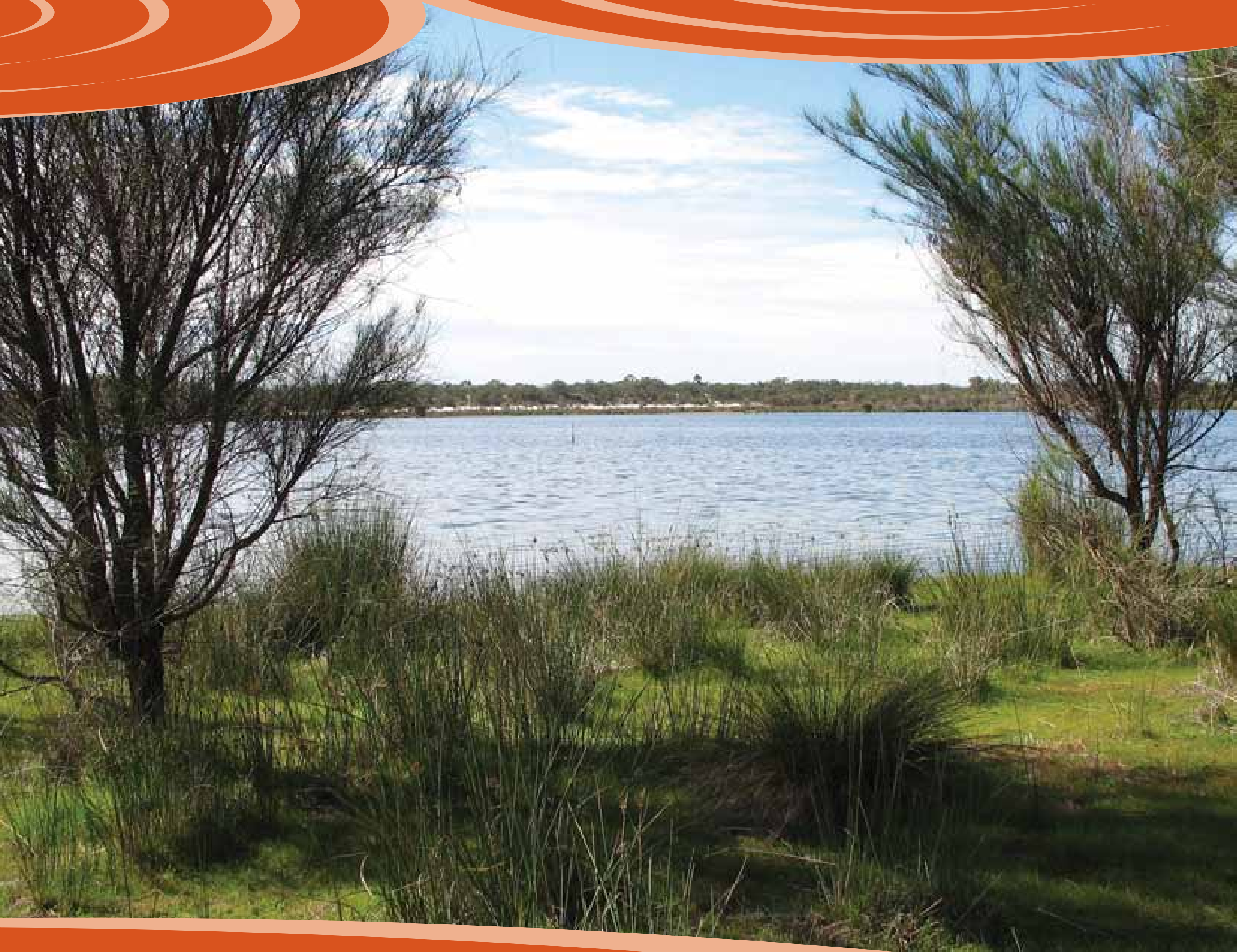
Government of **Western Australia**
Department of **Water**



Looking after all our water needs

Perth Shallow Groundwater Systems Investigation

Lake Muckenburra

Hydrogeological record series

Report no. HG46
January 2012

Perth Shallow Groundwater Systems Investigation

Lake Muckenburra

Looking after all our water needs

Department of Water
Hydrogeological record series
Report no. HG46
January 2012

Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone	+61 8 6364 7600
Facsimile	+61 8 6364 7601
National relay service 133 677
www.water.wa.gov.au

January 2012

ISSN 1329-542X (print) ISSN 1834-9188 (online)
ISBN 978-1-921736-90-2 (print) ISBN 978-1-921736-91-9 (online)

This project was part funded by the Australian Government under its $12.9 billion Water for the Future plan.

Australian Government
Water for the Future

Acknowledgements

This report was prepared by Brad Degens and Glenn Bathols, Water Resource Assessment Branch and Michael Hammond, Water Allocation Planning Branch. Sandie McHugh, Andrew Paton and JP Pigois provided assistance with reviewing and editing. The Department of Water would like to thank the following for their contribution to early drafts of this publication:

- Entura (formerly Hydro Tasmania Consulting): Vila Gupta, Chris Gill, Katie Izzard, Nita Marcus, Alona Mattvey, Toni Radcliffe, Eric Rooke, and Eleni Taylor-Wood.
- Crisalis: Chris Barber and Selva Marimuthu.

For more information about this report, contact Sandie McHugh, Water Resource Assessment Branch   sandie.mchugh@water.wa.gov.au

Recommended reference

Degens, BP, Hammond, MJ and Bathols, GR 2012, *Perth Shallow Groundwater Systems Investigation: Lake Muckenburra*, Hydrogeological record series HG46. Department of Water, Perth.

Disclaimer

Contents

Appendices

Figures

Tables

Preface

This report is based on work carried out as part of the Perth shallow groundwater systems investigation. This was a four-year (2007–10) investigation program undertaken by the Groundwater Review Section of the Water Resource Assessment Branch within the Department of Water. Funding for the program has been provided jointly by the Government of Western Australia and the federal government's Water Smart Australia initiative.

The investigation focuses on many of the wetlands situated on the Gnangara and Jandakot groundwater mounds, which are the most significant sources of groundwater for the Perth metropolitan area. The groundwater mounds also sustain numerous ecosystems that depend on shallow groundwater. Currently, many of these ecosystems are stressed by land-use changes, increased groundwater abstraction and a shift to a drier climate, resulting in a general deterioration in their social, cultural and environmental values.

The formulation of the Perth shallow groundwater systems investigation arose from the outcomes of a management area review conducted in 2006 (McHugh & Bourke 2007). This review summarised the current monitoring and management issues facing selected wetlands on the Gnangara and Jandakot mounds, and identified the information and data required to address these issues. The report recommended an investigation program that incorporates 28 wetlands on the Swan Coastal Plain, prioritised by a combination of ecological significance, management issues and geomorphic setting.

The specific objectives of the Perth shallow groundwater systems investigation were to:

- redesign and upgrade the existing monitoring infrastructure and install new monitoring networks at ecologically important sites
- investigate the hydrogeology of selected lakes, wetlands and remnant wetlands to determine the interactions and connectivity of surface water bodies and groundwater
- investigate the palaeoclimate of some selected wetlands to provide an appreciation of how lakes have functioned in the past and to enable us to place the current changes within this long-term context
- investigate the chemistry of wetlands and wetland sediments to give a detailed understanding of the ability of wetlands to alter lake and groundwater quality.

The outcomes of this investigation will aid the development of management strategies based on site-specific, scientific data that will promote the sustainable use of the groundwater resources of the Gnangara and Jandakot mounds.

Summary

Lake Muckenburra was selected as one of the 28 sites in the Perth shallow groundwater system (SGS) investigation as being broadly representative of basin wetlands in the north-eastern Gnangara Mound. Previous studies classified Lake Muckenburra as a permanently inundated lake (Hill et al. 1996) but did not determine the interaction of the lake with the Superficial aquifer. This investigation reports on local-scale hydrogeological and hydrochemical investigations at Lake Muckenburra to determine the interaction between the Superficial aquifer, the lake and associated groundwater-dependent vegetation.

A groundwater monitoring network was installed at Lake Muckenburra in 2008 with construction of clusters of groundwater monitoring bores along the western (down-gradient) and eastern (up-gradient) margins of the lake. These bores and the lake were comprehensively monitored over 15 months.

This study shows that Lake Muckenburra is now a seasonally inundated basin wetland where the groundwater-dependent ecosystem (GDE) depends on a localised perched groundwater system and not the regional Superficial aquifer. Ponding of water in the lake is dependent on an intermittent connection with upper parts of the localised perched groundwater system, with occasional reliance on surface inflows. Hence, the health of the lake and associated ecosystems can be regarded as being independent of the regional Superficial aquifer.

The perched groundwater system at Lake Muckenburra forms on shallow (~4–6 m) sequences of sandy clays and clayey sands in the Bassendean Sand Formation. These impede vertical groundwater movement and promote shallow lateral flow (allowing the lake to fill) and occasional shallow overland flow (where artificial channels have been constructed). The lake and perched groundwater system are not in direct hydraulic connection with the Superficial aquifer, with the regional watertable being more than 1.5 m below that of the perched groundwater system. However, there is hydrogeological and hydrochemical evidence of subdued recharge from the localised perched groundwater system to the shallow Superficial aquifer, including freshening of the Superficial aquifer with flow beneath the lake. The subdued recharge results in a tendency for salts to concentrate in the perched groundwater system, along with nutrients and dissolved organic carbon. Groundwater gradients and spatial and seasonal patterns in groundwater quality beneath the lake indicated that there was limited flow within the Superficial aquifer in the vicinity of the lake.

Vegetation condition assessments conducted during the SGS monitoring period (Wilson et al. 2009) did not detect any clear evidence of water stress. Overall, the vegetation community shows a high level of tree health despite land disturbance and surrounding agricultural land use (Wilson et al. 2009). Given the good health and condition of the vegetation assessed, Lake Muckenburra is not considered to have been affected by changes observed in perched groundwater levels. Continued decreases in groundwater levels in the perched groundwater system over the last 30 years (indicated in nearby bore GB9) may result in future stress on the ecology of the lake and adjacent groundwater-dependent vegetation. These declines are likely to be

due to decreasing rainfall rather than to abstraction. A consequence of these changes is that there are likely to be shorter periods of inundation at Lake Muckenburra. Despite the likely declines in the localised perched groundwater system, groundwater-dependent vegetation at the lake has remained in good condition.

Based on the limited data available, the quality of surface water in Lake Muckenburra is moderate to good, although some properties have exceeded guideline values for aquatic species protection. It is expected that water quality in the lake will remain stable in the medium term (3–5 years), with concentrations of major ions, salts and nutrients varying in response to rainfall driven fluctuations in water level.

Protection of the environmental values of Lake Muckenburra requires the following:

- a minimum water level of 49.5 m AHD within the localised perched groundwater system (measured at bore MKB_Ed)
- a minimum annual wetland inundation period of three months for at least two out of three years.

Since the ecological values of Lake Muckenburra are not affected by the regional Superficial aquifer, no management is required under the Perth shallow groundwater system management strategy. However, the threatened ecological community is listed as vulnerable and may require local action to prevent degradation related to eco-hydrology, particularly if the declining trend in annual rainfall persists. The most significant effects of this trend are likely to be on levels in the localised perched groundwater system.

The effects of rainfall decline could possibly be mitigated by managing runoff rates and recharge to the perched groundwater system in the catchment of the wetland. This could be achieved by managing drainage and vegetative water use in the landscape surrounding the lake. An increase in runoff and/or recharge could be produced by:

- thinning and/or burning of native vegetation
- directing surface drainage towards the wetland
- minimising replanting of the catchment.

However, it is recommended that a feasibility assessment be conducted before any action is taken, to ensure that the benefits are worthwhile.

Recommendations

These recommendations are the result of this study and aim to build-on the outcomes. Their implementation will depend on the normal process of prioritising within the available resources.

Management actions

- Ecological water requirements have been identified for Lake Muckenburra but are not suitable for adoption as Ministerial criteria due to the reliance of the lake's ecology on the localised perched groundwater system, rather than the regional Superficial aquifer.
    - Implementation and responsibility: Department of Water to apply recommended vegetation based ecological water requirements in assessing water levels in the perched groundwater system (bore MKB_Ed).
- Design a local area model that incorporates the new hydrogeological understanding gained from this study, and includes scenarios that model changes in recharge to the perched groundwater system through rainfall variability, managing the density of vegetation and managing changes in drainage.
    - Implementation and responsibility: Department of Water to design the north Gnangara local area model and evaluate various scenarios. Results to be related to similar perched systems and inform the next Gnangara water allocation plan.

Future monitoring

- As the data associated with the MKB series bores is limited, it is recommended that monitoring be maintained at bore GB9 for a minimum of five years, concurrent with the MKB series bores.
    - Implementation and responsibility: Department of Water to ensure monitoring at GB9 continues for a minimum of five years concurrent with the MKB bores.

- Installation of two additional monitoring bores is recommended when the opportunity arises. These should include a shallow bore on the western side of the lake in close proximity to the vegetation transect and a shallow bore near the threatened ecological community to the south of the lake. These bores should be screened in the perched groundwater system (upper Bassendean Sand Formation) above the semi-confining sandy clays and clayey sands (~1 to 2 metres below ground-level). Removal and redrilling of the bore screened in the shallow Superficial aquifer (MKB_Wc) is also recommended.
    - Implementation and responsibility: Department of Water to install these bores as part of bore construction works in any future shallow groundwater systems investigations.

1 Context and objectives

Lake Muckenburra is a seasonally inundated wetland of the Mungala suite located in the Gingin groundwater area. The lake is a 'conservation category' wetland that supports a threatened ecological community, waterbird species and other wetland-dependent vertebrates (Froend et al. 2004a; 2004b; 2004c).

The 'herb-rich saline shrublands in clay pans' threatened ecological community at Lake Muckenburra is a species rich vegetation community on heavy clay soils and requires regular inundation in winter to summer, with the vegetation dependent on soil moisture in the drier months. The community is endemic to the Swan Coastal Plain, is one of only two known occurrences within the Gnangara groundwater system and is listed as vulnerable (Froend et al. 2004a; 2004b; Gibson et al. 1994).

The most recent review of environmental conditions guiding management of the Gnangara and Jandakot mounds (Department of Water 2008) identified Lake Muckenburra as an ecologically significant groundwater-dependent ecosystem that should be managed to protect its ecological values.

Prior to this study, there was insufficient data available to assess the relationship between groundwater levels and the ecological condition of Lake Muckenburra. The management area review of shallow groundwater systems on the Gnangara and Jandakot mounds (McHugh & Bourke 2007) recommended hydrogeological investigation of Lake Muckenburra. The investigation was recommended as the hydrogeology of the lake was not well understood and because of the lake's environmental significance.

The review recommended that site-specific data be collected and analysed to improve the understanding of the connectivity between groundwater and surface water and of groundwater quality at Lake Muckenburra.

In line with these recommendations, the specific objectives of the Lake Muckenburra study were to:

- upgrade the groundwater monitoring network around the lake
- improve the department's understanding of how Lake Muckenburra functions hydrogeologically
- determine the distribution of acid sulfate soils in and around the lake, and their effects on water chemistry
- develop a conceptual model of the relationships between wetland hydrogeology, chemistry and ecosystem function to provide a basis for improved management strategies
- highlight the water and land-use issues to be addressed in the next Gnangara groundwater management plan.

2 Background

2.1 Location, characteristics and climate

Lake Muckenburra is located in a small subcatchment of Gingin Brook east of the Quin Brook catchment on the northern edge of the Gnangara Mound, approximately 67 km north of Perth, Western Australia (Figure 1). The lake is part of a suite of wetlands that includes sumplands to the south and east. It was previously classified as a permanently inundated lake (Hill et al. 1996). With regular drying of the lake now apparent, the lake has been reclassified as a sump wetland (Table 1).

