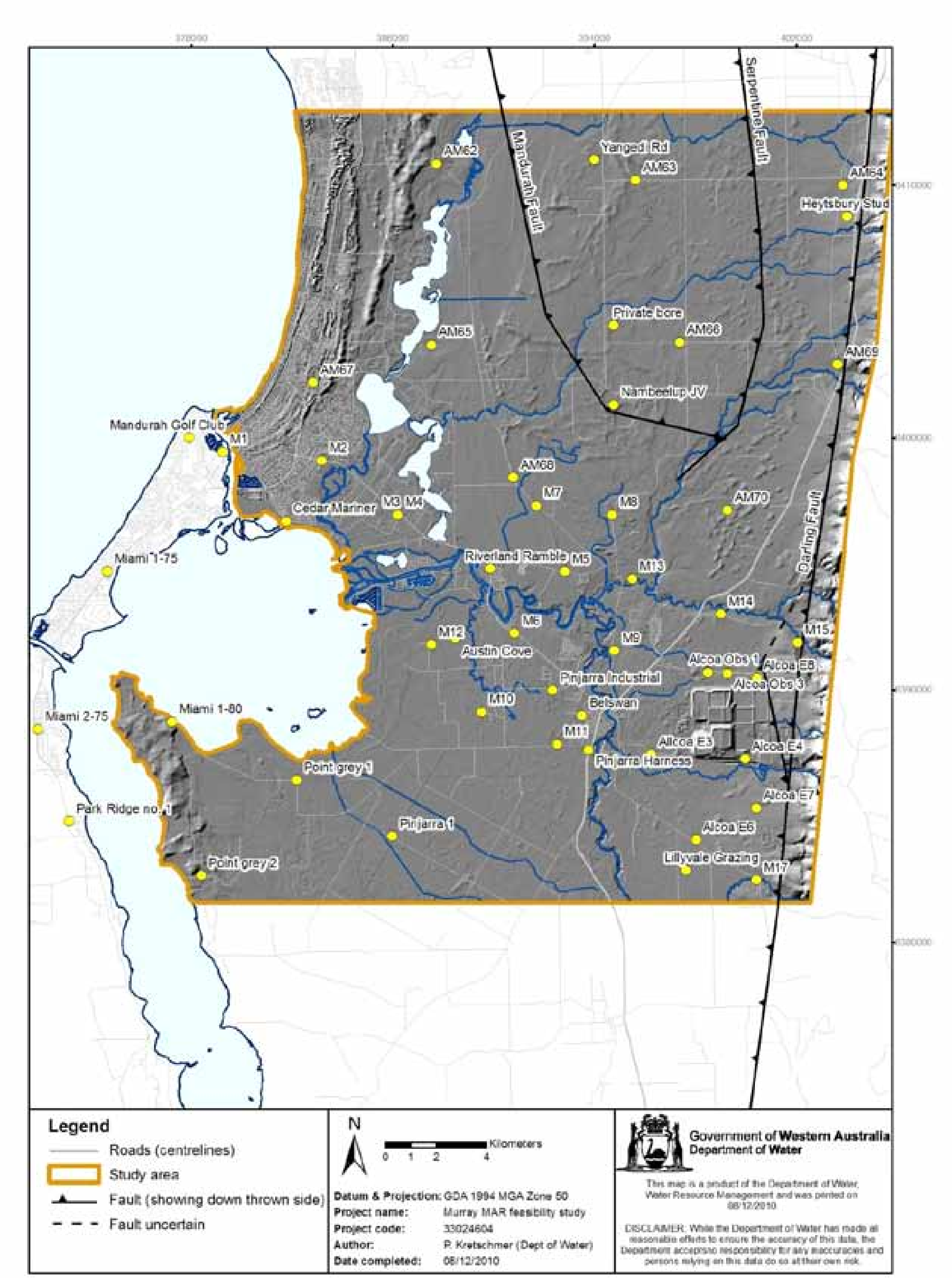


Figure 2.1 Location of bores with geophysical logs used in the revised geologic interpretation

Table 2.1 Stratigraphy of the Murray study area

Era	Period	Epoch	Date (Ma)	Stratigraphy		
Cenozoic	Quaternary	Holocene	0 - 0.01	Superficial formations (TQ)	Alluvium, estuarine and swamp deposits	
					Safety Bay Sand (Qs)	
		Middle to upper Pleistocene	0.01 - 1.0		Tamala Limestone (Qt)	Bassendean Sand (Qb)
		Lower to upper Pleistocene	1.0 - 1.8		Guildford Formation (Qg)	
	Tertiary	Late Pliocene to early Pleistocene	1.0 - 3.0		Ascot Formation (Ta)	Yoganup Formation (Ty)
Mesozoic	Cretaceous	Upper	91 - 113	Osborne Formation (Kco)	Kardinya Shale (Kcok)	Henley Sandstone (Kcoh)
		Lower	112 - 130	Leederville Formation (Kwl)	Pinjar Member (Kwlp)	
					Wanneroo Member (Kwlw)	
					Mariginiup Member (Kwlm)	
			125 - 136	South Perth Shale (Kws)		
			136 - 140	Gage Sandstone (Kwg)		
	Jurassic	Upper	144 - 181	Yarragadee Formation (Jy)		
		Lower	181 - 200	Cattamarra Coal Measures (Jc)		

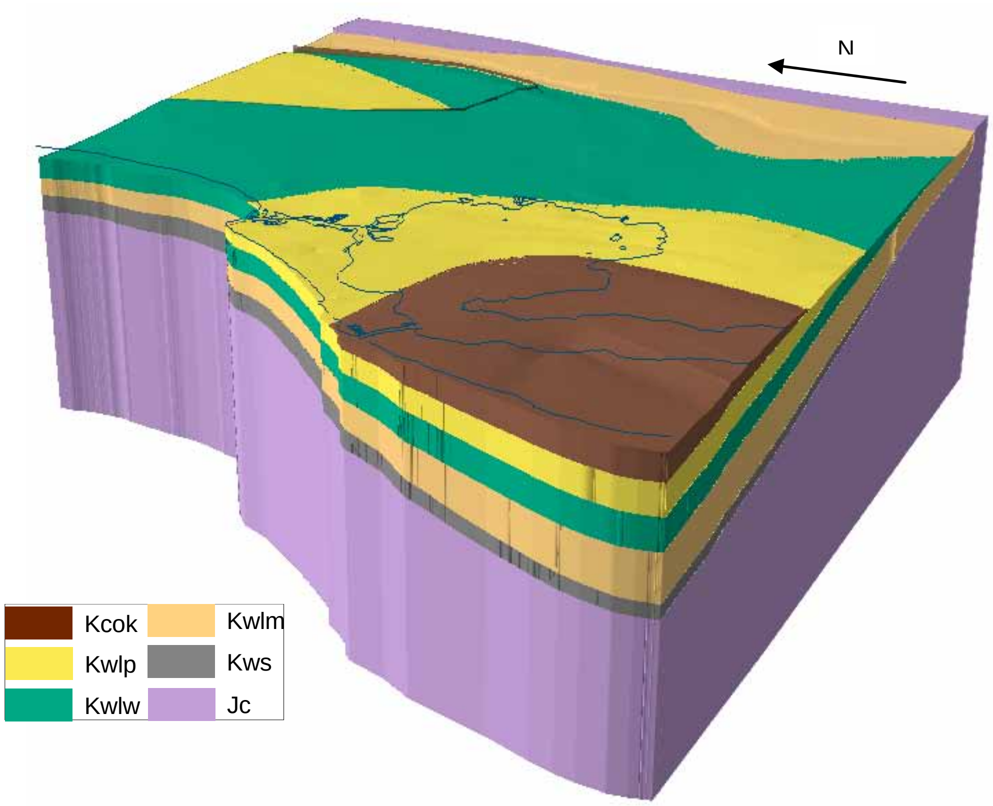
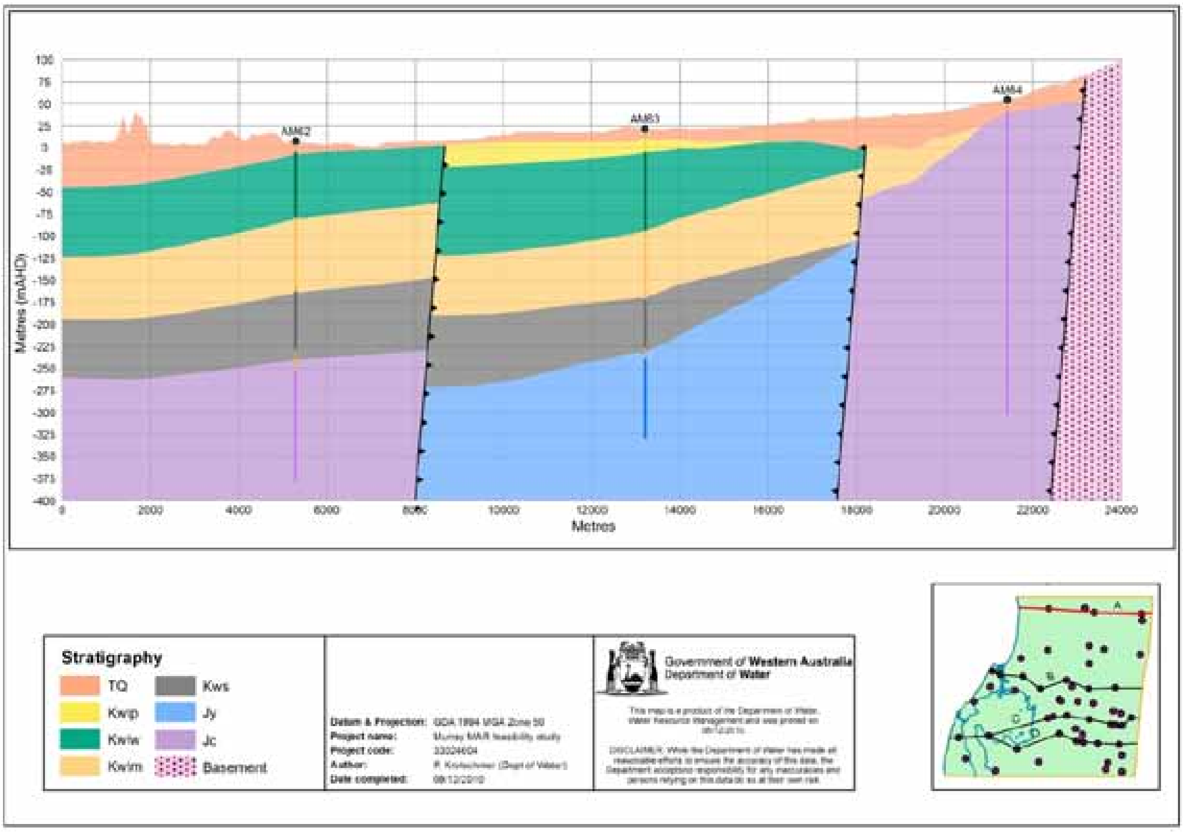


Figure 2.2 Three-dimensional illustration of the Cretaceous and Jurassic formations in the study area

It should be noted that this study has not separated the Gage Sandstone from the Jurassic units. This is due to the Gage Sandstone's similarity to the Jurassic units in the geophysical logs and unreliable palaeontology caused by down-hole contamination during drilling. The cross-sections shown in figures 2.3 to 2.5 are taken from the three-dimensional model.



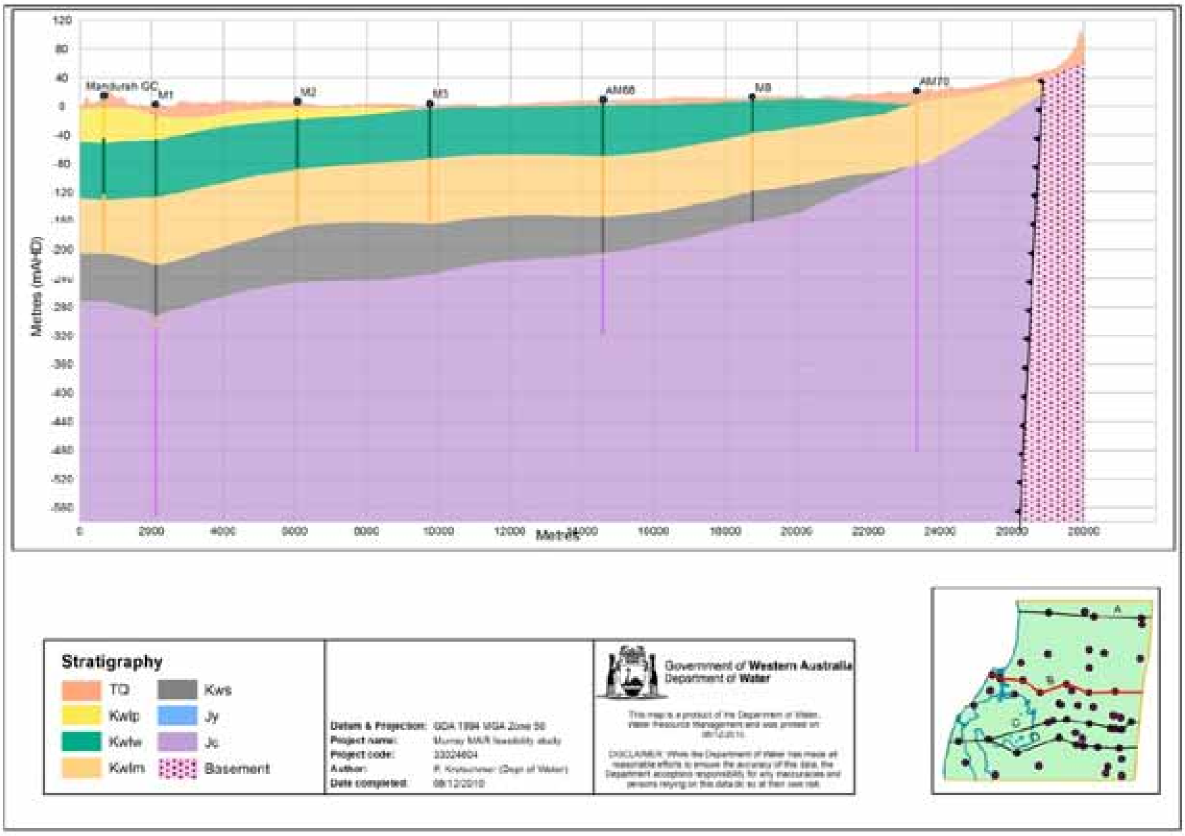
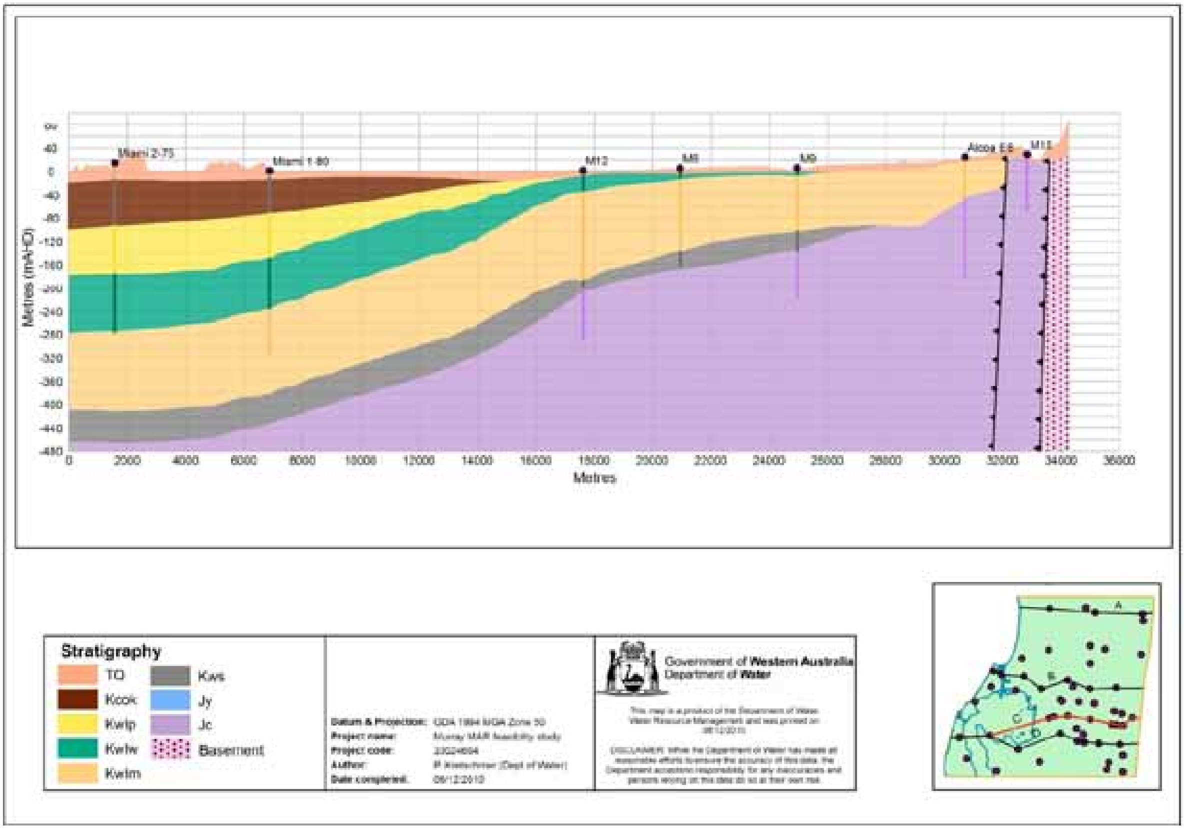


Figure 2.3 (top) and Figure 2.4 (bottom) Cross-sections of the revised geology interpretation



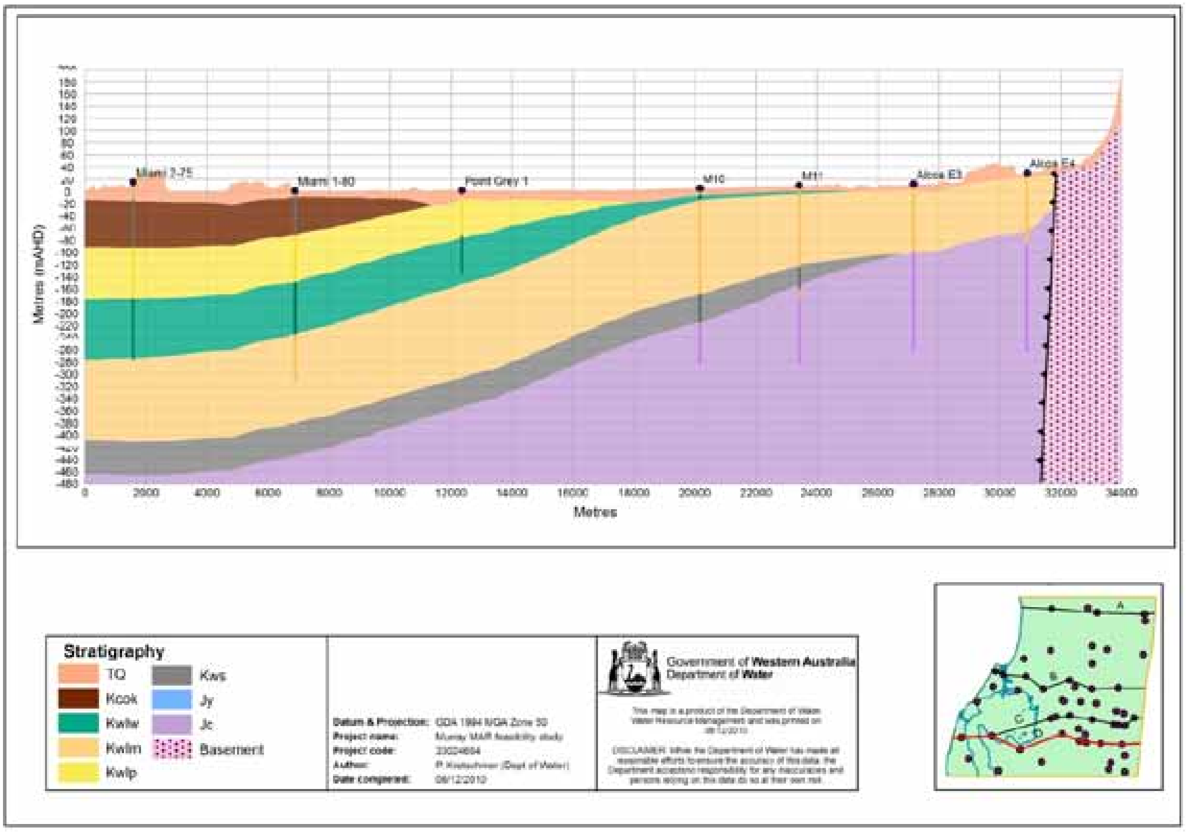


Figure 2.5 (top) and Figure 2.6 (bottom) Cross-sections of the revised geology interpretation

Below is a description of the study area's geology between the Darling Scarp and the coastline.

Cattamarra Coal Measures

The Lower Jurassic Cattamarra Coal Measures underlies the Cretaceous units in all parts of the study area except between the Mandurah and Serpentine faults where the Yarragadee Formation is present. It unconformably underlies the Gage Sandstone or South Perth Shale west of bore M9 and the Serpentine Fault, and the Mariginiup Member for much of the area between the Serpentine Fault and the scarp. In the study area's very far-eastern margins it directly underlies the superficial formations, such as around bores AM64 and M15. The deepest hole drilled in the study area, oil exploration well Pinjarra 1, found the Cattamarra Coal Measures extended down to 1203 m bgl, where it was underlain by the Eneabba Formation (Crostella & Backhouse 2000).

It consists of non-marine interbedded probably fluvial sands, silts and clay beds, with dark carbonaceous fine-grained clastic rocks and coal seams (Crostella & Backhouse 2000; Davidson 1995). The geophysical logs indicate the sandy beds can be as much as 50 m thick, being predominantly composed of medium- to very-coarse-grained subangular to subrounded quartz with occasional silt and minor clay. Separating the sand beds are silt and clay layers usually less than 30 m thick, although these are not thought to be extensive enough to act as aquitards at a regional scale.

Yarragadee Formation

The Upper Jurassic Yarragadee Formation lies below the Gage Sandstone and South Perth Shale where the Gage Sandstone is absent, and on top of the Cattamarra Coal Measures. In the study area it is bound by the Serpentine Fault to the east and the Mandurah Fault to the west.

The Yarragadee Formation consists of laterally discontinuous interbedded sandstone, siltstone and shale (Davidson 1995). The geophysical logs indicate the sandstone beds are in many instances greater than 30 m thick and the siltstone and shale layers tend to be less than 20 m thick. The lithology consists of pale grey, medium- to coarse-grained, poorly sorted, slightly feldspathic and weakly cemented sand, and was probably laid down in a shallow marine environment (Davidson 1995).

Gage Sandstone

The Gage Sandstone is the oldest Cretaceous unit in the study area. While generally thought to be quite thin in the region, its thickness is difficult to accurately assess because its signature in the geophysical logs is quite similar to the Yarragadee Formation and Cattamarra Coal Measures. It is best defined with palaeontology, however interpreting it using palaeontology reports from old investigation holes (e.g. the Mandurah series) is difficult because the mud-rotary drilling method used causes contamination. To highlight the subjectiveness of picking the Gage Sandstone, in Becher Point bores 1 and 2 (AM57 and AM58) the thickness was originally interpreted to be less than 30 m (Allen 1978), yet more recently it was estimated to be approximately 60 to 70 m thick in the same locations

(Davidson 1995). Its lithology predominantly consists of alternating beds of silt and sand, with sand beds varying between 3 to 30 m in thickness and silt beds generally less than 6 m thick. The sands are mostly coarse-grained and vary in colour from grey to brown and orange. The silts are mainly dark grey to brown with pyrite and carbonaceous material. Palaeontological evidence indicates a mainly terrestrial deposition environment with intervening periods of shallow marine. Due to the constraints of the available data this unit has not been separated from the Jurassic formations in the revised interpretation.

South Perth Shale

The South Perth Shale underlies the Leederville Formation west of the Serpentine Fault in the northern two-thirds of the study area (its eastern extent in the southern third is not as well understood). Over much of this area it is in conformable contact with both the overlying Mariginiup Member and underlying Gage Sandstone. Where the Gage Sandstone is not present it directly overlies the Cattamarra Coal Measures. It ranges in thickness from east to west, being between 30 to 60 m thick, and was deposited in a predominantly marine environment. The South Perth Shale consists of a thick sequence of interbedded silt and clay with minor sand content. It is dark grey to black and commonly pyritic and glauconitic. It forms a major confining bed that separates the overlying Leederville Aquifer from the underlying Cattamarra Aquifer.

Leederville Formation

In the study area, the Leederville Formation underlies the entire region with the exception of a narrow margin directly adjacent to the Darling Fault where the Cattamarra Coal Measures are present. It increases in thickness to the north-west, being over 200 m thick near Mandurah. The Leederville Formation predominantly consists of interbedded sandstones, siltstones and shales, and is subdivided into the Mariginiup (lower), Wanneroo (middle) and Pinjar (upper) members. The Pinjar Member has either been eroded or was never deposited in much of the study area. It is still found in a narrow section in the study area’s north between the Mandurah and Serpentine faults, and also under the Peel Inlet and surrounding area. In the central and western areas the upper-most Cretaceous layer is the Wanneroo Member, while in the eastern areas it is the Mariginiup Member; with both increasing in thickness and depth from east to west. In the study area, the sands of the Wanneroo Member are beige to dark grey, and occasionally green with glauconite, mostly uncemented, poorly sorted fine- to medium-grained quartz with feldspar and trace heavy minerals. The siltstones and shales are generally dark grey, black, mottled olive green or brown. They are usually micaceous, with minor carbonaceous material, and commonly associated with pyrite and glauconitic grains (Davidson & Yu 2008).

The Mariginiup Member is similar to the Wanneroo Member but the proportion of siltstone and shale beds to sandy beds is much higher. It can be identified in resistivity logs by sharp resistivity spikes from cemented carbonate layers.

The Leederville Formation conformably overlies the South Perth Shale in the study area. It is unconformably overlain by the Osborne Formation south and west of the Peel Inlet and superficial formations everywhere else. Depth to the Leederville Formation varies between 12 m in the east to greater than 60 m in the south-west.

Osborne Formation

The Cretaceous Osborne Formation has only a very limited extent in the study area's south-western corner, mostly under Point Grey Peninsula and west of the Peel and Harvey estuaries. It underlies the superficial formations and overlies the Leederville Formation. The Kardinya Shale is the main member present; however, a thin section of the underlying Henley Sandstone Member may be picked in some geophysical logs. In areas where the Kardinya Shale is present it may act as a confining aquitard over the underlying Leederville Formation, making the underlying aquifer more suitable for MAR.

Superficial formations

The study area's surface is covered by the collective superficial formations, which range in thickness from about 10 to 20 m and have been deposited on a gentle westerly downward-sloping surface. However, the thickness increases to more than 50 m in the coastal dunes. They tend to vary from sandy clay in the east to sand and then limestone in the west. An extended discussion of the superficial formations in the study area is provided in Hall et al. (2010a).

These units unconformably overlie the Cretaceous Leederville Formation, a minor region of the Jurassic Cattamarra Coal Measures adjacent to the Darling Scarp, and ramp up against the Archean basement of the Darling Range.

The Rockingham Sand is normally discussed as a separate geological unit that has a strong hydraulic connection with the overlying superficial formations. After reviewing the geophysical logs and palaeontology recorded in the area, the Rockingham Sand has been interpreted to be part of the Wanneroo Member, and is therefore discussed in this report as part of the Leederville Formation. An extended discussion on the revised interpretation can be found in Appendix A.

2.2 Regional hydrogeology

The Murray area has four aquifers, of which the lower three are of interest to this study (Table 2.1). The Superficial Aquifer is discussed in detail in earlier reports (Hall et al. 2010a; 2010b; 2010c; Kretschmer et al. 2011). The Superficial Aquifer is largely filled to capacity during an average-rainfall winter and has limited capacity for additional storage as a result. For this reason, its hydrogeology and artificial recharge opportunities are not discussed further in this report. The Leederville Aquifer is composed of several geologic members and varies from unconfined to confined. For allocation purposes it is separated into an upper and lower aquifer, the border of which is a green-clay marker bed. Finally, the Cattamarra Aquifer (similar to the Yarragadee Aquifer north of this region) is a confined aquifer that extends under most of the study area.

Table 2.2 The relationship between stratigraphy and hydrogeology

Superficial formations (TQ)	**Superficial Aquifer**
Osborne Formation (Kco)	**Aquitard**
Leederville Formation - Pinjar Member (Kwlp)	**Upper Leederville Aquifer**
Leederville Formation - Wanneroo Member (Kwlw)	
Leederville Formation - Marijiniup Member (Kwlm)	**Lower Leederville Aquifer**
South Perth Shale (Kws)	**Aquitard**
Gage Sandstone (Kwg)	**Cattamarra Aquifer** (including Yarragadee Aquifer)
Yarragadee Formation (Jy)	
Cattamarra Coal Measures (Jc)	

Superficial Aquifer

Groundwater abstraction

At January 2010, allocation from the Superficial and Rockingham aquifers within the Murray groundwater area was approximately 4.6 GL/yr, with a total allocation allowance of 28.5 GL/yr. It should be noted that these aquifers have a limited capacity to yield large volumes of water from a single drawpoint without causing adverse impacts; that is, up-coning of salt water, soil acidification and impacts on groundwater-dependent ecosystems including conservation category wetlands (DoW 2010a).

Leederville Aquifer

Hydrodynamics

The Leederville Aquifer extends under much of metropolitan Perth where it predominantly has an east-to-west hydraulic gradient. Within the study area the Leederville Aquifer has been the subject of research by Commander (1975), Davidson (1995), Lindsay (2004) and Pennington Scott (2009), and has had a model built for it as part of the Perth Regional Aquifer Model System (PRAMS) (Davidson & Yu 2008). The Leederville Aquifer is made of three members, all of which contain varying amounts of interbedded sand, silts and clays.

The uppermost member is the Pinjar Member, which mostly consists of silts and clays with minor lenticular sand beds. In some locations the Pinjar Member may be consolidated enough to act as an aquitard (Martin et al. 2009), however in the study area it has either never been deposited or been completely eroded away except for a limited extent between the Mandurah and Serpentine faults and underlying the Peel Inlet. This means the middle Wanneroo Member is unconfined to semi-confined in much of the study area. The Pinjar and

Wanneroo members are referred to as the upper Leederville Aquifer in allocation plans. The sandy lithology of the Wanneroo Member means it is usually a high-yielding aquifer zone.

The lower member is the Mariginiup Member, which is sandy in places but tends to become siltier with depth and to the study area's north. In allocation plans the Mariginiup Member is also referred to as the lower Leederville Aquifer. The hydraulic connectivity of the upper and lower Leederville aquifers is restricted by the green-clay marker bed (Emmenegger 1964; Commander 1975), as well as the interbedded silts and clays which lower the vertical hydraulic conductivity. Underlying the Leederville Formation is the South Perth Shale which forms a significant aquitard separating the Leederville Aquifer and the underlying Cattamarra Aquifer. The eastern extent of the South Perth Shale is interpreted to be the Serpentine Fault in the north and approximately in alignment with, but not related to, the Murray River in the south.

Groundwater heads indicate that hydraulic gradients are mainly east to west, with high levels of recharge entering the study area from the north-east (figures 2.7 and 2.8). Recharge is also likely to occur more gradually in the central areas where it is in direct contact with sandy superficial formations and there are downward hydraulic gradients; however; high clay content in parts of the superficial formations and low vertical hydraulic gradients are likely to reduce recharge rates. It is unclear whether the Serpentine Fault has any influence on east-west flow patterns in the Leederville Aquifer in the study area.

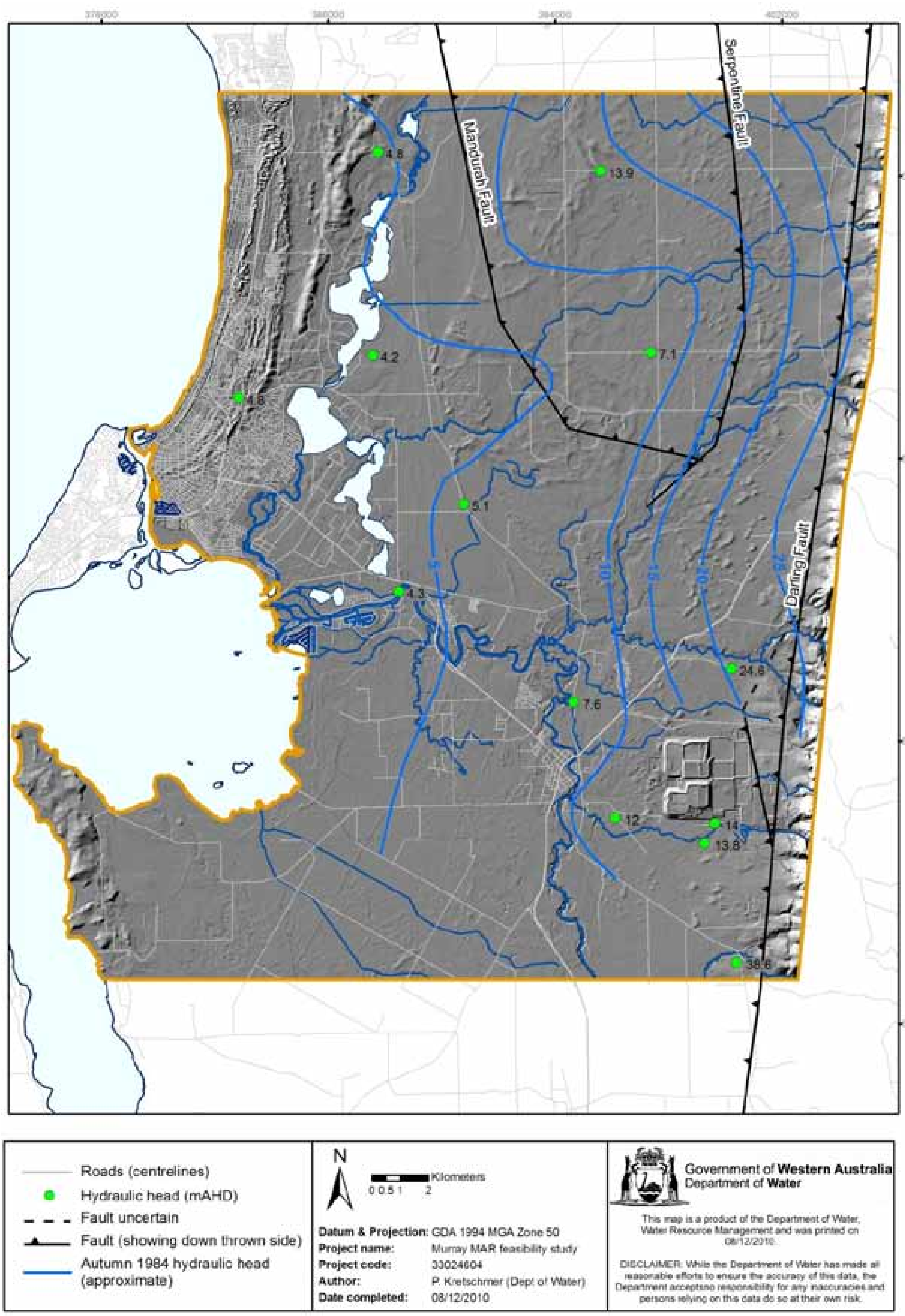


Figure 2.7 Leederville Aquifer hydraulic head contours in autumn 1984

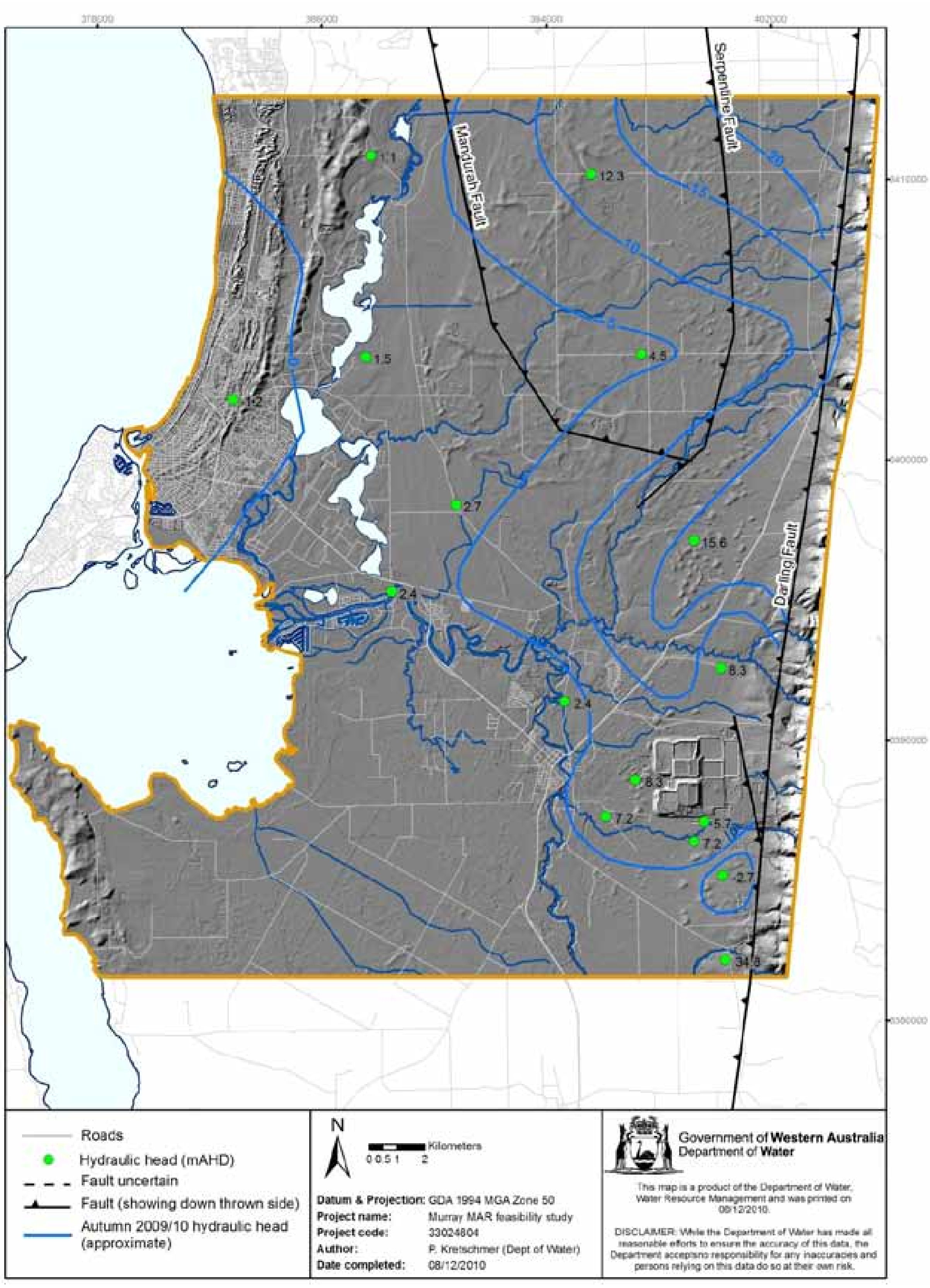
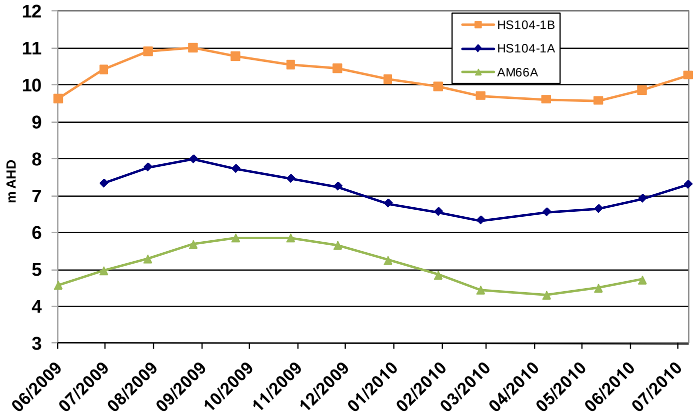


Figure 2.8 Leederville Aquifer hydraulic head contours in autumn 2009

In much of the study area the upper Leederville Aquifer is in direct contact with the superficial formations between the Mandurah Fault and Peel Inlet. This effectively means much of this unit is predominantly unconfined, although clayey sand beds within the aquifer will reduce rates of vertical flow and potentially provide weak confining layers. The upper Leederville Aquifer is more likely to be confined between the Mandurah and Serpentine faults where the overlying Pinjar Member is present. It is also confined south and west of the Peel Inlet. An aquifer model has been built as part of the Perth Regional Aquifer Modelling System (PRAMS) (Davidson & Yu 2008), although the modelling only extends south to a line passing through the Murray and North Dandalup rivers.

Few bores have been installed for investigating the hydrodynamics of the upper Leederville Aquifer in the study region (most of the Leederville artesian monitoring bores are screened in the lower Leederville Aquifer). In 2009, two nested bore sites were established in the upper Leederville Aquifer in the middle of the study area as part of the *Murray hydrological studies* (Hall et al. 2010a). These bores provide some information on the interaction between this aquifer and the Superficial Aquifer where it is unconfined. At site HS104, HS104-1B was screened in the Superficial Aquifer, and HS104-1A screened between 55 to 58 m bgl just above the green-clay marker bed at the base of the upper Leederville Aquifer. At site HS97 three bores were installed: HS97B in the upper Superficial Aquifer, HS97A at the base of the Superficial Aquifer, and HS097 from 62 to 68 m bgl at the base of the upper Leederville Aquifer.

The hydrographs of the nested bores HS104-1A and HS104-1B, plus lower Leederville bore AM66A located 7 km east, are illustrated in Chart 2.1A. It shows there is a 3 m head gradient from the watertable to the base of the upper Leederville Aquifer. This downward head gradient extends into the lower Leederville Aquifer and illustrates that the study area’s central regions are potential recharge areas for the aquifer. However, the green-clay marker bed is likely to be acting as an aquitard (Emmenegger 1964; Commander 1975). At the HS97 site there was a downward gradient from the watertable (HS97B) to the base of the Superficial Aquifer (HS97A). HS97A and HS097 at the base of the upper Leederville have a matching head throughout the year, indicating a high level of vertical connection. For comparison AM65A was added to Chart 2.1B. It is screened in the lower Leederville Aquifer and is located approximately 3 km away. Again, the temporal changes in hydraulic head differential suggest the green-clay marker bed may indeed be acting as an aquitard in the area.



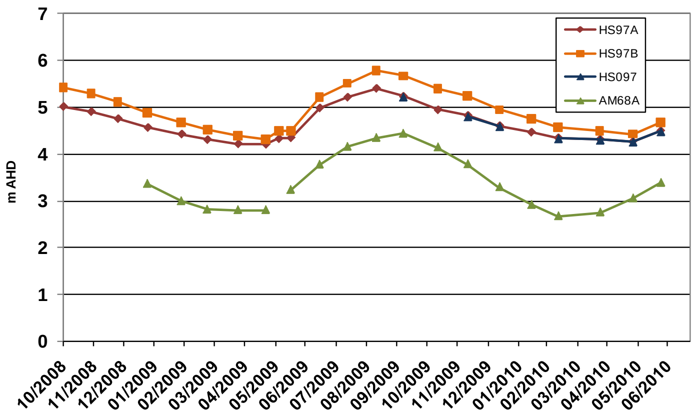


Chart 2.1 Hydrograph for the Superficial – Leederville Aquifer interaction. A) HS 104-B – Superficial Aquifer; HS104-1A – upper Leederville Aquifer; AM66A – lower Leederville Aquifer. B) HS97A; HS97B – Superficial Aquifer; HS097 – upper Leederville Aquifer; AM66

Groundwater abstraction

In the study area, there are more than 160 in-force and proposed licensed abstraction points in the Leederville Aquifer, with over half licensed to abstract less than 10 ML/yr. Information about total licensed volumes either approved or pending licensing decisions is provided in Section 2.3.

During the 25-year period between the two potentiometric surfaces illustrated in figures 2.7 and 2.8, hydraulic heads have declined by approximately three to four metres in much of the study area. Groundwater abstraction is likely to be the main driver of this decline as opposed to climate-induced declines, as the hydraulic heads in the Superficial Aquifer in this area have changed little over time (Hall et al. 2010a). Hydraulic heads at AM67A screened in the lower Leederville Aquifer now decrease below 0 m AHD every summer due to high seasonal demand.

Water quality

The following section discusses the quality of the Leederville Aquifer's native groundwater. Knowledge of the existing water quality is important for understanding the aquifer's environmental values and how MAR source water might relate to those values.

Electrical conductivity

Most data for the upper Leederville Aquifer has been collected incidentally during investigations into either the Superficial or lower Leederville aquifers. Groundwater in most of the aquifer is fresh, with total dissolved solid (TDS) concentrations at HS104-1A of 460 mg/L, and at HS97, of 600 mg/L. Importantly, salt water moves up the Serpentine River into its lower lakes over summer. Infiltration of salt water into the underlying aquifer may occur in stretches of the river if the head gradient is downward.

For the lower Leederville Aquifer, electrical conductivity was plotted in temperature compensated µS/cm due to a general lack of TDS values being recorded from bore sites. The contour map constructed using these values shows a general trend of fresh to saline water from north-east to south-west in the Leederville Aquifer (Figure 2.9). The values ranged from 592 µS/cm (AM59A) to 24 665 µS/cm (M2 bore) (Chart B.1). The high electrical conductivity in M2 bore and elevated electrical conductivity in M3 bore may indicate saltwater intrusion into the aquifer from the Peel Inlet. In the study area's north, the saltwater interface has been inferred from geophysical logs in artesian monitoring bores AM54, AM57 and AM58 at around -65 m AHD (Davidson 1995). The Miami 1-80 bore located on Point Grey, south of the Peel Inlet, has a resistivity log which indicates saline water within the Wanneroo Member of the upper Leederville Aquifer. However, no record of a water sample exists for the Miami 1-80 bore to provide a quantitative estimate of the concentration.

In relation to the potential development areas, electrical conductivity is lowest (freshest) in the North Dandalup, Nambeelup and Ravenswood development areas, ranging to brackish in the southern-most development areas of Buchanans and Nerrima. Assuming an approximate relationship of TDS (mg/L) = electrical conductivity (µS/cm) x 0.6, areas south and west of the 2500 µS/cm (~1500 mg/L) contour are likely to contain water that has TDS in excess of irrigation water guidelines (ANZECC & ARMCANZ 2000).

Alkalinity and hardness ($CaCO_3$)

Alkalinity is a measure of the buffering capacity of water to acidification: the higher the concentration, the higher the buffering capacity. It was generally lower in the study area's northern and eastern parts, which correlates with the indicative recharge areas. As the water moves through the aquifer it will slowly dissolve carbonates, silicates and the alkaline base – which leads to a general relationship of alkalinity increasing with the direction of the historical flow paths.

The maximum alkalinity of 276 mg/L was recorded at Mandurah bore M10, and the minimum of 57 mg/L at M17 and AM70A, with an overall mean value of 166 mg/L (Chart B.2).

Water hardness is understood to be a measure of the capacity of water to precipitate soap (ADHA 2005). The maximum water hardness was recorded at M2 with a concentration of 3694 mg/L, where saltwater intrusion is an influencing factor. The groundwater was softest at AM61B with a value of 33 mg/L, located north-east of the study area (Chart B.3). Excluding bores M2 and M3 due to the influence of saltwater intrusion, the mean hardness was 231 mg/L. Most samples were in the range of moderately-hard to hard on the Hardness Scale (Davidson 1995).

Nitrate-Nitrogen

Nitrate-Nitrogen ranged from 0.07 to 0.56 mg/L with a mean of 0.16 mg/L (Chart B.4). There appears to be no spatial relationship.

Phosphorus

Phosphorus concentrations were relatively low, ranging from the reporting limit of 0.005 mg/L to 0.140 mg/L with a mean of 0.038 mg/L (Chart B.5).

pH

The pH of the groundwater was generally close to neutral, ranging between 5.0 to 8.8 with values tending to be slightly acidic (<7.0) nearest the scarp, increasing to slightly alkaline (>7.0) in the west (Chart B.8).

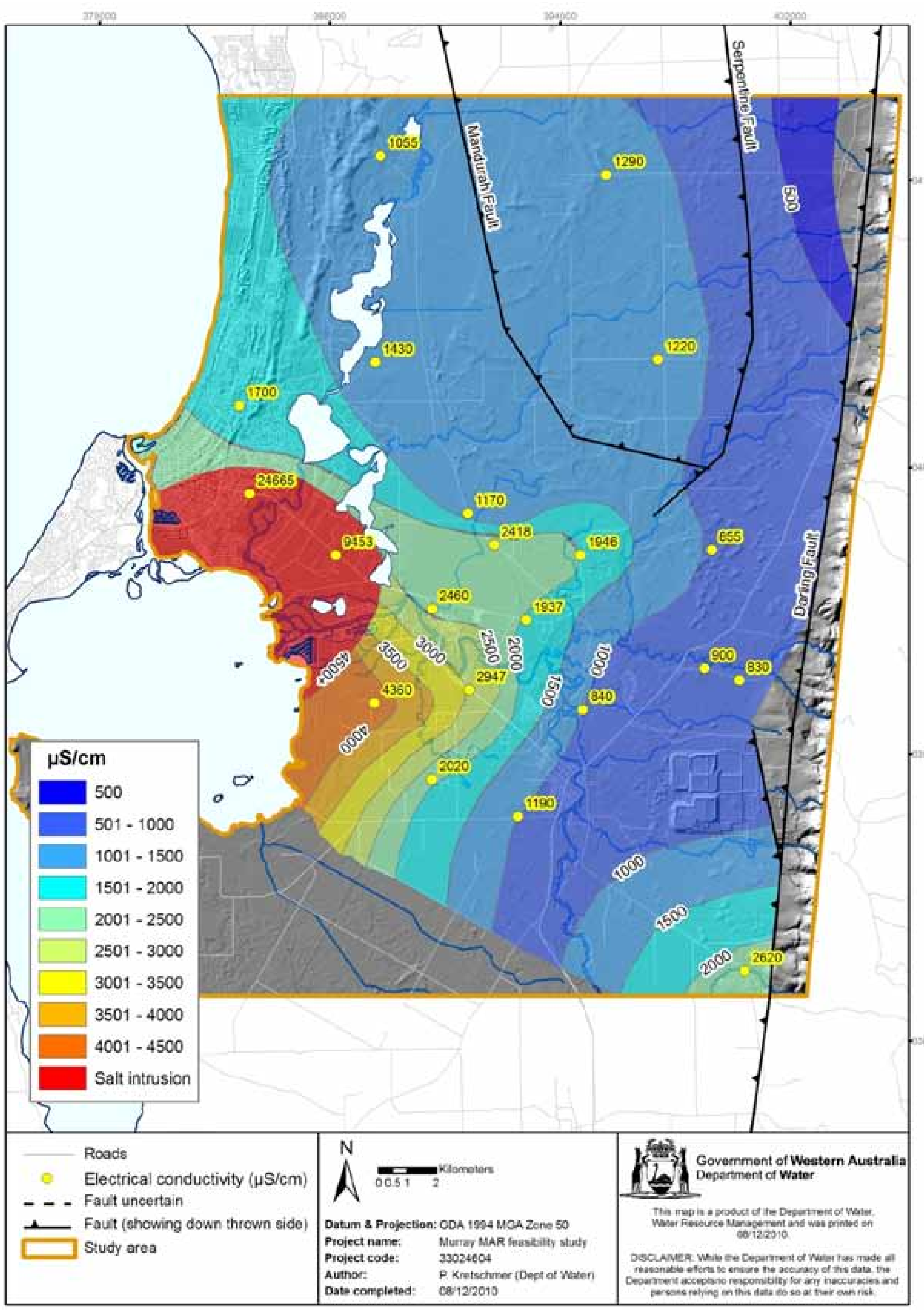


Figure 2.9 Combined lower Leederville Aquifer electrical conductivity (temperature compensated to 25°C)

Cattamarra Aquifer

Hydrodynamics

In this report we refer to the Cattamarra Aquifer for simplicity, but it has also been referred to as the Yarragadee Aquifer (in reference to the Yarragadee Formation that occurs between the Mandurah and Serpentine faults in the study area, and more extensively under the coastal plain north of the study area). The Yarragadee Formation and Cattamarra Coal Measures are thought to be hydraulically disconnected across the Serpentine Fault, and this is supported by the electrical conductivity contours. The influence of the Mandurah Fault on their hydraulic connection is less certain. For the purposes of this study it is assumed the two formations are hydraulically connected across the Mandurah Fault. In addition, the Gage Sandstone is encountered in several bores at the top of the Jurassic formations. It appears to be less than 30 m thick and is connected hydraulically to the Cattamarra Aquifer. Therefore in the study area the Cattamarra Aquifer is comprised of three geological units in total.

The Cattamarra Aquifer extends under much of Perth where they predominantly have an east-to-west hydraulic gradient. In the study area the Cattamarra Aquifer's eastern extent is the Darling Fault and it extends westwards under the ocean where it eventually discharges to the sea. In the study area the overlying South Perth Shale acts as a confining bed separating the Cattamarra and Leederville aquifers. Recharge to the aquifer occurs along narrow areas east of the extent of the South Perth Shale, where the Cattamarra Coal Measures is overlain by either the Mariginiup Member or directly overlain by the superficial formations. The hydrographs for monitoring bores AM70 and AM70A in Appendix B illustrate the connection between the Leederville and Cattamarra aquifers. The connection can be seen in the response of the hydraulic heads to increased abstraction in the Cattamarra Aquifer in 2001, which elicited a corresponding response in the Leederville Aquifer. The historic potentiometric surface illustrated in Figure 2.10 indicates the region north of monitoring bore AM64 is a particularly significant recharge window in the study area.

The hydraulic gradient is generally small and the horizontal conductivity (K_h) can be quite variable, ranging between $1x10^{-6}$ and 10 m/day, with an average rate of flow of around 0.9 m/yr (Davidson & Yu 2008). Geophysical logs of several deep bores in the study area indicate sandy sequences up to 40 m thick, with interbedded clay and silt beds ranging between 2 and 20 m thick. An aquifer model has been built as part of the Perth Regional Aquifer Modelling System (PRAMS) (Davidson & Yu 2008), although the modelling stops at the northern end of the Murray River.

Groundwater abstraction

Figure 2.11 shows a significant decline in the potentiometric surface as a result of abstraction north of the study area and in the south-eastern corner. Hydrographs in Appendix B show declines in the hydraulic head of up to 9 m in AM series bores, and a cone of depression around the borefield servicing the alumina processing facility east of Pinjarra. The rate of hydraulic head decline appears to have become steeper since 2000, due to increased demand during a period of low rainfall. The aquifer is 99% allocated in the Nambeelup groundwater subarea, while the Pinjarra groundwater subarea is fully allocated with additional requests pending allocation decisions.

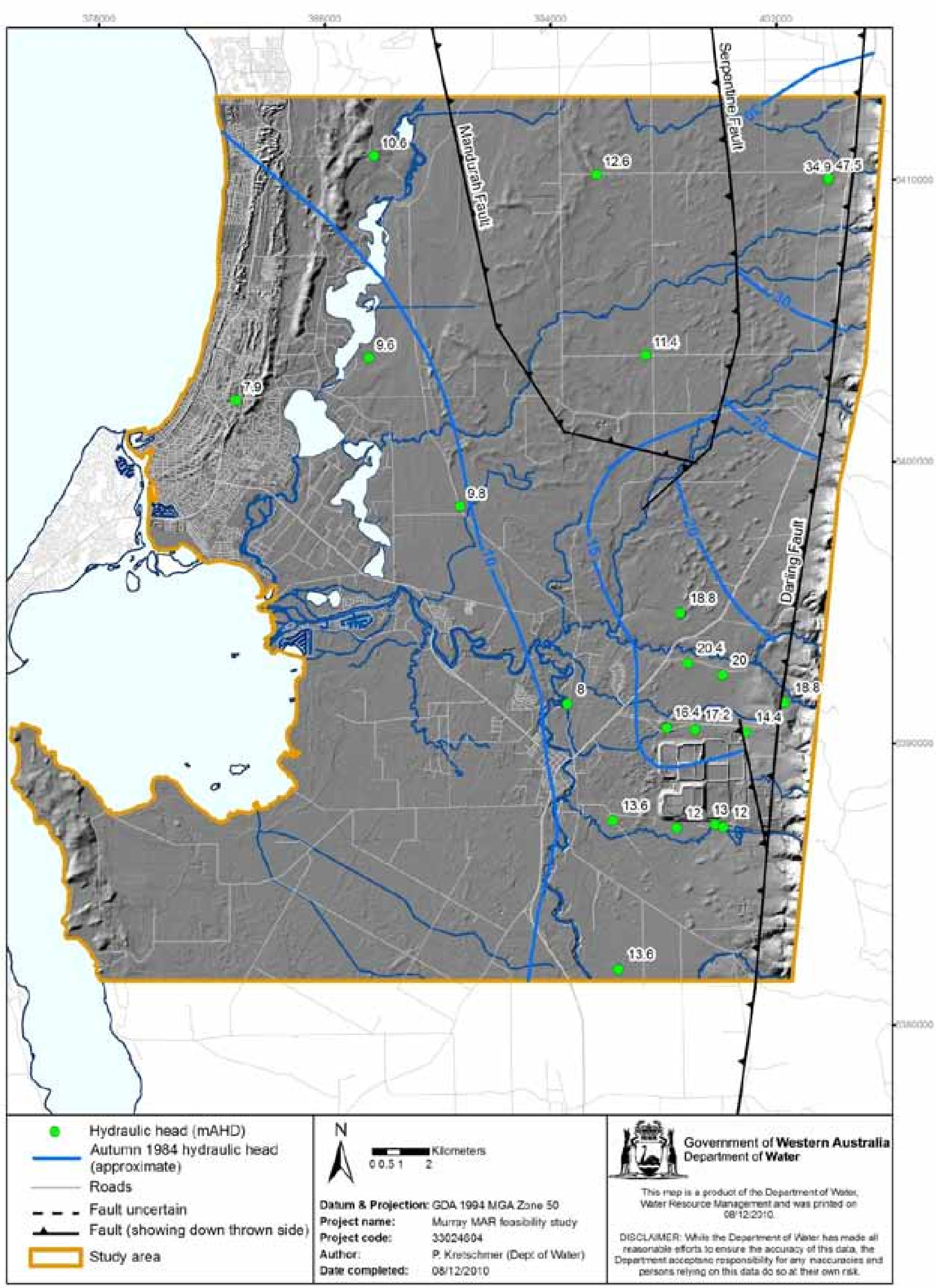


Figure 2.10 Estimate of Cattamarra Aquifer hydraulic head contours in autumn 1984

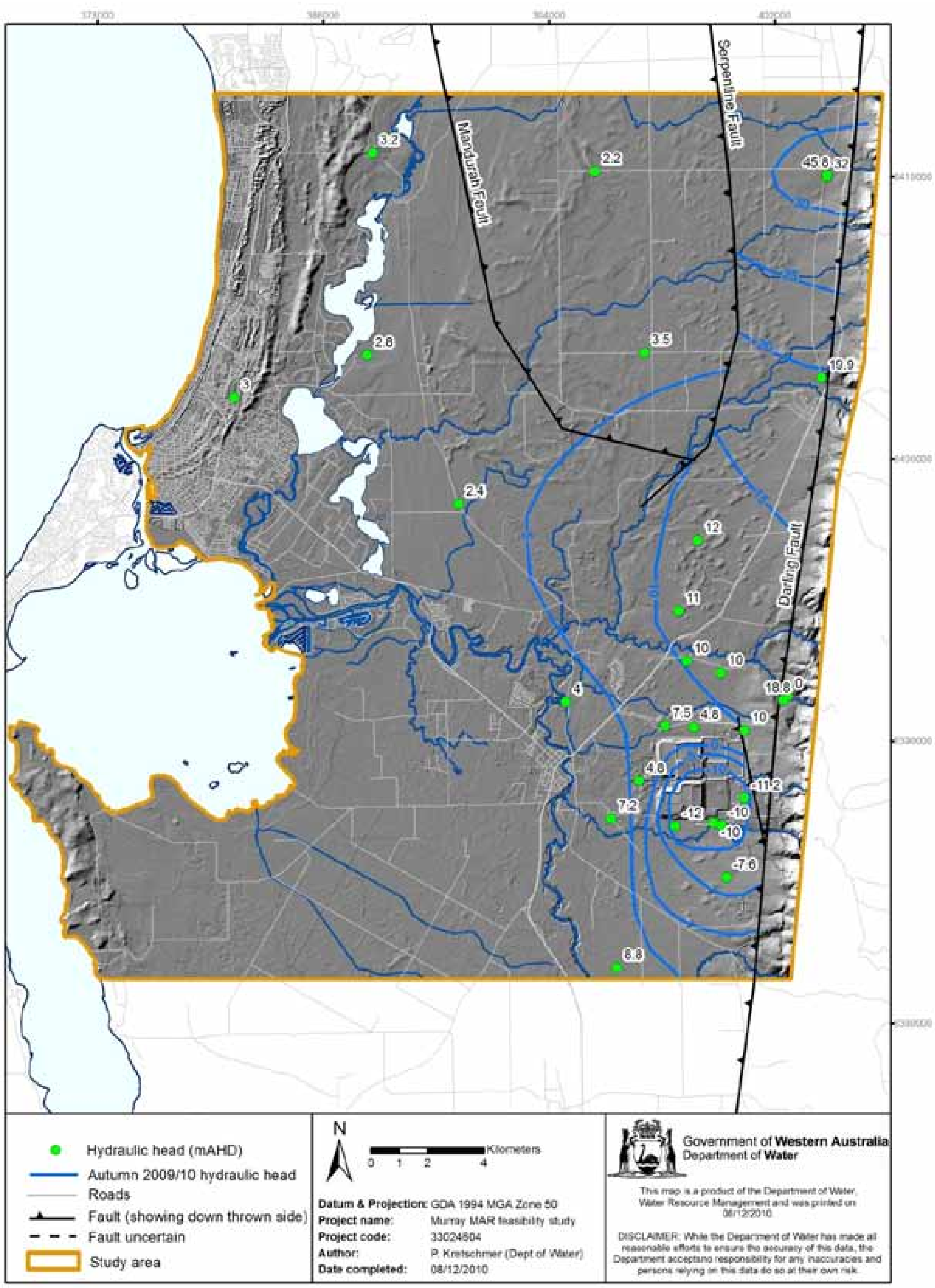


Figure 2.11 Cattamarra Aquifer hydraulic head contours in autumn 2009-10

Water quality

The following section outlines the water quality of the native groundwater in the Cattamarra Aquifer. Knowledge of the existing water quality is important for understanding the aquifer's environmental values and how MAR source water might relate to those values.

Electrical conductivity

The electrical conductivity is lowest (freshest) near the artesian monitoring bore AM64 where the Cattamarra Coal Measures directly underlies the superficial formations. The electrical conductivity and hydraulic head isolines both indicate that recharge around this area may be concentrated near Myalup Brook and Dirk Brook where they flow off the Darling Scarp. The isolines then indicate the groundwater is prevented from flowing directly west from the recharge areas due to the Serpentine Fault acting as a hydraulic barrier. Thus the groundwater is diverted north and south, and under the historical 1984 gradients it appears that water was able to then move westwards once it reached the southern mapped extent of the Serpentine Fault (Figure 2.12). The maximum electrical conductivity value was 6001 µS/cm recorded at AM67, and the minimum was 344 µS/cm recorded at AM64 (Chart B.9). Although the tabulated data shows the lowest electrical conductivity was recorded at AM64A, a different dataset recorded from bore AM64 was used in the contour map because it had multiple measurements over a longer time compared with AM64A. For reference the electrical conductivity at AM64A was 279 µS/cm.

The electrical conductivity contours and hydraulic data also support mapping of a hydraulic barrier fault east of the Alcoa refinery (Commander 1975; Rockwater 2010). The groundwater on the fault's eastern side is brackish and the potentiometric data recorded in M15 shows little correlation with nearby wellfield drawdown. Some components of the data also suggest the presence of a north-west trending fault separating M10 to the south from M11 and M12 to the north. This is reflected in M10's significantly higher electrical conductivity, thicker South Perth Shale and greater depth to the Cattamarra Coal Measures compared with M11 and M12. Contours were not drawn for the area south of this line because of a paucity of data. Future investigations are being planned to expand knowledge of the confined aquifers south of the Murray River.

In relation to the development areas, electrical conductivity is lowest in North Dandalup and brackish in Pinjarra and Carcoola. The electrical conductivity increases to the west of these areas with concentrations of >2500 µS/cm; thus these areas would exceed ANZECC irrigation water guidelines.

Alkalinity and hardness ($CaCO_3$)

Alkalinity is quite variable in the Cattamarra Aquifer. North of the study region, a gradual increase in concentration from west to east occurs – with the maximum concentration in alkalinity of 400.7 mg/L recorded at AM61. South of this area, alkalinity appears to decrease from west to east with the lowest alkalinity concentration of 25 mg/L occurring at AM64A along the scarp, atypically below AM61 where the maximum was recorded (Chart B.10). This is contradictory to the pattern observed in the Leederville Aquifer and does not appear to correlate with recharge areas.

The maximum water hardness was recorded at M15 with a reading of 347 mg/L, and the softest water was 8.2 mg/L recorded at AM61 (Chart B.11). The average hardness was 108 mg/L, with most of the samples ranging between moderately-soft to slightly-hard water on the Hardness Scale (Davidson 1995). There appears to be no spatial correlation between the samples.

Nitrate-Nitrogen

Nitrate-Nitrogen had a minimum concentration of 0.07 mg/L with four bores – AM63, AM64A, AM66 and AM67 – recorded at this level. A maximum concentration of 0.56 mg/L was recorded at the M15 bore, but most Nitrate-Nitrogen concentrations at the various bores were low, with an overall mean of 0.16 mg/L (Chart B.12).