Table 1 Summary attributes of Lake Muckenburra (after Hill et al. 1996)

Location (coordinates)	E: 384175, N: 6532151
Wetland/GDE type and description	Permanently inundated lake (revised – sump wetland)
Ecological recognition	Environmental protection policy (EPP)
Aboriginal heritage	Recognised by Department of Indigenous Affairs as a site of specific interest. Part of a larger recognised area of significance (Wright 2007b)
Wetland suite	Mungala (B/P.2)
Physiographic wetlands unit	Bassendean Dunes
Management	Department of Environment and Conservation

The lake experiences a Mediterranean climate with hot, dry summers and mild, wet winters with most rainfall occurring between May and September. The annual rainfall recorded at the nearest monitoring station to the lake, at Gingin (Bureau of Meteorology 2011), shows a declining trend over a 100–year period of the record (1907–2007), although no change is evident in the past decade (Figure 2).

2.2 Geomorphology and geology

2.2.1 Regional geomorphology and geology

Lake Muckenburra is located on the northern Swan Coastal Plain on the eastern margin of the Bassendean Sand Dune system abutting the Pinjarra Plain (Gozzard 2007). The Swan Coastal Plain is an area of gently undulating north–south aligned dunes in the west grading to broad plains in the east. The plain extends from south of Geraldton to Dunsborough, bounded by the coast in the west and by the Darling and Gingin scarps to the east.

In the Perth region, the superficial formations are expressed as four geomorphic units (Gozzard 2007), which trend sub-parallel to the present day coastline. The oldest is the Pinjarra Plain, which comprises alluvial fans abutting the Darling Scarp. Adjacent to the Pinjarra Plain are a series of dune systems. These dunes represent various shorelines which decrease in age from east to west. These units, in order of deposition, are the Bassendean Dunes, the Spearwood Dunes and the Quindalup Dunes. The latter are still forming and represent the present day coastline (Gozzard

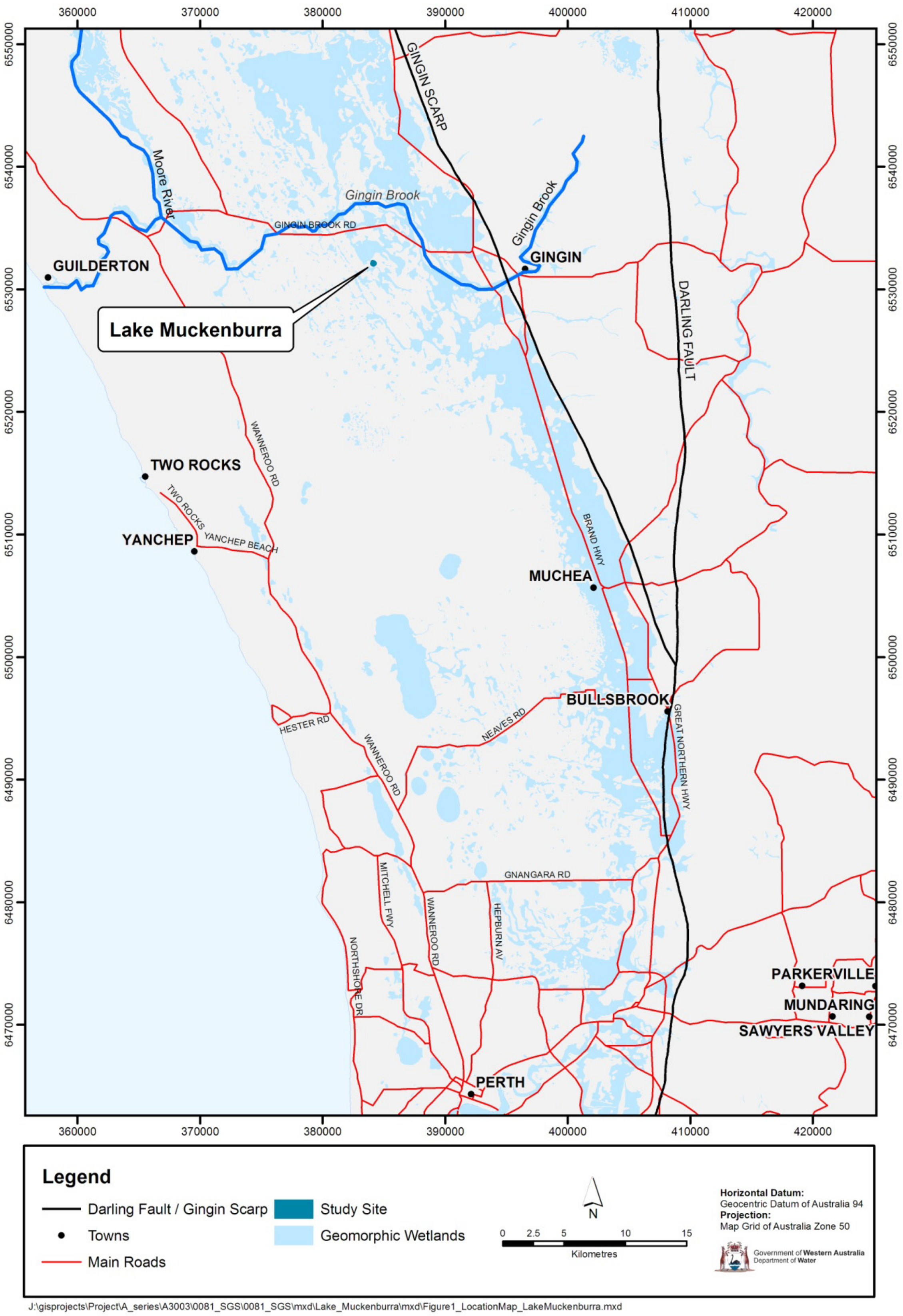


Figure 1 Location of Lake Muckenburra

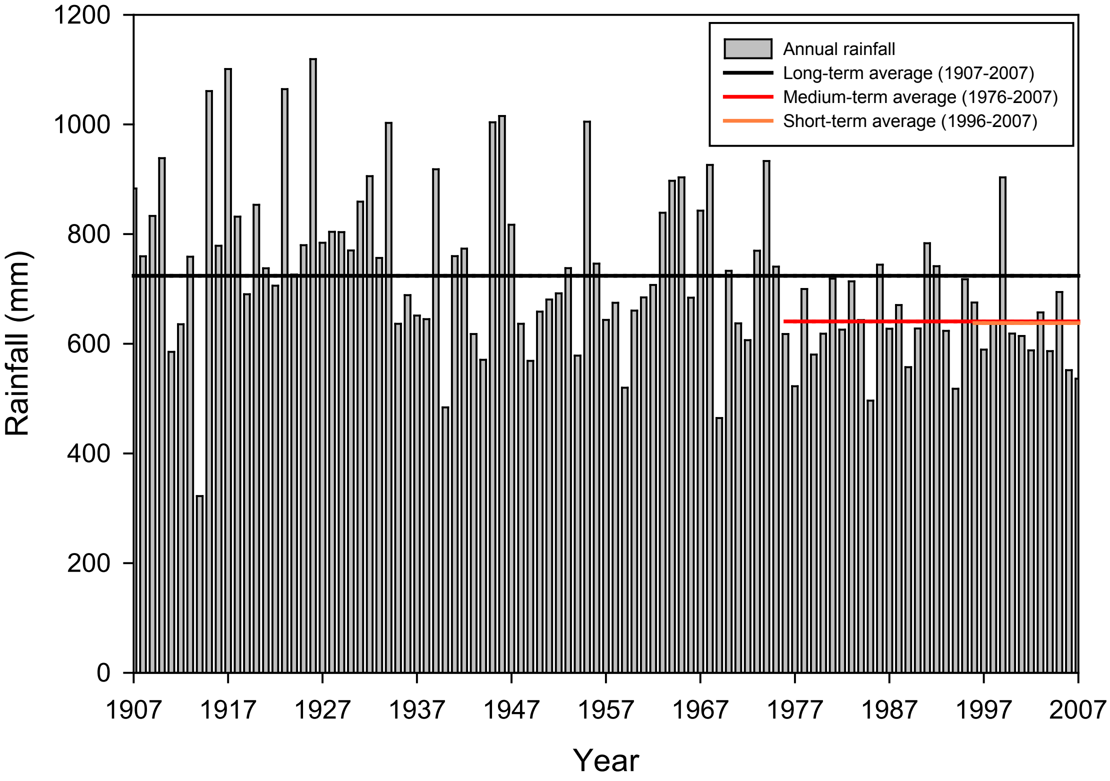


Figure 2 Annual rainfall at Gingin showing short and mid-term averages relative to the long-term average

2007). The Bassendean Dune System is generally of low relief and is typically a series of gently undulating dunes and swales. Lake Muckenburra is situated in an interdunal swale of the Bassendean Dune System (McArthur & Bettenay 1960; Davidson 1995) corresponding with the surface outcrop of the Bassendean Sand Formation (Figure 3 and Figure 4).

The superficial formations in the area around Lake Muckenburra unconformably overlie the Leederville Formation (Warnbro Group) (Table 2) which broadly consists of interbedded sandstones, siltstones and shales of the Wanneroo Member (Table 2). The superficial formations consist of the basal Ascot Formation, occasional occurrences of Gnangara Sands, Guildford Clay and Bassendean Sand formations (Table 2). Recent interpretations have suggested that the Gnangara Sand Formation may be part of the Bassendean Sand Formation (Pigois 2011), but in the present report it is referred to as Gnangara Sand due to the rounded nature of the sand, feldspar content and occurrence at the base of Bassendean Sand Formation.

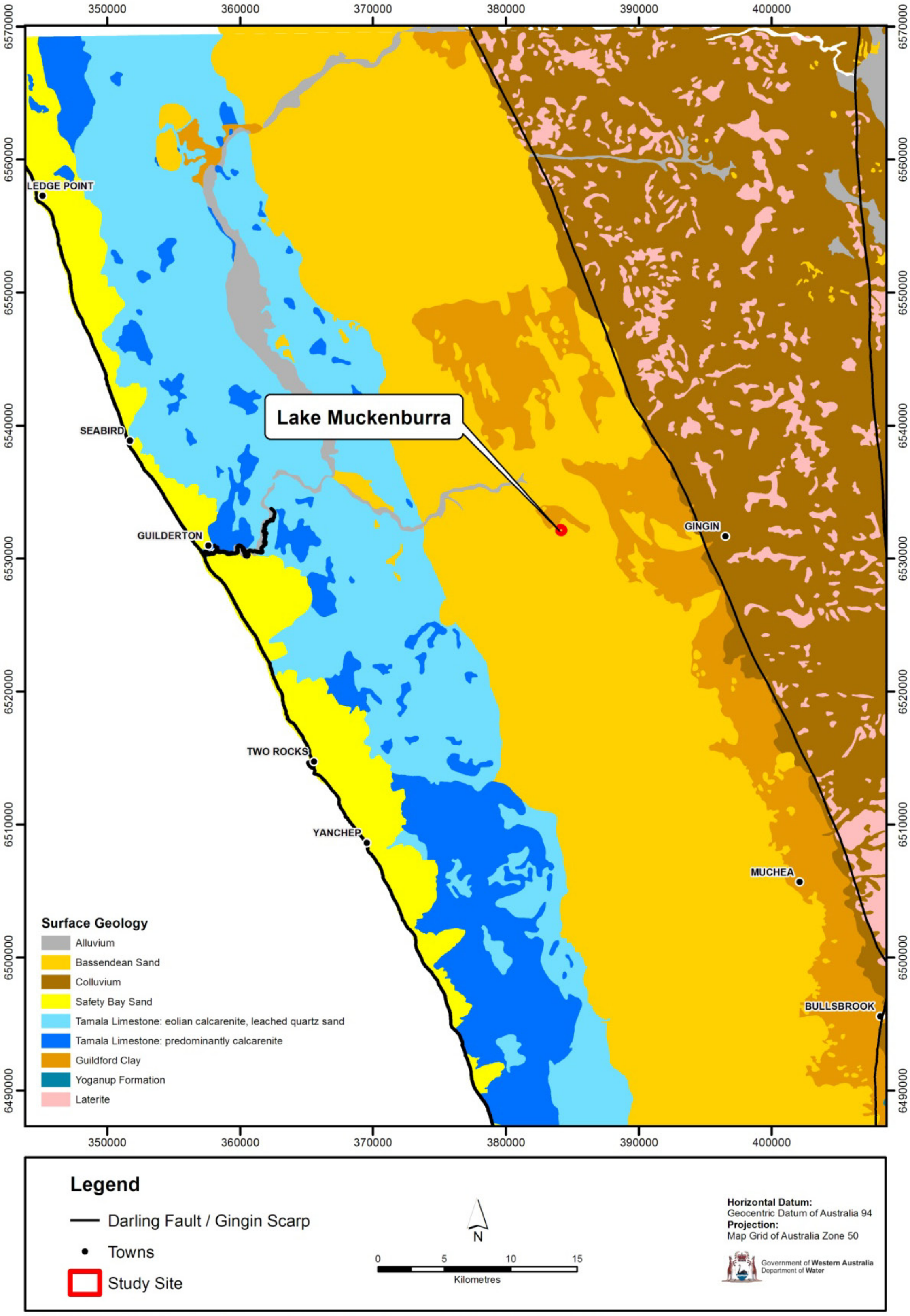
The Guildford Clay Formation or Bassendean Sand Formation generally forms the upper part of the superficial formations (Table 2). The Bassendean Sand Formation in the area has been described by Moncrieff and Tuckson (1989) as light-grey to grey-brown quartzose sand being fine to coarse grained in size. The sand grains are typically well sorted, sub-angular to sub-rounded, commonly exhibit a fining upward sequence (Moncrieff & Tuckson 1989). A layer of friable, limonite-cemented sand, colloquially called ‘coffee-rock’ is present throughout most of the area near the watertable.

The Guildford Clay Formation is often reported to be between 2 and 35 m thick in the eastern extent of the Swan Coastal plain (Davidson 1995), but in the North Gnangara area in which Lake Muckenburra occurs it is typically less than 14 m thick (Table 2). The formation has been described as inter-fingering with the Bassendean Sand Formation (Pigois 2011), although previously it has been interpreted as underlying the Bassendean Sand and inter-fingering with sands to the west (Moncrieff & Tuckson 1989). This is presumably because of the difficulty in distinguishing sands in the Bassendean Sand Formation from the sands in the Guildford Clay Formation, from which the Bassendean were probably derived.