Phosphorus

Phosphorus concentrations were low, ranging from the detection limit of 0.005 to 0.090 mg/L with a mean of 0.020 mg/L (Chart B.13).

pH

The pH of the groundwater was variable, ranging between 5.6 and 9.77. There appears to be no spatial relationship (Chart B.16). Samples with low pH also had relatively low alkalinity, so the analyses are internally consistent.

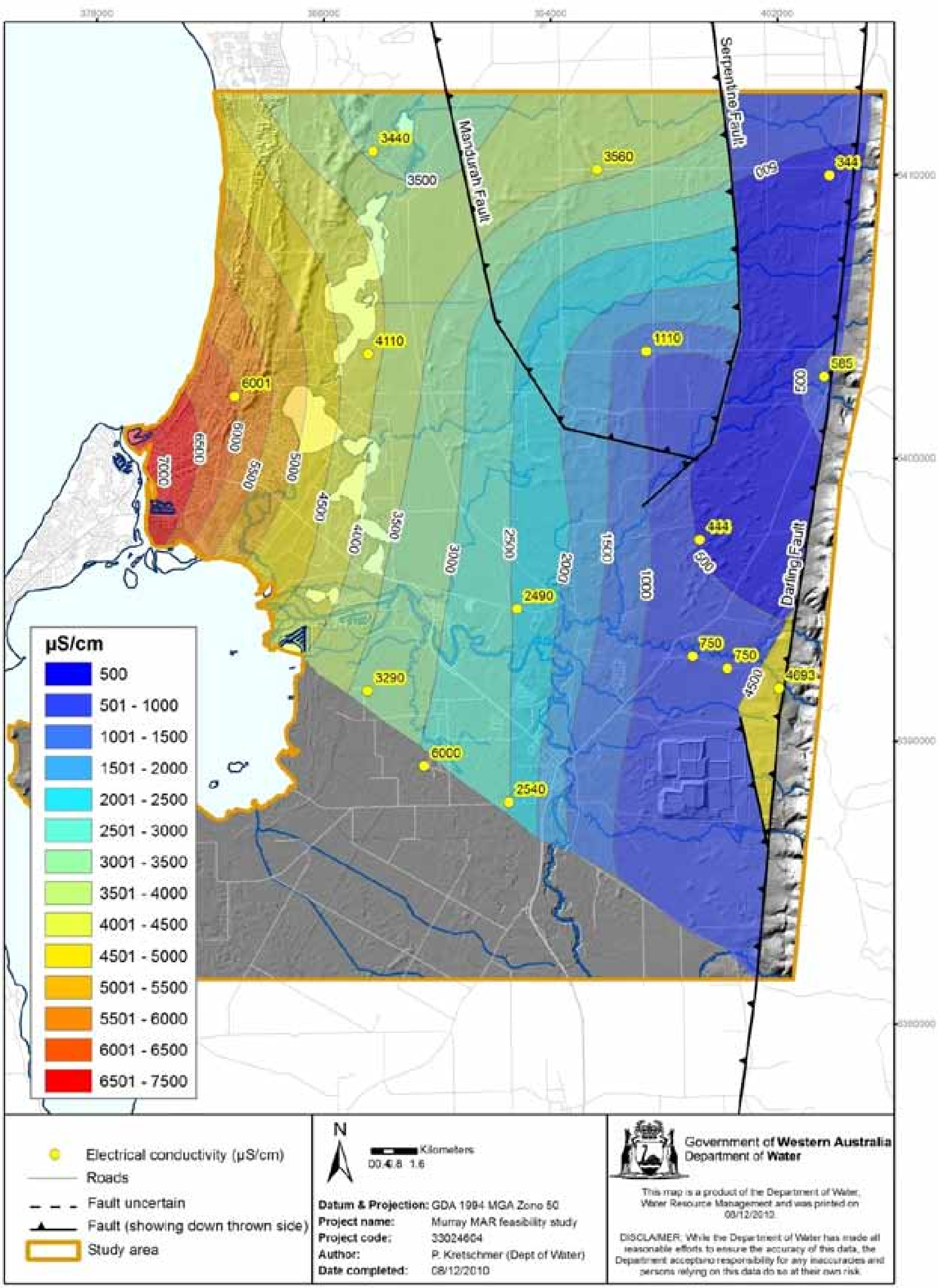


Figure 2.12 Cattamarra Aquifer electrical conductivity (temperature compensated to 25°C)

Comparison of water quality data to ANZECC guidelines

This section compares the water quality of the groundwater in the Leederville and Cattamarra aquifers with the ANZECC guidelines. This comparison helps to identify the aquifer's environmental values and its suitability for general use and irrigation after MAR.

Electrical conductivity

By comparing the aquifers' electrical conductivity concentrations to the 'irrigation water salinity ratings' (based on EC) from the ANZECC guidelines, we can make assumptions about plant suitability. Salinity in the Leederville Aquifer rated from very low to high, for which 'sensitive' through to 'tolerant' crops would be suitable (Table 2.3). This excludes the region of the Leederville Aquifer where saltwater intrusion is suspected (Figure 2.9).

In the Cattamarra Aquifer, higher electrical conductivity values were recorded and salinity rated from very low to very high, with corresponding plant suitability ranging from 'sensitive' to 'very tolerant' crops.

Table 2.3 Irrigation water salinity ratings based on electrical conductivity (adapted from ANZECC-ARMCANZ 2000)

EC (µS/cm)	TDS (mg/L)*	Water salinity rating	Plant suitability
<650	<390	Very low	Sensitive crops
650-1300	390-780	Low	Moderately sensitive crops
1300-2900	780-1740	Medium	Moderately tolerant crops
2900-5200	1740-3120	High	Tolerant crops
5200-8100	3120-4860	Very high	Very tolerant crops
>8100	>4860	Extreme	Generally too saline

* A conversion factor of 0.6 was used to convert Electrical Conductivity to TDS

Alkalinity

The bicarbonate (HCO_3^-) ion is one of the major contributors to alkalinity in irrigation waters and soil. No trigger value is recommended for bicarbonate in irrigation waters in the ANZECC guidelines (ANZECC-ARMCANZ 2000).

Hardness

The ANZECC guidelines recommend that waters be maintained at a hardness level of >60 mg/L ($CaCO_3$) to minimise the corrosion that can be associated with soft water (ANZECC-ARMCANZ 2000). Hard water can lead to encrustation and scaling of distribution systems (e.g. drip irrigation lines) or other equipment. For general agricultural water, a trigger value of 350 mg/L $CaCO_3$ is recommended to limit excess encrustation and take into account the influence of hardness on fouling rates.

The Leederville Aquifer was within the recommended limits for the prevention of corrosion and fouling, with the exception of one concentration that was below the recommended minimum. The average water hardness, excluding the two outlying bores (M2 and M3), was below the recommended upper limit (fouling) with a concentration of 231 mg/L.

The average hardness concentration in the Cattamarra Aquifer was more often than not within the recommended limits to prevent corrosion and fouling. However six samples were below the minimum value and thus corrosion could be problematic in these cases.

Nitrogen and phosphorus

The ANZECC guidelines state that the long-term trigger value (up to 100 years) for all inorganic forms of nitrogen present in water is 5 mg/L, and the short-term trigger value (up to 25 years) is 25 to 125 mg/L (requires site-specific assessment) (ANZECC-ARMCANZ 2000). All nitrogen concentrations recorded for the Leederville and Cattamarra aquifers were well below these trigger values.

The long-term trigger value (up to 100 years) for phosphorus is 0.05 mg/L: this is to minimise bioclogging of irrigation equipment only. The short-term trigger value (up to 25 years) is 0.8 to 12 mg/L (requires site-specific assessment) (ANZECC-ARMCANZ 2000). Again the concentrations recorded for the Leederville and Cattamarra aquifers were well below the trigger values.

pH

To limit corrosion and fouling of pumping, irrigation and stock watering systems, the ANZECC guidelines recommend that pH should be maintained between 6 and 8.5 for groundwater systems and between 6 and 9 for surface water systems (ANZECC-ARMCANZ 2000).

The pH values recorded in most Leederville Aquifer bores were within the recommended values stated for the pH of groundwater, with the exception of three bores. The Cattamarra Aquifer bores showed similar results, with the exception of five bores that were not within the recommended range.

2.3 Regional demand and supply

To warrant investment in an MAR project, proponents need to understand the likely demand for the recovered water. As development has not yet occurred in the region, it is not possible to be entirely confident of future demand, although various recently-published reports provide some estimates. It is important that MAR proponents undertake their own investigations into future demand as part of any *Australian guidelines for water recycling* (Stage 2) process to establish whether a proposed concept is financially viable.

Water supply and demand

Current supply

Current groundwater allocation for confined aquifers in the region is nearing full allocation in several key groundwater management areas (Table 2.4). Groundwater allocations in the Murray groundwater area were recently reviewed (DoW 2010a). As a consequence the allocation limit in the Nambeelup subarea (Figure 2.13) was recently reduced in the upper Leederville (Wanneroo Member) from 6 to 4 GL/yr (DoW 2010a), reducing the available water to meet growing demand. Current applications for groundwater, if approved, would exhaust all remaining capacity available in the Leederville Aquifer in the Nambeelup subarea. It should be noted that despite the allocation reductions, the 7 GL/yr allocation limit for the combined upper and lower Leederville aquifers remains higher than the estimated 5.8 GL/yr of total recharge (DoW 2010a). It is possible that over-allocated aquifers will negatively affect or delay demand for alternative water supply schemes.

Table 2.4 Groundwater allocation status for allocation areas within the study area

	Superficial			Leederville combined			Yarragadee combined		
Sub-region	Allocation limit	Allocated & requested	%	Allocation limit	Allocated & requested	%	Allocation limit	Allocated & requested	%
Serpentine & Stake Hill groundwater allocation area									
Keysbrook & Keysbrook Confined	720 000	0	0	150 000	0		450 000	0	0
Keysbrook 1	2 000 000	1 578 606	79	750 000	874 690	117	0	0	
Keysbrook 2	2 600 000	295 220	11	860 000	448 229	52	0	0	
Mandurah	5 000 000	3 523 702	70	1 000 000	935 637	94	0	0	
South west coastal groundwater allocation area									
Falcon	1 800 000	572 064	32	2 200 000	1 444 170	66	0	0	
Murray groundwater allocation area									
Nambeelup	12 100 000	2 810 771	23	7 000 000	7 055 874	101	600 000	592 500	99
Coolup	15 100 000	1 256 930	8	6 000 000	2 286 287	38	0	0	0
Pinjarra	1 250 000	549 343	44	1 800 000	631 375	35	2 6000 00	5 588 500	215

Figures for groundwater allocation areas as at August 2010. Note all values are subject to change.

The Cattamarra Aquifer is already fully allocated in the Nambeelup and Pinjarra subareas. Any future allocation increases would depend on the outcome of extensive investigations and modelling by the proponent. Given that investigations can be costly, the water quality may be unsuitable and any increase in allocation may be small, it is difficult to envisage this aquifer becoming a major source for supplementing increasing water demands without MAR supplementing its natural recharge rates.

With the confined aquifers at or near full allocation, the Superficial Aquifer will become a target for more extraction – but it has both physical and environmental constraints. As the aquifer is unconfined, large-scale extraction can result in large cones of depression in the watertable, which in turn can increase the risk of acid sulfate soils developing (Kretschmer et al. 2011) and ecologically significant wetlands being affected by reduced water levels (Hall et al. 2010c). In the study area it is likely the Superficial Aquifer will mostly be suitable only for low-yielding domestic bores distributed over an extensive area.

Connecting new developments solely to the IWSS will provide a stable supply of very high quality water, however this shifts the onus of meeting water demand onto the Water Corporation. In some instances, the cost of water being treated to drinking-quality standard and supplied through the IWSS may limit its economic viability for large water users (industry or local governments), which do not necessarily require water to be treated to such a high standard. The issue of economic viability is compounded given that current retail prices are forecast to increase. Over time as the IWSS increases its unit price, the development of alternative water supply schemes will become more economically viable.

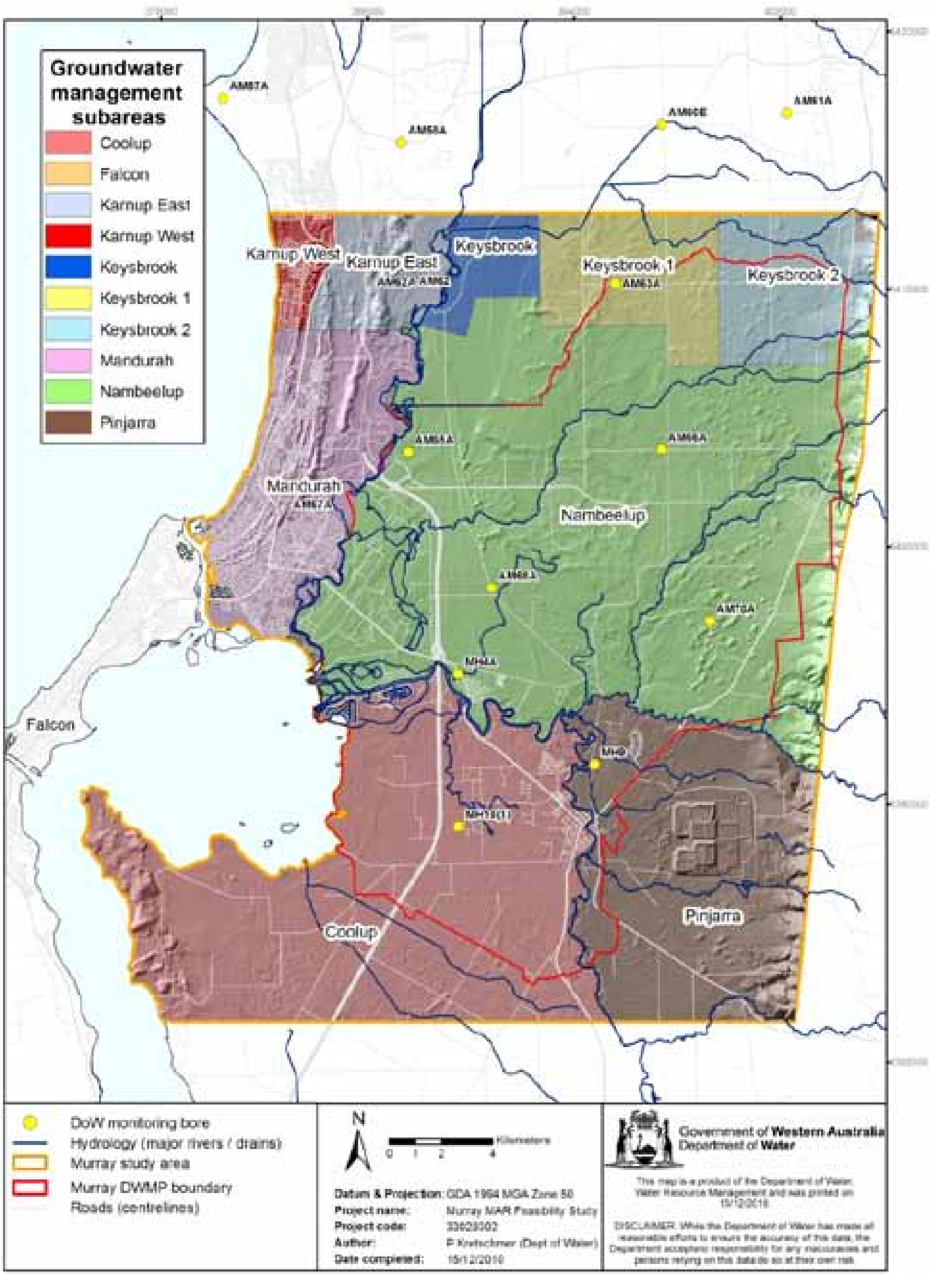


Figure 2.13 Groundwater allocation subareas within the study area

Projected demand

Since 2001, per capita consumption of water supplied by the IWSS to the Perth metropolitan area has averaged 155 kL/yr, including an average of 107 kL/yr per residential customer (DoW 2009c). These figures exclude self-supply through garden bores, which provide a significant reduction in demand on the IWSS.

The population of the Mandurah, Murray and Serpentine-Jarrahdale regions is predicted to grow by 50 900 people between 2009 and 2031 (WAPC 2009), not including proposals for the Keralup district. A simple calculation implies an increased demand of between 5.5 and 7.9 GL/yr on the IWSS from these regions alone. For domestic usage, approximately 47% of water is used outside the home, 14% in the laundry and 12% in the toilet. This means up to

73% of domestic usage may not require drinking-standard water (DoW-DPC 2008). If third-pipe reticulation was installed for all proposed residential development, demand for recycled water might exceed 4 GL/yr.

Table 2.5 Peel region estimated water demand through to 2030 (DoW 2009)

Peel region Demand scenarios	Demand (GL/yr)
Current demand (2008)	15
2030 demand - existing per capita consumption	28
2030 demand - 100kL/yr per capita consumption	28
2030 demand - all sectors 10% efficiency gain	26
2030 demand - all sectors 20% efficiency gain	23

Data from: Strategic directions to 2030: Perth - Peel regional water plan discussion paper. Note the 'Peel region' mentioned is larger than this report's study area

Self-supply from domestic garden bores will mitigate water demands on the IWSS and should be further investigated. However large-scale garden bore abstraction has risks associated with effects on protected groundwater-sensitive ecosystems and acid sulfate soil disturbance. Modelling indicates that garden bore abstraction will cause an approximate 1 m decline in summer minimum groundwater levels compared with an equivalent scenario without garden bores (Hall et al. 2010c).

With the aquifers approaching full allocation in the region, meeting the increased demand will require new sources of water to be developed. MAR, in conjunction with significant improvements in water use efficiency, would be highly beneficial for balancing water supply and demand. The *State water plan* sets a target of 20% of wastewater to be recycled by 2012, increasing to 30% by 2030 (DPC 2007).

Community and government attitudes

The community strongly supports the use of recycled wastewater (91%) on public open space, parks, public playgrounds and golf courses (DoW 2009d). There is also proven industry support demonstrated by the Kwinana Water Reclamation Plant which has been successfully recycling up to 6 GL/yr of treated sewage for industrial use since 2004. There is more concern about using recycled water for drinking and cooking, with only 48% of people supportive (DoW 2009d).

The *State water recycling strategy* (DoW-DPC 2008) states that all future heavy and general industrial areas will be required to investigate the installation of third-pipe reticulation to encourage the use of recycled water. The strategy also encourages the use of recycled water to irrigate public open space. The Department of Water's *Operational policy 1.01 – Managed aquifer recharge in Western Australia* outlines our favourable view of water recycling using MAR (DoW 2009b). We also support the banking of recharge in the aquifer over short periods – an important step toward building drought resilience in the water supply system.

The Water Corporation also intends to increase how much wastewater is recycled from the current 6% to 30% by 2030, and 60% by 2060 (Water Corporation 2009).

Potential source water availability for MAR

Drainage water

Much of the Murray region is a palusplain wetland where large areas become waterlogged each winter, despite its extensive network of paddock drains. To prevent the proposed urban areas becoming waterlogged, a significant upgrading of drainage infrastructure will be required. As part of the *Murray hydrological studies*, subsurface drainage was modelled in the areas designated for potential development. The modelling predicted that converting land use from agriculture (and native vegetation) to urban would greatly increase the volume of drainage water requiring management (Hall et al. 2010c). By modelling land, climate and drainage scenarios, Hall et al. (2010c) calculated the total volume of drainage water that would discharge from the proposed development areas. The study's estimates of how much drainage water would need to be managed under various scenarios are provided in Table 2.6 below.

It is important to note that these results are from a regional model. Modelling undertaken as part of a district water management strategy investigation should provide more precise estimates of how much drainage water needs to be managed.

The drainage scenarios are:

- subsurface drains at ground level with 1 m of clean fill
- subsurface drainage 1 m below ground level, no fill
- subsurface drainage at average annual maximum groundwater level (AAMaxGL) with 1 m of clean fill
- subsurface drainage at maximum groundwater level (MaxGL) with 1 m of clean fill

The climate scenarios are:

- current climate: climate as measured for the period 1975 to 2007
- future wet climate: -1.4% change in mean annual rainfall from 1975 to 2007
- future medium climate: -8.7% change in mean annual rainfall from 1975 to 2007
- future dry climate: -16.2% change in mean annual rainfall from 1975 to 2007

The development areas are the same as discussed in the modelling report and are reproduced in Figure 1.1, based on WAPC (2009). Domestic bore abstraction is detailed in Hall et al. (2010).

Table 2.6 Predicted drainage volumes from proposed development areas for future wet, dry and medium climate scenarios for each of the development areas under three different subsurface drainage scenarios

Total drainage volume from development area	Future wet climate		Future medium climate				Future dry climate		Historical wet
	Drains at ground level	Drains at 1 m bgl	Drains at ground level	Drains at AAMaxGL	Drains at MaxGL	Drains at ground level, domestic bores	Drains at ground level	Drains at 1 m bgl	No drains
	S11 (ML)	S15 (ML)	S20 (ML)	S26 (ML)	S39 (ML)	S40 (ML)	S29 (ML)	S33 (ML)	S36 (ML)
South Yunderup	45	367	19	75	5	12	6	168	80
Austin Cove	1084	1599	834	919	765	280	690	1004	617
Nerimma	2223	2785	1817	1994	1799	682	1841	1833	1211
Buchanans	4471	5715	3615	4014	3528	2177	3509	3626	3779
Pinjarra	441	418	401	436	395	394	349	333	463
South Murray	94	174	43	189	69	23	28	48	95
Barragup	82	493	40	297	56	18	15	145	178
Ravenswood	3394	4587	2597	3122	2609	226	2727	2742	1567
Nambeelup	3954	5554	2945	3460	2871	1182	2572	3137	2947
Carcoola	474	672	371	460	353	366	278	376	553
North Dandalup	720	1024	567	581	560	562	426	674	672
TOTAL	**16 982**	**23 387**	**13 249**	**15 546**	**13 008**	**5 922**	**12 441**	**14 087**	**12 161**

Subsurface drainage increases the volume of water to be managed because it intercepts the watertable before it rises to the surface where, under natural conditions, much of it would have evaporated (Hall et al. 2010c). The increased drainage volume is balanced by decreased evaporation and horizontal flow. This is best illustrated in Figure 2.14 below.

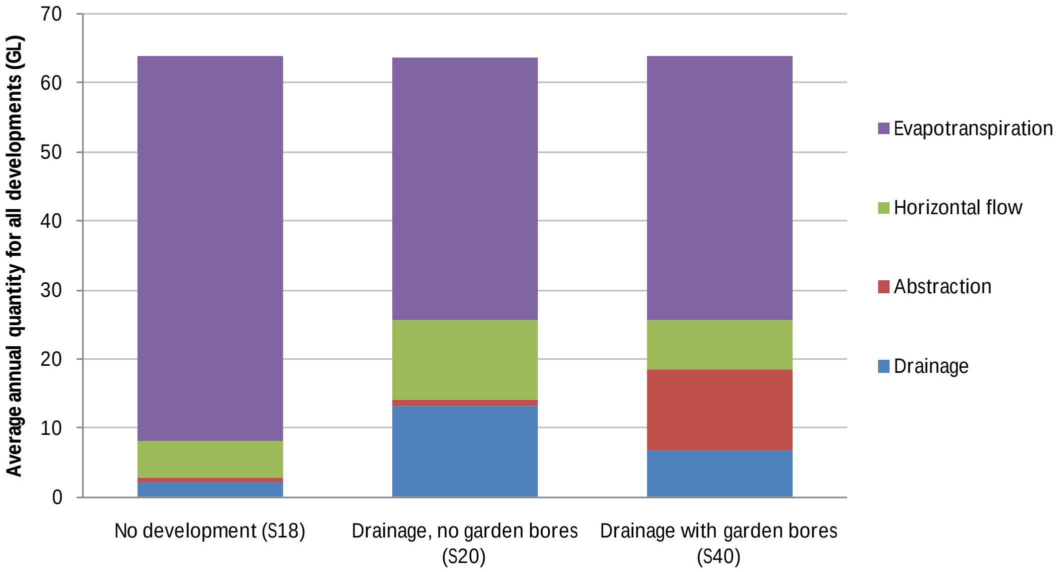


Figure 2.14 Water balance for the future medium climate scenario with no development, and development with drainage at ground level with and without garden bore extraction (source: Hall et al. 2010c)

Garden bore development will reduce the volume of drainage water available for MAR. It is therefore advisable to investigate how garden bore extraction may affect the feasibility of MAR when undertaking a district water management strategy investigation. Garden bore development will vary with the type of land use developed and its density.

2.4 Stormwater quality

In Australia subsurface drainage has primarily been installed to control waterlogging. It can also be used to alleviate high watertables under urban areas and intercept groundwater flow to surface features to protect valuable infrastructure such as pipes and roads (Christen & Ayars 2001). Further investigations are required into how to design and manage subsurface drainage to improve drainage water quality. For example, the use of appropriate fill when building up the landscape and adding soil amendments may contribute to significant ‘first-stage’ filtration and water quality improvement. For MAR/ASR schemes, well clogging and other issues requiring treatment are less likely to occur with higher-quality source water.

Stormwater quality data from residential developments was compared with the average concentrations of analytes from the Cattamarra Aquifer to determine a suitable water source for aquifer recharge (Table 2.7). The stormwater quality data was collected from a range of sources such as surface water drains, subsurface drains and piezometers. Unfortunately very limited data was available for residential development areas in Western Australia. Significant investigations are required in this area and the lack of available data and difficulty obtaining it is acknowledged.

The Ellenbrook northern catchment is the only site with stormwater quality samples across all three drainage sources (for 2008–09). From the available data it was determined that subsurface drainage generally had lower concentrations than groundwater and surface water drains for the variables measured, thus may be a preferable choice for aquifer recharge. The maximum concentration of the various parameters was used for comparison with the Cattamarra Aquifer to allow for error by assuming a worst-case scenario.

For proponents in situations where there is inadequate data on stormwater quality to support a risk assessment, the Australian guidelines on stormwater harvesting and reuse (NRMMC-EPHC-NHMRC 2009b) provide default concentrations and pathogen numbers. However, we recommend that proponents try to obtain the relevant water quality data because the default values in the guidelines are conservative.

A useful resource for understanding stormwater quality parameters is a report by Duncan (1999) entitled *Urban stormwater quality: a statistical overview*. On a broad scale this document assesses the behaviour of urban runoff, its quality, and its interaction with land use and other catchment characteristics. The *Non-structural controls, stormwater management manual for Western Australia* (DoW 2005) also provides useful information.

Table 2.7 Comparison of piezometer, subsurface and surface drainage water quality with an overall average of specific analytes from the Cattamarra Aquifer

Area	Source	TN (mg/L)	No_x -N (mg/L)	NH_3 -N/ NH_4 -N (sol) (mg/L)	P (sol) (mg/L)	EC @ 25 deg C (µS/cm)	TDS (cond) (mg/L)	pH
Cattamarra Aquifer	Mean: bores summary	0.38*	0.16	0.69	0.02	2504	1883	7.60
Ellenbrook Northern Catchment 2008/2009[1]	Mean: piezometer	2.4	1.77	0.15	0.078	650	357	5.09
	Range: piezometer	<0.01-17	<0.01-16	<0.01-0.86	<0.005-0.7	0-4860	0-2673	2.36-7.21
	Mean: subsurface drain	1.03	0.18	0.23	0.02	520	286	4.85
	Range: subsurface drain	0.79-1.40	0.08-0.38	0.14-0.33	<0.005-0.016	390-600	215-330	4.31-5.45
	Range: surface drain	1.6-6.2	<0.01-0.11	<0.01-0.01	0.06-0.43	710-1300	391-715	4.9-6.94
Ellenbrook Northern Catchment 2009/2010[2]	Mean: subsurface drain	1.91	1.08	0.33	0.009	560	308	4.54
	Range: subsurface drain	0.48-17.0	0.04-16.0	0.12-0.90	<0.005-0.1	170-1010	94-556	2.96-6.81
Riverland Ramble, Ravenswood[3]	Mean: piezometer	5.77	0.84	0.87	0.28	1580	868	5.94
	Range: piezometer	0.35-57	0-4.7	0-4.8	0-1.4	20-6040	11-3322	3.48-7.27
	Range: surface drain	1.7-9.6	<0.01-1.5	<0.01-1.1	<0.005-1.4	440-1340	198-737	5.6-7.33
Bletchley Park Development[4]	Range: piezometer	<0.01-3.23		<0.01-8.45	<0.01-3.05	381-3580	449-2092	3.52-7.44
	Range: surface drain	0.06-4.63		<0.01-4.63	0.05-6.4	862-4250	525-2720	5.84-8.02
Pinjarra Meadows: 2008 Stage 1 post development[5]	Mean: piezometer	2.2			<0.005			
	Range: piezometer	0.3-6.45	0-0.02			1210-7770		5.66-6.86
	Mean: surface drain	2.7			<0.005			
	Range: surface drain	2.6-2.8	0.07			730-2080		7.07-7.58
Pinjarra Meadows: 2009 Stage 1 & 2 post development[6]	Mean: piezometer	3.8						
	Range: piezometer	0.38-9.4	0-3.16		<0.005-0.13	800-8060		4.7-8.77
	Mean: surface drain	9.6						
	Range: surface drain	4.3-15	0.52-1.85		0.02-0.13	1110-1160		6.07-6.24
East Busselton post residential development monitoring[7]	Mean: piezometer	6.08	1.13	0.17	0.014	3130	715	6.8
	Range: piezometer	0.37-37	0.01-4.06	0.02-0.96	0.005-0.037	350-17000	0-5626	5.8-7.4
	Range: surface drain	0.56-4.1	0-0.70	<0.01-0.91	<0.005-0.21	660-1350	429-840	6.4-7.9
Byford Central Project[8]	Range: subsurface drain	1.7-4.8	0.63-1.02					

*NO_x

[1] JDA 2009a, *Ellenbrook northern catchment 2008/2009 annual monitoring report*, JDA Consultant Hydrologists.
[2] JDA 2010a, *Ellenbrook northern catchment 2008/2009 annual monitoring report*, JDA Consultant Hydrologists.
[3] JDA 2008, *Riverland Ramble, Ravenswood – monitoring data*, JDA Consultant Hydrologists.
[4] Bioscience 2010, *Bletchley Park water monitoring report*, Bioscience Pty Ltd, prepared on behalf of Wallis Consulting.
[5] JDA 2009b, *Pinjarra Meadows Stage 1: Post-development monitoring report 2008*, JDA Consultant Hydrologists.
[6] JDA 2010b, *Pinjarra Meadows Stage 1 & 2: Post-development monitoring report 2009,* JDA Consultant Hydrologists.
[7] JDA 2010c, *Provence year 3 post development hydrological monitoring report 2008–09*, Satterley Property Group Pty Ltd.
[8] Nichols, P 2010, Subsurface drainage water quality data for Byford Central (personal communication: email), Perth, Cardno, WA.

2.5 Identification of suitable aquifers

This section briefly summarises the suitability of the Leederville and Cattamarra aquifers for MAR using injection wells in an aquifer storage and recovery (ASR) scheme.

Leederville Aquifer

The Leederville Aquifer offers some prospects for ASR. The Wanneroo Member is thought to be mostly unconfined except where the Pinjar Member overlies it. Where it is overlain by the Pinjar Member it is possible that small-scale ASR schemes may be able to operate. It is difficult to ascertain the likely success of such a scheme because the Pinjar Member's extent is limited. If such a proposal were put forward it would need to be assessed carefully with local (as opposed to regional) information being of particular importance. The Wanneroo Member has a number of existing users that would need to be accommodated. It also has generally good water quality. Hence any proposal would need to ensure existing users were protected and that the native groundwater quality would not be negatively affected.

The Mariginiup Member is more likely to handle ASR injection pressures, but further investigations would be required to prove whether the clay layers were comprehensive enough to act as an aquitard under high pressure. The geophysical logs indicate the Mariginiup Member is sandier in the middle of the study area, becoming increasingly silty to the north. To help prove the feasibility of a concept, specific pump testing/monitoring would be needed to assess the interconnectedness of the horizontal beds within the formation. At low injection pressures the aquitard issues may not be as much of a concern, but field testing would still be required to check the concept's validity and ensure phreatic surfaces were not adversely affected. The Mariginiup Member also has a number of existing users and water quality which is generally quite good. Thus any proposal would need to ensure the native groundwater quality would not be negatively affected, and that the modification of hydraulic heads would not adversely affect existing users.

Cattamarra Aquifer

The most suitable aquifer for ASR in the region is the Cattamarra. Importantly, the South Perth Shale is likely to act as a comprehensive confining layer across the study area's western half. This means that injection pressures are unlikely to impact on the shallower aquifers and the phreatic surface. Excluding the Department of Water's artesian monitoring bore network, the aquifer has few existing users in the study area, with the western-most users being located near Pinjarra. The Cattamarra Coal Measures is likely to be conducive to the injection of water because its thick sandy sequences should provide reasonable rates of transmissivity around an injection well. The hydraulic head ranges between just-artesian to subartesian, with heads dropping in all areas over time causing an increasing area to become subartesian. The regional hydraulic gradient is small: reducing the risk of the injected water moving away from the injection point too rapidly, and increasing the prospect for longer-term storage or banking of injected water.