Table 2 Stratigraphic sequence in field area (after Davidson, 1995; Moncrieff & Tuckson 1989; Pigois 2011)

Age		Stratigraphy	Thickness m	Lithology	Aquifer
Quaternary – Late Tertiary	Superficial formations	Bassendean Sand Formation	4 to 53	Light-grey to light grey-brown, fine- to medium-grained quartz sand with discontinuous ferruginised sand horizons	Superficial aquifer
		Guildford Clay Formation	4 to 14	Light grey, buff, brown or grey-green sandy facies with black, light-grey to brown or green clayey facies that are variably sandy and exhibit occasional ferruginised horizons.	Local aquitard
		Gnangara Sand*	0 to 22*	Pale-grey, fine to very coarse grained, sub-rounded to rounded sand with abundant feldspar*	Superficial aquifer
		Ascot Formation	10 to 29	Calcarenite interbedded with sands, commonly containing glauconite and phosphatic nodules	Superficial aquifer
		Yoganup Formation	10 to 21	White to yellowish-brown, unconsolidated, poorly sorted sand, gravel and pebbles with local minor clay	Superficial aquifer
Cretaceous	Wambro Group Leederville	Wanneroo Member	77 to 175	Sand beds (up to 30 m thick) separated by clay horizons	Leederville aquifer
		Mariginiup Member	8 to 23	Finely interbedded clay, silt and sand layers	Local aquitard
		South Perth Shale	<21	Clay and silt with minor sand horizons	Confining bed

** After description of Gnangara Sand Formation in Davidson 1995*



J:\gisprojects\Project\A_series\A3003\0081_SGS\0081_SGS\mxd\Lake_Muckenburra\mxd\Figure3_SurfaceGeology_LakeMuckenburra.mxd

Figure 3 Generalised regional surface geology in the Lake Muckenburra area

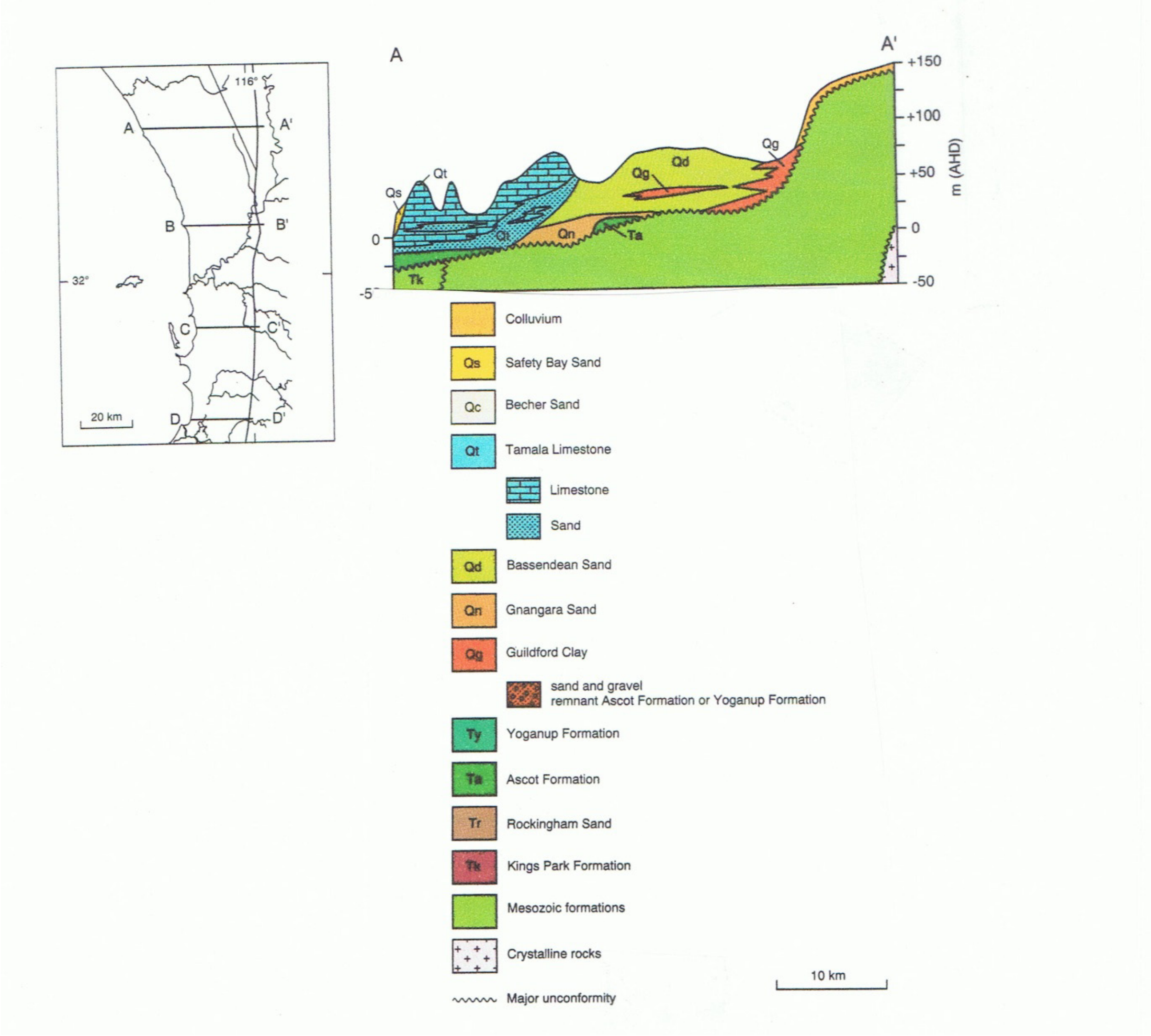


Figure 4 East-west geological cross-section through the superficial formation A-A' south of Lake Muckenburra (from Davidson 1995)

2.2.2 Acid sulfate soils

Lakes and wetlands on the Swan Coastal Plain are often associated with sediments containing sulfidic materials that are deemed to be acid sulfate soil (ASS) materials. Acid sulfate soils are sediments formed under waterlogged conditions that contain sulfidic materials, typically rich in iron sulfides such as pyrite, or sulfuric materials (Sullivan et al. 2010). When these soils are exposed to air by lowering of the watertable or excavation, oxidation of the sulfidic materials is triggered releasing sulfuric acid and iron. The acidity associated with oxidation of the soils can also result in release of other associated metals and increase mobility of these from soils into groundwater systems (Appleyard et al. 2006; Fältmarsch et al. 2008).

The term ASS in this report includes materials containing both potential and actual acidity. Sediments with potential acidity are referred to as potential acid sulfate soils (PASS) and contained sulfidic materials in an undisturbed, waterlogged state.

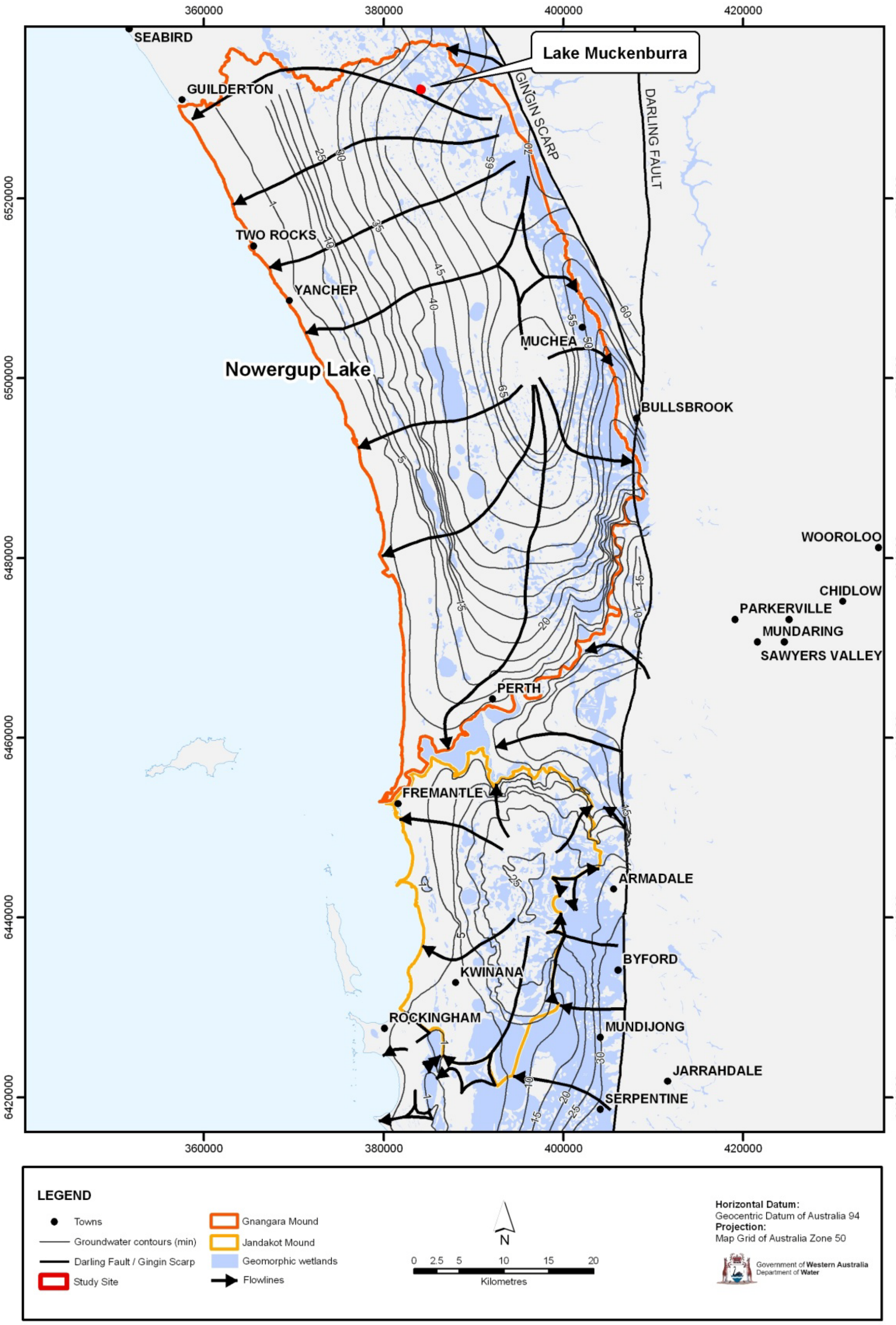
Sediments with actual acidity are referred to as actual acid sulfate soils (AASS) and contained sulfuric materials.

As many of the wetlands situated on the Gnangara Mound are progressively drying, there is an increasing likelihood that sediments containing ASS materials will be exposed which presents a threat to their ecology (Sommer & Horwitz 2009) and to the quality of groundwater (Appleyard & Cook 2008). Broadscale mapping of ASS risk, based on 1:50 000 urban geology mapping in the area (Degens 2006), indicated that there was a high to moderate risk of shallow ASS (within 3 m of the ground surface) occurring at Lake Muckenburra and the adjacent sumpland to the south, with the surrounding superficial formation having a low to moderate risk of ASS (increasing with depth).

2.3 Hydrogeology and hydrology

Lake Muckenburra lies on a part of the Swan Coastal Plain where regional groundwater flows in the Superficial aquifer out from the Gingin Scarp in a north-westerly direction (Figure 5). The lake lies within a zone of moderate hydraulic gradient with groundwater levels falling from >60 m AHD to the south-east of the site to <40 m AHD to the north-west. Mesozoic semi-confined aquifers of the Leederville Formation unconformably underlie the predominantly Bassendean Sand Formation that dominates the Superficial aquifer (Davidson 1995). Variation in groundwater interaction with the lake is likely dominated by the variable presence of the locally semi-confining Guildford Clay Formation inter-fingering with the Bassendean Sand Formation.

The local surface water hydrology in the area is dominated by flows from the south-east to the north-west, although the dunes surrounding the lake would have restricted flow of surface water directly into the lake prior to clearing for agricultural development. There is evidence of shallow surface water having entered the lake on the south-eastern side via a constructed channel. The entry point corresponded with a sandy supra-littoral zone approximately 70 m wide on the south-eastern side of the lake. Some of this has been washed into the lake, forming a small alluvial fan. This channel drains from closed interdunal swales at marginally higher elevation to the south-east of the lake. However, the significant vegetative growth in the channel and lack of evidence of recent fluvial action at the time of preparing this report indicated that it has been some time since significant flows occurred in the drain.



J:\gisprojects\Project\A_series\A3003\0081_SGS\0081_SGS\mxd\Lake_Muckenburra\mxd\Figure4_RegionalHydrogeology_LakeMuckenburra.mxd

Figure 5 Gnangara and Jandakot groundwater mounds showing flow lines

Previous investigations considered a number of wetlands on the Swan Coastal Plain to be ‘flow-through’ lakes, where groundwater discharges into the wetland on the up-gradient (generally eastern) side and surface water from the wetland discharges into the groundwater system on the down-gradient (generally western) side (for instance, see Townley et al. 1991; Townley & Trefry 2000).

Prior to this investigation, there was little recorded information on trends in water levels in Lake Muckenburra, although Froend et al. (2004b) described Lake Muckenburra as being seasonally waterlogged and Hill et al.(1996) previously classified the lake as permanently inundated. However, aerial photography between 2003 and 2009 indicates that the lake frequently dries in summer (Judd & Horwitz 2010). Watertable levels around the lake were noted to have increased by 0.75 m between 1995 and 2003 (Froend et al. 2004b) leading to the conclusion that the duration of flooding may be increasing (Froend et al. 2004b). However, more detailed analyses of hydrographs for bores in the Superficial aquifer to the west and east of the lake (GB8 3.8 km west and GB19 6 km south-east) have found that water levels have been slowly decreasing by more than 0.6 m over the last two decades, mostly attributed to declining rainfall (Yesertener 2008). The reason for differences in reported water level trends may relate to analysis of trends in bores in the perched watertable compared with bores screened in deeper in the Superficial aquifer.

Predictions of future regional watertable changes are consistent with local water level trends. Modelling of regional water balance for the Gnangara Mound has indicated that groundwater levels in the Superficial aquifer around Lake Muckenburra can be expected to decline by 1.0 to 2.0 m between 2008 and 2031, even with a stable rainfall pattern (De Silva 2009).

The predicted magnitude and rate of drawdown represent a significant to severe level of possible hydrological impact in a situation where there is direct connectivity between the shallow watertable and the regional Superficial aquifer. In a generalised sense, if surface water is not adequate to meet the requirements of vegetation and fauna, there is likely to be a decline in the condition of fringing vegetation and loss of habitat (Froend et al. 2004c).

Due to the lack of local-scale data, the aim of this study was to identify and understand the main factors dominating hydrogeological interactions at Lake Muckenburra. The investigative approach is described in Section 3 and the main hydrogeological findings (with specific emphasis on the shallow groundwater mechanisms) are discussed in Section 5.

2.4 Ecology

Lake Muckenburra is a ‘conservation category’ wetland and is listed as an ecologically-significant groundwater-dependent ecosystem for the following ecological values (Froend et al. 2004a; 2004b; 2004c):

- supports a threatened ecological community
- supports waterbird species and other wetland-dependent vertebrates.

The threatened ecological community (TEC) in the area to the south of Lake Muckenburra is a herb-rich saline shrubland associated with clay pans (indicated in Figure 6). The TEC is listed as vulnerable and is endemic to Swan Coastal Plain, with the community at Lake Muckenburra one of only two occurrences within the Gnangara groundwater system (Froend et al. 2004a; Valentine et al. 2009). The TEC at Lake Muckenburra is a species-rich vegetation community that occurs on heavy clay soils and requires regular inundation in winter-summer, with the vegetation typically dependent on soil moisture in the drier months (Horwitz et al. 2009a; Froend et al. 2004a; Froend et al. 2004b). Froend et al. (2004b) considered that the maintenance of the TEC is likely to be proportionally groundwater dependent, which is where changes in groundwater levels would not result in direct responses in vegetation health, composition or structure.