The water is brackish in much of the study area, with the exception of the area east of the Serpentine Fault/Murray River where the water quality is generally fresh. In the western areas the aquifer tends to have less restrictive environmental values due to its TDS being in excess of 1500 mg/L and no known interaction with recognised groundwater-dependent ecosystems.

Storage capacity of the Cattamarra Aquifer

With the Cattamarra Aquifer being identified as the most suitable for ASR, the aim of this section is to provide conservative estimates of the aquifer's storage capacity for receiving treated stormwater. The volume quantified is the additional volume of water that may be stored in the aquifer at pressures above that shown in the autumn 2010 potentiometric surface, owing predominantly to elastic storage.

The capacity of a confined aquifer to store additional water is a function of the aquifer's size, storage coefficient and potentiometric head. The formula used to calculate the additional storage is:

$$\Delta V = A.h.b.S$$

Where $A = surface$ area

$h =$ available head

$b =$ aquifer thickness

$S =$ storage coefficient

(Hodgkin 2004)

This calculation assumes the aquifer is able to hold the water under confined, fully saturated conditions. Storage coefficients are not commonly measured in the deep formations due to the cost of installing monitoring infrastructure and conducting large-scale pump-tests. Fortunately, in the early 1970s a one-year-long pump test of the Cattamarra Aquifer (in the study area) was undertaken for development of the Alcoa alumina refinery's borefield (Legette Brashears & Graham 1971). This study estimated a storage coefficient of 5.0 x 10^{-4}. Other values have been published from this pump test, ranging between 1.0 x 10^{-4} to 7.2 x 10^{-4}, with a geometric mean of 3.7 x 10^{-4} (Legette Brashears & Graham 1973, cited in Hydrosearch 2010). A more recent pump test was completed on the Wanneroo Member of the Leederville Formation for an ASR research program being undertaken at the Beenyup wastewater treatment plant, north of the Swan Estuary (Martin et al. 2009). The geometric mean for this latter study yielded values of 1.24 x 10^{-3} during drawdown and 8.03 x 10^{-4} during recovery. For modelling, a storage coefficient of 1 x 10^{-4} has previously been used for the Cattamarra Aquifer (Davidson & Yu 2008).

Given the range of values, the volume estimates presented here are based on two different storage coefficients: a lower value of 1 x 10^{-4} and an upper value of 5 x 10^{-4}. Higher values may be encountered which would serve to increase the storage capacity.

The thickness of the Cattamarra Aquifer used for these calculations is a subjective decision. It is known the aquifer is up to 1100 m thick at the Pinjarra 1 oil exploration well (Costello & Backhouse 2000), however most of this thickness would be filled with groundwater that is too saline and too deep to be economically exploitable. The layer of brackish water at the top of the aquifer would be a preferential target as it would help avoid the issue of saline deep groundwater mixing with the injected water along steep concentration gradients. The individual sandstone beds range up to 50 m in thickness and therefore a conservative assumption of a 50 m thick Cattamarra Aquifer is used. The sandstone beds' vertical connectivity is assumed to be negligible in this scenario but this would need to be assessed on a site-by-site basis. Further information is required on the benefits and drawbacks of using such a thick aquifer, including potential issues with salt-wedging during storage and up-coning during the recovery phase.

The resultant hydraulic head increase following injection and the total volume stored is linearly related. A doubling in hydraulic head results in a doubling of the volume of stored water. The increase in head will depend on a number of factors such as transmissivity of the aquifer and rate of injection, among other parameters. A maximum safe hydraulic head can be estimated by calculating the effective stress and the fracture pressure of the overlying aquitard (see Hodgkin 2004), but this was not deemed necessary for this regional investigation.

Two hydraulic head scenarios have been computed. One is calculated by assuming that hydraulic heads are raised by 10 m in the potential development areas alone, and there is no head increase outside of those areas. This is the most simplistic and conservative calculation, and will obviously not hold true in reality as heads will be increased over a much larger area. The result of these calculations is shown in Table 2.8.

Table 2.8 Estimates of storage capacity of the Cattamarra Aquifer for each development area by raising the heads by 10 m

Development Name	Development area (km^2)	Storage ($s = 5x10^{-4}$) (GL)	Storage ($s = 1x10^{-4}$) (GL)	Kws base depth (m AHD)
Nambeelup	19.3	4.8	1.0	200-220
Barragup	4.6	1.2	0.2	200-250
South Yunderup	1.2	0.3	0.1	200-250
Austin	4.9	1.2	0.2	200-260
Nerrima	8.7	2.2	0.4	220-280
Buchanans	17.7	4.4	0.9	130-230
South Murray	2.3	0.6	0.1	150-190
Pinjarra	1.5	0.4	0.1	120-160
Carcoola	2.8	0.7	0.1	100-140
Dandalup	2.1	0.5	0.1	not applicable
Ravenswood	16.5	4.1	0.8	150-220
SUM	81.6	20.4	4.1	130-280

This scenario indicates that between 4.1 and 20.4 GL of storage is available in the Cattamarra Aquifer within the development areas, using the assumptions mentioned above. The lower estimate is very conservative, but should enable a number of local-scale schemes to operate – during which information could be gained to further develop the aquifer in both the study area and surrounding areas. The upper estimate is sufficient to store the average drainage volumes for all but the 'future wet – drains at 1 m bgl' scenario (23.4 GL drainage) (Hall et al. 2010c), assuming all drainage water could be captured, treated and injected into the aquifer at a suitable rate.

The second scenario calculates the storage increase that would occur if hydraulic heads were raised from the autumn 2010 potentiometric surface to the 1984 potentiometric surface. The area over which this was calculated is that bounded to the north and south by the study area boundary, to the east by the eastern extent of the South Perth Shale and Serpentine Fault, and to the west by the coastline: creating a polygon with an approximate area of 700 km^2. The extent of the South Perth Shale was used because it constitutes the known extent of the strongly confined areas of the Jurassic formations. Using ArcGIS™ for the calculation, the average hydraulic head difference over this area between the 1984 and 2010 potentiometric surfaces was 5.9 m. Using the two different storage coefficient formulas and aquifer thickness assumptions, the volume of water able to be placed in storage is:

- 103.3 GL assuming a storage coefficient of 5×10^{-4}
- 20.7 GL assuming a storage coefficient of 1×10^{-4}

These numbers illustrate the aquifer's capacity to store large volumes of water during winter, which can then be kept for use during dry periods. The benefit of having a storage capacity in excess of one year's injection volume is that banking of multiple years' injection volumes can occur, thus developing a high-reliability supply to aid in drought-proofing the region.

3 Addressing the MAR guidelines

The intent of the *Australian guidelines for water recycling* is to provide principles and a framework for safe implementation of recycled water schemes and hence support the transition from after-treatment testing to a more integrated approach to managing water recycling activities. They form an integral part of the National Water Quality Management Strategy. The risk management approach they use is based on the framework already implemented in the *Australian drinking water guidelines* (NHMRC-NRMMC 2004). The Department of Water's *Operational policy 1.01 – Managed aquifer recharge in Western Australia* requires application of these guidelines.

This entry-level assessment was carried out within the context of the *Australian guidelines for water recycling: managing health and environmental risks, Phase 2: managed aquifer recharge* (MAR guidelines) (NRMMC-EPHC-NHMRC 2009a). The study has closely followed the steps involved in an MAR guidelines Stage 1 investigation (desktop study and entry-level assessment), and outlines some of the subsequent steps required to meet the assessment/regulatory process.

The two other sections of the guidelines relevant to this assessment are the *Australian guidelines for water recycling: managing health and environmental risks, Phase 1* (NRMMC-EPHC-AHMC 2006), and *stormwater harvesting and reuse, Stage 2* (NRMMC-EPHC-NHMRC 2009b). Both also apply to the development of full schemes, with the Phase 1 guidelines in particular focusing on the 12-element risk management framework required for all water recycling schemes. These elements include aspects such as the proponent's commitment to the responsible use and management of recycled water quality, employee awareness and training, and community involvement and awareness. Proponents seeking to implement a full scheme will need to provide such information for regulators to be able to determine the full level of risk. A table outlining the 12 elements, with useful cross-references, can be found in Appendix 1 of the stormwater guidelines. For the purpose of this study, however, the assessment and management of the MAR guidelines' risk framework has been followed. Section 3.2 of this report contains additional information on subsequent requirements to meet regulatory approvals, including the 12-element risk management plan framework.

As a part of the National Water Quality Management Strategy, the guidelines require an understanding of the relevant environmental values requiring protection. By default, all environmental values apply, with the proponent being required to demonstrate either how they do not apply, or how they are going to be protected. The Department of Water's policy on MAR (DoW 2009a) and *Draft approval framework for the use of non-drinking water* in Western Australia (DoW 2010b) are consistent with this approach. The environmental values requiring protection include drinking water, those of a cultural or spiritual nature, aquatic ecosystems, primary industries (stock water to irrigation water), recreation and aesthetics, and industrial water.

This study makes an assumption about the nature of the MAR scheme to be developed. Proponents should use the information given below as an indication of what is required in addressing the guidelines, but should not be limited by this.

The concept being addressed in the following section involves a MAR scheme targeting the confined Cattamarra Aquifer. A conceptual diagram is shown in Figure 3.1. In this simplified concept, water is captured from an urban area, potentially using subsurface drainage. The water is initially stored in a wetland to buffer inflow volumes, and to monitor and potentially treat pollutant loads before injection. An additional treatment facility may be required depending on the target water quality. The water is then injected below the South Perth Shale, raising the Cattamarra Aquifer's potentiometric heads but not affecting the phreatic surface.

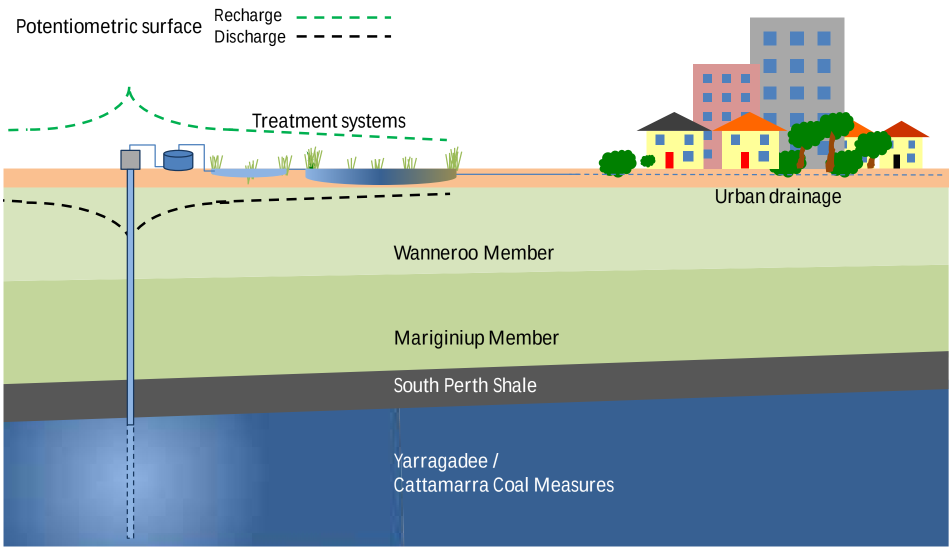


Figure 3.1 Conceptual diagram of an ASR scheme in the study area

The various components of the conceptual Murray MAR scheme are summarised in Table 3.1. This conceptual scheme forms the basis for the subsequent viability and degree-of-difficulty assessment, as per Stage 1 of the MAR guidelines.

Table 3.1 Generic MAR scheme proposed components

Component	Conceptual Murray MAR scheme
1. Capture zone	Subsurface drainage water from Murray development areas
2. Pre-treatment	No pre-treatment is assumed for the purpose of this study
3. Recharge	Injection bores: 150 to 250 m deep
4. Subsurface storage	Confined aquifer
5. Recovery	Recover as required for non-potable purposes
6. Post-treatment	As required to meet requirements for end use
7. End use	Irrigation, e.g. public open space, agriculture etc. (non-potable)

3.1 Stage 1: entry-level assessment

The first step of Stage 1 of the MAR guidelines is an entry-level assessment, designed to inform potential stakeholders of the degree of difficulty of a potential project. The entry-level assessment is divided into two parts: a viability assessment and a degree-of-difficulty assessment. Note that at this stage, given that stormwater is the proposed source, the stormwater guidelines should also be followed. Table 3.1 in the stormwater guidelines offers a project-screening-tool checklist for stormwater reuse in public open-space irrigation, along with cross references to other sections of the guidelines with more information to help proponents. For the purpose of clarity, however, the MAR framework will be followed (NRMMC-EPHC-NHMRC 2009b).

Part 1: Viability assessment

A brief account of the information required for the viability assessment is given in Table 3.2. The intent is to inform proponents of any fatal flaws in their intended project, based on existing readily-available information.

Table 3.2 Entry-level viability assessment

Attribute	**Answer**
1. Intended water use	
Is there is an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	Yes. The harvesting and reuse of stormwater captured within development areas will address issues related to discharge into sensitive waterbodies, as well as provide a source option consistent with the objectives of the *Perth-Peel regional water plan discussion paper* (DoW 2009c) See Section 2.3.
2. Source-water availability and right of access	
Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	Yes Catchment modelling indicates that across all development areas, up to 15.5 GL of source water is available under medium climate scenarios. Harvesting and reuse of this water would prevent untreated stormwater from entering sensitive aquatic ecosystems such as the Peel-Harvey estuary which is subject to an environmental protection plan. See Section 2.3.
3. Hydrogeological assessment	
Is there at least one aquifer at the	Yes.

proposed MAR site capable of storing additional water? Is the project compatible with groundwater management plans?	The Cattamarra Aquifer is confined, has few existing users, is largely non-potable in the study area and has minimal interaction with known groundwater-dependent ecosystems. It can potentially store between 20 and 100 GL in the study area. The Leederville Aquifer is partially confined, has many existing users, and the salinity is low over a large part of the development area. It therefore may be less suitable for MAR. See Section 2.6.
4. Space for water capture and treatment	
Is there sufficient land available for capture and treatment of the water?	Yes. The area is currently undeveloped. Appropriate planning, particularly at the district water management strategy stage of investigation, could allow public open space, passive treatment areas, flood management areas and MAR/ASR sites to be closely aligned to minimise cost to developers.
5. Capability to design, construct and operate	
Is there a capability to design, construct and operate a MAR project?	Yes. Capacity does exist in Western Australia in terms of the capability required. The Beenyup groundwater replenishment trial is an example of one such scheme. This capability would need to be secured by the proponent of an MAR scheme (e.g. through the commissioning of appropriate consultants).

Based on the hydrogeological assessment, the Cattamarra Aquifer appears more favourable for an MAR scheme: it is confined, has few existing users, is largely non-potable in the study area, and has minimal interaction with known groundwater-dependent ecosystems. Conversely, the Leederville Aquifer is partially confined, has many existing users, and the water quality is generally higher. As a consequence, this study focuses on the Cattamarra Aquifer for further assessment. However, this should not prevent proponents from considering other aquifers.

Part 2: Difficulty assessment

An assessment of the project's likely degree of difficulty is the second part of the entry-level assessment. Coming after a viability assessment, it broadly informs the proponent about the amount of effort likely to be needed to establish a successful scheme (one which is sustainable and meets regulatory approval requirements).

As per the requirements of the guidelines, the degree-of-difficulty assessment is based on existing data and information. It assumes the generic scheme shown in Figure 3.1, with subsurface drainage water captured, treated and injected into the confined Cattamarra Aquifer, and an intended end use of irrigation of public open space. Although this project is broad in nature (covering ~84 km^2 of pre-development area), and not focused on one specific location, the intent is to demonstrate to proponents what is required to meet the guidelines.

Information required for assessment	*Questions and indicators of degree of difficulty*
1 Source-water quality with respect to groundwater environmental values	
Where multiple samples are available, the highest concentration of each analyte should be used in the evaluation, unless there is justification that events resulting in those values will be prevented when the MAR project is established. In the absence of water-quality data from actual source water, data may be used from existing, similar MAR projects that use the same type of source water and recharge the same aquifer. In the absence of either of the above data sources, generic data from *Australian water recycling guidelines* may be used, as follows: Appendix 2 of the stormwater guidelines (NRMMC-EPHC-NHMRC 2009) gives generic data on concentrations of selected hazards in stormwater from roof catchments and urban catchments; in the absence of other information, use 95th percentile data. Assessment of quality variability and factors affecting quality are deferred to the maximal risk assessment.	**Q1. Does source water meet the water-quality requirements for the environmental values of ambient groundwater?** (Note: environmental values of water are listed in Appendix 1 of the MAR guidelines along with a reference to water-quality criteria for each where those exist. While cultural and spiritual values are not listed in the MAR guidelines, these also should be considered) *If the answer is 'Yes', a low risk of pollution is expected.* *If the answer is 'No', a high maximal risk is likely. Stage 2 investigations are likely to be necessary to assess preventive measures to reduce the risk of groundwater contamination beyond the attenuation zone (and the size of the attenuation zone).* **A1. <u>No</u> is the provisional answer based on <u>existing data</u> – but many of the parameters are at or near what could be expected to be suitable, therefore treatment could be expected to be in the low to moderate difficulty range** *Source water quality:* In Western Australia there are no schemes similar to the generic scheme proposed here that can be used to provide information on source water quality with respect to MAR of subsoil drainage water to the Cattamarra Aquifer. Available post-development monitoring data from recent developments on the Swan Coastal Plain has been used for this purpose (Table 2.7). In most of the proposed development area the subsurface source water salinity is generally lower than the native groundwater quality. Nutrient levels are generally higher but are not likely to pose a high level of difficulty for treatment to acceptable levels. Environmental values applicable to specific sites should be determined with detailed investigations. Using available information, guidance is provided on assessment against the environmental values below: *Aquatic ecosystems – low difficulty, moderate difficulty in the eastern plain* - Excluding North Dandalup, the Cattamarra Aquifer is confined within the other proposed development areas and has no known interaction with groundwater-dependent ecosystems. Previous investigations undertaken for the Leederville Aquifer have indicated that stygofauna are

unlikely to be found in the Cattamarra Aquifer where confined (Inter Agency Working Group 2008).

Aquaculture – low difficulty

- Not applicable. The Cattamarra Aquifer is not drawn on for aquaculture purposes within the proposed development areas. There is no known plan or intention to use the aquifer for aquaculture in the future.

Recreation and aesthetics – low difficulty

- There are no known instances of groundwater from the Cattamarra Aquifer being used for or likely to impact on recreation in the study area.

Drinking water – low difficulty, potentially moderate to high difficulty in the eastern plain

- Excluding North Dandalup, the native groundwater chemistry is unsuitable for direct potable use in the development area: salinity is generally greater than 1000 mg/L.
- In the study area the aquifer is fully allocated and unlikely to be suitable for additional large-scale extraction without recharge being supplemented.
- Proponents should ensure they are not negatively affecting areas of the aquifer that contain potable water. Where a proposal does affect either actual or potential future drinking water sources, the degree of difficulty is much higher.

Irrigation – low difficulty, moderate difficulty in the eastern plain

- Water from the Cattamarra Aquifer is used for irrigation purposes in or near the Carcoola, North Dandalup and Pinjarra development areas. As a consequence, MAR schemes should ensure the environmental values for irrigation are not negatively affected.
- Closer to the coast the salinity of the groundwater is higher, often in excess of 1500 mg/L, and therefore it is currently not suitable for irrigation.
- Where the source water is of a lower salinity than the native groundwater, there is potential to use MAR to reduce the groundwater salinity to make it suitable for irrigation.

Cultural and spiritual values – difficulty uncertain

- ‘…Indigenous cultural and spiritual values may relate to a range of uses and issues including

	spiritual relationships, sacred sites, customary use, the plants and animals associated with water, drinking water or recreational activities' (Chapter 2, ANZECC-ARMCANZ 2000) - Currently there are no specific guidelines, however it is recommended that local Indigenous groups and representatives are consulted.

2 Source-water quality with respect to recovered water end-use environmental values	
If the source water does not meet the water-quality requirements for the environmental values of intended end uses of recovered water, then there is a reliance on attenuation of hazards within the subsurface.	**Q2. Does the source water meet the water-quality requirements for the environmental values of the intended end uses of the water on recovery?** *If the answer is 'Yes', a low risk of pollution of recovered water is expected. However, due to aquifer reactions, this is not a sufficient condition for low risk.* *If the answer is 'No', a high maximal risk is likely. Stage 2 investigations will be necessary to assess this risk.* **A2. <u>Unknown,</u> based on <u>existing data:</u> further information is required and a number of specific issues need to be further investigated.** *Low to moderate difficulty expected.* - It is likely there will be no need for reliance on attenuation of hazards within the aquifer used for storage. If available subsurface drainage water quality data is indicative of the raw water quality expected in Murray subsurface drainage, many water quality parameters will meet irrigation guidelines - For nutrients, the short-term (<20 years) guideline values are met for TN and TP. For long-term irrigation guidelines, indications are that TP might be an issue with respect to bioclogging. - Data for pesticides, heavy metals, sodicity, major ions etc. would also need to be assessed against the irrigation guidelines (ANZECC-ARMCANZ 2000).
3 Source-water quality with respect to clogging	
Where source-water quality is poor and soil or aquifer are fine-grained, clogging of the infiltration basin and gallery or recharge well is likely to occur, unless the water is pre-treated *before recharge.* Clogging is most prevalent when water contains moderate or high levels of	**Q3. Does source water have low quality; for example:** *total suspended solids >10 mg/L* *total organic carbon >10 mg/L* *total nitrogen >10 mg/L?* *Also, is the soil or aquifer free of macropores?*

suspended solids or nutrients, such as nitrogen or labile organic carbon.

Clogging can also occur when oxygenated water is introduced into an aquifer that contains iron. If the soil or aquifer are coarse grained or contain macropores, clogging with such waters is less likely, but the risk of pollution of groundwater is high (as covered in questions 1 and 2).

Lack of evidence of clogging is insufficient to indicate that risk of pollution is low, even in fine-grained media.

A3. Currently there is insufficient data to answer this. A number of specific issues need to be further investigated. *Moderate to high difficulty, however additional data may lower this rating.*

- Available post-development monitoring data for subsurface drainage water does not include many of the relevant physical and chemical parameters required to answer this question. Available data indicates there will be occasions where source water is above guideline values for total nitrogen to avoid clogging.
- A further potential risk that needs to be characterised is that of oxygenated source water reacting with iron-rich sediments such as pyrite, as oxidised iron can lead to clogging of pores.

4 Groundwater quality with respect to recovered water end-use environmental values

Where samples are available, the highest parameters detected in each sample should be used in the analysis, unless there is the justification that events resulting in those values will be prevented when the MAR project is established.

In the absence of data on groundwater quality from the proposed site, data from nearby wells in the same aquifer may be used.

Q4. Does ambient groundwater meet the water-quality requirements for the environmental values of intended end uses of water on recovery?

If the answer is ‘Yes’, a low risk of inadequate recovery efficiency is expected. If the answer is ‘No’, some risk of inadequate recovery efficiency is expected. In this case, see Table A1.2 for degree of difficulty expected.

A4. <u>No</u> is the provisional answer based on existing data, for most of the development areas. *Moderate to high difficulty*

Assuming the intended use is irrigation of public open space, groundwater from the Cattamarra Aquifer:

- is too saline (>1500 mg/L below most of the development area)
- contains concentrations of the following metals above the long-term irrigation water guideline values: boron, iron and manganese
- if clay content at specific sites is high, sodicity may cause swelling of irrigated soils

5 Groundwater and drinking water quality	
The environmental values of the aquifer need to be defined by the relevant authority. These will depend on the ambient groundwater quality and any groundwater-affected ecosystems, as identified in the NWQMS groundwater protection guidelines (ARMCANZ–ANZECC 1995). If defined environmental values (for entry-level assessment purposes) are lacking, all environmental values that are met by the native groundwater quality need to be protected. Such environmental values may include raw water for drinking supplies, irrigation, aquaculture, recreation or livestock water, and support of aquatic ecosystems with various conservation values.	**Q5. Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?** *If the answer is 'Yes', there is a high risk of groundwater pollution if the aquifer is recharged by harvested water, if the answer to Question 1 is 'No'.* *If the answer is 'No', a low risk of groundwater pollution is expected. However, this is not a sufficient condition for low risk.* **A5. Currently the Cattamarra Aquifer in the study area is not a drinking water source, nor is it likely to have significant interaction with groundwater-dependent ecosystems.** *Drinking water – low difficulty* - Excluding North Dandalup, the native groundwater chemistry is unsuitable for direct potable use in the development area: salinity is generally greater 1000 mg/L. *Aquatic ecosystems – low difficulty* - Excluding North Dandalup, the Cattamarra Aquifer is confined within the other proposed development areas and has no known interaction with groundwater-dependent ecosystems.
6 Groundwater salinity and recovery efficiency	
If native groundwater has high salinity, the proportion of native groundwater that can be present as a mixture with source water in recovered water is limited. At such sites, density-affected flow may also occur. Fresh recharge water can form a lens above the native saline groundwater, making recovery difficult and reducing recovery efficiency (i.e. the	**Q6. Does the salinity of native groundwater exceed either of the following:** *(a) 10 000 mg/L* *(b) the salinity criterion for uses of recovered water?* *If the answer to both parts of the question is 'Yes', there is a high risk of achieving only low recovery efficiency. Aquifer hydraulic characteristics, especially layering within the aquifer, will need careful examination in Stage 2.* *If the answer is 'Yes' only to Part (b), then a moderate risk of low recovery efficiency is expected.*

volume of recovered water meeting the environmental values for its intended uses as a proportion of the volume of recharged water).	*However, this is not a sufficient condition for low risk (e.g. in brackish aquifers with high rates of ambient lateral flow).* *If the answer is 'No' to both parts of the question, there is a low risk of low recovery efficiency.* **A6. (a) No, (b) Yes. The Cattamarra Aquifer exceeds the guideline salinity values for irrigation in a large portion of the development areas.** *Low to moderate difficulty.* - Native groundwater salinity varies from 180 to 5120 mg/L TDS. Highest values are located on the western margin. Areas west of the 2500 µS/cm line in Figure 2.12 are in general going to be above the guideline value for irrigation of 1500 mg/L TDS. - TDS values in subsurface drainage water are typically much lower than 1500 mg/L. MAR offers an opportunity to displace and dilute groundwater of an unsuitable water quality.
7 Reactions between source water and aquifer	
Reactions between source water and aquifer minerals may result in deterioration of water quality for recovered water, and possibly for water in the aquifer beyond the attenuation zone; alternatively, they may cause excessive clogging or dissolution of the aquifer. A full evaluation may be undertaken in Stage 2, but a simple indicator of the likelihood of potential problems at entry-level stage is to note the extent of contrasts between the quality of source water and native groundwater.	**Q7. Is redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?** *If the answer is 'Yes', a low risk of adverse reactions between source water and aquifer is expected. However, this is not a sufficient condition for low risk.* *If the answer is 'No', a high risk of adverse reactions between source water and the aquifer is possible, and will warrant geochemical modelling in Stage 2.* **A7. For the most part, currently there is insufficient data to answer this.** - For nutrients, the short-term (<20 years) guideline values are met for TN and TP. For long-term irrigation guidelines, indications are that TP might be an issue with respect to bioclogging. - Many other properties are site-specific and will require more detailed investigation. Examples of potential issues that may negatively affect source water suitability include acid sulfate soils, fill geochemistry, land use, iron concentration and dissolved oxygen levels. - More detailed evaluation and testing of subsurface drainage water quality is required.

8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries

Proximity of nearest existing groundwater users and groundwater-connected ecosystems is likely to influence the extent of investigations required in Stage 2.

Typically, attenuation zones will have aquifer residence times of up to a year.

If property boundaries are close to the MAR site, then the attenuation zone may extend beneath a neighbouring property.

Groundwater pressure effects in confined aquifers due to MAR may propagate over considerably longer distances than water quality effects.

Q8. Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100 to 1000 m of the MAR site?

If the answer is 'Yes', a high risk of impacts on users or ecosystems is possible, and this will warrant attention in Stage 2.

If the answer is 'No', a low risk of impacts on users or ecosystems is likely. However, this is not a sufficient condition for low risk.

A8. There are no existing users nearby for all development areas except Carcoola. Distance to property boundaries is not applicable to this study. *Low to moderate risk.*

- The nearest existing user is located in the Carcoola development area. All other users located in the study area are towards the plain's eastern side, well away from proposed development areas.
- The Serpentine Fault is thought to be a hydraulic barrier which will mitigate the likelihood of increased hydraulic heads affecting unconfined areas of the Cattamarra Aquifer or groundwater-dependent ecosystems to the east.

9 Aquifer capacity and groundwater levels

Groundwater mound height induced by MAR depends on aquifer hydraulic properties, size of recharge area and recharge rate.

Mounding is normally calculated in Stage 2 when aquifer properties are measured. However, excessive mounding can cause waterlogging, soil heave, flooding of below-ground infrastructure, salt damp and soil salinisation.

Unconfined aquifers with shallow

Q9. Is the aquifer:

(a) confined and not artesian?

(b) unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?

A9. The Cattamarra Aquifer is confined in all areas proposed for development excluding North Dandalup.

- Most confined areas of the aquifer are subartesian to slightly artesian, however hydraulic heads are decreasing rapidly over a large area, increasing the extent of subartesian heads.
- Estimates indicate the aquifer has considerable capacity to store a large volume of water under increased hydraulic pressure (see Section 2.3).

watertable sites are thus generally unsuitable as storage targets for large-scale recharge projects. For confined artesian aquifers, care needs to be taken against over-pressurisation, and to seal existing wells that might otherwise start to flow.	- The South Perth Shale formation is not present under the North Dandalup subarea, therefore the aquifer may be unconfined.
10 Protection of water quality in unconfined aquifers	
If the aquifer is unconfined and the intended recovery is for drinking water supplies, then overlying land and waste disposal (including intensive horticulture and septic tanks) should be managed carefully or precluded from the groundwater capture zone.	**Q10. Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?** **A10. The aquifer is confined in all development areas excluding North Dandalup. Any intention to use recovered water to supplement drinking water supplies is a decision of the proponents.** *Low to moderate difficulty.* - The Cattamarra Aquifer is confined and too saline (>1500 mg/L) for direct potable use or irrigation in many of the development areas. In those areas it has no known interaction with surface waters or aquifers which have higher environmental values due to an extensive overlying aquitard. - Intended use of the water will be the decision of the proponents and risks will have to be investigated and managed accordingly. - The South Perth Shale formation is not present under the North Dandalup subarea, therefore the aquifer may be unconfined.
11 Fractured rock, karstic or reactive aquifers	
If the aquifer is fractured rock or karstic, the ability to recover stored water will require evaluation, especially if the ambient groundwater is saline or the hydraulic gradient is steep.	**Q11. Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?** **A11. <u>Yes.</u> The aquifer does contain reactive minerals.** - The Cattamarra Aquifer consists of lightly consolidated predominantly medium- to coarse-grained

Provision will also need to be made for a larger attenuation zone, due to more rapid migration of recharge water from the recharge area.	sand with clay and shale interbeds. The common minerals most likely to react with source water are pyrite and carbonate. The presence of these minerals in the aquifer is heterogeneous.
12 Similarity to successful projects	
A founding principle of MAR is that all validation and verification monitoring data should be in the public domain, and that these data should be accompanied by sufficient operational data to enable accurate interpretation. This information is of value for future MAR projects, for improving design and operation, reducing costs, and for further refining these guidelines. A national or state repository for these data should be accessible to proponents.	**Q12. Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?** *If the answer is 'Yes', validation and verification data from the existing projects needs to be taken into account when designing the current project – in the Stage 2 investigations and in subsequent risk assessments.* *If the answer is 'No', all uncertainties are likely to need to be addressed in the Stage 2 investigations.* **A12. There are no other projects in the immediate area. The most similar area is a trial occurring at Beenyup wastewater treatment plant. Numerous technical reports from this trial are available online.**
13 Management capability	
A proponent new to MAR operation needs to gain appropriate expertise in parallel with Stage 2 investigations, to demonstrate a low level of residual risk for the precommissioning risk assessment.	**Q13. Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty (see Table A1.2), or with water treatment or water supply operations involving a structured approach to water-quality risk management?** *If the answer is 'Yes', there is a low risk of water-quality failure due to operator inexperience.* *If the answer is 'No', there is a high risk of water-quality failure due to operator inexperience. The proponent should gain instruction in operating such systems (e.g. a MAR operator's course or ASR course), or engage a suitable manager committed to effective risk management in parallel with Stage 2, to reduce precommissioning residual risks to low.*

	A13. This is not applicable to the feasibility study as there is no specific scheme being proposed. - There is management capability in Western Australia to construct and manage such a scheme as illustrated by the Beenyup wastewater treatment plant injection trial.
14 Planning and related requirements	
Planning and related requirements include - proximity of nearest neighbour - provision for safe public access or exclusion - dimensions and slopes of water-holding structures - location, dimensions and design of any buildings or engineering structures - method by which power will be brought to site and water connections - nuisance insect abundance before and after construction, and proposed control measures - noise emissions of any mechanical plant, and noise abatement measures - earthmoving and construction plans and measures for dust and noise control - provision of information to neighbours	**Q14: Does the proposed project require development approval? Is it in a built-up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (e.g. from waste products of treatment processes)?** *If the answer is 'Yes' to any of these, a development-approval process will require that each potential issue is assessed and managed. This may require additional information and steps in design.* *If the answer is 'No', the process for development approval, if required, is likely to be considerably simpler.* **A14. Yes. Development approvals are required for all MAR proposals.** - Planning for an MAR study/proposal should be incorporated into the relevant water management strategies (required by *Better urban water management*) and structure plans to maximise the benefits and minimise the construction costs and disturbance. MAR approvals should also be addressed in accordance with the cross-agency *Draft approval framework for the use of non-drinking water in Western Australia* (DoW 2010). This framework links to the department's *Operational policy 1.01 – Managed aquifer recharge in Western Australia*, which sets out our licensing requirements for MAR.

concerning the development

- *information to address other provisions of planning and development regulations.*

The difficulty assessment is summarised below. A grey box indicates there is insufficient data to answer the question or it is not applicable.

Table 3.3 Summarised degree-of-difficulty assessment for MAR of stormwater to Cattamarra

	Degree-of-difficulty questions													
Development area	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
Austin	L		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H
Barragup	L		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H
Buchanans	L		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H
Carcoola	M/H		M/H	L	L	M/H		M/H	L	L	M/H	M/H		M/H
Nambeelup	L		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H
Nerrima	L		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H
North Dandalup	M/H		M/H	L	L	M/H		L	M/H	M/H	M/H	M/H		M/H
Pinjarra	M/H		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H
Ravenswood	L		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H
South Murray	L		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H
South Yunderup	L		M/H	M/H	L	M/H		L	L	L	M/H	M/H		M/H

Note: L= low difficulty, M = moderate difficulty, H = high difficulty, grey = insufficient data / not applicable

3.2 Further requirements (stages 2 to 4)

Before approvals can be granted, or a scheme constructed, the MAR guidelines' further requirements need to be addressed. These are described in stages 2 to 4, as shown in Figure 1.2. In Western Australia, these requirements should be submitted to the Department of Water in accordance with the *Draft approval framework for the use of non-drinking water in Western Australia.*

Stage 2: Further investigations to assess viability and risk

After completion of Stage 1 of the guidelines for a specific proposed scheme, knowledge gaps or key issues requiring further investigation will become evident. The broadscale assessment provided for the entire development area using existing data (see Section 3.1) demonstrates that each development area – and even sites within those areas – have their own distinct characteristics. For example, North Dandalup development area is not confined to the same extent as others, and the Carcoola development area has relatively fresh water compared with others. As a consequence, individual proposals for schemes will have to address these different characteristics.

Stage 2 of the MAR guidelines calls for investigations to properly assess viability and risk, including:

- source water and groundwater sampling and analysis
- detailed hydrogeological studies
- catchment studies
- basic groundwater modelling and geochemical evaluation.

Stage 2: Maximal risk assessment

The maximal risk assessment assumes no preventative measures have been put in place. In the Phase 1 water recycling guidelines, the maximal risk assessment is referred to as Phase 2 – following the preliminary screening. For the purposes of consistency and to avoid confusion, proponents are advised to follow the framework outlined in the MAR guidelines (see Figure 1.2). By characterising maximal risk, the nature of the preventative measures required as well as the frequency of sampling and monitoring can be determined.

In the scenario proposed in the Stage 1 assessment for this project, the maximal risk would be related to untreated stormwater being injected directly into an aquifer. To assess maximal risk, the quality of the source water needs to be evaluated. Section 2.4 of this report has summarised the limited available post-development monitoring data. More will be required to complete a risk assessment, particularly for subsurface drainage water quality, which appears to be a likely source option.

In the absence of actual water quality data from the proposed development, the stormwater guidelines (NRMMC-EPHC-NHMRC 2009b) provide indicative data. This, however, is not likely to be comparable, as it is derived from an established residential area in Sydney. If the development implements proper water sensitive urban design principles, the quality of subsurface drainage water should be much higher than the values presented in the guidelines. As a consequence, proponents are encouraged to obtain actual source water quality data, or more comparable data as is presented in Section 2.2.

The MAR guidelines provide a substantial level of detail on hazards (NRMMC-EPHC-NHMRC 2009a) including those posed by pathogens, nutrients, salinity, inorganic chemicals, turbidity, etc. These hazards apply not only to human or environmental health, but also to the scheme in terms of its operation. Further information on potential operational risks relating to stormwater is given on page 23 of the stormwater guidelines (NRMMC-EPHC-NHMRC 2009b). The stormwater manual also contains information of use to proponents looking to implement structural and non-structural controls for the management of stormwater quality (DoW 2005).

Appendix 5 of Phase 1 of the national water recycling guidelines (NRMMC-EPHC-AHMC 2006) contains reference tables for risk assessment. These present guideline values from documents such as the *Australian drinking water guidelines* (NHMRC-ARMCANZ 1996), *Australian and New Zealand guidelines for fresh and marine water quality* (ANZECC-ARMCANZ 2000), *Guidelines for environmental management* (EPAV 2004) and *Guideline on the investigation levels for soil and groundwater* (NEPC 1999). It should be noted that at times the various modules do vary in terms of criteria, an example being the stormwater guidelines' criteria (for disinfection and turbidity) for stormwater irrigation, which is less stringent than what is given in the Phase 1 guidelines for wastewater irrigation.

Stage 2: Preventative measures

When the maximal risk assessment has been completed, preventative measures need to be evaluated for reducing the risk to an acceptable level. The MAR guidelines provide details on suggested preventative measures that can be used to mitigate the effects of hazards (NRMMC-EPHC-NHMRC 2009a). Preventative measures described in the MAR guidelines include:

- treatment of recharge water to remove hazards
- adequate detention time for treatment within the aquifer
- treatment of recovered water before distribution
- recharge control system (i.e. shut down system if monitored indicator variables are outside of critical control limits).

Other preventative measures could be applied if suitable. One such example could be that soil amendments are applied before development, in order to improve the quality of subsoil drainage water. Soil amendments help to control contaminants at the source and can be used to improve the soil's phosphorus retention index (PRI). The *Peel-Harvey coastal catchment water sensitive urban design technical guidelines* suggest that for areas such as grass, gardens and swales, soil amendments should be used where infiltration of stormwater is to occur (Peel Development Commission 2006).

Some examples of soil amendment materials that can be used are:

- sands high in iron (e.g. yellow Spearwood sands)
- calcareous or lime-rich sands (e.g. Karrakatta soils)

- brown loams (foothill slope soils which may be blended with sands)
- neutralised used acid (NUA) (Duncan 1999; Wendling et al. 2009c).

For information on water quality and options for soil and water amendments, some useful documents and references are listed below:

- *Urban stormwater quality* (Duncan 1999) gives a statistical overview of urban stormwater quality and information on water quality parameters. This report assesses the broadscale behaviour of urban runoff quality, and its interactions with land use and other catchment characteristics.
- A report by Wendling et al. (2009c) on best management practices assessed the ability of a suite of materials to remove high concentrations of dissolved organic carbon, organic nitrogen and dissolved phosphorus from typical urban drainage waters from the Swan Coastal Plain.
- Douglas (2008) documents the results from a comparison between soils amended with neutralised used acid (NUA) and untreated (control) soils from over three-and-a-half years of field trials.
- Two other useful reports (Wendling et al. 2009b; Wendling & Douglas 2009a) look at mining and industrial by-products for potential use as soil or surface water amendments. Two main added advantages of using industrial by-products as environmental amendments are economic viability and waste reduction.

Stormwater harvesting typically requires a storage facility for treating and capturing water. Often open storages such as wetlands are a preferred option; not only for public amenity, but also for playing a role in treatment through settling and removal of solids (if designed correctly). Constructed wetlands and ephemeral detention basins can be used to detain stormwater, as described in the Chapter 9 of the stormwater manual (DoW 2005).

Ephemeral wetlands/detention areas offer a number of advantages compared with constructed lakes. They minimise the creation of areas of stagnant water, reducing the likelihood of mosquito breeding or algal blooms in summer. (Algal blooms have significant costs associated with their management, including aeration and treatment of nutrients.) Other issues associated with constructed lakes include flood risk, odour, and acid sulfate soils and acidity. They also defeat the purpose in terms of water conservation by creating a need for water during the summer months. Many of these issues are recognised in the Department of Water's *Interim position statement on constructed lakes* (DoW 2007a).

Ephemeral wetlands are increasingly becoming a preferred option in that they are 'natural' considering the nature of our environment and climate. They need to be designed to be aesthetically pleasing with and without water, with appropriate vegetation to meet those requirements. They can also form part of a 'treatment train' approach to management of water in a catchment (DoW 2007b).

Stage 3: Residual risk assessment

The residual risk assessment evaluates the ability of the preventative measures to mitigate the risks identified in the maximal risk assessment (if any were identified). Chapter 5 of the MAR guidelines provides assessment criteria and requirements for validation monitoring.

Initially, a forecast or precommissioning residual risk assessment identifies those hazards for which a degree of uncertainty exists. The degree of risk or uncertainty is the determining factor for the scope of validation monitoring required. High-risk projects will already have been identified in the entry-level assessment. For the purpose of this particular project, questions have resulted in criteria of moderate to high difficulty: this should not discourage proponents as it simply indicates the broad nature of this feasibility assessment. Furthermore, water quality data will need to be collected to address the identified gaps and enable a determination of risks and identification of preventative measures. It is expected that specific projects with more detailed designs should be able to address most of the gaps in knowledge and reduce the degree of difficulty.

Commissioning trials, validation stage

A full residual risk assessment is only possible when a project trial allows validation monitoring, providing the level of detail required on the project's long-term viability. Given the approvals required at this stage (e.g. those regarding construction of bores), it is reasonable to expect a degree of confidence in the proposal had emerged in order to make the investments required for validation monitoring.

During a project or commissioning trial, monitoring is undertaken to make adjustments to elements of the scheme such as treatments, as well as recharge and recovery in order to improve performance. It allows demonstration of the suitability of the monitoring program design to meet the requirements of the operational monitoring plan. Regulators will, as a result, have confidence that the scheme will operate in a way in which hazards are controlled to an acceptable level of risk.

Monitoring also forms a key component of the risk management framework described in Chapter 3 of the MAR guidelines, and is particularly pertinent to element 4 (operational procedures and process control), element 5 (verification of recycled water quality and environmental performance) and element 9 (validation, research and development).

Stage 5: Developing risk management plans

Formulating a risk management plan is the final step in the MAR guidelines. A MAR risk management plan is a documented system for the management of aquifer recharge. It encompasses more than the assessment and management of risk that is shown in Figure 1.2, because it deals with other key issues for the entire system. Figure 3.2 below shows the 12 elements of the risk management plan that were adopted in the Phase 1 guidelines (NRMMC-EPHC-AHMC 2006).

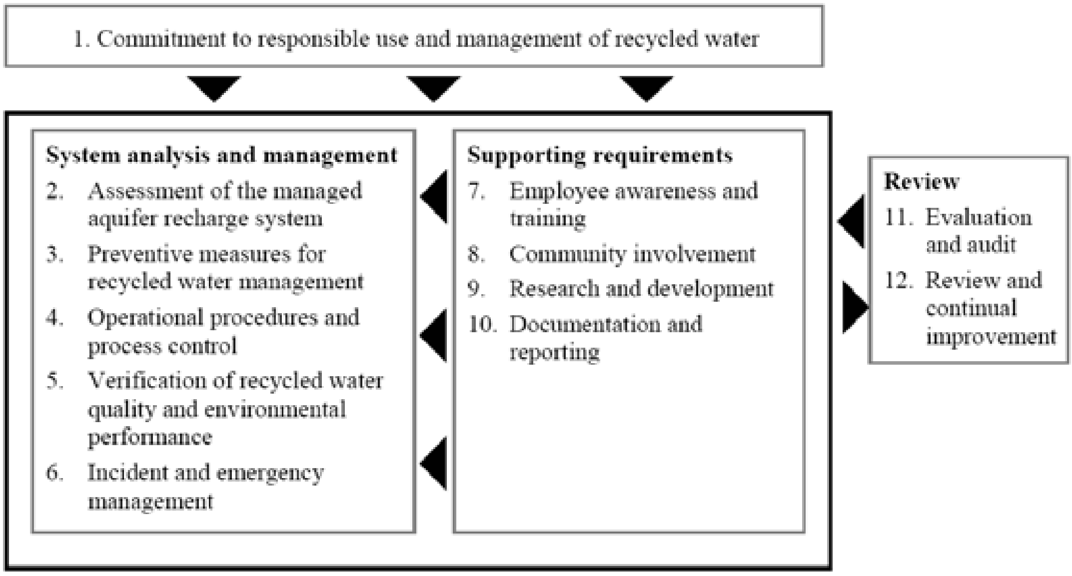


Figure 3.2 The 12 elements of the risk management plan (NRMMC-EPHC-AHMC 2006).

For a detailed discussion on each of these elements with respect to MAR, see Chapter 3 of the MAR guidelines (NRMMC-EPHC-NHMRC 2009a).

Risks to human health and the environment can occur within each component of the MAR system. So that regulatory and approvals processes are met, and to ensure development of a sustainable project, proponents are required to address each of the 12 elements. While the elements are not necessarily sequential, they should all be followed to ensure the risk management plan is comprehensive.

3.3 WA MAR approvals process

The Department of Water supports water recycling in principle, and as such has formulated a draft MAR policy and a non-drinking water approvals framework. Both of these are available on our website at <www.water.wa.gov.au> and should be used by any proponent wanting to develop an MAR scheme in Western Australia. The department should be considered the lead agency in the approvals process. Other regulatory agencies also play a role in assessing MAR schemes (typically the Department of Health, the Department of Environment and Conservation and the Economic Regulatory Authority), but the intent is for the Department of Water to provide consolidated, cross-agency advice.

MAR policy

O*perational policy 1.01 – Managed aquifer recharge in Western Australia* (DoW 2009a) outlines the Department of Water's position on MAR, particularly with respect to allocation and water quality management. This document is available in draft form (soon to be in final format) online at <www.water.wa.gov.au>.

The policy has a number of key messages. In general, the Department of Water encourages suitable MAR activities that maximise the use of our limited water resources, and through the policy aims to facilitate the development of MAR projects by providing a management framework. However, under the *Rights in Water and Irrigation Act 1914* (WA), MAR schemes must not have unacceptable impacts on the groundwater system, the environment or existing users through changes in water quality or quantity. The Department of Water will support banking or storage of the recharge water within the aquifer over a short period, provided the proponent demonstrates the water will be available for use when required, and that the impacts of abstraction will be acceptable.

Non-drinking water approvals framework

The following information summarises the *Draft approval framework for the use of non-drinking water in Western Australia* (DoW 2010b). For more specific or updated information, please refer to the full document, which can be found online at <www.water.wa.gov.au>.

The framework guides proponents step-by-step through the general considerations and specific approval requirements for establishing a non-drinking water system. The Department of Water is the lead agency for the approval process (contact details for the Water Recycling and Efficiency Branch are found in Appendix A of the framework).

Because the use of non-drinking water is an evolving field, the framework is intended only as a guide. Regulatory requirements for non-drinking water will likely change as further information becomes available. To ensure appropriate consideration is given to the necessary approval requirements of each specific proposal, it is recommended that proponents discuss the steps and requirements for their proposal with the relevant approving agencies early in the process.

In regard to stormwater, the Department of Water encourages the infiltration of stormwater at or near its primary sources. This is a means of managing urban stormwater to keep the water balance as close as possible to the pre-development situation. A likely outcome is that large quantities of stormwater (for use as a non-drinking water source) may only be able to be harvested from:

- high-density development or commercial areas
- areas with limited infiltration potential (due to high groundwater levels or less permeable soils)
- areas with existing large-scale stormwater discharge systems (such as traditional drains or large sumps).

Some level of pre-treatment of the source water will generally be required before recharge to the aquifer, depending on the outcome of environmental and health risk assessments.

MAR may not be feasible on all sites, due to hydrogeological, environmental or cost limitations. Yet there are opportunities for collection or redirection of urban stormwater for MAR, subject to satisfying the ecological water requirements of ecosystems that previously received stormwater input.

The approval framework has four stages that will be assessed and an overview of the approvals process is provided in Figure 3.3. By following this process, proponents can gain a better understanding of their particular project's opportunities and constraints, and thus more confidence in their assessment of its viability.

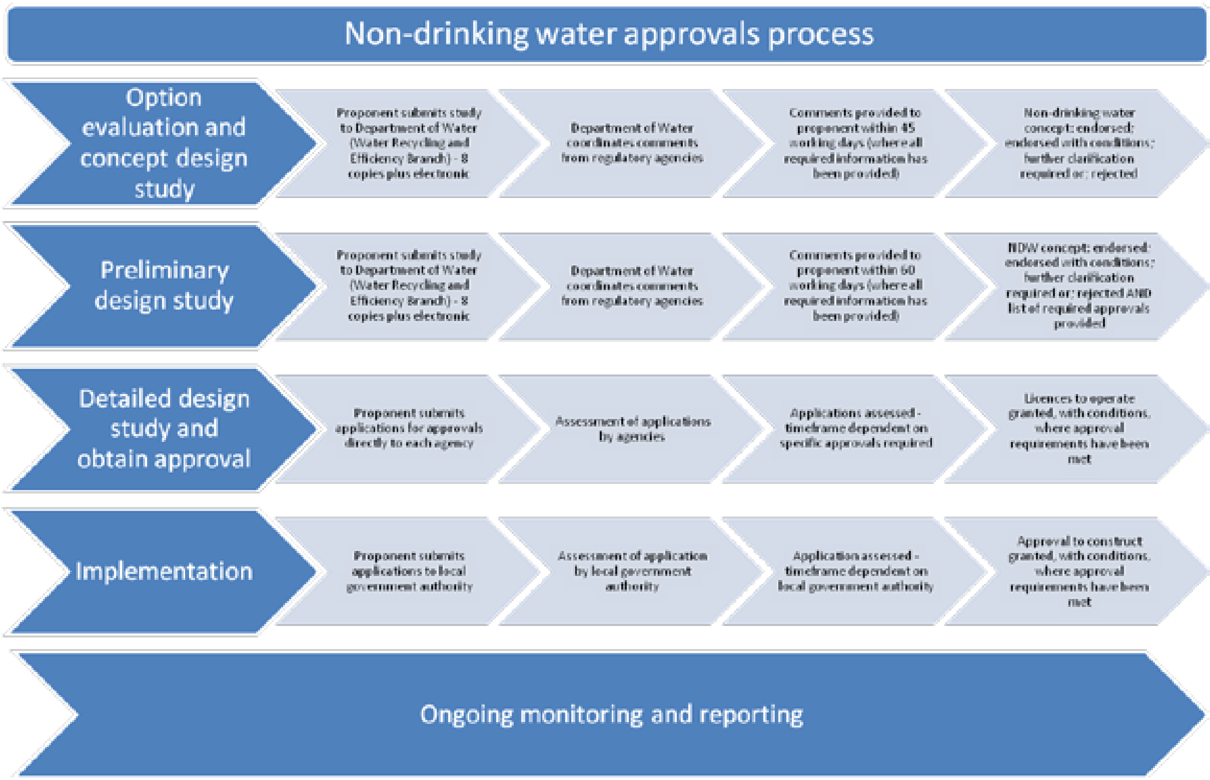


Figure 3.3 Overview of approval requirements (DoW 2010b)

The ideal relationship between the stages in developing a non-drinking water project and the land planning and *Better urban water management* stages is shown in Figure 3.4. *Better urban water management* is intended to ensure that an appropriate level of consideration is given to the total water cycle at each stage of the planning process. Note that the relationship between the four non-drinking water approval stages and *Better urban water management* in Figure 3.4 is indicative only.

The framework has aligned the timing of the approval requirements for non-drinking water schemes with the planning stages of *Better urban water management*. This is because the greatest opportunities for establishing non-drinking water schemes exist early in the land planning process.

Proponents should make themselves aware of any regional-scale water planning documents relevant to their development. Non-drinking water developments should be consistent with any regional water planning objectives.

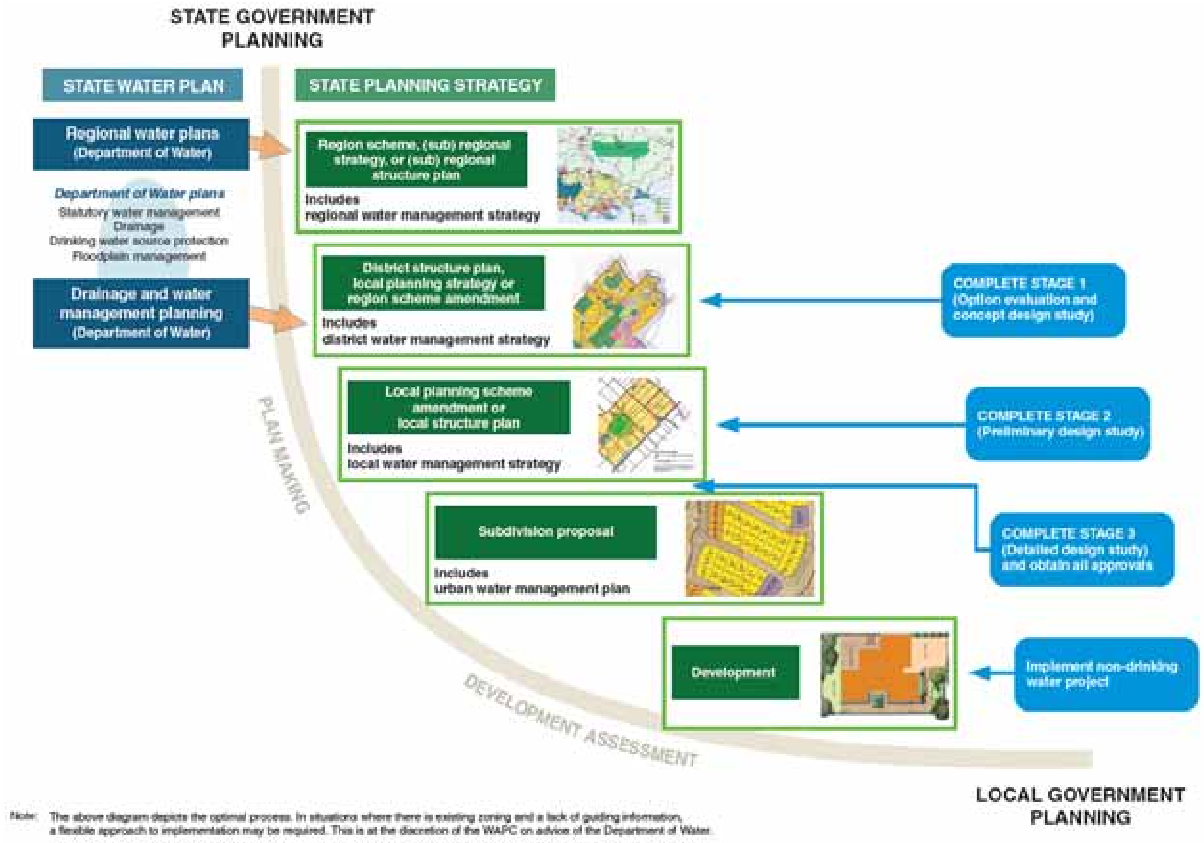


Figure 3.4 Non-drinking water project stages and relationship to Better urban water management (DoW 2010b)

4 Conclusions and recommendations

This study involved a desktop assessment of the viability and degree of difficulty of a conceptual stormwater MAR scheme. The national MAR guidelines have been applied in a unique way, in that this assessment has been carried out pre-development. The study area covers approximately 84 km^2 of the development areas covered by the *Murray drainage and water management plan*. Based on this desktop assessment, in broad terms it appears that stormwater, particularly that which is collected through subsoil drainage systems, offers potential for harvesting and MAR.

Catchment modelling has estimated, under a range of scenarios, that 12.4 to 20.3 GL of drainage water would be available for harvesting. Given the current groundwater uses from the Cattamarra Aquifer, as well as its hydrogeology, groundwater quality and environmental values, this aquifer is more suitable for MAR than others. Storativity has also been conservatively assessed, indicating there is between 4 and 20 GL of storage below the development areas, assuming a 10 m increase in potentiometric head; and between 20 to 100 GL of confined storage available in the study area if the hydraulic heads were restored to the 1984 level.

A number of difficulties and issues have been identified through this assessment, which, if addressed, would further streamline the uptake and approval of MAR proposals:

1 **Lack of access to post-development monitoring data:** At present developers are required to monitor surface and groundwater quality post-development. This data is most beneficial in the context of this study, particularly as subsoil drainage water is the source water for the conceptual scheme. Indicative water quality data from existing developments would have been most useful. However, only very limited data was available to be reviewed for this report.

   Recommendation: That the Department of Water coordinates the collection, storage and administration of post-development monitoring data. This should include facilitating the analysis of data to evaluate existing opportunities for stormwater harvesting. Proponents would benefit greatly from having access to such data through the Water Information (WIN) database, for example.

2 **Confusing use of terms between Phase 2 MAR guidelines and Phase 1 guidelines:** The focus of this assessment has been the Phase 2 MAR guidelines. They offer a logical, relatively straightforward approach for risk assessment and the development of a risk management plan. Some of the terminology varies between the two documents, for example: ‘Phase 1 initial screening-level risk assessment’ in the Phase 1 guidelines is equivalent to ‘entry-level assessment’ in Phase 2; and the Phase 1 guidelines refer to phases 1, 2 and 3 of the risk assessment.

   Recommendation: Subsequent revisions of the guidelines should endeavour to use consistent terminology between the various documents.

3 **No examples of projects:** Despite the high potential that exists, no stormwater MAR project has been formally proposed, approved or implemented that could show proponents how to meet the national guidelines and obtain regulatory approvals.

Recommendation: that 'icon' or 'demonstration' projects are given at least in-kind support by the Department of Water. This would address a current gap in understanding the degree-of-difficulty assessment component entitled 'similarity to successful projects'.

4 **The estimates of aquifer storage capacity are coarse.** There is an inadequate understanding of how MAR injection pressures will alter the potentiometric surface regionally. A better understanding of the Cattamarra Aquifer's vertical connectivity is required to improve the accuracy of these estimates. Modelling of mixing processes between native groundwater and the injectant would allow estimates of recovery efficiency to be made.

Recommendation: A thorough review of historical data will aid assessment of specific storage in the Cattamarra Aquifer. Modelling scenarios will help us understand possible changes to the potentiometric surface, and help identify the potential risks in areas that lack a strong confining layer. This could be incorporated into a pilot ASR project.

5 **It is critical that the potential for stormwater harvesting and MAR is realised through the planning process.** More detailed local structure plans, for example, need to include requirements such as surface storage and treatment. Without such awareness, the planning process in itself can become a barrier to full implementation.

Recommendation: We propose that a workshop be held in which a published version of this report be launched. The intent will be to share the information with key stakeholders such as local government and the Department of Planning – to ensure the potential for stormwater harvesting and MAR is taken into account throughout the planning process. The Department of Water would be able to use such a forum to promote our role in coordination and advice on proposed schemes, as outlined in the *Draft approval framework for the use of non-drinking water in Western Australia* (DoW 2010b).

6 **Coordination**: Examples of integrated stormwater harvesting schemes in South Australia demonstrate the need for coordination between various developers/proponents so that efficient or cost-effective schemes are developed.

Recommendation: The Department of Water will assist, facilitate and provide support to meet this need. In the long term, the capacity of local government needs to be increased such that these integrated water management schemes may be developed in accordance with the *Better urban water management* policy document.

5 Appendices

5.1 Appendix A:

Murray study area geology reinterpretation and the Rockingham Sand/Wanneroo Member relationship

Peter Kretschmer, Water Science Branch, Department of Water, Western Australia

This appendix has been written independently of the main body of the report due to the significant content not directly related to the MAR feasibility study.

Acknowledgements

This component of the study was not initially included in the scope of the MAR feasibility project, but when assessing the existing information available, we realised it was insufficient for the project's needs. This new interpretation required the knowledge, time and assistance of several Department of Water staff I would like to thank. In particular I would like to acknowledge the significant contribution of the following staff:

- Philip Denby and Carey Johnston for providing much assistance and time in interpreting the geophysical logs and discussing the results.
- Philip Commander, for providing advice and additional data for analysis, as well as reviewing the revised interpretation.
- Ben Marillier, Spatial Analyst, for helping to develop the three-dimensional geology model of the Murray study area.
- Alex Kern, for providing advice and assisting with the review of this report.
- Fiona Mullen, for the provision of geophysical logs formatted in Petrel™.

Introduction

The geology review was designed to provide information on the thickness and extent of the aquifers and aquitards in the study area, so it could then be used to produce a 3-D geology model for the MAR feasibility study. The geology interpretation discussed has used the highest number of bores to date in the study area, and in doing so some significant new findings have been made.

When reviewing the existing published geology interpretations for the study area it became apparent that there were significant inconsistencies in the existing interpretations. The investigation completed by Commander (1975) on the Mandurah bores is still extensively referenced in new studies; however, since 1975 no updated interpretation has used all the geophysical logs, lithology information and water quality data from all the Mandurah bores, and integrated it with an extensive set of new information from bores that have been drilled in the past 35 years. The reports of Davidson (1995) and Davidson and Yu (2008) neither extend through the entire study area, nor include the Mandurah bores. *The Southern Perth Basin groundwater bulletin* (Pennington Scott 2009) includes some of the Mandurah bores but again does not extend through the entire study area. Where the work of Davidson and Yu (2008) and Pennington Scott (2009) overlap, there are several areas and stratigraphy layers with very poor alignment in areas critical to rapidly occurring development. In summary, the existing interpretations could not be used to reliably delineate the thickness nor the extent of the South Perth Shale – which is critical knowledge for any major aquifer storage and recovery scheme.

In response the Water Science Branch discussed the problem with staff from the Department of Water's Groundwater Branch and the Kwinana-Peel regional hydrogeologist to initiate a review. Over several weeks the authors methodically reviewed the geology of the study area. This study incorporates 59 geophysical logs, many of which have not been described in any previous published work. This information was interpreted with the aid of palynological records dating back to the 1960s, lithology logs where available, and existing published literature.

There are several areas where the findings of this report differ significantly from previous interpretations. These changes are the result of <u>new</u> information being incorporated into this study that has not previously been used, in particular private bores. The most significant revision is the reinterpretation of the Rockingham Sand as being equivalent to the Wanneroo Member of the Leederville Formation.

Before publication the Rockingham Sand interpretation generated considerable debate. The aim of this report is to summarise the extensive body of evidence in a cohesive format for those interested, thus allowing informed comment and discussion to take place

Current status

During the past 50 years several geological studies have been conducted in and around the Murray region. Figure D.1 illustrates the contours of the South Perth Shale (Kws) from two of these studies, the *Perth Regional Aquifer Modelling System model development: Hydrogeology and groundwater modelling* (Davidson & Yu 2008), largely based on Davidson (1995), and the *South Perth Basin groundwater bulletin* (Pennington Scott 2009). As can be seen in Figure A.1, there is poor agreement between the two sets of contours, particularly in the region of the potential development subareas of Barragup, Nambeelup and Ravenswood. It was therefore decided that a review of all data from previous studies would be undertaken, as well as data that has previously not been used, and incorporate these into a revised geology interpretation for the whole study area that the authors could feel confident in using for calculations and discussion.

Below is a summary of the data and methods used in the revised interpretation.

Geophysical logs

Data from all the above-mentioned studies as well as geophysical logs from a variety of sources were obtained. Because many of the geophysical logs from the Mandurah bores (Commander 1975; Emmenegger 1963; Emmenegger 1964; Passmore 1962) had not been incorporated into recent studies, one of the first tasks undertaken was the digitisation of the Mandurah bore's geophysical logs. Having the Mandurah geophysical logs in a digitised format allowed for the information to be projected in software with all other bores that had digitised geophysical logs and equally scale them for ease of interpretation. In addition, former Public Works Department bores Miami 1-80 and Miami 1-75 were also digitised for this purpose. A review of deep private bores was also completed and several of those were added to the interpretation where they provided information in areas sparse of data. The dataset of geophysical logs also included all artesian monitoring bores located in the study area, and several immediately to the north known as the Becher Point line (Allen 1978). A list of all bores used in the geological study is provided in Table A.1.

Lithology logs

Lithology logs are held by the Department of Water for most AM bores, but many have not been included in published in reports. Allen (1978) summarised the lithology for the Becher Point bores (AM57 to AM61). Passmore (1962) published logs for Mandurah 1, while Emmenegger (1963; 1964) published logs for Mandurah 2 to 5 and several other private bores in the area. Unpublished composite logs (combined geophysical and lithology) produced in the 1970s by P. Commander for the Geological Survey of Western Australia were used for lithology information on Mandurah bores 6 to 18. Lithology logs have not been located for Miami 1-80 or Miami 1-75. Lithology information on private bores is often very basic and comes from the driller's report where available.