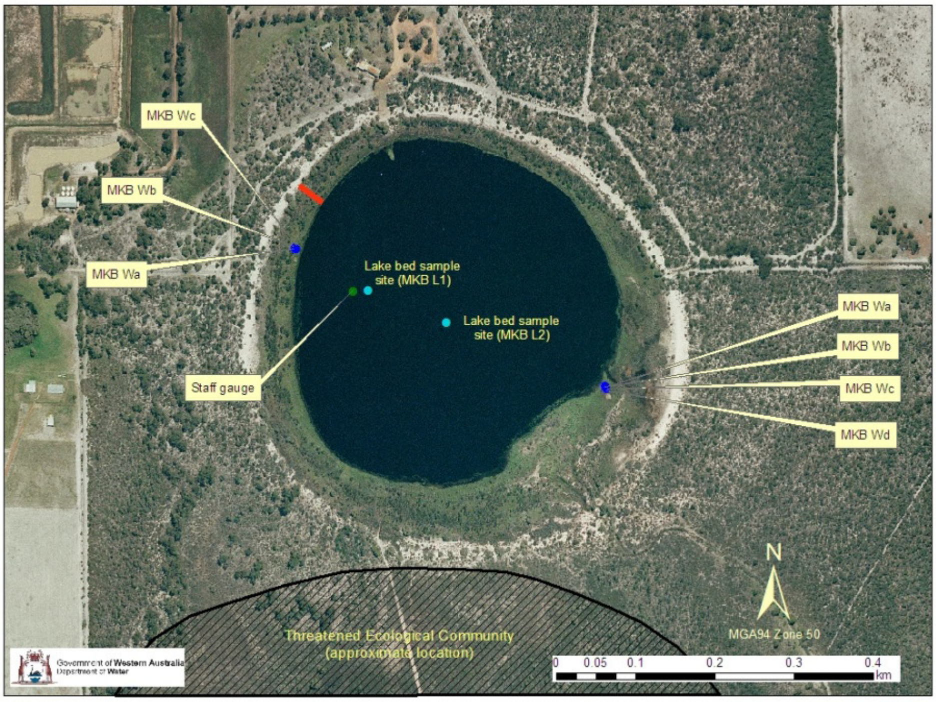


Figure 6 Location of the east and west cluster bores installed at Lake Muckenburra, staff gauge and lake bed sample sites (red line shows wetland vegetation transect)

The vegetation community surrounding Lake Muckenburra shows a high level of tree health despite land disturbance and surrounding agricultural land use. A total of 30 species have been recorded along the wetland vegetation monitoring transect which extends from the north-west of the lake basin (see Figure 6), including two key wetland species *Melaleuca rhaphiophylla* and *Baumea articulata*. Young, healthy *M. rhaphiophylla* dominate the overstorey while the understorey is minimal and species-poor, although large stands of healthy *B. articulata* are present in wetter areas. The site is moderately weedy, with 15 exotic species recorded (Wilson et al. 2009).

Two years of aquatic macroinvertebrate surveys indicate that the lake supports a moderate macroinvertebrate species richness, although this can vary significantly between seasons (Judd & Horwitz 2010). The information available does not cover a period long enough to determine trends in macroinvertebrate communities. Although Lake Muckenburra is known to support a range of waterbirds and other water-dependent vertebrates, no vertebrate fauna monitoring has been conducted to date. However, the diversity and abundance of these communities are certain to be associated with the hydrologic regime of the lake. Wading birds require access to shallow water in summer and early autumn for feeding, along with higher winter water levels to maintain the distribution of open water and vegetated habitats (Froend et al. 2004b). Any changes to the hydrologic regime of the lake (timing, duration, frequency and extent of inundation) will affect waterbirds and other wetland-dependent vertebrates.

2.4.1 Ecological water requirements

As the vegetation monitoring program only began in 2009, there is only limited data available for determining the minimum groundwater requirements. The distributional range of key species (*M. rhaphiophylla* and *B. articulata*) is only known from one year of sampling. However, given the current good health and condition of these key species, it has been assumed that the current ranges reflect unstressed conditions and can therefore be used to identify minimum water requirements for these species.

Using the methodology cited in Froend and Loomes (2004), the following minimum groundwater level requirements for vegetation at Lake Muckenburra have been determined:

- *Melaleuca rhaphiophylla* – 48.52 m AHD
- *Baumea articulata* – 49.44 m AHD.

2.5 Cultural significance

Wetlands across the Swan Coastal Plain are spiritually significant to Indigenous groups (the Nyungar people) and were used extensively in traditional times (Wright 2007a). Many lakes and swamps were used as hunting and gathering areas for flora and fauna (McDonald et al. 2005).

Lake Muckenburra is registered as a site of significance (Department of Indigenous Affairs site 19138) reflecting Indigenous values in water features in the landscape. This area falls under the Yued native title claim, which abuts the Perth metropolitan claim to the south. The wetlands south-west of Gingin were surveyed using a team of six traditional owners plus an anthropologist and two archaeologists. The technique included making use of the traditional owners to widen the scope of the archaeological surveys (Wright 2007a).

Most of the Gingin area has mythological significance. With the exceptions of the three artefact scatters (Department of Indigenous Affairs sites 18076, 18078 and 18079), all other sites registered within 5 km of the proposed SGS bore locations are mythological sites associated with the Dreamtime figure, the Waugul (Wright 2007b).

The survey found that there were no areas of ethnographic cultural significance of sufficient importance to impede the drilling program at Lake Muckenburra (Wright 2007b).

2.6 Land and water management

The *Gnangara groundwater areas allocation plan* (Department of Water 2009b) sets out the approach for the allocation and licensing of all water users of the Gnangara groundwater system. The Department of Water determines the volume and spatial distribution of water abstracted from the Gnangara Mound (the Superficial aquifer) by assessing proximity to groundwater-dependent ecosystems, ecological condition and rate and magnitude of groundwater level change.

For allocation purposes, the Gnangara groundwater system is divided into groundwater areas and subareas. Lake Muckenburra is located in the proclaimed Gingin groundwater area on the northern boundary of the Deepwater Lagoon South groundwater subarea. Groundwater use in this subarea is nearing the allocation limit (Table 3). The adjoining Beermullah Plain South allocation subarea to the north is over-allocated.

Lake Muckenburra is surrounded by a reserve of crown land managed for conservation purposes by the Department of Environment and Conservation. The reserve is encircled by freehold land that is predominantly cleared rural landholdings (Wilson et al. 2009).

Table 3 Superficial aquifer allocation limits, licensed entitlements and water availability for new licences for the Deepwater Lagoon South and Beermullah Plain South groundwater subareas

Subarea	**Deepwater Lagoon South**	**Beermullah Plain South**
Allocation limit	3.50 GL/a	3.00 GL/a
Licensed entitlements[1]	3.45 GL/a	3.01 GL/a
Public water supply (reserved)	None	None
Water available[2,3]	Limited	None

[1] Licensed entitlements include the total of private and public water supply licensed entitlements as at 5 August 2009.

[2] Water availability = allocation limit – total of licensed entitlements (private and public water supply), public water supply reserved (future use) and other commitments (e.g. staged developments).

[3] Resources less than 100% allocated but over 70% allocated have limited availability.

(This table is adapted from Table 6, Department of Water 2009b).

There is some private groundwater abstraction from the Superficial aquifer area around Lake Muckenburra, with bores in a 1 km radius licensed to abstract up to 90 ML per annum. At the time of preparing this report the Department of Water's water resource licensing database recorded 35 private abstraction licenses for the Superficial within a 5 km radius of Lake Muckenburra, with most being to the north-west of the lake (Figure 7). This level of abstraction is not anticipated to increase in the foreseeable future and there are currently no plans to develop the groundwater area for public abstraction (Department of Water 2009a).

Lake Muckenburra falls within Gnangara Sustainability Strategy (GSS) Zone 5 (Department of Water 2009a). For Zone 5, the GSS recommends that in the future, water should be allocated as a periodic share of available water, which will enable allocations to reflect the inter-annual and seasonal availability of water. The GSS also recommends:

- that there be no net expansion of horticulture in the zone and that abstraction for horticulture and public open space be reduced through greater water use efficiency
- total private abstraction should be reduced by around 20% by 2030
- the area that recharges the Yarragadee aquifer needs special management to maintain recharge rates in a drying climate.

3 Investigation program

3.1 Bore construction

The management area review of McHugh and Bourke (2007) recommended upgrading the groundwater monitoring network at Lake Muckenburra to enable further hydrogeological, hydrochemical and geochemical investigation. It was recommended that groundwater monitoring bores be installed in two clusters in an attempt to intercept both the perched and Superficial aquifers thought to underlie the lake. One of the bore clusters was positioned up-hydraulic gradient (east of the lake) and the other down-hydraulic gradient (west of the lake) so that both horizontal and vertical groundwater flows could be measured (Figure 6). The bores were screened within what was interpreted as different units within the perched and the Superficial aquifers (Table 4).

The cluster of three bores placed on the western (down-gradient) side of the lake were identified as MKB_West series bores (Table 4). While the shallow western bore (MKB_Wc) was screened to the near surface in the Bassendean Sand Formation, the intermediate (MKB_Wb) and deep western (MKB_Wa) bores were screened in the upper and lower sections of the Ascot Formation (Table 4). The lower part of the Ascot Formation at this site was in contact with the Leederville Formation.

The cluster of four bores on the eastern (up-gradient) side are identified as MKB_East series bores (Table 4). The deep bore (MKB_Ea) was screened in the Ascot Formation that was in direct contact with the Leederville Formation. The shallower bores (intermediate and shallow) were screened in the overlying 7 m thickness of Gnangara sand and the mid-part of the Bassendean Sand Formation (Table 4). The perched bore was screened to near surface in the upper part of the Bassendean Sand Formation in a zone containing numerous sequences of sandy clay and clayey sand lenses (interpreted as reworked Guildford Clay Formation). Details of lithology and construction details of all the bores are reported in Searle (2009) and reproduced in Appendix A.

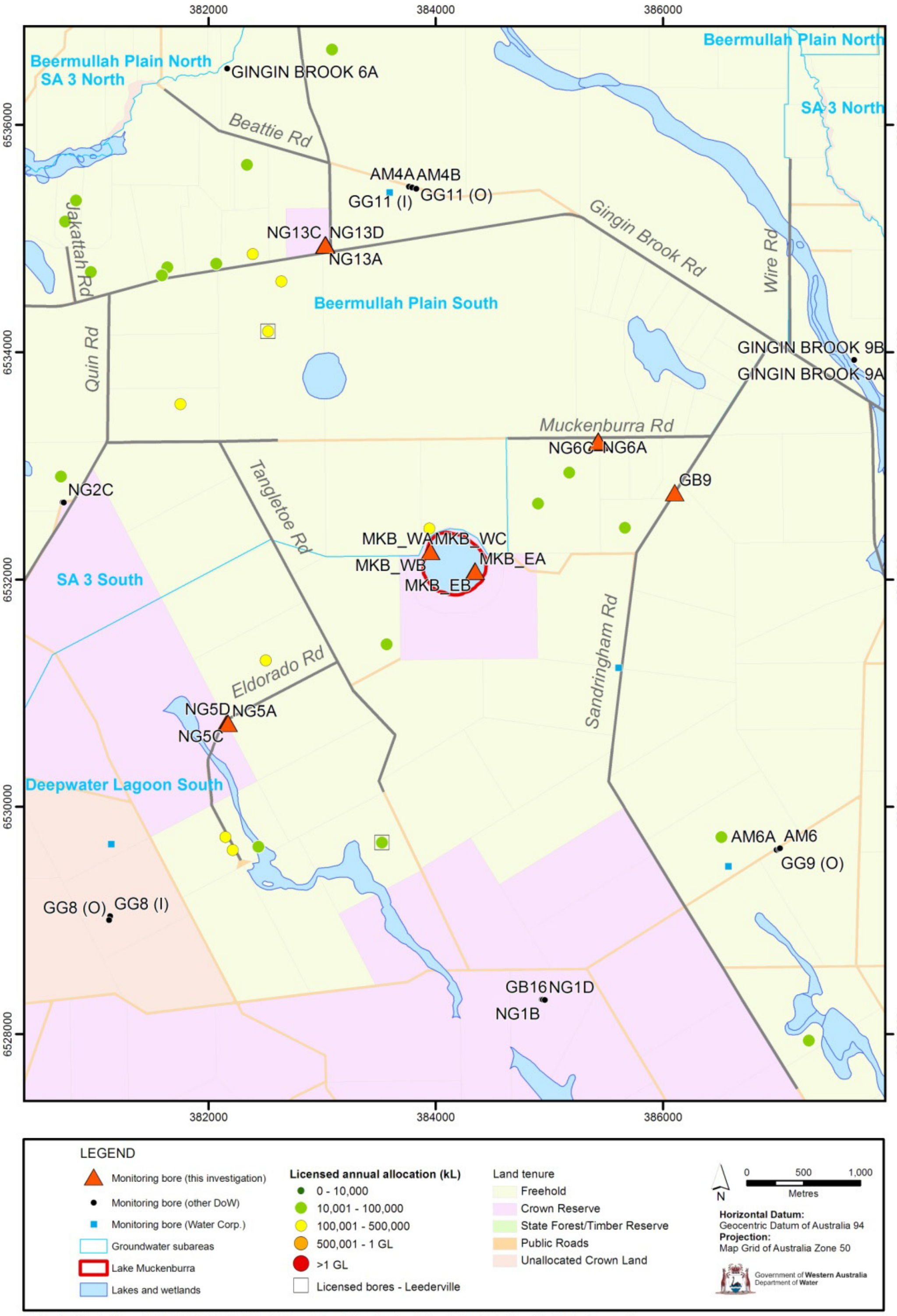
The shallow bores were installed using a Geoprobe 7720DT track mounted push-core rig, which provided continuous core samples to depth for acid sulfate soil testing. The Geoprobe rig was also used to extract cores from the lake bed for acid sulfate soil testing. Intermediate and deep bores were installed using a GSD77 Aircore drill rig with aggregate samples of drill cuttings collected every metre to depth.

Bores were cased with 50 mm Class 12 PVC, with slotted 50 mm Class 12 PVC of varying lengths installed at the base of the hole (Table 4). Shallow bores were backfilled to surface with gravel. The annulus of deep and intermediate bores was filled with gravel from the base of the hole to 2 m above the screened interval and then grouted to the surface. Head works consist of either steel standpipes cemented in with a height of approximately 0.5 m above ground level, or flush mount well covers which sit close to the ground surface.

Table 4 SGS investigation bores installed at Lake Muckenburra

Bore ID (AWRC name)	AWRC number	Depth	Drilled depth mbgl	Screen interval m AHD	Formation
Cluster bores on the eastern site Lake Muckenburra (MKB_East series)					
MKB_Ea	61710471	Deep	48	16.8–14.8	Ascot
MKB_Eb	61710472	Intermediate	23	32.1–30.1	Gnangara
MKB_Ec	61710473	Shallow	10	44.2–42.2	Bassendean Sand
MKB_Ed	61710474	Perched	5	51.1–47.9	Bassendean Sand
Cluster bores on the western site Lake Muckenburra (MKB_West series)					
MKB_Wa	61710476	Deep	43	15.0–13.0	Ascot
MKB_Wb	61710477	Intermediate	23.56	30.6–28.6	Ascot
MKB_Wc	61710475	Shallow	9.4	51.1–45.1	Bassendean Sand

Existing bores in the region were used in understanding the local hydrogeology and assessment of groundwater hydrographs (Figure 7). Most of the bores within 5 to 6 km of the lake were screened in the lower part of the Superficial aquifer and underlying formations or had limited historic water level monitoring data. Water levels in the bores NG6B, NG6C and NG6D to the north-east of the lake, bores NG5B, NG5C and NG5D to the south-west of the lake and bores NG13C and NG13D to the north-west of the lake were included as part of the investigation. NG6B and NG5B were screened in the upper Leederville Formation whereas the remaining bores were generally in the Ascot Formation (Appendix B). Long-term monitoring data from bore GB9, consisting of 33 years of water level measurements, was also evaluated. This bore was screened in the upper superficial formation, most likely in the perched groundwater system (based on lithology at NG6A). Summary lithology and construction of all existing bores used in the investigation are presented in Appendix B.