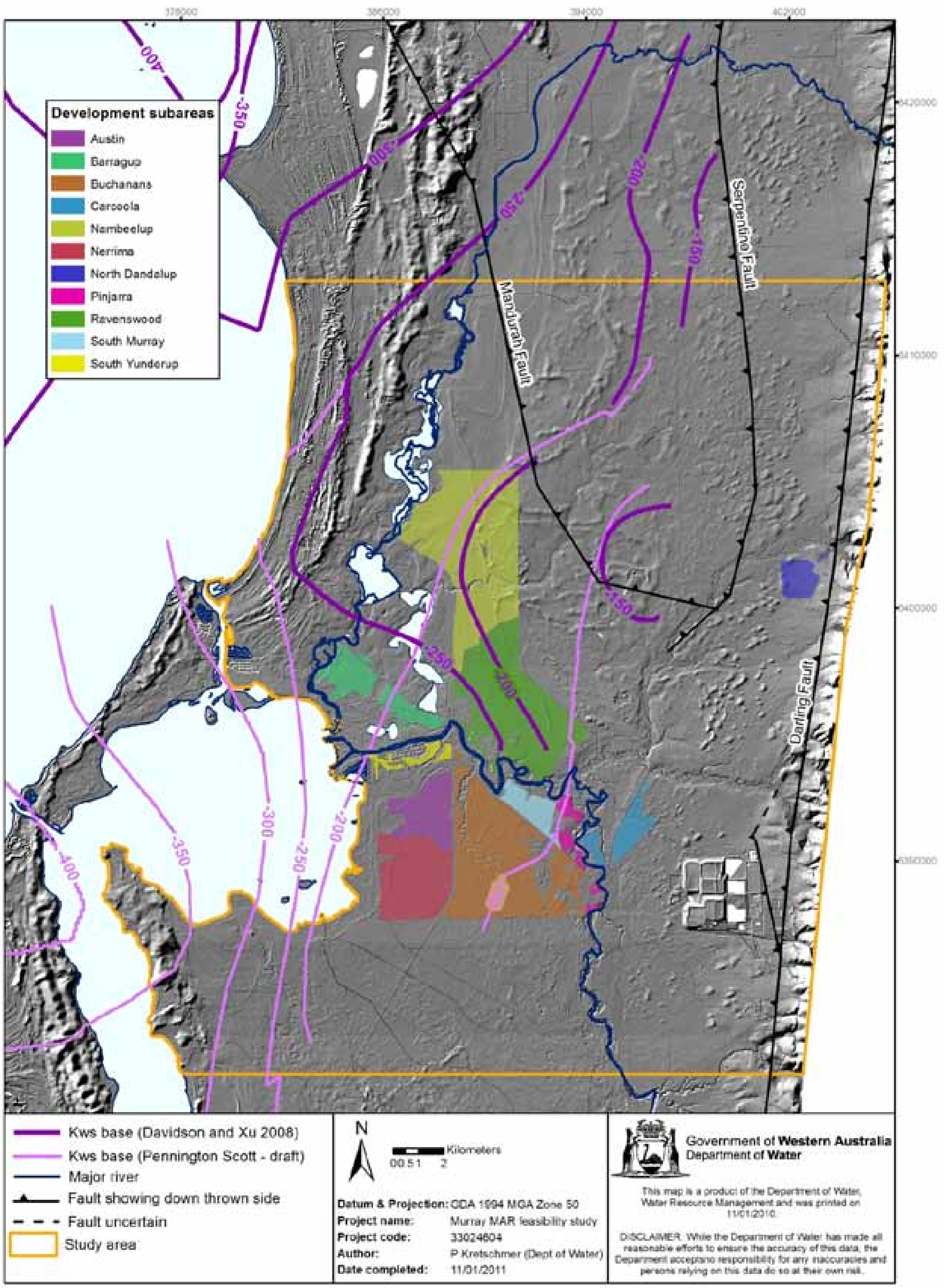


Figure A.1 Existing contours for South Perth Shale (Kws) base contours in m AHD

Table A.1 Names and locations for bores with geophysical logs that were used for the revised interpretation of the geology in the Murray study area

Bore	Easting	Northing	Drilled Depth (m)	Top Screen (mBGL)	Bottom Screen (mBGL)	Ground level (mAHD)
AM57	380392	6417422	801	483	488	2
AM58	387338	6415685	746	379	384	9
AM59	392454	6417800	796	375	380	8
AM60	397359	6416394	810	483	495	16
AM61	402244	6416861	802	603	608	37
AM62	387727	6410862	386	333	339	8
AM63	395615	6410203	349	312	320	22
AM64	403825	6410003	357	307	318	55
AM65	387523	6403674	363	114	123	2
AM66	397363	6403772	384	341	347	21
AM67	382835	6402182	376	343	348	12
AM68	390782	6398413	327	296	304	9
AM69	403632	6402890	198	192	198	41
AM70	399256	6397116	505	457	465	22
Mandurah 1	379247	6399426	574	136	193	2
Mandurah 2	383193	6399080	174	94	101	7
Mandurah 3	386197	6396937	208	Abandoned		3
Mandurah 4	389529	6395062	154	47	89	3
Mandurah 5	392802	6394678	255			8
Mandurah 6	390826	6392235	165			6
Mandurah 7	391682	6397302	201	Abandoned		10
Mandurah 8	394683	6396932	174			13
Mandurah 9	394782	6391546	222	93	96	7
Mandurah 10	389517	6389118	287			6
Mandurah 11	392521	6387833	291			10
Mandurah 12	387531	6391781	290			2
Mandurah 13	395491	6394398	218			7
Mandurah 14	399000	6392990	206	181	192	15
Mandurah 15	402035	6391866	95	6	77	30
Mandurah 16	400225	6392575	130	87	96	17
Mandurah 17	400403	6382450	107	30	42	44
Miami 1-75	374671	6394695	307	105	177	5
Miami 2-75	371937	6388435	290			15
Miami 1-80	377235	6388728	313	80?		1
Pinjarra Light Industrial	392337	6389978	96			8
Belswan	393502	6388979	105			11
Pinjarra Harness	393738	6387591	93			12
Lillyvale Grazing	397621	6382839	144			23
Yangedi Rd	393967	6411003	165			19
Weymouth Kerford	400522	6408233	60			32
Heytsbury Stud	403985	6408761	152			57

Table A.1 continued.

Bore	Easting	Northing	Drilled Depth (m)	Top Screen (mBGL)	Bottom Screen (mBGL)	Ground level (mAHD)
Nambeelup Joint Ventrue	394742	6401296	155			18
Dawkins	394764	6404448	30			20
Cedar Mariner	381764	6396686	210			3
Austin Cove	388472	6392043	251	46	82	2
Riverland Ramble	389854	6394796	120	74	98	4
Pinjarra 1	385984	6384195	4574			5
Point Grey 1	382200	6386421	137			2
Point Grey 2	378416	6382633	149			3
Mandurah Golf Club	377921	6399992	215			9
Park Ridge No. 1	373164	6384780	194	145	155	22
Halls Head Sports	377514	6397274	195	165	195	5
Alcoa E8	400416	6390469	208	151	187	25
Alcoa Obs 3	399249	6390639	180	107	132	17
Alcoa Obs 1	398490	6390688	232	128	223	15
Alcoa E7	400407	6385315	217	85	156	41
Allcoa E3	396243	6387432	271	80	108	12
Alcoa E4	399956	6387255	293	149	168	30
Alcoa E6	398013	6384047	305	126	151	21

Palaeontology

An extensive electronic database of palaeontology reports from the Geological Survey of Western Australia was published by the Department of Industry and Resources. Entitled *Geological Survey of Western Australia palaeontology reports 1962–1996*, it contains the palaeontology reports written for the Mandurah bores, many of the AM bores and several other private bores in the study area. Each geophysical log was notated with the palaeontology information, which greatly improved the accuracy of the interpretation.

Analysis

Initially the digitised geophysical logs were loaded into Petrel™, a software package designed to aid three-dimensional (3-D) geological interpretation. Cross-sections of the gamma logs were created, with the transects of bores running in a general east-west direction across the coastal plain. Each geophysical log was shaded, depending on the gamma count, an example of which is shown in Figure A.2.

As subsequent logs were located through the investigation period and added to the interpretation, new transects were created in the more traditional manual method.

The resistivity log was also used in the interpretation, particularly to locate the typical resistivity spikes of the Mariginiup Member. The examples of interpreted geophysical logs which are found in Davidson (1995) and Pennington Scott (2009) were used to guide interpretation. Initially a first-pass interpretation of the full dataset of geophysical logs was conducted using only the geophysical logs.

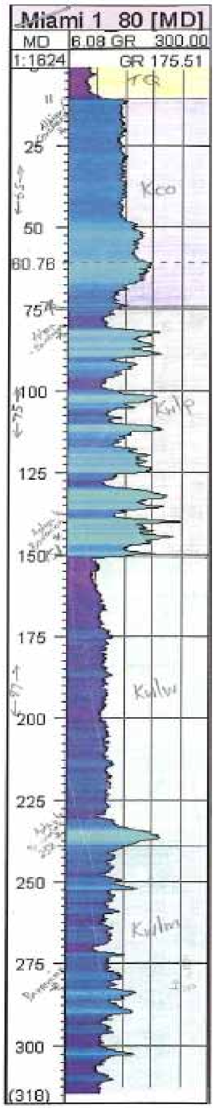


Figure A.2 Miami 1-80 gamma log. An example of how stratigraphic picks were completed manually based on gamma, resistivity logs, lithology logs and palaeontology reports where available.

Review of the stratigraphy picks that had been made initially found there were inconsistencies in some of the picks where transects overlapped. To improve the consistency, more time was dedicated to reviewing the available literature for the bores, and the important components of the lithology and palaeontological measurements were notated onto the geophysical logs. In general the stratigraphy picks were close to those given in Allen (1978), Davidson (1995) and Pennington Scott (2009). In areas where the base of the older formations were not encountered, such as south of the Peel Inlet, linear extrapolation of the base levels was made based on the increase in thickness and depth of the shallower formations.

Once the picks had been made, contouring of both the isopach and formation base height was completed manually using linear interpretation. The main differences between the old and new interpretations are the result of contouring to additional data points, however, the process did result in a significant reinterpretation of the Rockingham Sand, previously described as a Tertiary-aged palaeochannel fill (Davidson 1995; Passmore 1962). The additional data now indicates the Rockingham Sand is equivalent to the Wanneroo Member of the Leederville Formation.

Three-dimensional model

To complete the analysis, a 3-D model of the study area's stratigraphy was developed so that it could be used for first-pass calculations and potentially be used for modelling at a later stage. This model was constructed in ArcGIS^{TM} by 'stacking' the hand drawn and digitised isopach layers of each stratigraphic unit in succession above and below the upper surface of the Mariginiup Member / base of the Wanneroo Member. This surface was selected as the foundation surface to stack the isopach layers on because it had the most bores which penetrated it, thus improving base contour mapping. By selecting the middle stratigraphic unit to build on, the amount of error that could be propagated though the model was minimised when compared with starting at the very bottom or top of the stratigraphic layers. To ensure accuracy of the geology model, the surfaces were checked to ensure they aligned with the stratigraphic picks in the bores. All surfaces intersect the stratigraphic picks in the bores with little error (<2 m) (Figure A.3).

Figure A.4 shows the 3-D model in an expanded view, and Figure A.5 shows the revised base contours for the South Perth Shale.

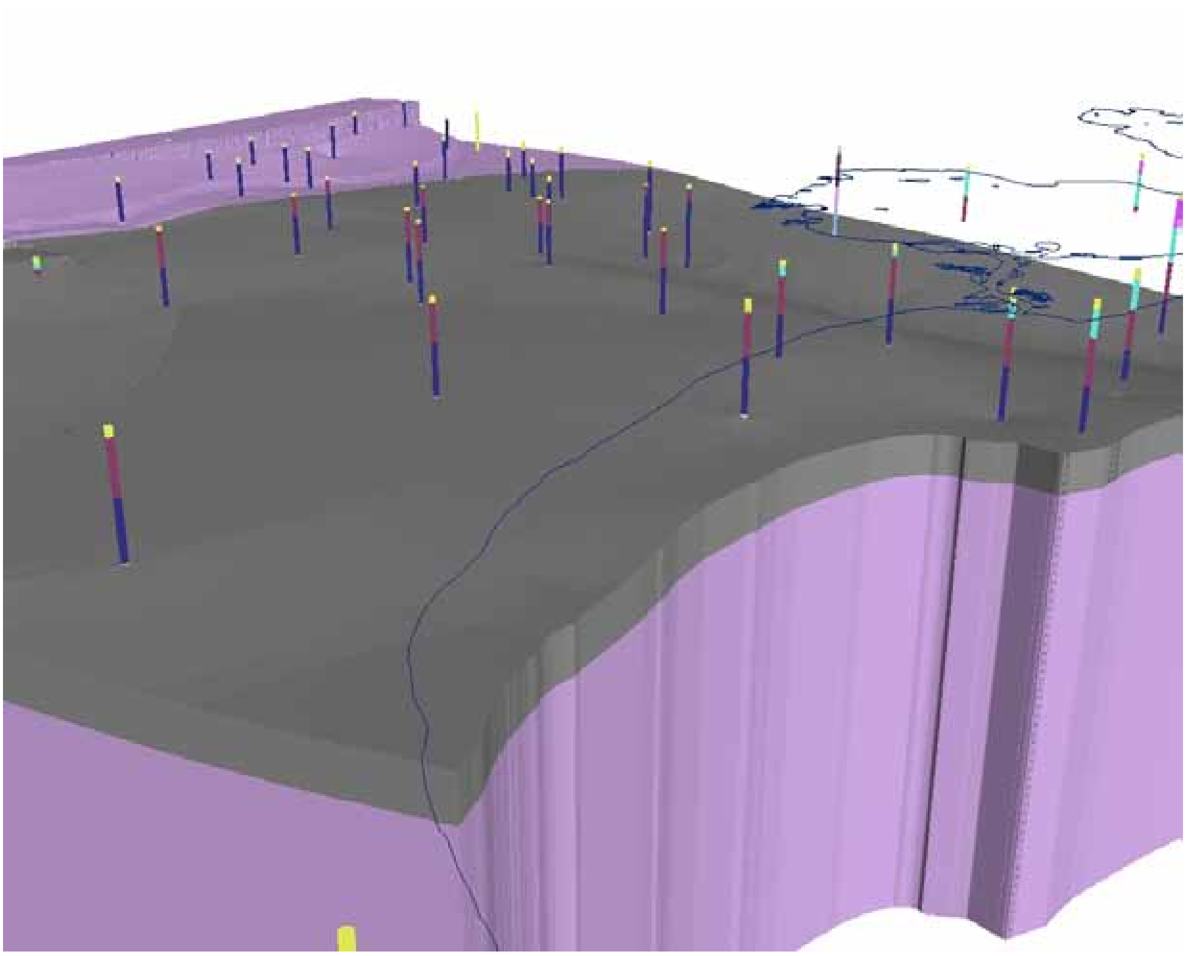


Figure A.3 An example of the surface for the South Perth Shale (grey) fitting through the picks in the bores. The South Perth Shale is pink in the bores (just visible at the base of some bores), the Mariginiup Member is marked dark blue, and the Wanneroo Member dark red. The underlying purple-coloured unit is the Cattamarra Coal Measures.

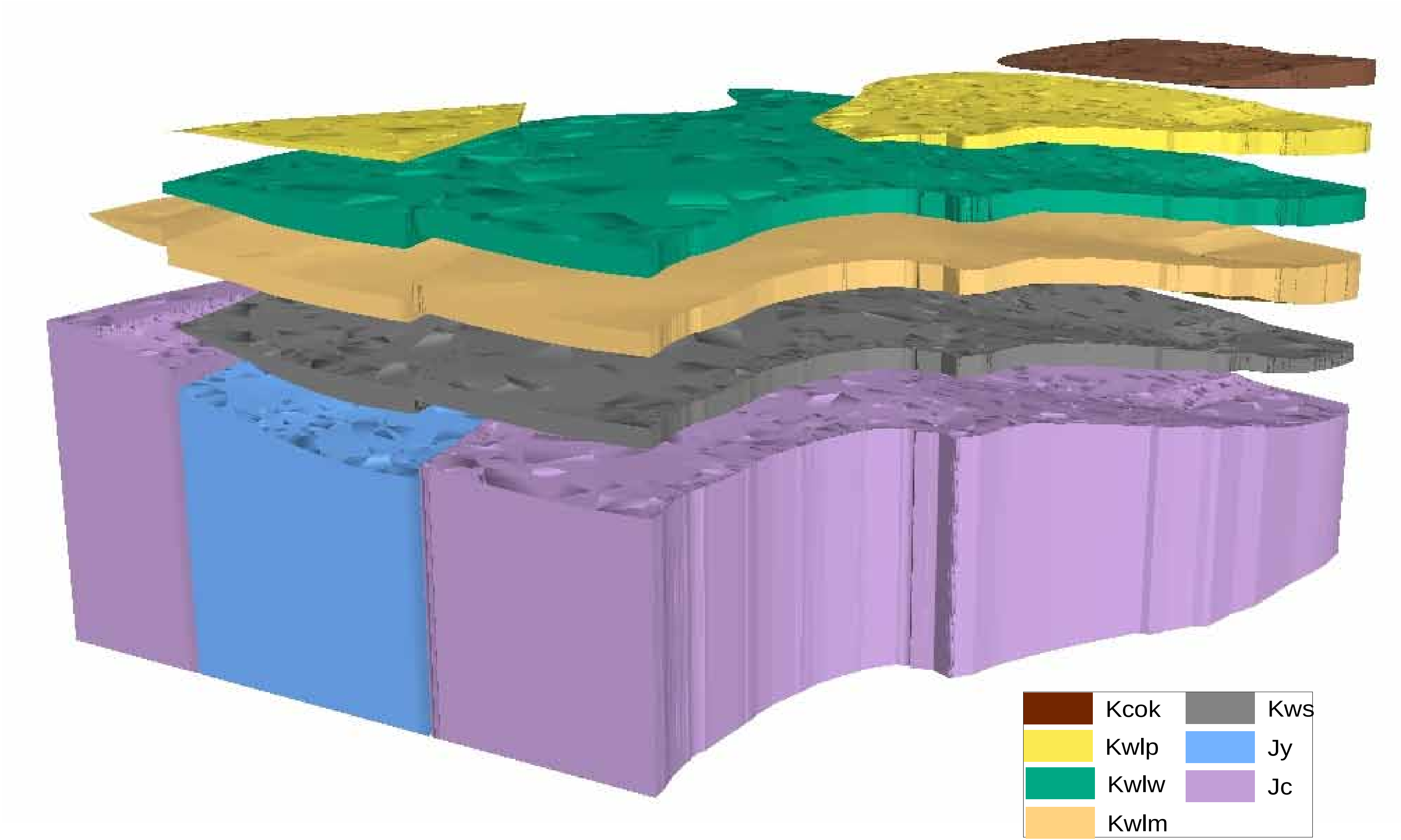


Figure A.4 An expanded view of the 3-D geology model viewed from the north-west.

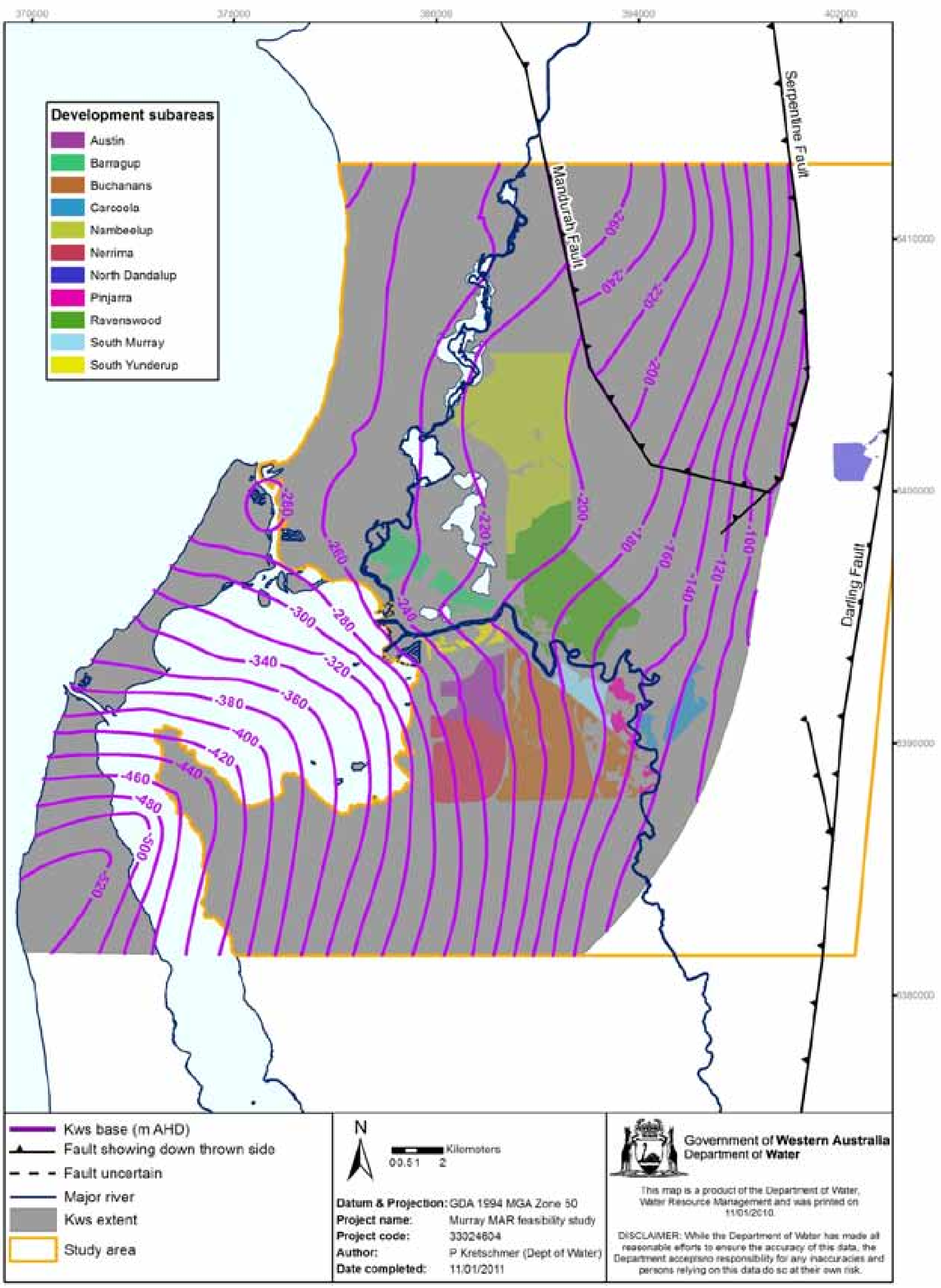


Figure A.5 Revised South Perth Shale (Kws) base contours

Reinterpretation of the Rockingham Sand

The following section summaries the evidence supporting reinterpretation of the Rockingham Sand to be equivalent to the Wanneroo Member.

During the geology interpretation process it became clear the Serpentine and Mandurah faults have influenced the height, thickness and extent of the Jurassic *and* Cretaceous formations in the Murray region. It has subsequently been realised that the palaeochannel the Rockingham Sand occupies is more likely to be a feature equivalent in age to the Wanneroo Member of the Leederville Formation, and very unlikely to be a palaeochannel.

The existing Rockingham Sand interpretation

The first published account of the Rockingham Sand is a description of Quaternary channel fill encountered in Mandurah 3 (M3) (Emmenegger 1964). Subsequently, Passmore (1970) published a detailed account of the channel fill and supported the hypothesis of it being palaeochannel fill. This study was located around the Point Peron Peninsula near Rockingham, with the deepest bore, Rockingham No. 1 (R1), encountering the sandy lithology that became the type-section of the Rockingham Sand.

Palynology investigations were undertaken on all Mandurah bores, with a sample taken at 54 m in M3 within the coarse sand material being identified as Quaternary. Allen (1978) described the geology of the Becher Point bores, a series of five bores extending east-west from Becher Point to the Darling Scarp, all approximately 800 m deep, and now known as AM57 to AM61. These bores also encountered a very sandy unit to -155 m AHD in Becher Point 1 (AM57) and -131 m AHD in Becher Point 2 (AM58). Later, AM62, AM65, AM67 and AM68 also encountered the sandy formation on the western side of the coastal plain; however, it was inferred from the geophysical logs and not sampled for either lithology or palaeontology. Consequently this data supported the palaeochannel hypothesis of Emmenegger (1964), and it was subsequently inferred that a palaeochannel extended between the Peel Inlet and Point Peron. The first map of the palaeochannel's extent is found in Allen (1976), where it encompasses artesian monitoring bores AM52Z, AM54, AM57, AM58, AM62, AM65 and AM67. The extent of the formation was later updated in Davidson (1995).

The most recent study to describe the extent of the Rockingham Sand was completed as part of the *Murray hydrological studies* (Hall et al. 2010c). This study mostly used a large dataset of shallow bores, but importantly two deep bores were drilled, HS097 (71.0 m bgl) and HS104-1 (61.5 m bgl). Both of these bores penetrated the full thickness of the Rockingham Sand until they intersected a glauconitic (dark copper green) lithology, thought to be the green-clay marker bed in the Leederville Formation. The lithology logs of the Rockingham Sand for these two bores consisted of mainly tan to beige medium- to coarse-grained, subangular to subrounded, mostly clear quartz, with 5 to 10% angular feldspar, and minor silt matrix. The feldspar content varied between <5% and up to 30%, and the colour varied to dark grey with fragments of shale (as seen in the lower sections of HS097), while the quartz grain size varied between fine (<0.5 mm) to very coarse (up to 5 mm), in parts having a clay matrix.

Figure A.6 Core from bore HS104-1 between 55.5 m bgl and 61.5 m bgl, illustrating the change from the Rockingham Sand to the green-clay marker bed at 58.5 m bgl (the photo was taken late in the day, described as 'dark copper green' in the lithology logs). Photo courtesy Claire Johnsen, GHD

Figure A.7 Core from HS097 before being placed in the core tray. Note the abrupt transition from the Rockingham Sand to the green-clay marker bed at 67.5 mbgl. Photo courtesy Claire Johnsen, GHD

These bores were interpreted to be the Rockingham Sand and the lithology is consistent with that described in the type-section (Passmore 1970). Their location along with several similar private bores led to a significant extension of the palaeochannel eastwards towards the Darling Scarp. Maps of the formation in the study area, including upper and lower surfaces, are included in Hall et al. (2010c). It is worth noting that the earlier interpretations of these bores were made by the author of this appendix. Consequently, there is considerable momentum behind the interpretation that the Rockingham Sand is a Tertiary unit that occupies a palaeochannel. However, new information provides a new insight into the age and its stratigraphic position.

There are two main reports that the existing palaeochannel interpretation relies on: the first is the report that discusses the type-section, *Shallow coastal aquifers in the Rockingham district Western Australia* (Passmore 1970). The other to a lesser extent is *Hydrogeology of the Mandurah-Pinjarra area, Perth Basin, WA* (Commander 1975). The latter work mainly concentrates on the deeper aquifers but it does discuss the Quaternary sands intersected in M3, which appears to have been used to mark the southern extent of the palaeochannel in Allen (1976) and Davidson (1995).

Passmore (1970) represents the palaeochannel in cross-section based on a transect of bores that crosses the Rockingham Peninsula and then deviates northwards to Cockburn Sound. This report describes the type-section of Rockingham Sand as it was encountered in Rockingham No. 1 (R1). R1 was drilled in 1964 using the rotary drill method to a total depth of 360 ft (109.7 m bgl). The type-section of the Rockingham Sand begins at 97 ft (29.6 m bgl) after passing through 26.5 m of the Safety Bay Sand and 3.1 m of greenish grey and dark grey clay (Passmore 1970). Rockingham No. 3 (R3; 35.3 m deep) encountered this clay bed but did not pass through it, and therefore R1 was the only bore in the study to encounter the Rockingham Sand as shown in Figure A.8.

An issue with the cross-section shown in Figure A.8 is that it is inferred that the Rockingham palaeochannel does not continue underneath R3, or any significant distance eastwards. What was also unlikely to be known at the time of its publication was that the additional ‘FPA’ bores used in the interpretation were located on the downthrown side of the yet to be mapped Mandurah Fault, and these shallow bores, which are less than 42 m deep, would not have intersected the Wanneroo Member, so no direct comparison between the lithology of the Rockingham Sand and the Wanneroo Member could be made.

On a side note, an additional bore – Garden Island bore B24 – drilled by the Department of Army in 1943, was added into one transect for interpretation. This particular bore is located at the southern end of Garden Island, nearby to where several other bores were installed in the 1980s and 1990s. Passmore (1970) interpreted B24 to have Rockingham Sand between 41.5 and 161.5 m bgl. Garden Island No. 4 located around 400 m away has a very sandy unit at similar depths. A palaeontology interpretation from 130 m bgl in Garden Island No. 4 has placed a date on this sandy lithology as Early Aptian (Backhouse 1980). This infers the sandy formation as being age equivalent to either the Wanneroo Member or Pinjar Member, with the low gamma reading suggesting the Wanneroo. However, it is worth noting that the lithology in B24 mentions ‘calcareous sands, friable, cemented with carbonate’ between 85.3 and 161.5 m bgl (Passmore 1970), which does not fit well with descriptions of either the Rockingham Sand or Wanneroo Member. The only other lithology log found for Garden Island belongs to the driller’s log for Artesian Bore No. 6 which describes the lithology at the respective depth as ‘sand, fine to medium with grey/green clay'.

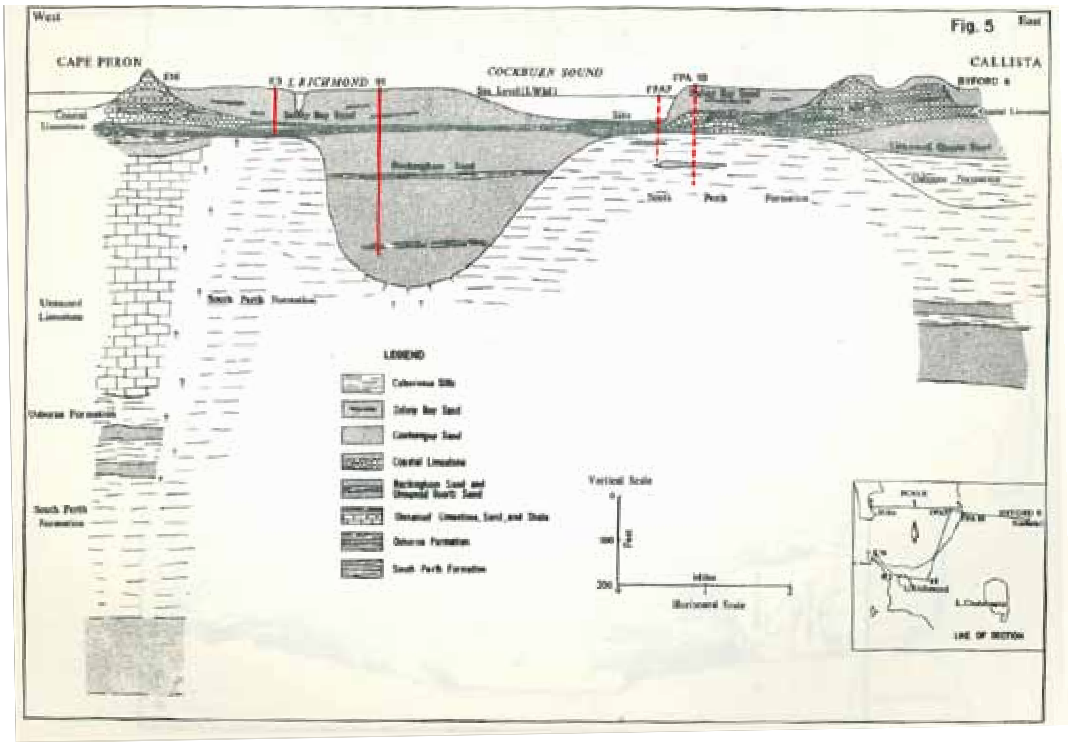


Figure A.8 Cross-section of the Rockingham Sand palaeochannel at its type-section on Point Peron Peninsula. Reproduced with minor edits (bores marked to scale) from Passmore (1970)

There is a remarkable likeness in the lithology descriptions for the R1 type-section and the lithology encountered in bores to the south. In its type-section the Rockingham Sand is described as:

> Rockingham No. 1: 96 – 360 ft (29.6 to 109.7 m)
>
> SAND, quartz, feldspathic, light brown, medium- to coarse-grained, subrounded to rounded, minor shell fragments. Light brown clay as minor constituent and as sandy clay interbeds, eg. 198 to 208 ft. (Passmore 1970)

This compares to other bores that have penetrated the Rockingham Sand such as:

> Mandurah 3: 30 – 220ft (9.1 to 67.1 m)
>
> SAND, quartz, brown and yellow brown, coarse to very coarse, unconsolidated, very well sorted, with angular to subangular grains. Ferruginous concretions, especially at 80 feet, 105 feet, and 130 feet. Rare intercalations of carbonaceous material. Rare thin layers of yellow and light grey clay. At 90 feet and 145 feet, fragments of calcareous siltstone with shells (?).(Emmenegger 1964)
>
> Becher Point bores
>
> The Rockingham Sand was encountered at No. 1 and No. 2 sites. It consists of brown to light grey, slightly silty, slightly feldspathic, medium to coarse-grained subangular sand. Within the formation are occasional layers of oxidised pyrite, rare pebbles, and grains tentatively described as oxidised glauconite.(Allen 1978)

Note that AM62, AM63, AM65 and AM67 do not describe the lithology for depths later interpreted to be Rockingham Sand.

> HS097 and HS104-1 (abbreviated)
>
> Mainly tan to beige medium to coarse grained, sub-angular to sub-rounded, mostly clear quartz, with 5-10% angular feldspar, and minor silt matrix. However the feldspar content can vary between <5% and up to 30%, the colour can vary to dark grey with fragments of shale as seen in the lower sections of HS97, and the quartz grain size can vary between fine (<0.5mm) to very coarse (up to 5mm), with occasional lenses of light grey clay matrix. In places iron staining was noticed, such as at 33.65 m in HS104-1.

Overall the descriptions are very similar, with the notable absence of feldspar in Mandurah 3. In regard to Mandurah 3 a shallow bore called HS87-1 was drilled very close (<100 m) to where M3 was located. The author was at this drill site and noted the lithology at the base of this hole was very similar to that seen in HS104-1, including abundant white feldspar grains. This indicates that reinterpretation of the Rockingham Sand in the Murray study area is likely to be applicable throughout its mapped extent, including the type section.

Palaeontology is also important to the history of dating the Rockingham Sand. The current interpretation of the sands encountered at 54 m in M3 is Quaternary (Edgell 1963). This would undermine the entire argument for a new interpretation of its age but a close review of the palaeontology report provides vital information. Seven species are recorded in the sample, one of these is dated Neogene, the remaining six are Cretaceous aged. Downhole contamination was a significant issue with palaeontological dating as a result of the mud-rotary drilling method used for the Mandurah bores. Based on the age and diversity of species listed, it is reasonable to conclude that downhole contamination contributed to the younger pollen grains contaminating the sample, and instead the sample should be viewed as reflecting a Cretaceous age.

Anecdotal evidence

There are various other pieces of anecdotal evidence which indicate the existing interpretation does not fit with the regional interpretation. For example:

- The Rockingham Sand palaeochannel as mapped in all existing literature does not have a western extent delineated by data from bores, rather it is an interpreted line drawn under the ocean designed to delineate a ‘channel’ shape. Mandurah 2 is the possible exception to this in the Mandurah area.
- The eastern extent of the Rockingham Sand palaeochannel is delineated by bores that penetrate the Pinjar Member, thus the underlying sandy Wanneroo Member could be easily dated based on the stratigraphic sequence.
- The Wanneroo Member, as defined in Davidson (1995), has a much sandier signature in the gamma logs, similar to that of the Rockingham Sand in the study area compared with north of the Mandurah Fault closer to Perth.
- Previous interpretations of the Rockingham Sand do not appear to have taken into account the Mandurah Fault on its eastern flank. There are likely to be unmapped

faults in the area of the Peel Inlet which would mark the southern limit of the unit directly underlying the superficial formations.

- M3 was thought to have a unique, almost straight gamma log for the Rockingham Sand compared with the AM bores, whether they were labelled Rockingham Sand or Wanneroo Member. The geophysical log for Miami 1-80 shows an equally homogenous sandy unit between 150 and 238 m bgl, similar to that in M3. The bores Point Grey 1 and Point Grey 2 also appear to encounter the top of the very sandy Wanneroo Member with a similar signature to M3. A private bore known as PGPB1, located on Point Grey, south of the Peel Inlet, also illustrates a similar sandy signature between 140 to 225 m bgl, including the green-clay marker bed at the bottom (RustPPK 1996).
- The glauconitic 'green-clay marker bed' is very frequently at the base of the Rockingham Sand in existing interpretations. See M3, Nambeelup JV and AM68 for example. The green-clay marker bed is a Cretaceous, thin, sandy clay unit present throughout the extent of the Wanneroo Member in the study region and it is used to identify the division between the Wanneroo Member and the Mariginiup Member of the Leederville. It seems unlikely that a Tertiary palaeochannel would erode through the entire thickness of the Wanneroo Member over a large area but never erode through just a few metres of the green-clay marker bed.
- The base of the existing Rockingham Sand interpretation increases in depth at approximately the same degree of dip as the Mariginiup Member and South Perth Shale towards Point Peron. One would normally expect a palaeochannel to operate more independently given the one-hundred million years between their depositions, with more localised erosional lines, similar to the Kings Park Formation north of the study area.

The conundrum – Rockingham or Wanneroo

The initial evidence that suggested the Rockingham Sand may be a misinterpretation was based on four gamma logs, three of which had never been used in previous studies. Two of these bores are private bores colloquially known to the Department of Water as Yangedi Rd and Nambeelup JV, the other two are Public Works Department bore Miami 1-80 and GSWA bore Mandurah 3. Figure 2.1 shows the location of these bores.

Nambeelup JV bore is located near the Department of Water's intermediate depth bore HS104-1 discussed in Hall et al. (2010c), of which a full 61.5 m deep core was obtained in 2009. They both record similar sandy lithology below the superficial formations and both of these bores were used to interpret a large eastern extension of the Rockingham Sand by the author of this appendix (Hall et al. 2010c). Yangedi Rd bore is located near AM63 where lithology logs and palynology were recorded and used to help interpret its geophysical log. When the Yangedi and Nambeelup JV bores are plotted next to each other there are several points of similarity. These points, as marked in Figure A.9, are:

1. Small peak in gamma
2. Medium peak in gamma
3. Large peak in gamma

4 Approximately 40 m of low and flat gamma count through the sandy unit

– Not shown is a similar relationship in resistivity with the lowest resistivity occurring at point 1

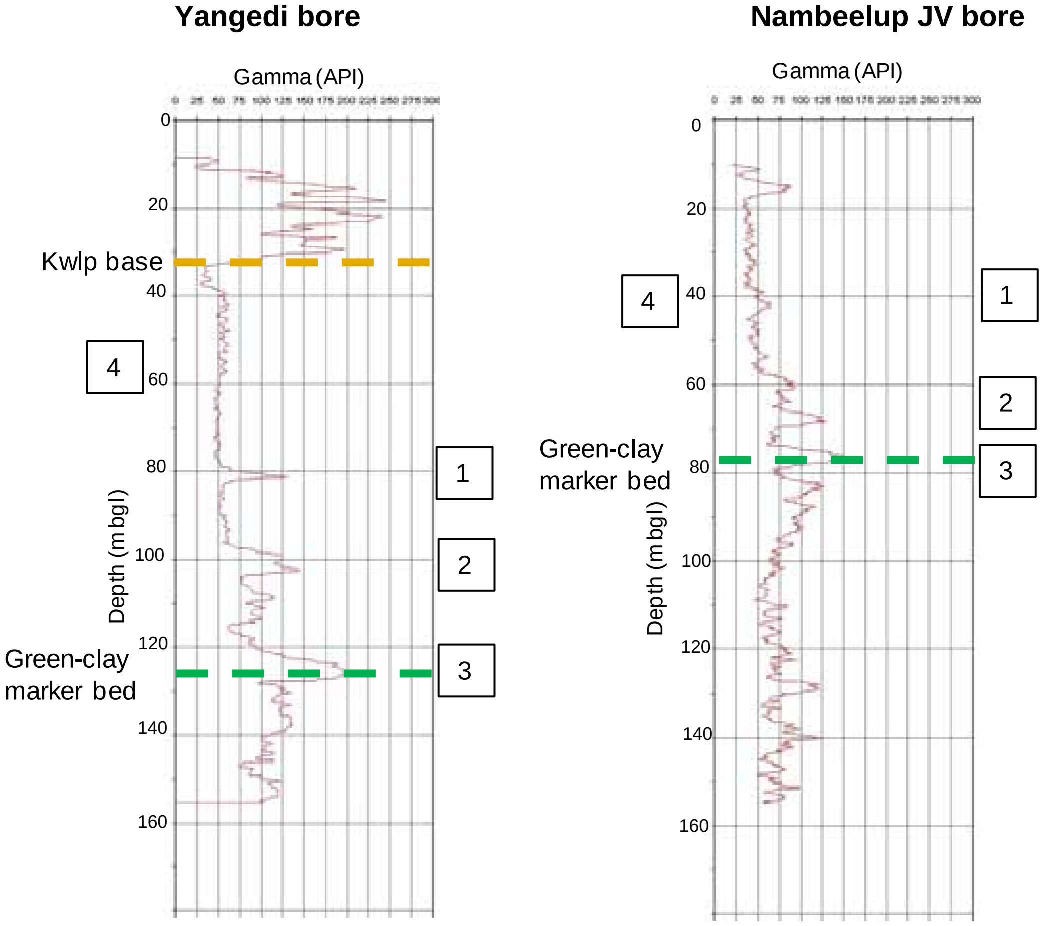


Figure A.9 Gamma and resistivity logs for Yangedi Rd and Nambeelup JV private bores. Note the overlying Pinjar Formation (Kwlp) in the Yangedi bore and the large gamma peak at the green-clay marker bed.

Based on the similar lithology and geophysical logs the evidence indicates they illustrate the same formation. Significantly, Yangedi Rd quite obviously underlies the Pinjar Member, a formation recognised at the top of nearby AM63 (Davidson 1995). This means that the sandy member intersected in the Yangedi Rd bore is the Wanneroo Member, and the sands intersected in Nambeelup are not a feature of a Tertiary palaeochannel, but rather are equivalent to the Wanneroo Member. A comparison of the Miami 1-80 and M3 illustrate a similar conundrum. M3 has been used to map the southern extent of the Rockingham Sand since at least 1976 (Allen 1976). The gamma logs for Miami 1-80 and M3 shown in Figure A.10 have very similar gamma signatures for the Rockingham Sand in M3 and the Wanneroo Member in Miami 1-80. Significantly the depth of the green-clay marker bed has decreased from 77 m bgl to 238 m bgl within the short distance from the northern side to the southern side of the Peel Inlet. This may indicate some unmapped faults in the area.

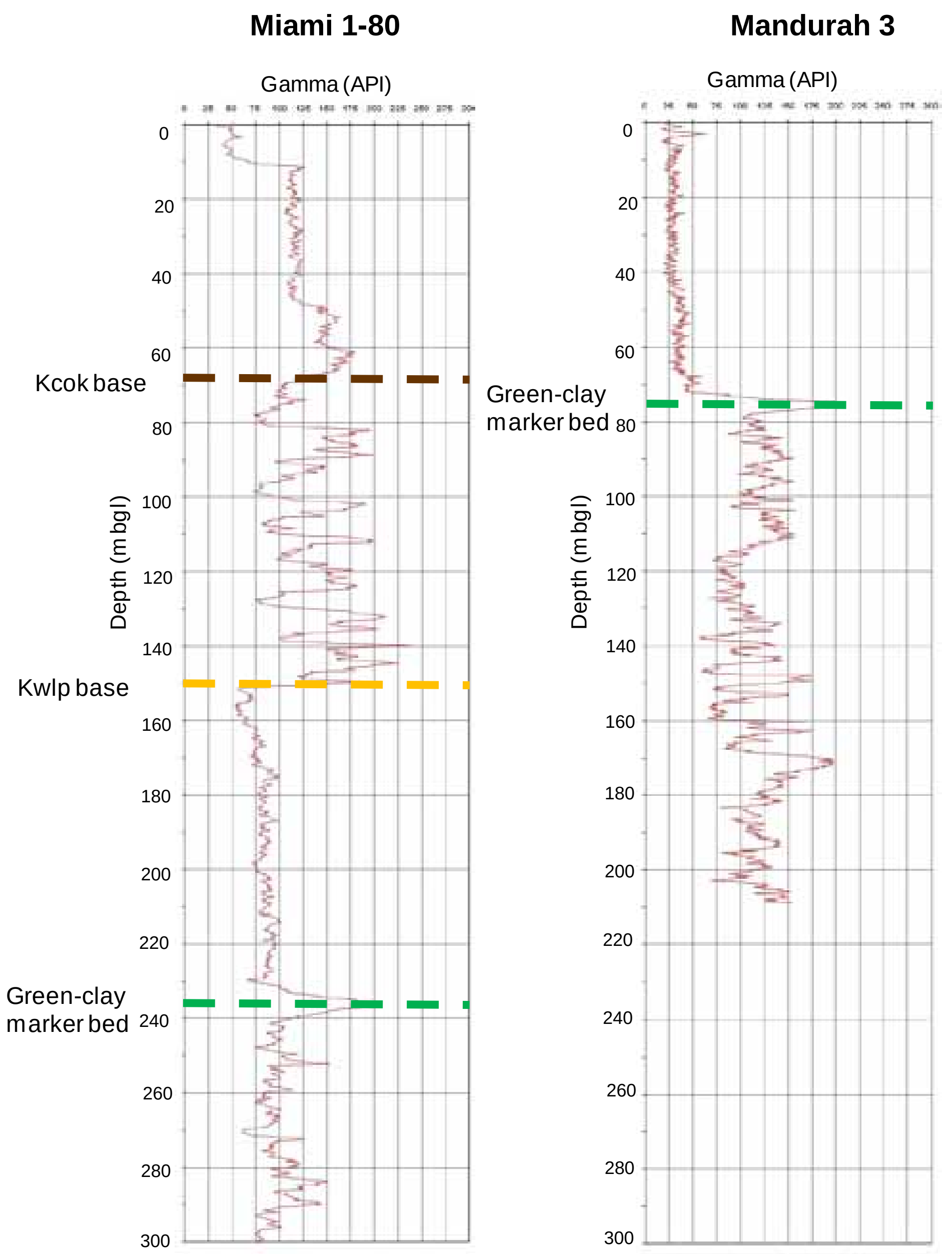


Figure A.10 Gamma and resistivity logs for Miami 1-80 and Mandurah 3 bores

Reassessing the gamma logs in light of this new evidence, it could be seen that AM62 has a similar signature to Yangedi Rd and AM63 (Figure A.11). Importantly the base of the South Perth Shale, Mariginiup Member and Wanneroo (green-clay marker bed) all sit higher in AM62 than Yangedi Rd and AM63, and it is missing the Pinjar Member. This can be related to the Mandurah Fault which marks the south-western edge of Swan Syncline. The Mandurah Fault is not illustrated in the heavily referenced work of Davidson (1995), however it was added to maps in Davidson and Yu (2008). The relationship between AM62 and AM63 indicates the Pinjar Member was either eroded away or never deposited on the western side of the Mandurah Fault.

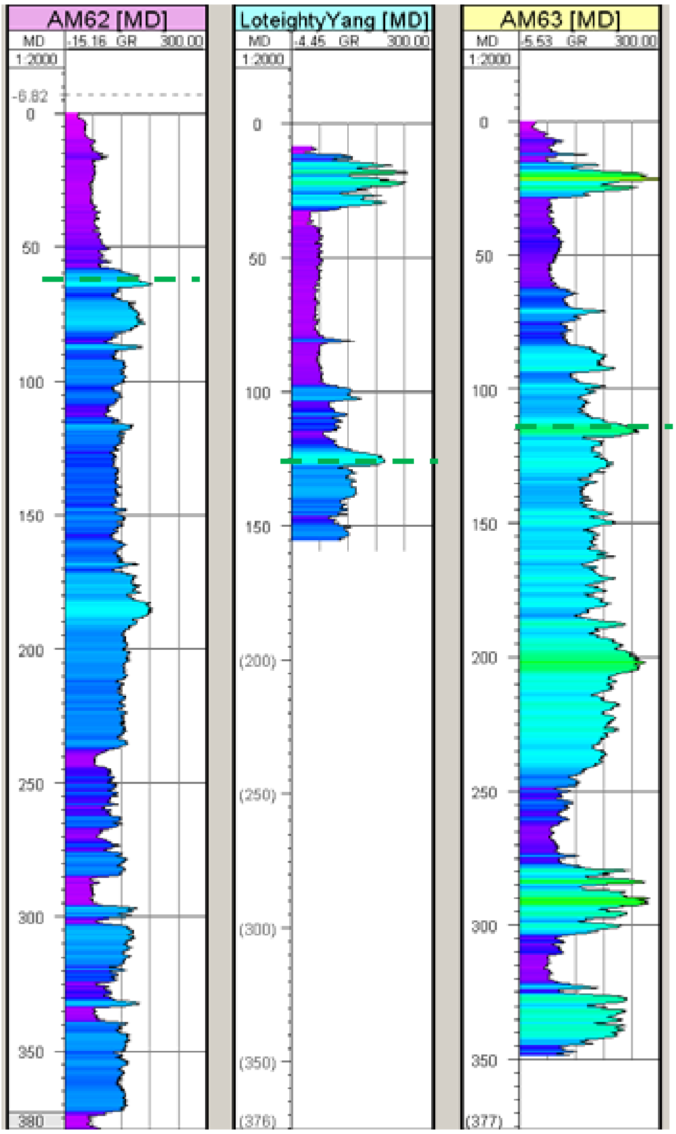


Figure A.11 Geophysical logs for AM62 (west), Yangedi Rd (centre), and AM63 (east). The Mandurah Fault is mapped between Yangedi Rd and AM62, with the formations on the east being downthrown relative to the units to the west. The green-clay marker bed is marked with the dashed green line.

Conclusion

It appears the Mandurah Fault and potentially an unmapped fault near the Peel Inlet have played an important role in locating the Wanneroo Member at the top of the pre-Quaternary deposits in the study area’s north-west. Because the mapping of the Mandurah Fault was only published recently, it had not been incorporated into existing interpretations of the Rockingham Sand. It is likely this is why the relationship of the Rockingham Sand to the surrounding Wanneroo Member had not been more closely analysed. In lieu of new evidence being put forward to support the interpretation of the Rockingham Sand as a Tertiary palaeochannel, it is reasonable to map the unit as equivalent to the Wanneroo Member of the Leederville Formation.

5.2 Appendix B: Summary of available aquifer water quality data

Leederville Aquifer:

Table B.1 Mean summary of water quality data for Leederville Aquifer

Bore	EC @ 25 deg C (µS/cm)	Alkalinity (tot) (CaCO3) (mg/L)	Hardness (tot) (CaCO3) {Ca+Mg} (mg/L)	NO_3-N (sol) (mg/L)	P (sol) (mg/L)	SO_4 (sol) (mg/L)	TDS (cond) (mg/L)	TDS (evap @180°C) (mg/L)	TDS (in situ) (mg/L)	pH
AM57A	1530	151	248	0.60	0.08	34				7.90
AM58A	1620	134	264	0.20	0.01	19		849		8.17
AM59A	592	119	134	0.16	0.14	14	380	340		8.28
AM60B	1477	108	191	0.19	0.04	15	950	865		6.32
AM61B		79	33	0.50		5				6.32
AM62A	1055	258	96	0.08	0.03	24				8.75
AM63A	1290	164	241	0.09	0.06	30				7.40
AM65	4620	249	149	0.08	0.01	111				8.45
AM65A	1430	210	246	0.08	0.02	29				7.80
AM66A	1220	194	261	0.09	0.05	31				7.95
AM67A	1700	192	163	0.12	0.01	18				7.90
AM68A	1170	185	264	0.09	0.01	22				7.75
AM70A	855	57	74	0.11	0.01	59				6.35
AM70B	1440	74				34		790		6.09
M1			248	0.11		86		2040		7.70
M2	24665		3694			1338	18312	21290	6066	8.06
M3	9453		1592			766	7830	8250	1206	7.43
M4	2460		364			67	1720	1490		7.50
M5	1937		225			94	1317	1074	508	8.18
M6	2947	218	205	0.09		86	1810	1618	440	7.55
M7	2418		364			19	1580	1323	1280	7.40
M8	1946		307			47	1025	1057	770	7.25
M9	840		119			22	590	480		7.00
M10	2020	276	240	0.11		73	1410	1280		7.30
M11	1190	83	65			73	830	750		8.40
M12	4360	253	749	0.23		171	3050	3090		7.80
M13	3330	268	560	0.01		83	2330	2040		8.80
M14	900	143	141	0.01		29	630	550		7.50
M16	830	110	118	0.23		26	580	540		6.80
M17	2620	57	243	0.17		27	1585	1493	1400	5.00
Miami 1-75		236	155	0.24		41			1190	8.11
SH1										8.20

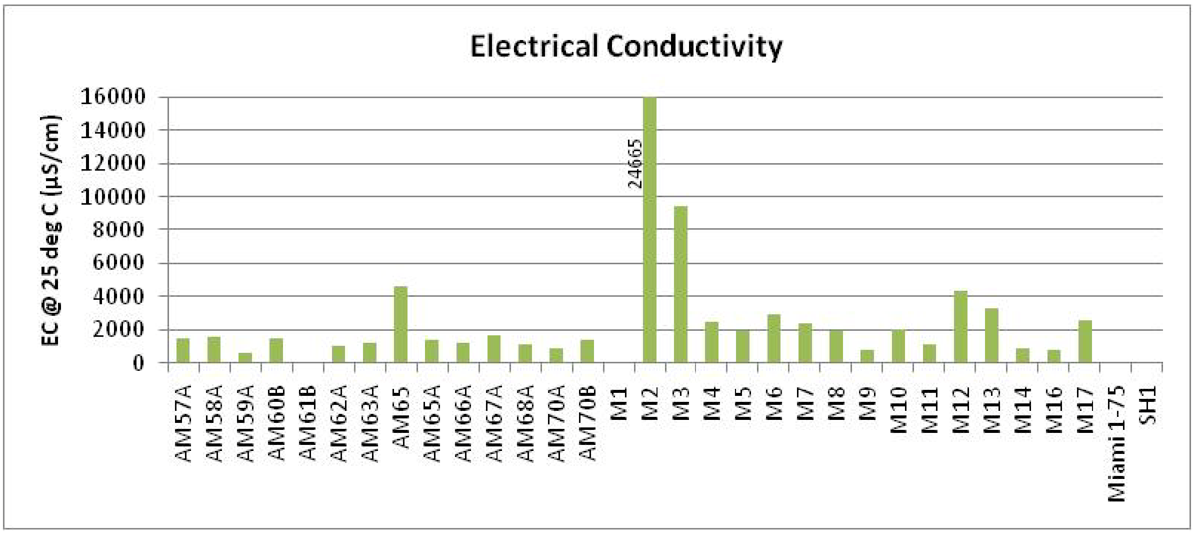


Chart B.1 Electrical conductivity values in groundwater within the Leederville Aquifer

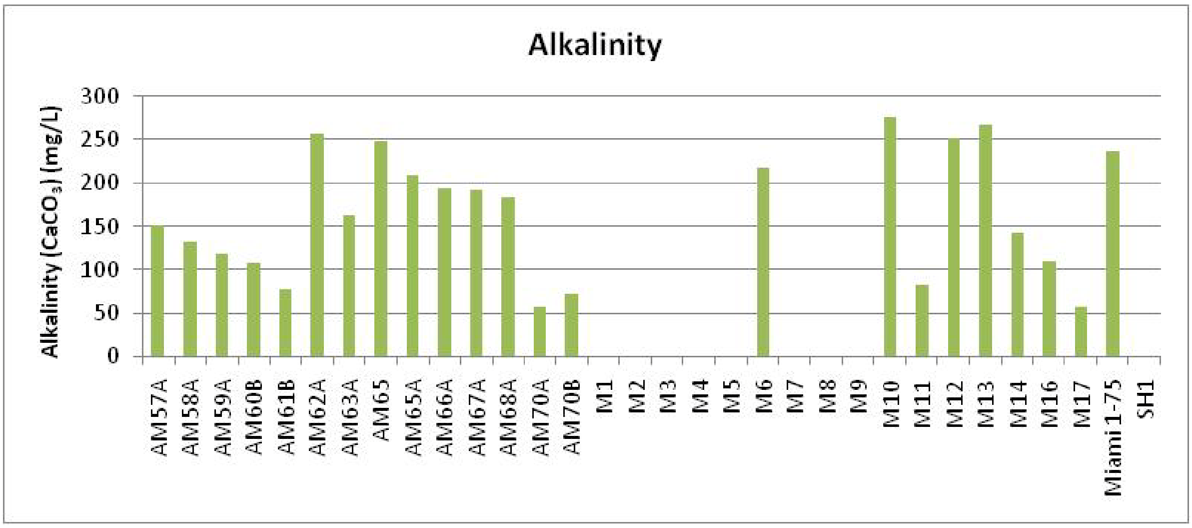


Chart B.2 Alkalinity values in groundwater within the Leederville Aquifer

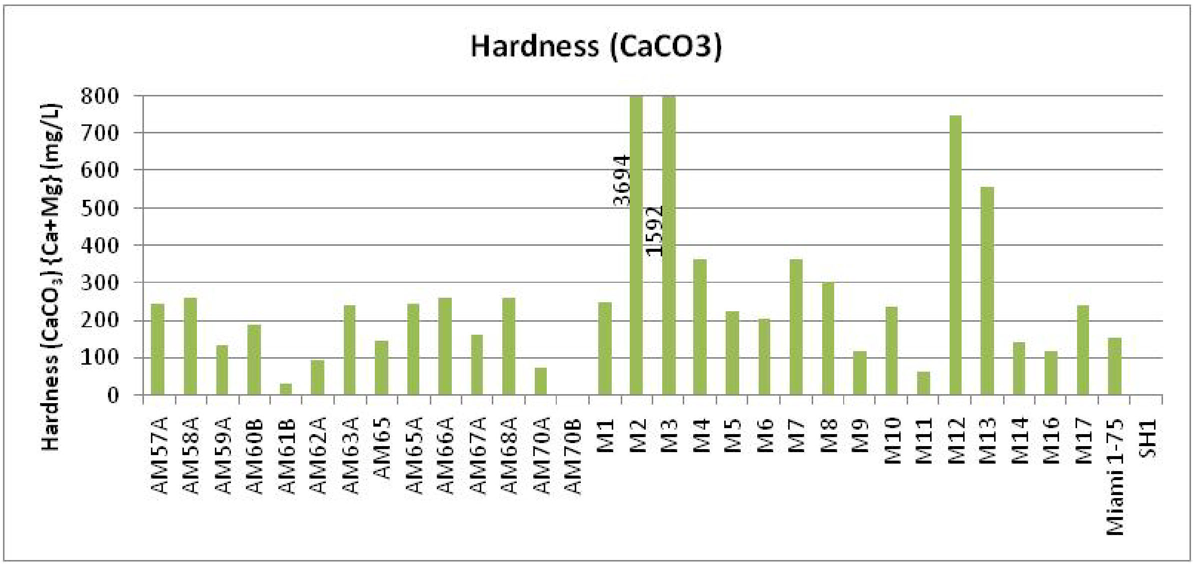


Chart B.3 Hardness concentrations in groundwater within the Leederville Aquifer

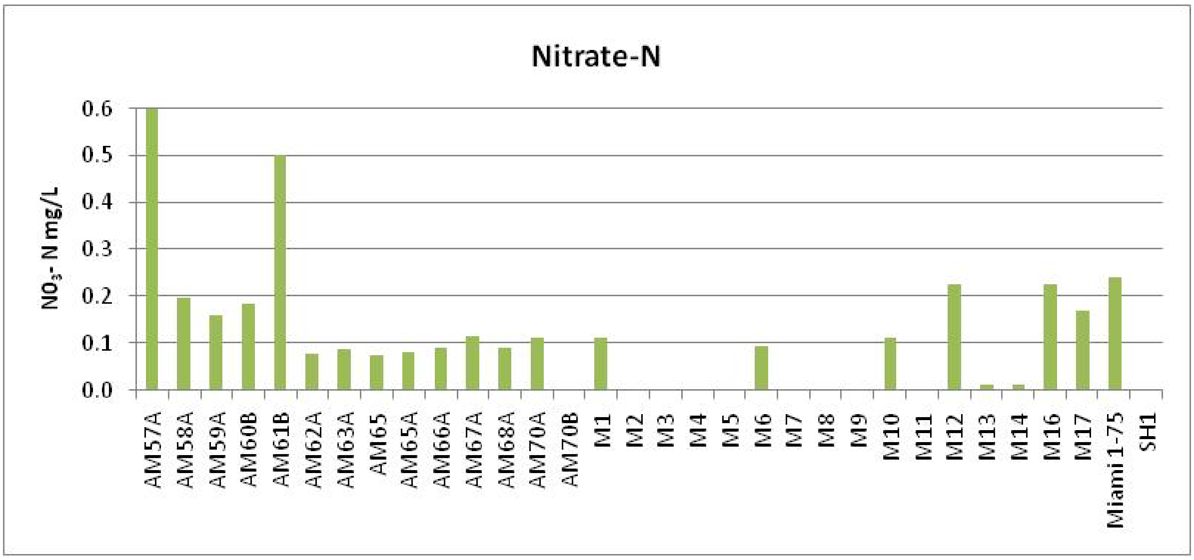


Chart B.4 Nitrate-Nitrogen concentrations in groundwater within the Leederville Aquifer

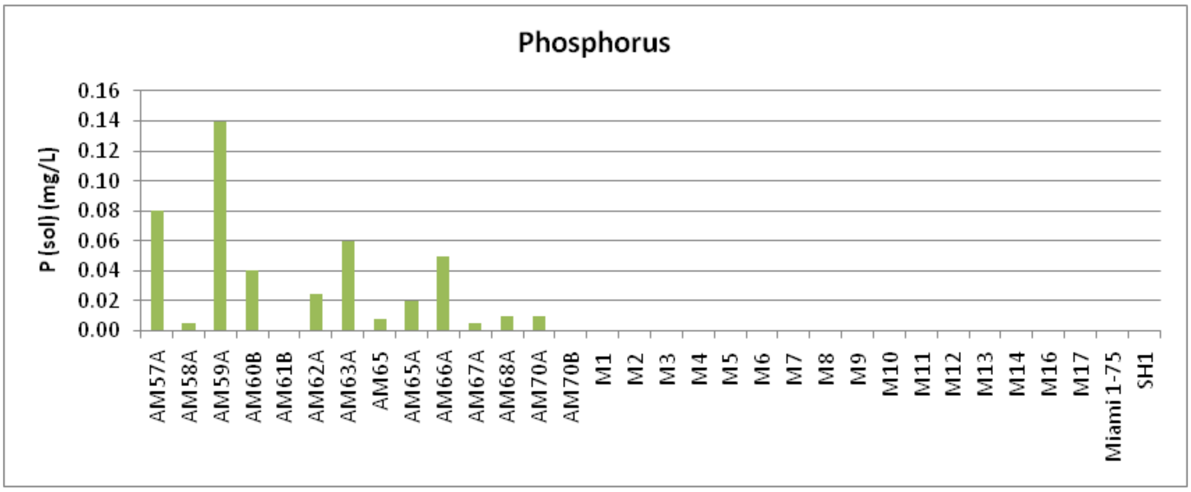


Chart B.5 Phosphorus concentrations in groundwater within the Leederville Aquifer

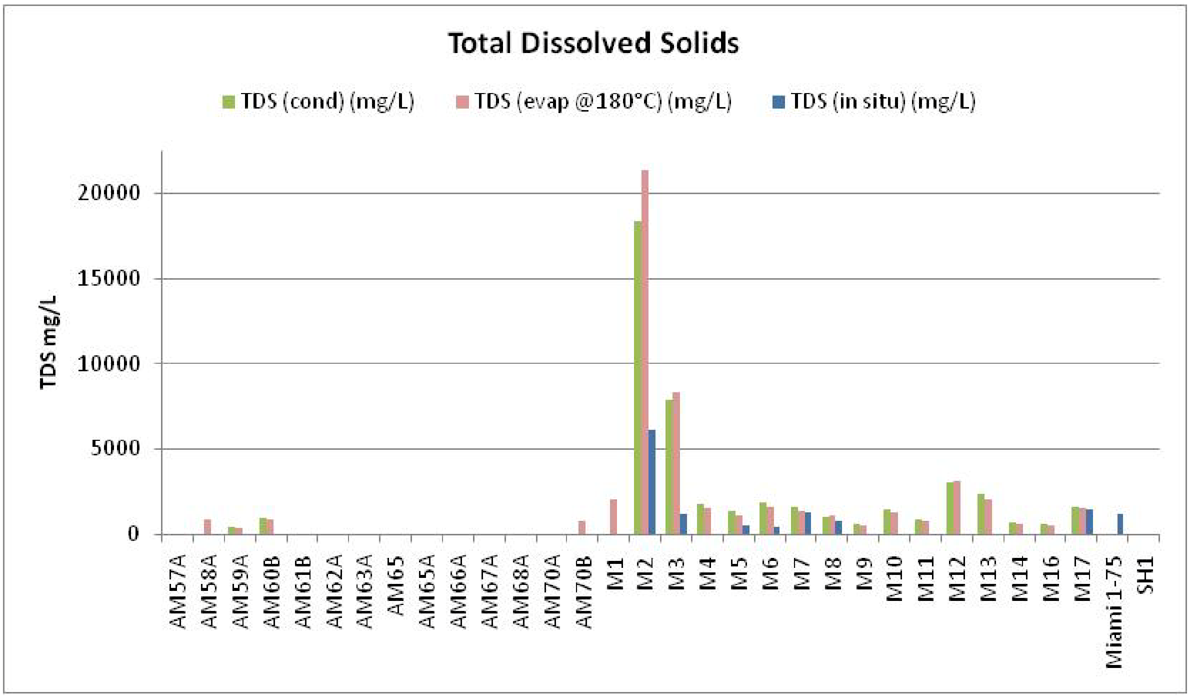


Chart B.6 Total dissolved solids concentrations in groundwater within the Leederville Aquifer.