J:\gisprojects\Project\A_series\A3003\0081_SGS\0081_SGS\mxd\Lake_Muckenburra\mxd\Figure6_LandWaterUse_LakeMuckenburra.mxd

Figure 7 Lake Muckenburra SGS investigation bores and other bore locations in the region including annual licence allocations

3.2 Acid sulfate soils analysis

Sediment samples were collected and tested during the course of investigations to determine the distribution and characteristics of sulfidic sediments at Lake Muckenburra and the potential of these to affect groundwater quality.

Field tests were conducted on sediment recovered by direct push core extraction during drilling of SGS investigation bores MCN_Ec and MCN_Wc and two sites in the lake bed (MKB_L1 and MKB_L2), with selected samples submitted for laboratory analysis. Acid sulfate soil assessment in the field was undertaken according to the Department of Environment and Conservation's guidelines (Department of Environment and Conservation 2009a) (see Appendix C for full methods). Samples were stored in ziplock plastic bags with all air excluded and refrigerated until delivery to the laboratory for analysis, generally within 48 hours. Potential and actual acidity were analysed by determination of chromium reducible sulfur (CRS) suite and the suspension peroxide oxidation combined acidity and sulfur (SPOCAS) suite of analyses (see Appendix C for laboratory methods) by the National Measurement Institute (NMI). For the CRS suite this was carried out according to the Queensland Acid Sulfate Soils Investigation Team (QASSIT) methods 22B, 23A, 23F and 19A1 (Ahern et al. 2004). The SPOCAS suite was analysed according to QASSIT methods 23A, 23B, 23F, 23G, 23C to 23E (inclusive), 23V to 23X (inclusive), 23S to 23T (inclusive) and 23Q (Ahern et al. 2004).

Laboratory analysis allowed assessment of the net acidity of sediments by accounting for the acid generating materials against neutralising materials such as carbonates. This is commonly known as acid-base accounting (ABA; Ahern et al. 2004). The overall equation for acid-base accounting is:

$$\textbf{Net acidity} = \textbf{potential sulfidic acidity} + \textbf{actual acidity} + \textbf{retained acidity} - \frac{\textbf{measured ANC}}{\textbf{fineness factor}}$$

Where:

- *Potential sulfidic acidity* is latent acidity contained within sulfides that will be released if the sediments are fully oxidised
- *Actual acidity* (TAA) is the soluble and exchangeable acidity already present in the soil (determined as TAA and deemed evident when $pH_{KCl}<4.5$).
- *Retained acidity* is the 'less available' fraction of the existing acidity which may be released slowly into the environment
- *Acid neutralising capacity* (ANC) is a measure of the soil's ability to buffer acidity and resist the lowering of soil pH (determined when $pH_{KCl}>6.5$)
- *Fineness factor* is a factor applied to the acid neutralising capacity to allow for the poor reactivity of coarser carbonate or other acid neutralising material.

Net acidity results were compared with Department of Environment and Conservation management action criteria of 18.7 mol H^+/tonne (Department of Environment and

Conservation 2009a), which indicate that the sediments may require management to mitigate acidification if at risk of oxidation by land or water disturbances. This criteria also includes risks posed by acidity in actual ASS by assessing actual and retained acidity, regardless of potential acidity or neutralising capacity.

Samples were also analysed for major metals (Al, Fe and Mn), trace metals (Cd, Cr, Ni and Zn), As and Se concentrations. This involved nitric and hydrochloric acid digestion followed by extraction and analysis by inductively coupled plasma mass spectrometer (ICPMS) and inductively coupled plasma atomic emission spectrometer (ICPAES) depending on the concentrations and detection limits required. Anhydride generation was carried out prior to ICPMS analysis for As and Se.

3.3 Water monitoring and sampling program

Lake water and groundwater were sampled and analysed to determine the hydrochemical characteristics of each site, the distribution and availability of potential pollutants and the interaction between the wetland, the perched groundwater system and the Superficial aquifer. Groundwater sampling was carried out from the seven bores installed for the project (Figure 6 and Table 4) and grab samples of lake surface water were collected near the staff gauge (Figure 6).

Water samples were collected using low flow pumping methods (from bores) and grab sampling as described in Appendix E. Analyses of water samples were conducted for major ions, metals and nutrients (Table 5). Samples were taken for pesticides from groundwater bores on three occasions during the investigation – 2 July 2008, 25 February 2009 and 10 June 2009. Details of sample analysis techniques and detection limits are given in Appendix E.

Table 5 Summary water sample collection and analysis details

Description	Collection details	Element or compound[*]
Total metals	Direct collection	Hg, Al, As, Cd, Cr, Fe, Mn, Ni, Se, Zn
Dissolved metals	On-site 0.45 μm filtration	Ca, Mg, Na, K, B, Fe, Al
Nutrients	Direct collection	NH_3-N, TN, TP, NOx, FRP
Other inorganic constituents	Direct collection	EC, TSS, TDS, HCO_3, CO_3, Cl, F, SiO_2, SO_4, pH, acidity, alkalinity, DOC, DON
Pesticides	Direct collection	Aldrin, Atrazine, Azinphos-ethyl, Azinphos-methyl, Bromophos-ethyl, Chlordane, Chlorfenvinfos, Chlorpyrifos (tot), Chlorpyrifos-methyl (tot), DDD-p,p, DDE-p,p, DDT-p,p, Diazinon, Dimethoate, Dieldrin, Diuron, Endosulf sulfate, Endosulf-a, Endosulf-b, Endrin aldehyde, Endrin ketone, Enthion, Fenchlorphos, Fenitrothion, Fenthion, HCH (BHC) a,b,d, HCH (BHC), Heptachlor, Heptachlor epoxide, Hexachlorobenzene, Hexazinone, Linuron, Malathion, Methoxychlor, Metolachlor, Mevinphos, Molinate, Oxychlordane, Oxyfluorofen, Parathion {Ethyl par.} , Parathion-methyl, Pendimethalin, Pirimiphos-ethyl, Pirimiphos-methyl, Simazine, Tetrachlorvinphos, Trifluralin

[*] *Abbreviations*

TN – total nitrogen	*TDS – total dissolved salts*
TP – total phosphorus	*DOC – dissolved organic carbon*
TSS – total suspended solids	DON – dissolved organic nitrogen

3.4 Data accuracy and precision

There is a degree of uncertainty attached to measured chemical parameters, and results from laboratory chemical analysis are not absolute. This uncertainty is caused by several contributing error sources, mainly precision errors or accuracy errors. Precision errors result from random fluctuations in the analytical procedure. Precision can be calculated by performing repeat analyses on the same sample. Accuracy, or systematic errors, reflect faulty procedures or interference during analysis. An electrical balance, also known as an ion balance, is used to check the accuracy of analytical results. The sum of positive and negative charges in the water should be equal (Appelo & Postma 2005), so the sum of the cations in solution should equal the sum of the anions:

$$\textbf{Electrical balance \%} = \frac{\textbf{sum cations + sum anions}}{\textbf{sum cations - sum anions}} \times (\mathbf{100})$$

where ions are expressed as milliequivalents per litre (meq/L).

Deviations of more the 5% signal that sampling and analytical procedures should be examined (Appelo & Postma 2005). For this investigation, if the electrical balance was greater than 6%, without satisfactory explanation, then this sample was left out of the analysis. All samples met this criteria, with deviations of up to 7% explained by rounding errors in reported chloride concentrations. To allow plotting and calculations, the widely accepted practice of converting values below laboratory reporting limits to be half the limit was applied (Hounslow 1995).

There are numerous reasons for a difference between field and laboratory pH readings (and for other unstable parameters such as dissolved oxygen (DO) and oxidation reducing potentials (ORP)). These include reactions involving oxidation, precipitation and release of dissolved gas. Only on-site analyses for pH, temperature, DO and ORP were used in the data analysis reported below to avoid introducing uncertainties in the dataset, as recommended in state and national groundwater sampling procedures. ORP was converted to redox potential (*Eh*) (relative to the standard hydrogen electrode) using the correction values recommended by the manufacturers of the field measurement equipment or internal factory set values.

3.5 Data presentation and interpretation

The following data presentation and interpretation methods were used to determine the hydrogeological and hydrochemical characteristics of the Lake Muckenburra area:

- re-interpretation of historical lithological logs
- geological cross-sections based on historic and Perth SGS investigation drilling information
- analysis of hydrographs
- groundwater contour mapping and flow nets (for average groundwater levels)
- 'Piper' diagrams for major ions
- time series plots for physical properties, major ions, nutrients and trace elements.

Where possible, summary water chemistry for physical parameters (e.g. pH), nutrients and trace elements were compared with guideline values for water quality. The water quality properties of the lake water were compared with guideline levels for south-west Australian wetlands and, for trace elements and pesticides, compared with the moderate protection level (with 95% confidence of protection) for aquatic species in freshwater ecosystems (ANZECC & ARMCANZ 2000). Where the 95% protection levels were exceeded for trace elements an indication of the next confidence level of protection that is met is also provided. Groundwater quality (trace metals and pesticides) was also compared with drinking water guideline values

(NHMRC & NRMMC 2004) because the use of the water for potable supply represents the greatest risk, with guideline values for many water quality parameters being conservatively set lower than for other uses (Department of Environment and Conservation 2010). Notably, the salinity of the groundwater in the Superficial aquifer would impose greatest constraints on use as a potable supply.

Drinking water guidelines were also used to give a perspective on sample water quality and, where no irrigation trigger level existed, were used for reporting purposes, in accordance with the methods described in the Department of Environment and Conservation’s assessment guidelines (Department of Environment and Conservation 2010).

The department considers that any untreated waters taken from the environment are unsafe for human drinking.

4 Geology

4.1 Superficial and Mesozoic formations

Investigation of the lithology while drilling the deep bores at Lake Muckenburra showed the thickness of the superficial formations to be up to 44 m (Table 6 and Figure 8) and comprised mostly Bassendean Sands overlying the Ascot or Gnangara Sand formations.

Drilling indicated that the Bassendean Sand Formation consists of stratified medium to coarse grained silty sands and sands inter-fingered by sandy clays that were interpreted as reworked Guildford Clay Formation. Inspection of the drill cores indicated that the sandy clays were intermittently present in sequences (frequently <0.2 m thickness) at between ~1 m to 13 m below surface (~ 50 to 39 m AHD; Figure 8) being typically mottled greenish-grey and yellowish-brown. These were interbedded with mottled medium to coarse grained clayey sands and sand of varying thickness consistent with the lithology of the Guildford Clay Formation in the region described by Moncrieff and Tuckson (1989), although this interpreted the formation to underlie the Bassendean Sand Formation (being generally late Pleistocene). However, the thin interbedded sequences with poorly sorted sands were consistent with fluvial deposition of materials and therefore may have been reworked Guildford Clay Formation.

Below the Bassendean Sands, there is a facies change to coarse to very coarse sands with abundant heavy minerals and lithic fragments, conforming closely to the lithology of the Gnangara Sands described in Davidson (1995). The Gnangara Sand is approximately 10 m thick in on the eastern side of the lake (bore MKB_Ea) at between 25 and 35 m below surface (27–17 m AHD), but was absent on the western side of the lake (bore MKB_Wa) (Figure 8).

Sediments typical of the Ascot Formation were encountered beneath the Gnangara Sand (Figure 8). The lithology of the Formation beneath the lake was typically very coarse silty sands frequently containing shell fragments and occasional calcarenite and glauconite nodules. The Ascot Formation was approximately 18 m thick beneath the eastern side of Lake Muckenburra, lying between 26 and 44 m below ground surface (~26 – 8 m AHD). A similar occurrence was found beneath the western side of the lake (at bore MKB_Wa), with the formation occurring at 20 to 42 m below ground surface (32 – 10 m AHD). The Ascot Formation was interpreted to lie unconformably on the Leederville Formation (Warnbro Group) clearly evident at a depth of 44 m (~ 8 m AHD) on the eastern side of the lake. Drilling intersected less than 4 m of the formation, with the lithology being typical of the interbedded sandstones, siltstones and shales of the Wanneroo Member.

Table 6 Typical stratigraphy and lithology for the deep bore drilled on the eastern side of Lake Muckenburra (using MKB_Ea as an example)

From mbgl	To mbgl	Lithology	Formation	Code
0	2	Silty sand	Bassendean Sand	Qd
2	13	Silty clayey sand and sandy clay	Thin sequences of reworked (?) Guildford Clay	Qd
13	19	Sand, slightly Silty	Bassendean Sand	Qd
19	26	Sand	Gnangara Sand	Qn
26	44	Limestone and sand	Ascot Formation	Ta
44	48	Siltstone and fine sand	Leederville Formation (Warnbro Group)	Kwl

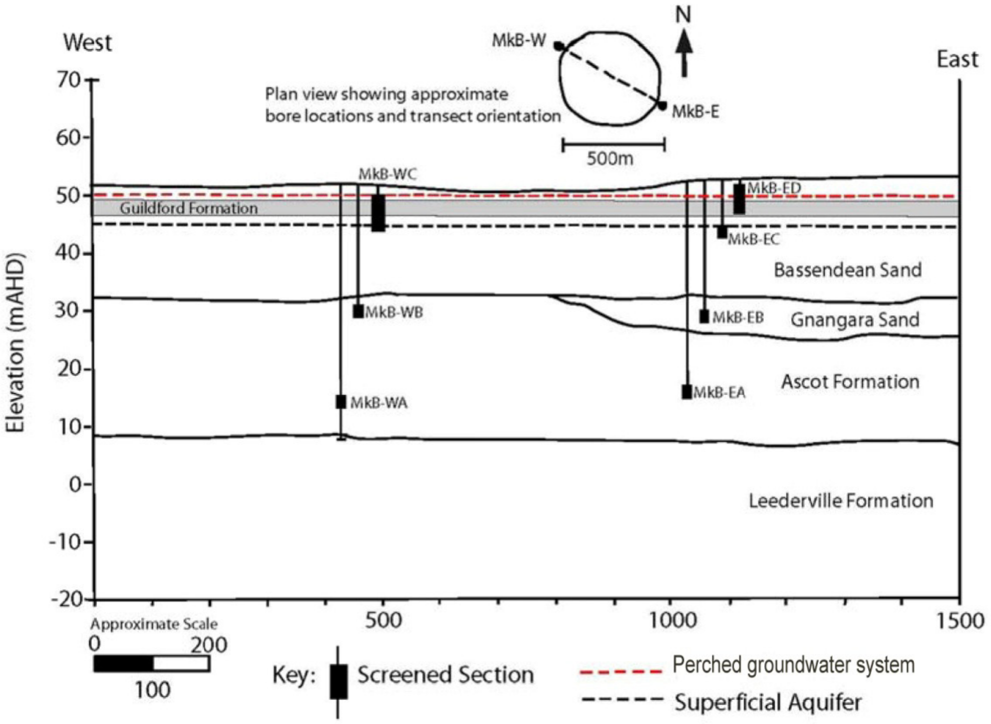


Figure 8 Interpreted local geology cross-section including monitoring bores for Lake Muckenburra (all units in metres)

4.2 Acid sulfate soil assessment

Field testing of the shallow superficial formation indicated that the pH of the profile (pH_F) generally increased with depth from 6 to more than 8 on the western side of the lake (at MKB_Wc and Figure 9). The trend was similar on the eastern side of the lake (MKB_Ec) except for a white sand lens at 6.0 mbgl where pH_F was 3.1 (Figure 10). This pH value was strongly indicative of actual ASS materials being present in the sand. A reverse trend was evident in field pH beneath the lake bed with testing at two sites with pH generally being greater near the lake bed surface.