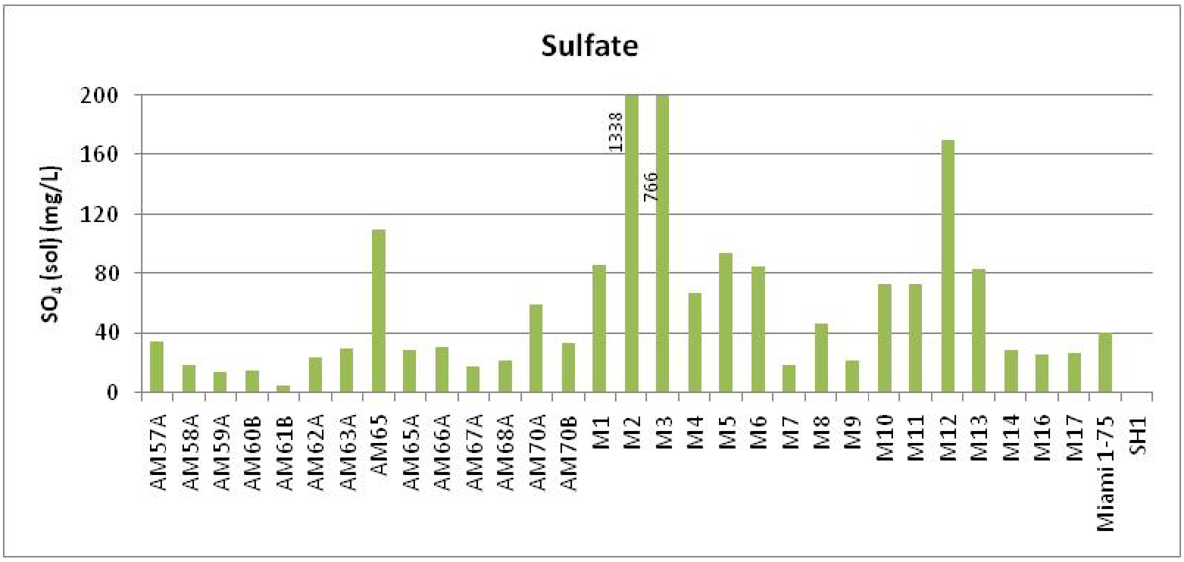


Chart B.7 Sulfate concentrations in groundwater within the Leederville Aquifer.

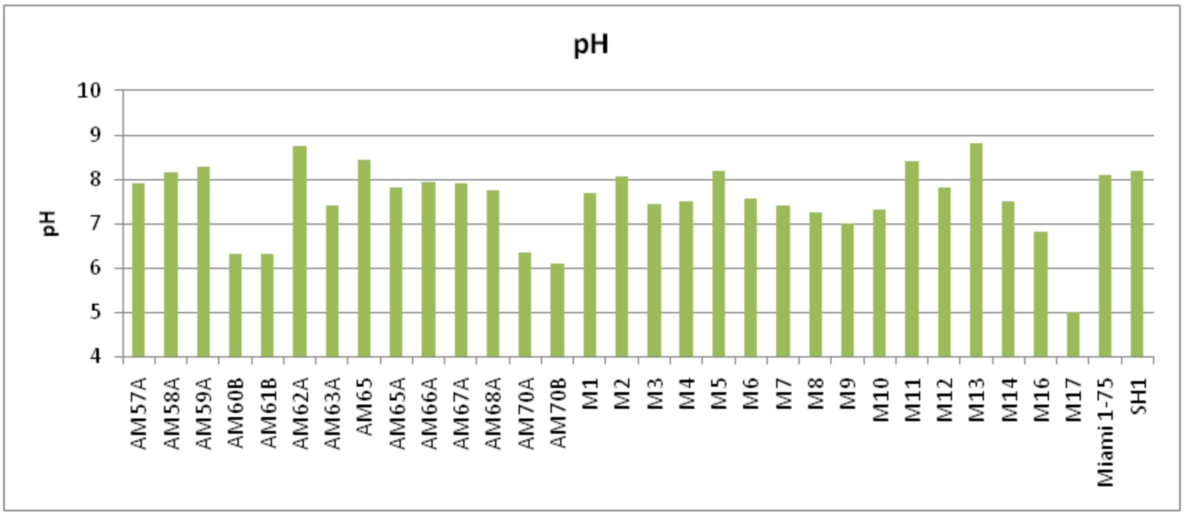


Chart B.8 pH values in groundwater within the Leederville Aquifer.

Cattamarra Aquifer:

Table B.2 Mean summary of water quality data for Cattamarra Aquifer.

Bore	EC @ 25 deg C (µS/cm)	Alkalinity (tot) (CaCO3) (mg/L)	Hardness (tot) (CaCO3) {Ca+Mg} (mg/L)	NO_3-N (sol) (mg/L)	P (sol) (mg/L)	SO_4 (sol) (mg/L)	TDS (cond) (mg/L)	TDS (evap @180°C) (mg/L)	TDS (in situ) (mg/L)	pH
Alcoa 0-8		153.99	52.77	0.14		2.0			525	7.58
Alcoa E2								4410	4410	8.10
Alcoa E7								180	145	6.00
AM57	4522.50	182.00	113.73	0.15	0.017	127.3	2915	2413		8.28
AM58	3146.67	197.05	102.62	0.16	0.010	69.0	2000	1740		8.10
AM59	3260.00	215.83	114.11	0.18	0.010	49.8	2030	1720		8.35
AM60	3970.00	287.69	86.43	0.20	0.008	108.3				8.87
AM60A	2025.00	186.05	98.67	0.09	0.020	36.5	950	750		9.77
AM61	1416.75	400.74	8.28	0.19	0.045	66.8				9.25
AM61A	466.00	76.74	51.51	0.22	0.040	11.7				6.20
AM62	3440.00	223.91	48.80	0.10	0.010	67.0				8.30
AM63	3560.00	241.34	97.17	0.07	0.015	77.0				8.30
AM64	343.63	110.31	50.49	0.08	0.005	7.5				7.90
AM64A	279.00	24.99	31.00	0.07	0.005	3.0				5.60
AM65B	4110.00	245.23	138.48	0.13	0.005	100.0				8.00
AM66	1110.00	172.24	72.02	0.07	0.020	24.0				7.10
AM67	6000.83	266.15	231.47	0.07	0.015	315.5		5120		8.15
AM69	585.00	148.78	67.23	0.11	0.090	19.0				7.10
AM70	444.00	69.71	96.52	0.11	0.005	18.0				7.30
M5	2490.00		147.00			107.0	1740	1540		7.60
M9	907.00		127.00			30.0	635	560		6.70
M10	6000.00	283.00	233.00	0.23		251.0	4200	3950		7.40
M11	2540.00	253.00	88.00			127.0	1780	1600		8.30
M12	3290.00	225.00	128.00	0.23		127.0	2300	2040		6.60
M14	750.00	83.00	79.00	0.11		29.0	520	440		6.30
M15	4693.15	318.50	347.50	0.56		161.0	2975	2600	2100	7.65
M16	750.00	97.50	89.50	0.17		18.0	555	450		6.40

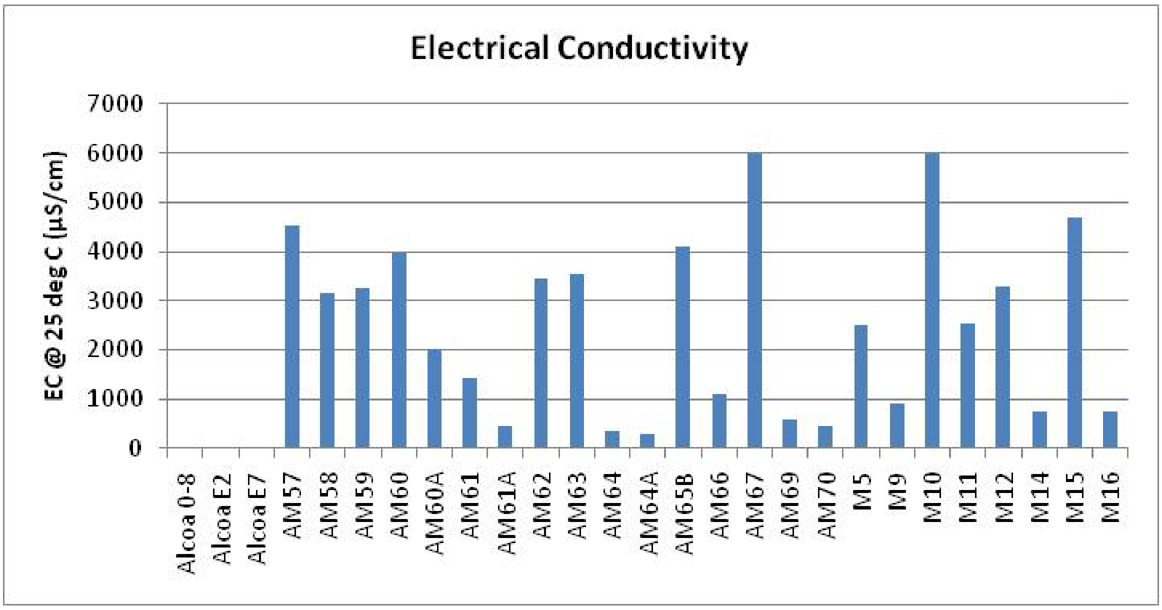


Chart B.9 Electrical conductivity values in groundwater within the Cattamarra Aquifer.

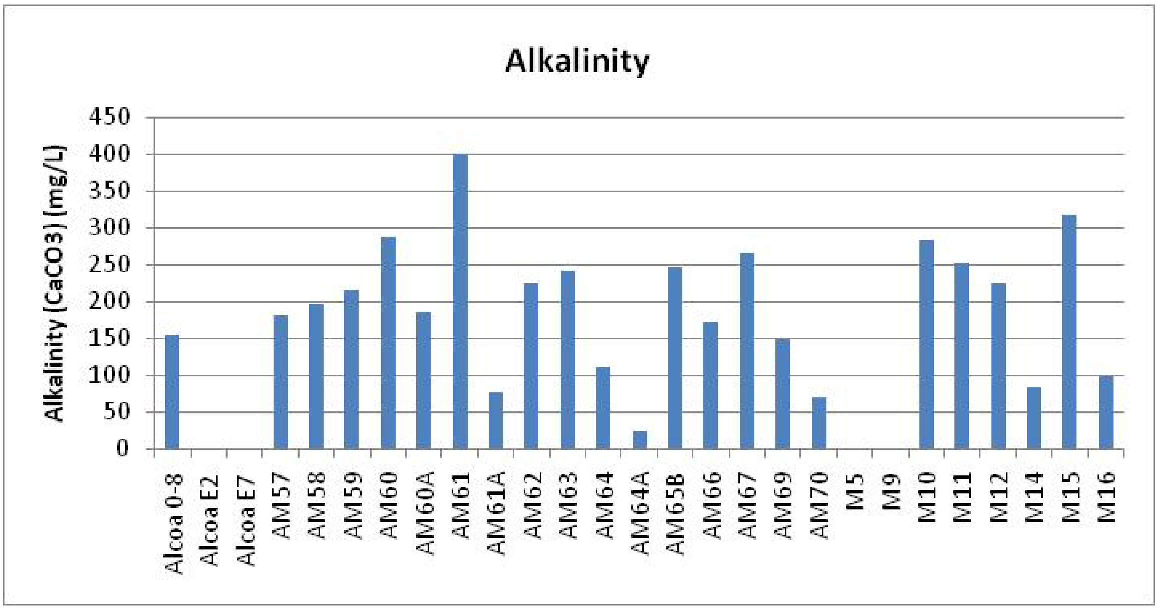


Chart B.10 Alkalinity values in groundwater within the Cattamarra Aquifer.

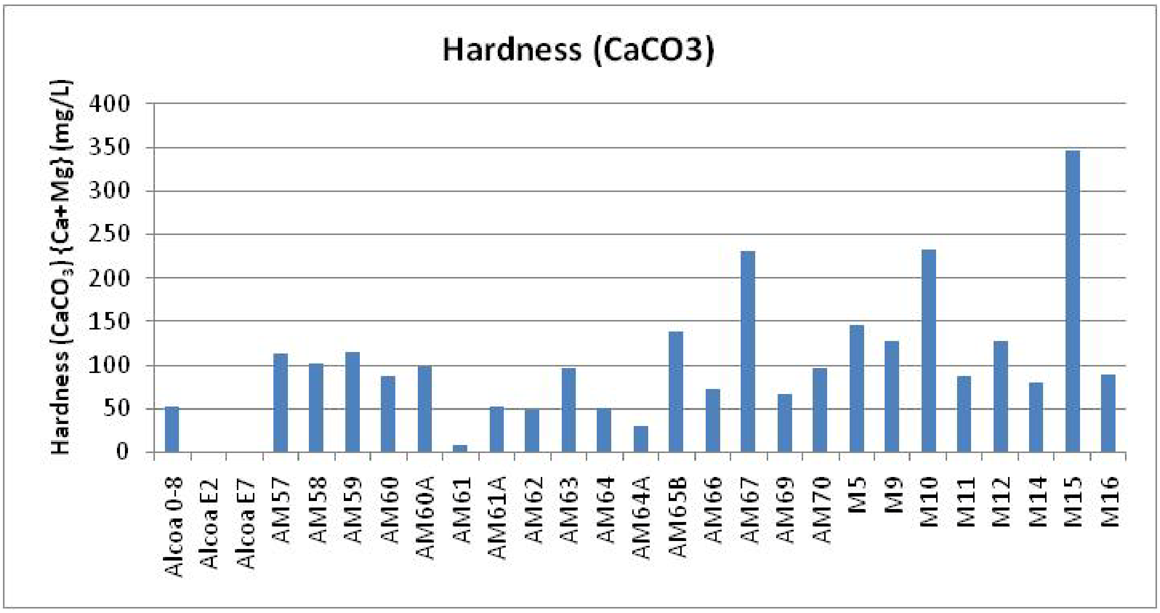


Chart B.11 Hardness concentrations in groundwater within the Cattamarra Aquifer.

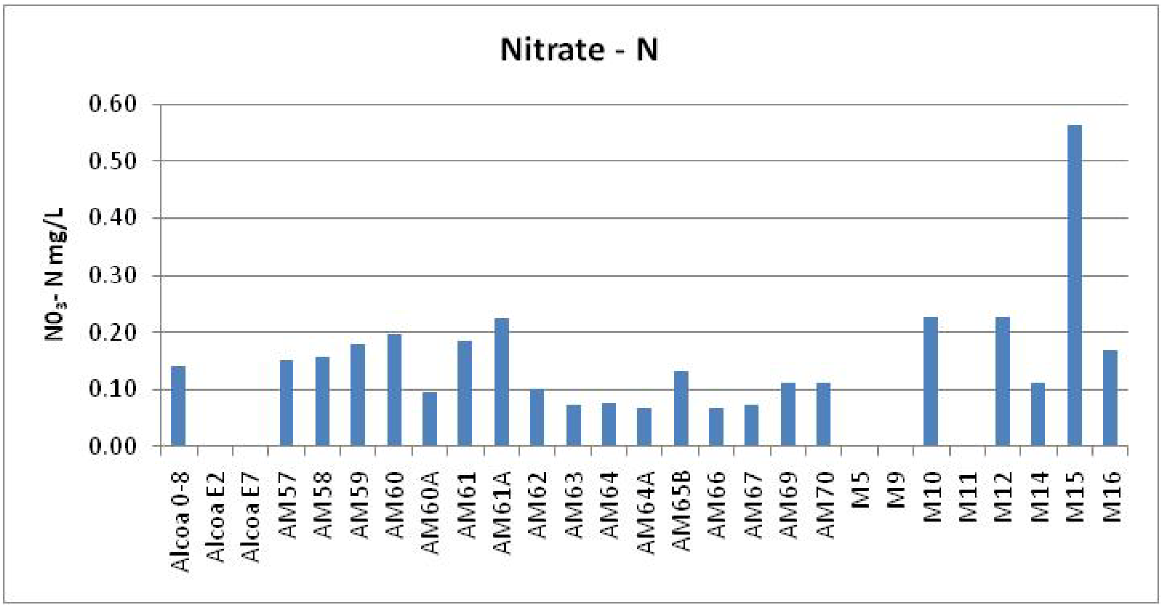


Chart B.12 Nitrate-Nitrogen concentrations in groundwater within the Cattamarra Aquifer.

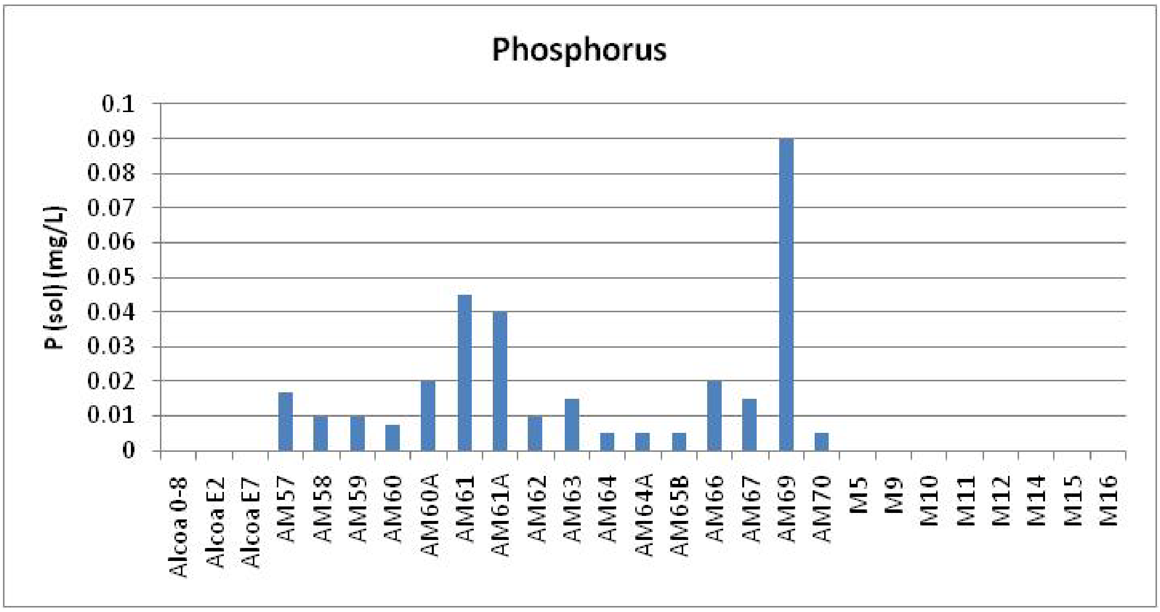


Chart B.13 Phosphorus concentrations in groundwater within the Cattamarra Aquifer.

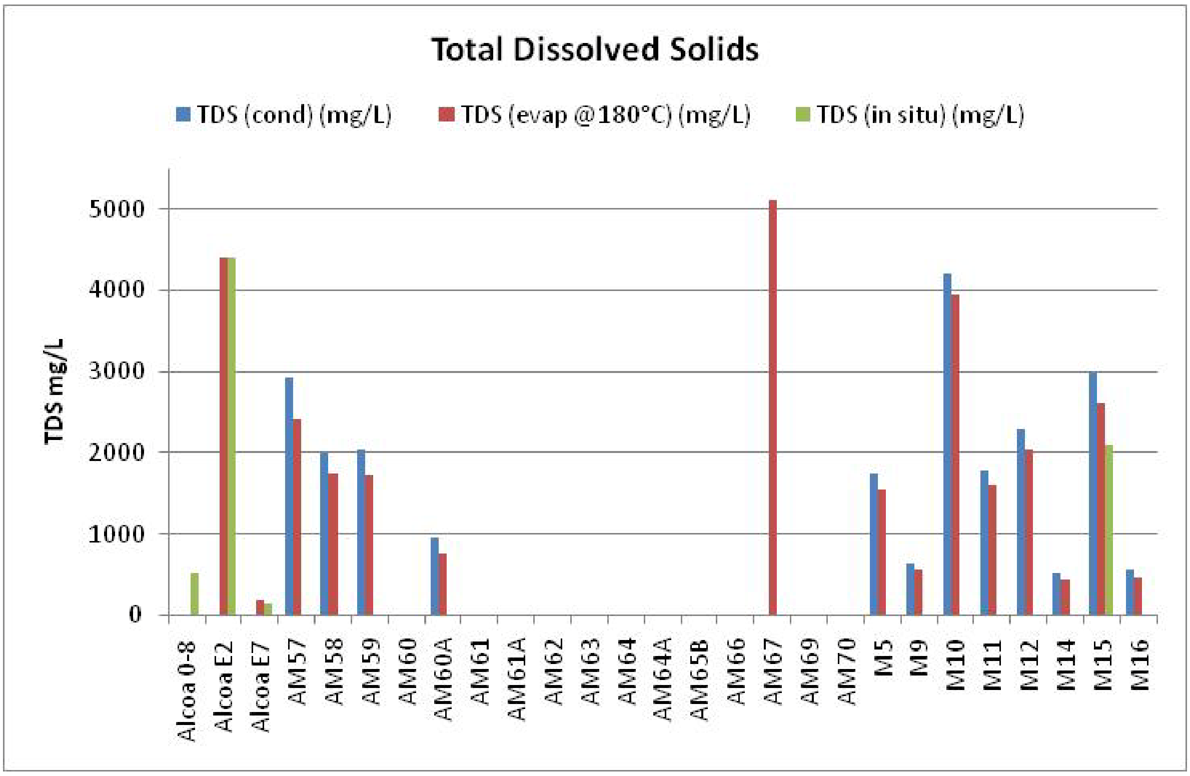


Chart B.14 Total dissolved solid concentrations in groundwater within the Cattamarra Aquifer.

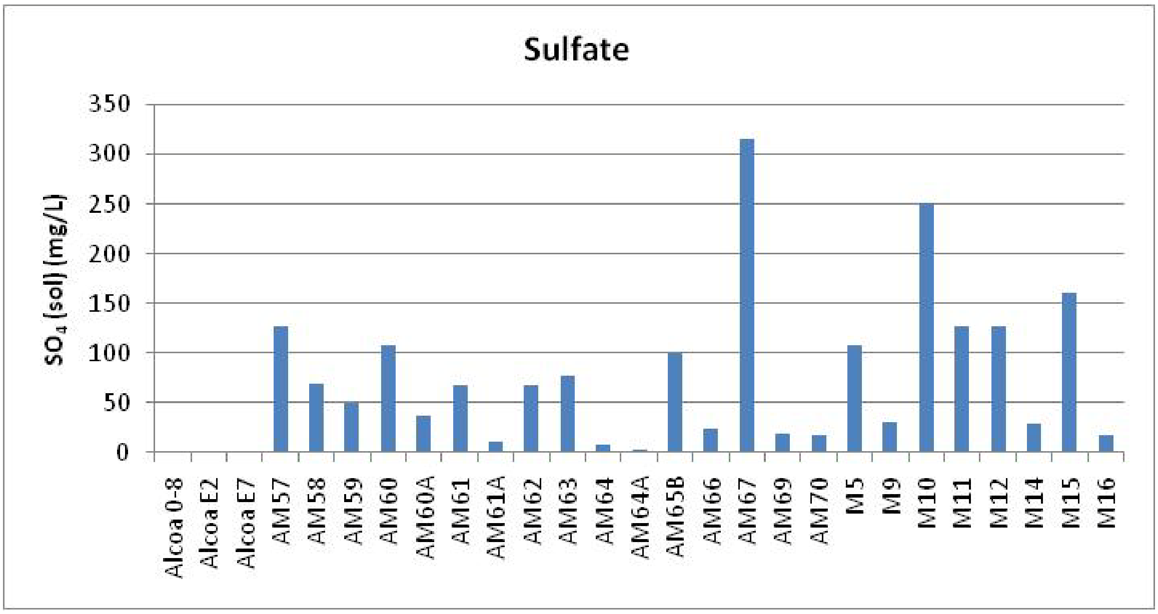


Chart B.15 Sulfate concentrations in groundwater within the Cattamarra Aquifer.

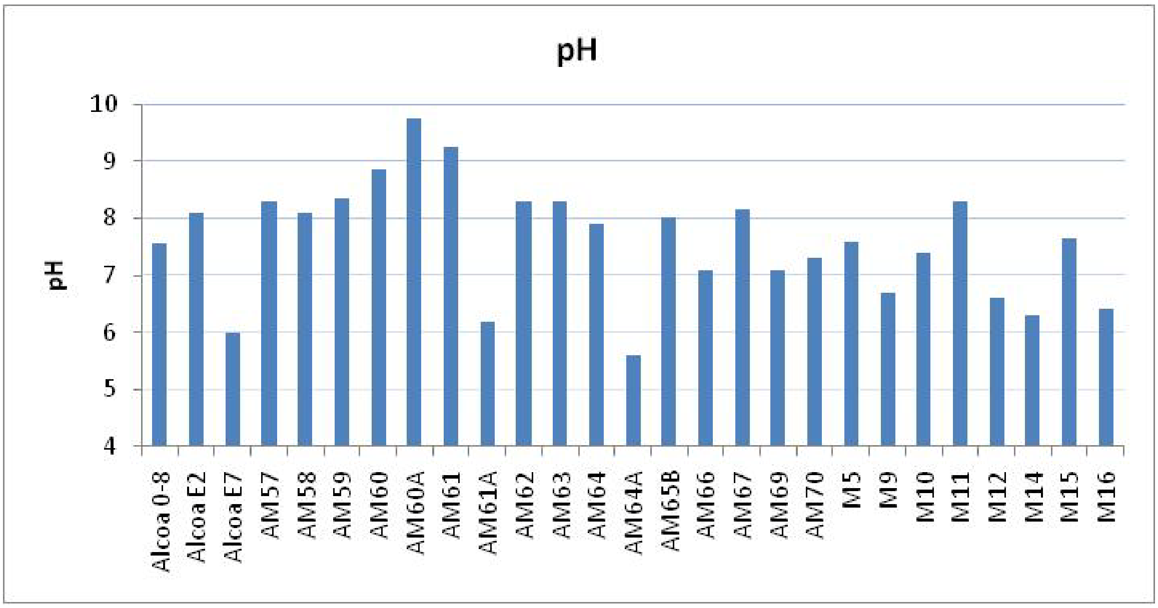
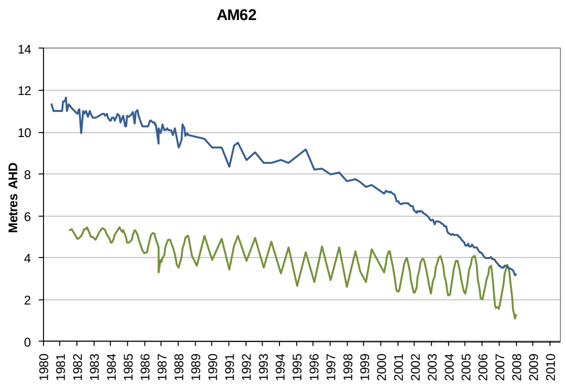
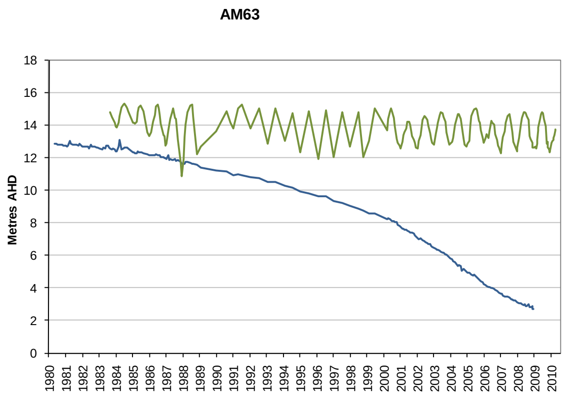


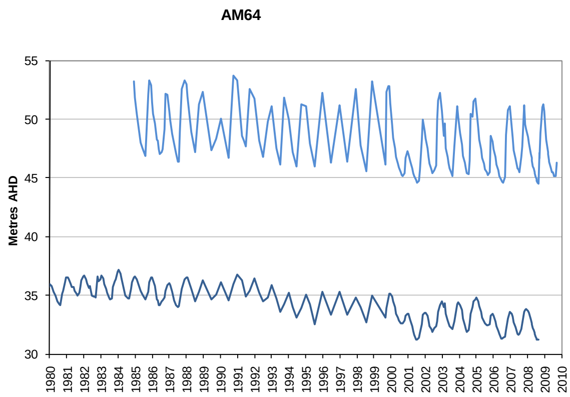
Chart B.16 pH values in groundwater within the Cattamarra Aquifer.

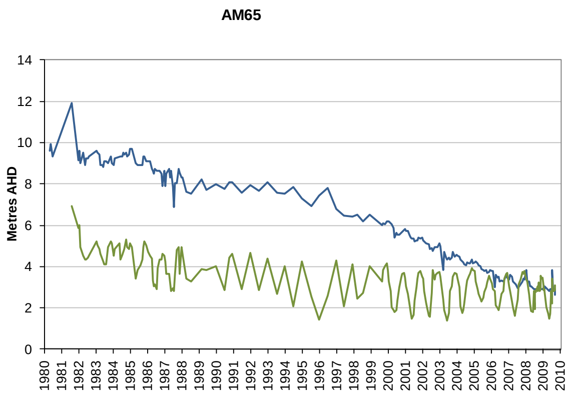
5.3 Appendix C: Monitoring bore hydrographs

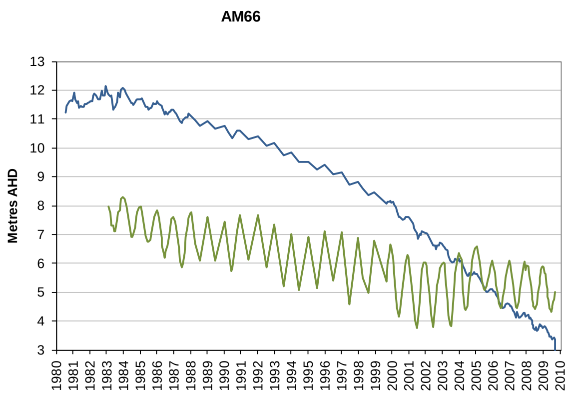
Paired bores screened in the Leederville Aquifer (green), and Cattamarra Aquifer (blue). At AM64 both the shallow and deep bore is screened in the Cattamarra Aquifer, the shallow bore has been shaded light blue.

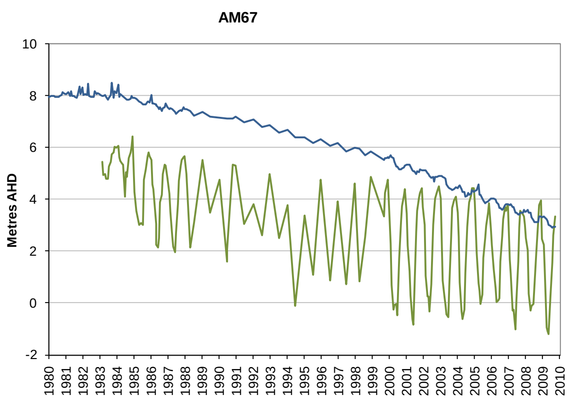


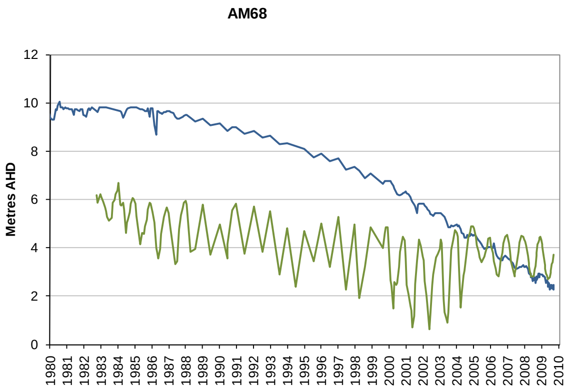








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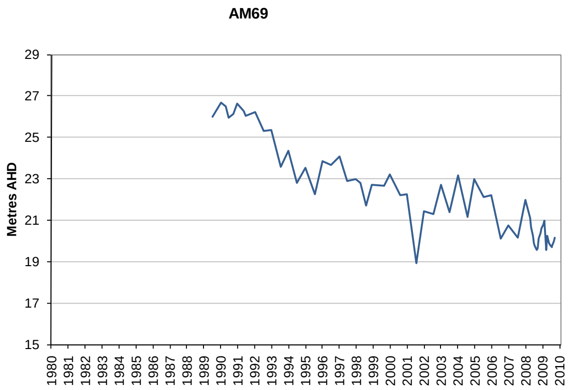
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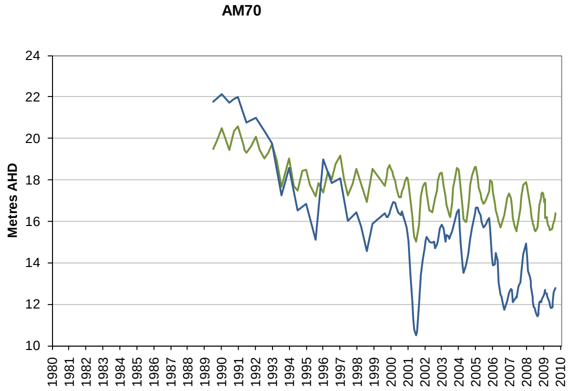
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