There were minor amounts of PASS materials within shallow and deeper clayey sand and sandy clay lithology at the eastern site, but not the western site. After peroxide oxidation, pH_{FOX} values at the western site (MKB_Wc) were less than 4.5 and more than 2 pH units less than pH_F from 0.75 to 1.6 mbgl (51.41 m AHD to 50.56 m AHD) and sporadically at 4.4 mbgl and 4.9 mbgl (Figure 9). Laboratory analyses indicated that minor concentrations of PASS materials were present (Table 7) with net acidity being marginally greater than the 18.7 mol H^+/tonne action criteria (Department of Environment and Conservation 2009a). These PASS materials were probably confined to the shallow clayey sand and sandy clay sediments (0.6 to 2.2 mbgl) with analyses showing no indication of significant net acidity in deeper sediments.

Field test results at the eastern site (MKB_Ec) exhibited weak indications of PASS materials based on sporadic occurrences where pH_{FOX} was more than 2 pH units less than pH_F (Figure 10). However, laboratory analyses indicated that it was likely that these sediments contained no significant net acidity. This conclusion was based on considering results from the CRS suite analysis rather than the SPOCAS, when there was a discrepancy between the methods (Ahern et al. 2004). Peroxide test results for the lens of actual ASS materials at 6 mbgl indicated that this did not contain any residual PASS materials.

There were no indications of PASS materials in field testing of sediments in the two cores taken from the lake bed (Appendix F).

None of the laboratory analysed samples were deemed to contain retained acidity or acid neutralising capacity (Table 7). The lack of acid neutralising capacity indicates capacity to buffer pH to greater than 6.5 which is considered to be due to the presence of carbonates and to a lesser extent exchangeable cations (Ahern et al. 2004). The absence of ANC does not indicate a complete absence of capacity to buffer against any acidifying processes, particularly since the field pH (pH_F) was generally greater than 6 throughout the shallow lithology on both sides of the lake, indicating that there was there was probably some inherent buffering capacity by way of exchangeable cations. This is also more likely given the clayey nature of the sediments. Analysis of ANC for samples from the lake bed were not conducted despite pH_{KCl} exceeding 6.5. However, the lithology for these samples contained no evidence of free carbonates suggesting that these were not likely to be a significant factor in the buffering capacity.

Element concentrations for all samples were below the Department of Environment and Conservation sediment ecological investigation limit (EIL) action criteria (Department of Environment and Conservation 2010) with Cd, Se and As commonly being below detection levels (Table 8). None of the metal concentrations were considered to pose a risk to groundwater and the ecology at Lake Muckenburra, based on the EIL criteria. Concentrations of trace elements were the greatest in the lake bed (MKB_L1 and MKB_L2), often 10 times more than samples from the adjacent Superficial formation. The samples with detectable potential acidity (PASS materials; Table 7) at site MKB_WC (0.6 m and 1.7 m) showed no preferential concentration of the major metals or trace elements. Concentrations of major metals such as iron and aluminium were also highest in the lake bed samples.

In summary, the combined field testing and net acidity results at Lake Muckenburra indicate that sediments contain minimal risk of becoming acidic should there be any changes in hydrological regime resulting in the complete drying of the lake sediments and adjoining shallow Superficial formation. There is also minimal risk of trace metal contamination from the metals contained within the soil materials.

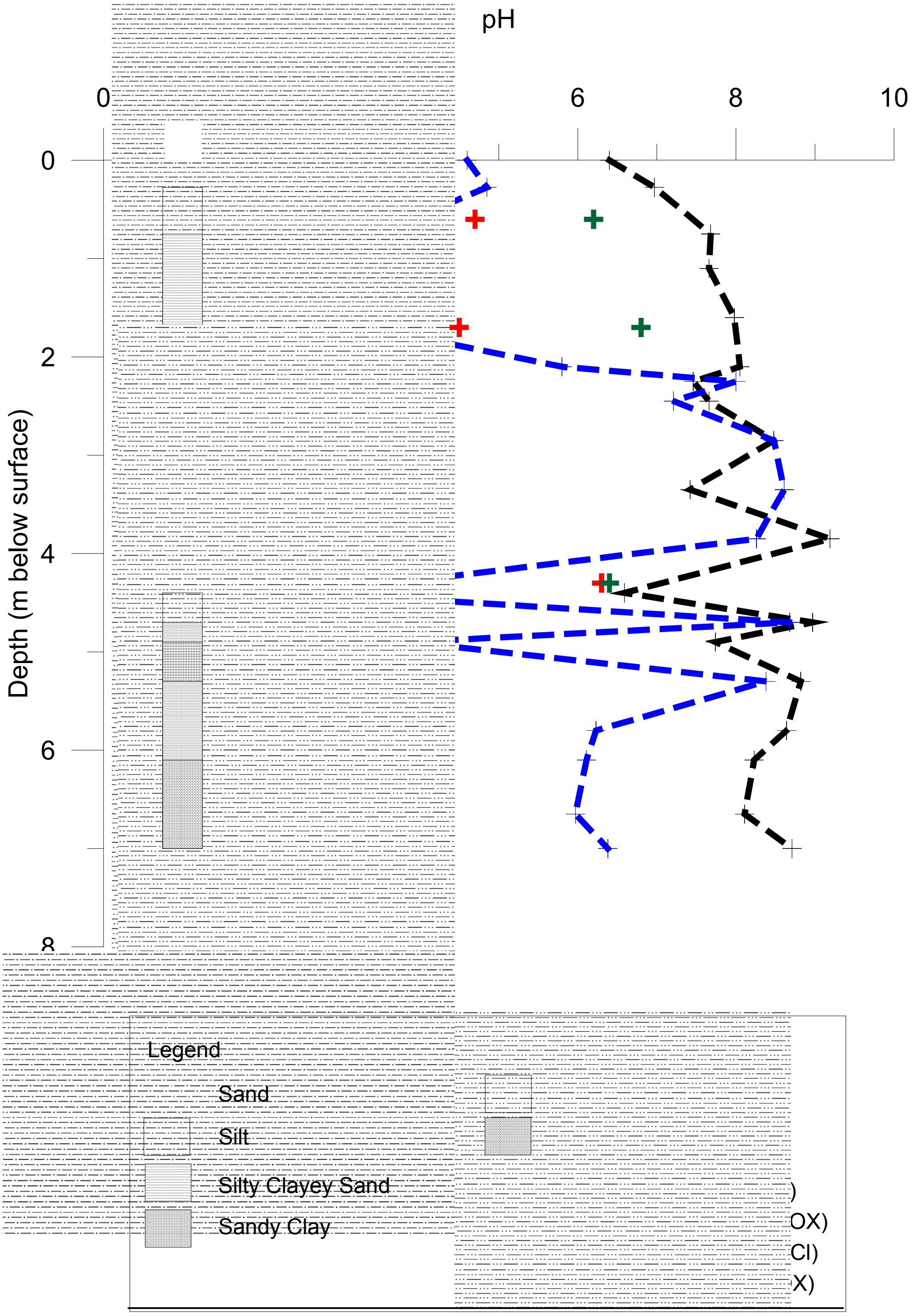


Figure 9 Field and laboratory results of natural and peroxide oxidised pH in relation to lithological units for MKB_Wc

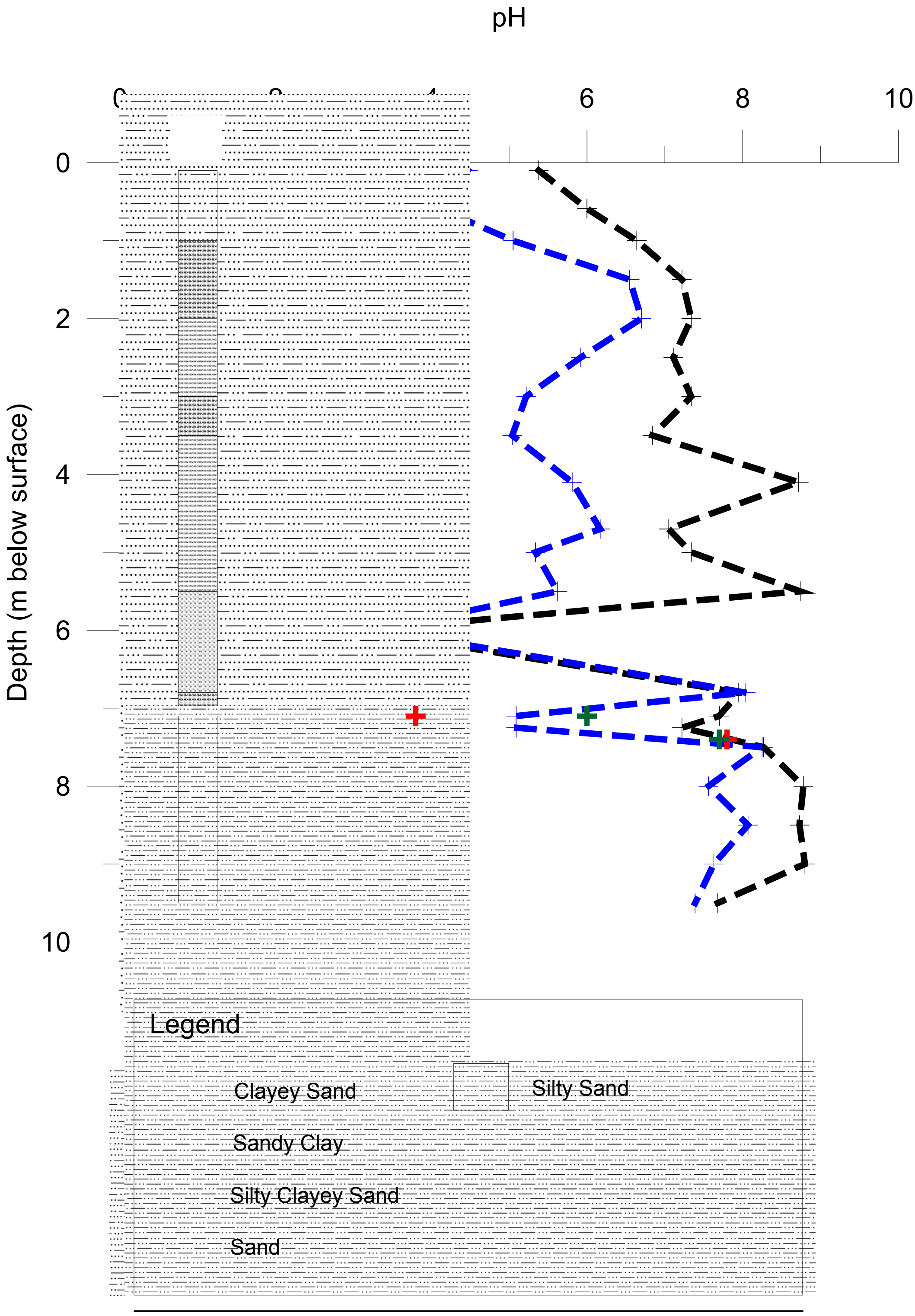


Figure 10 Field and laboratory results of natural and peroxide oxidised pH in relation to lithological units for MKB_Ec

Table 7 Summarised acid sulfate soil analyses by SPOCAS or CRS for sediments from Lake Muckenburra

Site	**Depth mbgl**	**pH_F**	**pH_{KCl}**	**pH_{OX} (SPOCAS)**	**Acid neutralising capacity mol H^+/t**	**Potential acidity mol H^+/t**		**Actual acidity mol H^+/t**		**Net acidity mol H^+/t**	
						SPOCAS (S_{POS})	**CRS** (S_{cr})	**SPOCAS**	**CRS**	**SPOCAS**	**CRS**
MKB_EC	7.1	7.7	6	3.8	0*	<6.2	<6.2	<1	<1	0	0
MKB_EC	7.4	8.3	7.7	7.8	10	<6.2	<6.2	<1	NA	0	0
MKB_WC	0.6	7.7	6.2	4.7	0*	31.2	12.5	<1	<1	31	12
MKB_WC	1.7	8.0	6.8	4.5	<10*	18.7	12.5	<1	<1	11	12
MKB_WC	4.3	6.6	6.4	6.3	0*	<6.2	<6.2	<1	<1	0	0
MKB_L1	0.25	7.5	7.5	5.8	0*	81.1	<6.2	<1	<1	53	0
MKB_L2	0.25	8.2	7.5	5.8	0*	12.5	<6.2	<1	<1	71	6

** Samples with pH_{KCl}<6.5 deemed not to contain any neutralising capacity therefore reported as 0 or <10, being less than reporting limits.*

NA – not available.

Table 8 Metals and metalloids in sediment at the Lake Muckenburra site

Site ref number	**Depth m**	**Al**	**As**	**Cd**	**Cr**	**Fe**	**Mn**	**Ni**	**Se**	**Zn**
		mg/kg								
MKB_EC	7.1	190	0.55	<0.5	38	2 460	13	2.8	<0.5	11
MKB_EC	7.4	1 420	<0.5	<0.5	3.6	730	1.2	0.69	<0.5	<0.5
MKB_WC	0.6	13 800	0.58	<0.5	19	4 680	4.6	8	<0.5	<0.5
MKB_WC	1.7	6 460	<0.5	<0.5	7.3	2 340	1.3	2.3	<0.5	<0.5
MKB_WC	4.3	3 320	<0.5	<0.5	15	3 660	7.3	3.4	<0.5	<0.5
MKB_L1	0.25	38 500	4.1	<0.5	50	14 800	89	28	9.6	6.7
MKB_L2	0.25	36 500	6	<0.5	48	18 700	130	25	8.9	17
EIL		NA	20	3	50	NA	500	60	NA	200

NA – not available

EIL – ecological investigation level (Department of Environment and Conservation 2010)

5 Hydrogeology

Hydrographs and watertable contours of the region were analysed to determine the general hydrology of the perched groundwater system and Superficial aquifer at Lake Muckenburra.

5.1 Water levels at Lake Muckenburra

Water levels for the bores and staff gauge at Lake Muckenburra were analysed in conjunction with levels recorded for bores in the area surrounding the lake (GB9, NG6 and NG5 series).

Lake levels were only recorded from August 2008 (after installation of the staff gauge) until January 2009 when the lake dried. Filling of the lake did not occur until late in winter – up to a month after the onset of winter rainfall. This indicated that direct rainfall input to the lake probably contributed little to lake levels and that interaction with the local watertable had a greater influence on lake levels.

The water levels in the bores adjacent to the lake (MKB series) displayed a typical seasonal pattern of fluctuations over the investigation period. This was more evident in the shallower bores than the deeper bores (Figure 11 and Figure 12). The seasonal pattern in the perched groundwater system (bore MKB_Ed) showed a response to seasonal rainfall patterns delayed by up to a month, indicating delayed recharge of the watertable. The ponding of water in the lake during this period occurred while the watertable in the perched groundwater system remained at the bed level of the lake, but below the lake water level. This may have been due to formation of a transient perched watertable in the surface sand sediments above the perched groundwater system, enabling through flow to occur to the lake before seepage to deeper layers in the perched groundwater system. There was visual evidence that seepage into the lake occurred on the eastern side of the lake (north of the MKB_East bores) during winter from a point above the maximum lake water level (Figure 13) and therefore the water level in the perched groundwater system (MKB_Ed).

Similar lagged responses to rainfall were also evident in the continuous logger data for selected bores. Daily rainfall events of at least 50 mm (at nearby Gingin) resulted in watertable responses in the perched groundwater system lagging by more than several days and no clear evidence of consistent watertable responses in the shallow Superficial aquifer (in MKB_Ec; Appendix G). These suggest that groundwater levels in the shallow Superficial aquifer are not directly connected with the perched groundwater system.

Peak levels in the shallow part of the Superficial aquifer (MKB_Ec) were delayed by at least a month relative to the peak in the perched groundwater system – occurring from October to February. This was most evident in the continuous water level data logged in selected bores (Appendix G). A similar pattern was not apparent in the shallow Superficial aquifer bores on the western side of the lake for reasons

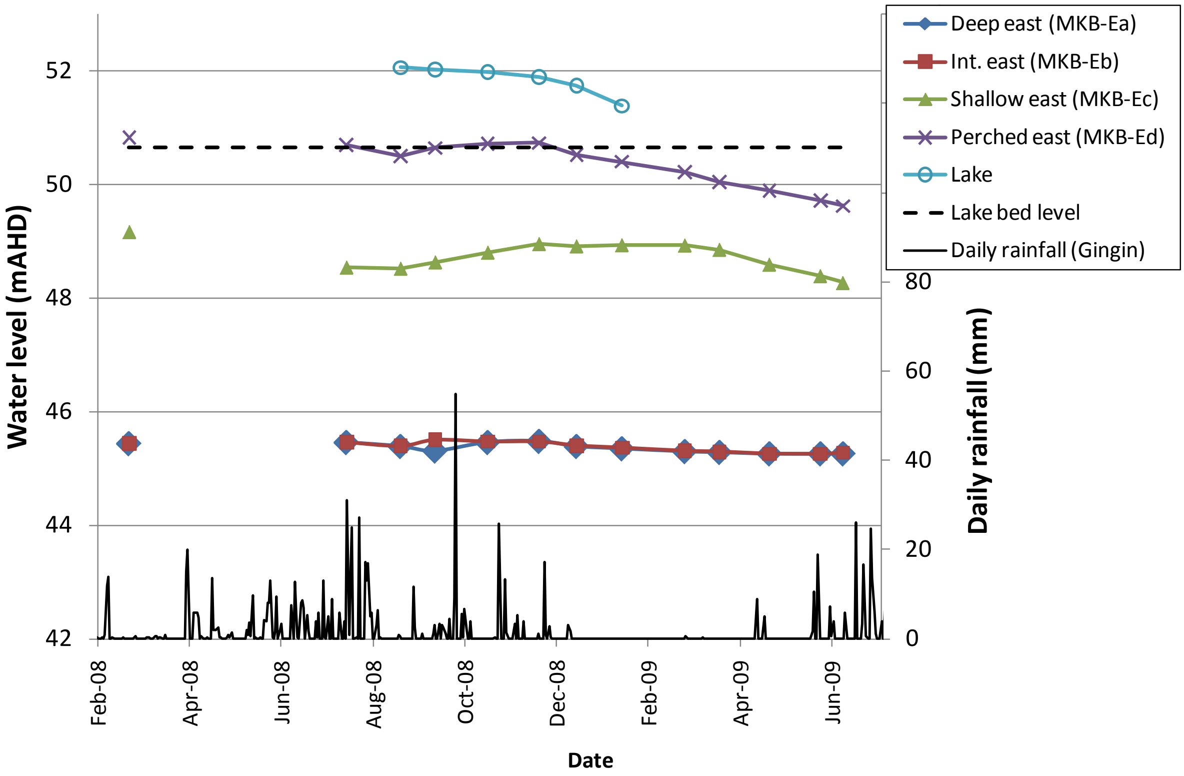


Figure 11 Hydrographs for bores on the eastern side of Lake Muckenburra with corresponding local rainfall

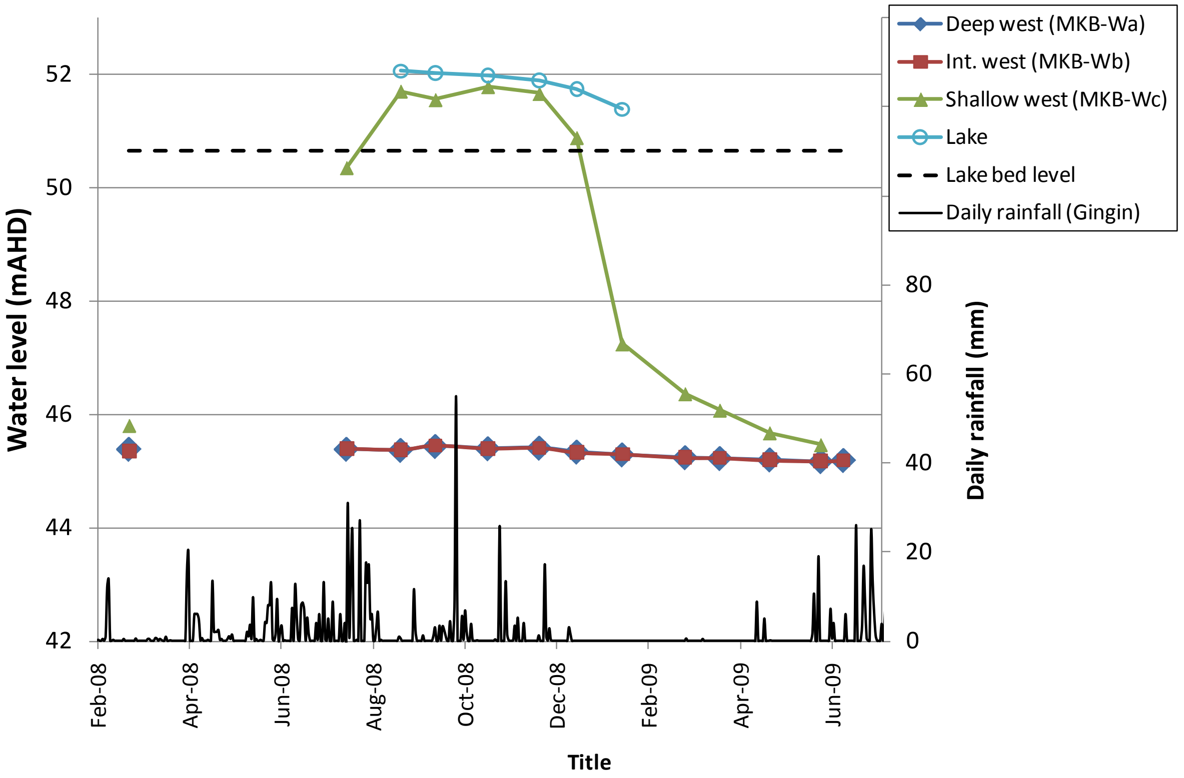


Figure 12 Hydrographs for bores on the western side of Lake Muckenburra with corresponding local rainfall

Figure 13 Seepage to Lake Muckenburra occurring on the eastern shore from above the high water mark in August 2008

explained below. In contrast, the seasonal water level peak in the deeper bores tended to correspond with those in the perched groundwater system (between September and November).

Groundwater levels for both the eastern and western bores were always lower than lake levels. Levels in the shallow western bore rapidly increased to above the lake bed for a period when the lake contained water (MKB_Wc in Figure 12), but this was probably because of a fault with the construction of the bore that led to leakage of lake water into the bore annulus when the lake contained water. There was further evidence that this had occurred with the similarity between the major ion composition of the water sampled in the bore and the lake (see anion and cation analyses in Section 6.2.1).

Groundwater levels recorded in the bore in the perched groundwater system (MKB_Ed) were consistently more than 1 m higher than those recorded in deeper bores near the lake, except for the levels in the shallow bore MKB_Wc (Figure 11 and Figure 12). This indicates that the watertable in the aquifer within which bore MKB_Ed is screened is perched above that in the local superficial formations. In contrast, although water levels varied significantly in the shallow west bore (MKB_Wc), probably as a result of direct recharge to the bore when the lake contained water, prior to lake filling and after lake drying the levels tended to be significantly below that of the eastern bore in the perched watertable.

Formation of the perched groundwater system was attributed to a semi-confining layer in the Superficial aquifer. Despite the absence of significant layers of stiff clays, the multiple layers of thin sandy clay with intermittent mottling in the shallow superficial formation underlying the lake (see Section 4.1) impeded vertical water movement. This conclusion was also supported by observation of water retention in above ground ponds constructed on the shallow sandy clay and clayey sands to the north-west of the lake.

The saturated thickness of the seasonal perched watertable in direct contact with the lake was estimated to be less than 2 m, with the depth to the watertable in the Superficial aquifer being more than 2 m (Figure 11 and Figure 12).

The pattern of water levels with depth in the superficial formations differed between the east and west side of the lake, but appeared to be in contact with the base of the sequences of reworked Guildford clays on both sides of the lake. Water levels in the mid part of the Bassendean Sand Formation on the eastern side of the lake indicated in bore MKB_Ec were several metres higher than both bores in the underlying Gnangara Sand Formation (MKB_Eb) and Ascot Formation (MKB_Ea). This difference was less in bores on the west side of the lake when only considering times when the groundwater levels in bore MKB_Wc were unlikely to be influenced by lake levels (22 February 2008 and 26 May 2009). On these occasions, groundwater levels in the shallow bore were only marginally higher than those in the deeper bores in the upper and lower Ascot Formation (Figure 12).

5.2 Water levels in the Lake Muckenburra area

Monitoring of intermediate and deep bores to the south-west and north-east of the lake indicated little seasonal variation in groundwater levels, although the pattern that was apparent indicated that maximum levels occurred between September and October. The groundwater levels in the bores were more elevated to the north-east of the lake (NG6 series; Figure 14) and were consistent with the low regional south-east to north-west aligned hydraulic gradient (Figure 5). Relative groundwater levels in the bores screened in the lower part of the Superficial aquifer (Ascot and Gnangara Sand formations) differed by less than 0.5 m (Figure 5), with the levels in NG6C and NG6D to the north-east of Lake Muckenburra being similar to those in the deep bores at the lake (Figure 14).

Groundwater levels recorded in the bore GB9 (Figure 15) to the north-east of the lake were also generally up to 10 m higher than in bores screened in the deeper part of the Superficial aquifer within 800 m of this site (NG6D in Figure 14). The water levels in bore GB9 exhibited seasonal maximum generally between late July and mid September (more evident in the early part of the record), which was consistent with the timing of maximum in the perched bore at Lake Muckenburra (MKB_Ed). Although there was only limited lithology available for the GB9 bore, the water levels indicated a perched watertable consistent with the bore being screened above 53.35 m AHD (bottom of the bore) and above semi-confining clays that were evident in the lithology for the NG6 series of bores (generally from 53.6 m AHD to 43.6 m AHD; Appendix B). The groundwater levels in the perched watertable at GB9 were approximately 6 m higher than in the perched bore near Lake Muckenburra (MKB_Ed) and broadly followed the difference in land elevation between the sites.

The upper level of the clays at the NG6 bore series were higher than that of the clays in the eastern bores at Lake Muckenburra. This indicated that a perched watertable possibly occurs at least several kilometres up gradient of the lake, but it is not clear whether the clay layers are continuous across this distance.

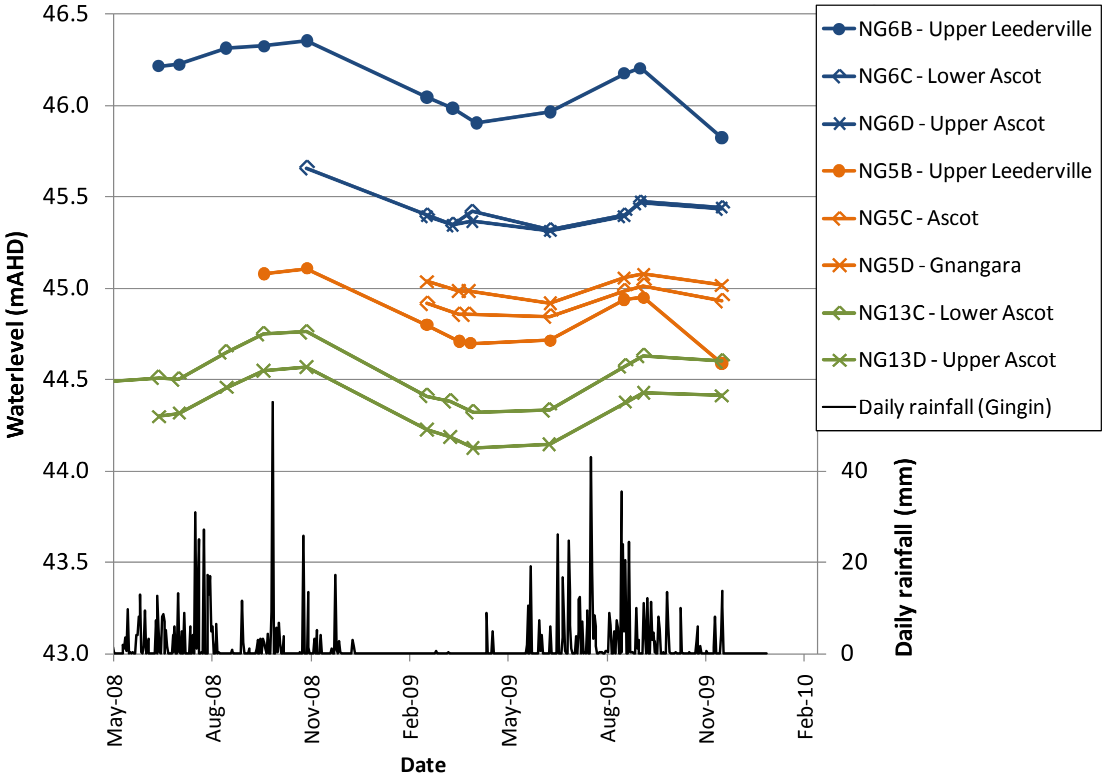


Figure 14 Hydrographs for bores in the region of Lake Muckenburra with corresponding rainfall (NG6 1.5 km NNE, NG5 2 km SW and NG13 3 km NNW of the lake)

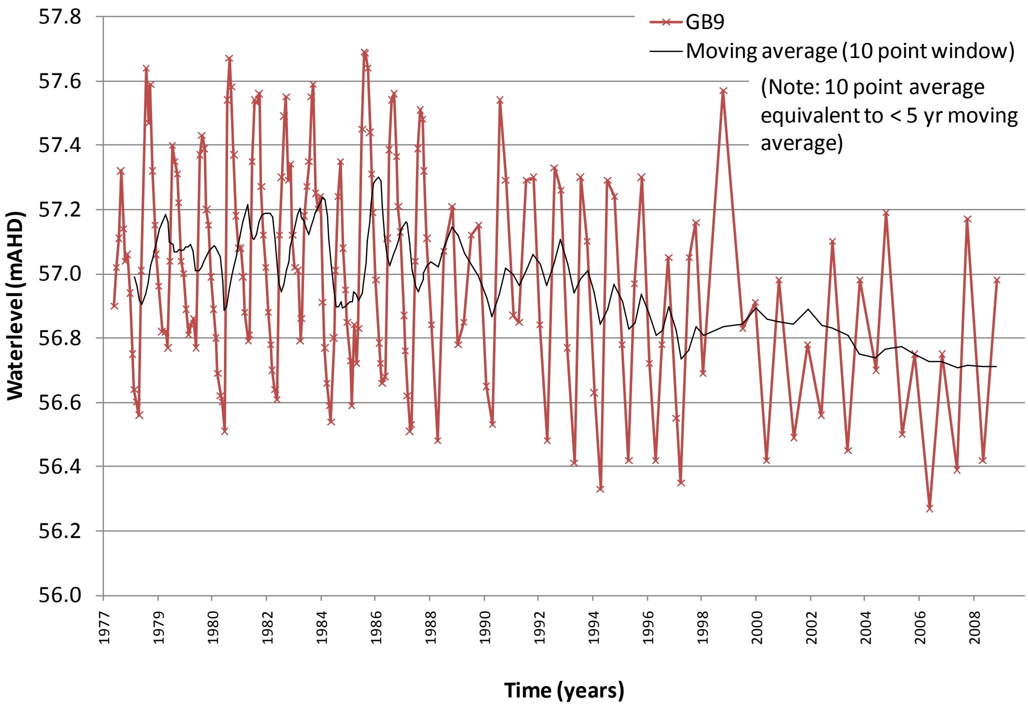


Figure 15 *Long-term hydrograph for bore GB9 (2 km north-east of Lake Muckenburra) with 12 point moving average*

Hydrographic data for bore GB9 were assessed to provide an indication of likely groundwater trends at the lake, given that no long-term records were available for the site. Groundwater levels in bore GB9 have declined by approximately 0.3 m over the last 30 years (Figure 15). Given the likely continuity of the perched watertable to the east of the lake, it is probable that water levels within the perched groundwater system at Lake Muckenburra have decreased by a similar magnitude over the same time period.

5.3 Groundwater flow

Interpreted groundwater flows in the Superficial aquifer follow local topography (Figure 5 in Section 2.3) flowing from south-east to the north-west. Groundwater flows in the perched watertable were also likely to follow the same flow path with the top elevations of the sequences of sandy clays and clayey sands trending similarly to the north-west. This conclusion was based on the lithology of the MKB_East, MKB_West, NG13, NG6 and NG5 series bores.

Downward hydraulic pressure gradients were evident at both sides of the lake although these greatly diminished with depth. These gradients were typical of a subdued shallow recharge zone in the Superficial aquifer (Figure 17). The vertical gradients were more evident on the east side of the lake than on the west (Figure 11 and Figure 17). These differences probably reflect variations in the local structure of the semi-confining layer and the influence of this on recharge.

Hydraulic gradients towards the base of the Superficial aquifer suggest that limited groundwater flow occurs in the zone immediately beneath the lake and to the north east of the lake (up gradient). This was evident as minimal differences between water levels in bores deeper within the superficial formations (e.g. between the C and D bores in the NG6 series; Figure 14). However, down gradient of the lake, downward vertical gradients were apparent deeper in the superficial formations to the south-west (NG5 series bores; Figure 14) whereas upward vertical gradients were evident to the north-north-west of the lake, possibly from the underlying Leederville Formation (NG13 series bores; Figure 14).

In summary, the main hydrological findings in this investigation relating to the interaction of surface and groundwater at Lake Muckenburra are:

- Lake water levels are not dependent on the regional flow in the Superficial aquifer, being consistently more than 2.5 m higher than groundwater levels in the Superficial aquifer. This indicates that the regional flow system does not interact with the perched groundwater system or the lake.
- Recharge of the lake most likely occurs from shallow through flow above the perched groundwater system with surface water inflows contributing during wetter years (via the drain on the south-east side of the lake). Although groundwater levels in the perched groundwater system were below the lake bed, there was visual evidence on the margin of the lake that seepage occurred on the shoreline on the eastern side of the lake.
- The perched groundwater system appears to be extensively developed around the lake, overlying clayey sediments in the upper Bassendean Sand Formation.
- Groundwater levels in the perched groundwater system were likely to have been higher in the past and have decreased progressively over time, as a result of decreasing rainfall. These levels may have maintained greater periods of inundation in the lake in the past with increased likelihood of flow through from the perched groundwater system.
- Subdued recharge of the shallow Superficial aquifer from the perched groundwater system is likely, probably increased by water storage in the lake. This was evident on the eastern side of the lake and it is likely that a similar process also occurs on the western side, although problems with the function of the bore in the shallow Superficial aquifer (MKB_Wc) did not allow this to be determined.
- It is likely that the ecology of the lake and surroundings depends on the water balance of the perched groundwater system. The lake water balance is possibly maintained by direct recharge from rainfall, and by discharge from the perched groundwater system, most likely occurring as shallow through flow. Losses from the perched groundwater system would include evapotranspiration, surface drainage from the area (to the north-west) and, to

a lesser extent, leakage to the Superficial aquifer in areas where the clay sequence becomes more sandy.

- It is likely that the effects of the sequences of reworked Guildford clays in the upper Bassendean Sand Formation contribute to variation in local hydraulic gradients beneath the lake. It therefore cannot be assumed that the interaction of the perched groundwater system with the shallow Superficial aquifer extends beyond the area immediately surrounding the lake.
- There is limited groundwater flow occurring deeper within the Superficial aquifer beneath and up gradient of the lake, with groundwater levels at intermediate and deep bores showing negligible gradient from east to west across the lake and up gradient. However, groundwater flow deeper within the Superficial aquifer occurs to the south-west and north-west of the lake, which may in part be due to interaction with the upper Leederville aquifer in the south-west.

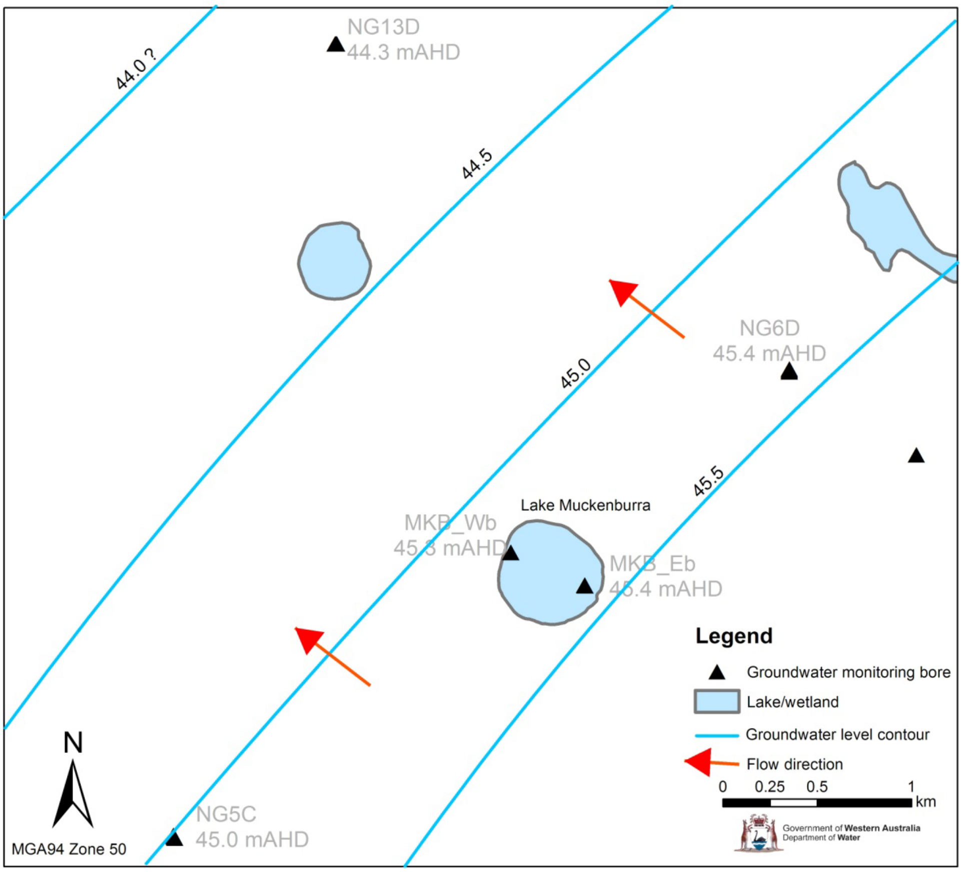


Figure 16 Average seasonal watertable contours for the Superficial aquifer (intermediate depth) showing regional groundwater flow paths around Lake Muckenburra

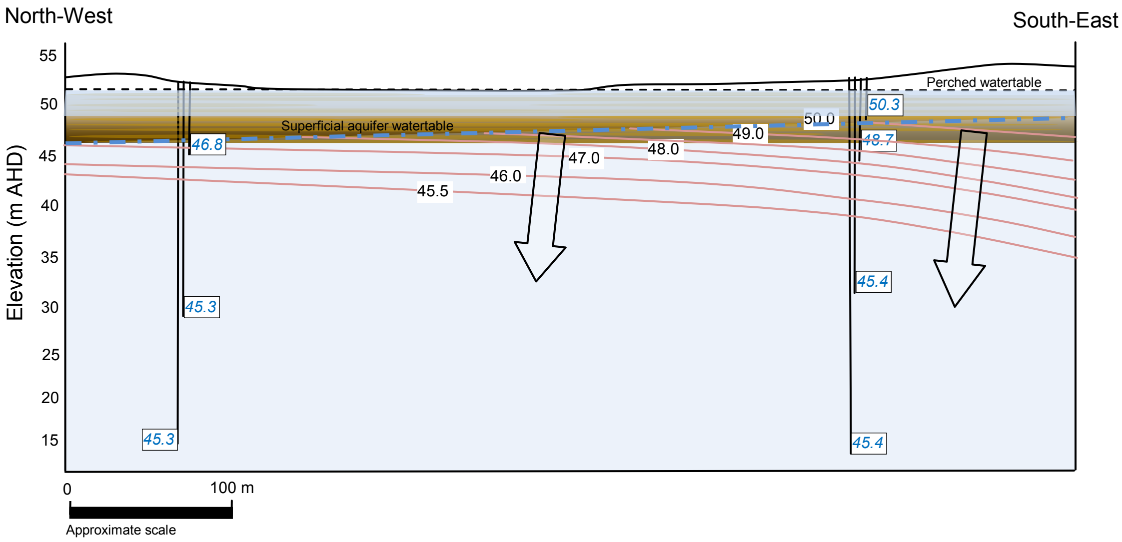


Figure 17 Seasonal average iso-potentials and interpreted groundwater flow paths (larger arrows) in the Superficial aquifer showing location of semi confining layer (brown)

6 Hydrochemistry

6.1 Physical characteristics

Differences were apparent between the physical properties of the lake water and shallow groundwater at Lake Muckenburra. The median value and range of pH of lake water fell in the neutral range (Table 9) and was within the recommended range (7.0–8.5) for south-west Australian wetlands (ANZECC & ARMCANZ 2000). The pH of groundwater beneath the lake was slightly lower than in the lake, but generally above 6 (Table 9). Significant seasonal variation in groundwater pH occurred in the perched bore (MKB_Ed) where pH ranged from more than 7.5 in winter and spring to less than 6.5 in summer and autumn (Table 9).

The lake water (when present) had consistently high dissolved oxygen (>7.5 mg/L) whereas concentrations in groundwater were less than 3 mg/L. Deeper and intermediate depth groundwater was typically more axonic than the perched and shallow groundwater. Substantial temporal variation in dissolved oxygen concentrations was evident, particularly in the shallower bores, which might indicate variable redox zones within the shallow aquifer, artefacts of sampling or faulty bore performance (in the case of MKB_Wc, see Section 5.1).

Table 9 Summary statistics for on-site measurements of pH, dissolved oxygen and redox potential in east and west MKB bores and in Lake Muckenburra

Bore or site	**pH**			**Dissolved oxygen mg/L**			**Redox potential mV**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
Lake water*	7.52	8.59	7.87	3.5	7.6	4.3	-90	-63	-77
MKB_Ea	7.15	7.25	7.17	0.32	2.2	0.63	-145	-10	-14
MKB_Eb	6.03	6.23	6.21	0.29	3.1	0.52	-135	56	45
MKB_Ec	5.95	6.11	6.01	0.2	3.2	0.84	0.4	60	56
MKB_Ed	6.48	8.19	6.94	0.49	2.2	0.82	-5	30	16
MKB_Wa	7.08	7.22	7.17	0.34	1.5	0.59	-140	-5	-11
MKB_Wb	6.80	7.04	6.94	0.22	4.0	0.37	-218	10	-1
MKB_Wc	5.81	6.94	6.22	0.73	7.1	2.9	-29	95	40

** data for September, October and December only*

The patterns in dissolved oxygen concentrations generally corresponded with redox potentials which generally indicate a trend of increasingly reduced conditions with depth. These assessments were also consistent with classification of redox conditions (Jurgens et al. 2009) using dissolved oxygen and relative nitrate (assuming all NOx was nitrate), Mn and Fe concentrations (assuming dissolved species were Mn^{2+} and Fe^{2+} respectively). This approach also indicated that deeper groundwater was predominantly anoxic with iron and sulfate reduction likely to be occurring, whereas the shallow and perched groundwater exhibited sub-oxic conditions.

There were no obvious seasonal patterns in dissolved oxygen or redox potentials in groundwater at Lake Muckenburra.

6.2 Water chemistry

6.2.1 Major cations and anions

The major ion composition of the lake and groundwater were assessed using ternary (Tri-Piper) plots, Stiff diagrams and time-series plots. These techniques were used to identify the dominant hydrochemical facies of groundwater at Lake Muckenburra and possible flow relationships between Superficial groundwater, perched groundwater and lake water.

Ternary plots of major ion composition indicated that groundwater deep in the Superficial aquifer in the Ascot Formation was typically Ca-Na-HCO_3 type water (bores MKB_Ea and MKB_Wa; Figure 18) with groundwater in shallower formations being predominantly Na-Cl type water. The differences in major ion composition were mostly due to the increased relative abundance of Ca in the deeper groundwater and is also illustrated as increased dominance of Ca in Stiff diagrams (Figure 19 and Figure 20). Within the upper superficial formations, the anionic composition of the perched groundwater system showed greatest divergence from the underlying Superficial aquifer, although on occasion it was similar to that of the shallow Superficial aquifer on both sides of the lake. Anionic composition mostly varied as a result of increasing dominance of SO_4 compared with HCO_3. In contrast, there were generally minor differences in cationic composition between most of the shallower groundwater.

The shallow Superficial aquifer (upper Bassendean Sand) exhibited groundwater with a major ion composition closest to that of seawater (Figure 18). However, these waters were significantly divergent from the composition of regional rainfall (after Hingston & Gailitis 1976). This indicated that significant alteration of ionic composition of water occurs during recharge to the perched groundwater system and Superficial aquifer.

The water chemistry of the shallow Superficial aquifer bore on the west side of the lake (in bore MKB_Wc) was strongly influenced by the water in Lake Muckenburra. This was evident as a shift in water type from Na-Cl type water to Na-HCO_3-Cl type water and back to Na-Cl type water (Figure 18). The changes occurred only while the lake contained ponded water and were consistent with leakage of lake water into the bore annulus and rapidly rising and falling water levels (see groundwater levels in Section 5.1). When water was absent in the lake, however, the major ion composition was similar to water in the shallow superficial formations on the eastern side of the lake (in bore MKB_Ec; Figure 18). These effects need to be considered when comparing the average concentrations of ions for the bore with other bores (Figure 20).

The major ion composition of the water in Lake Muckenburra was distinctly different from that of the perched groundwater system and shallow Superficial aquifer, being predominantly Na-HCO_3-Cl type water (Figure 18). This mainly reflected the decreased dominance of Cl relative to HCO_3-CO_3 constituents in the less saline lake water (Figure 19 and Figure 20). Average concentrations of cations in lake water were also an order of magnitude less than in the perched groundwater system (bore MKB_Ed) and shallow Superficial aquifer (MKB_Ec; Figure 19). This indicated that the perched groundwater system and shallow Superficial were not major sources of water for the lake. However, this does not exclude the possibility that the lake water consisted of a mixture of groundwater from the perched system (indicated at the time of likely discharge in Figure 18) and shallow through flow (likely to be dissimilar to the underlying perched groundwater). Additional investigations of the upper Bassendean Sand Formation would be necessary to verify the nature of transient lenses of perched groundwater in the perched groundwater system and the interaction of this with the lake.

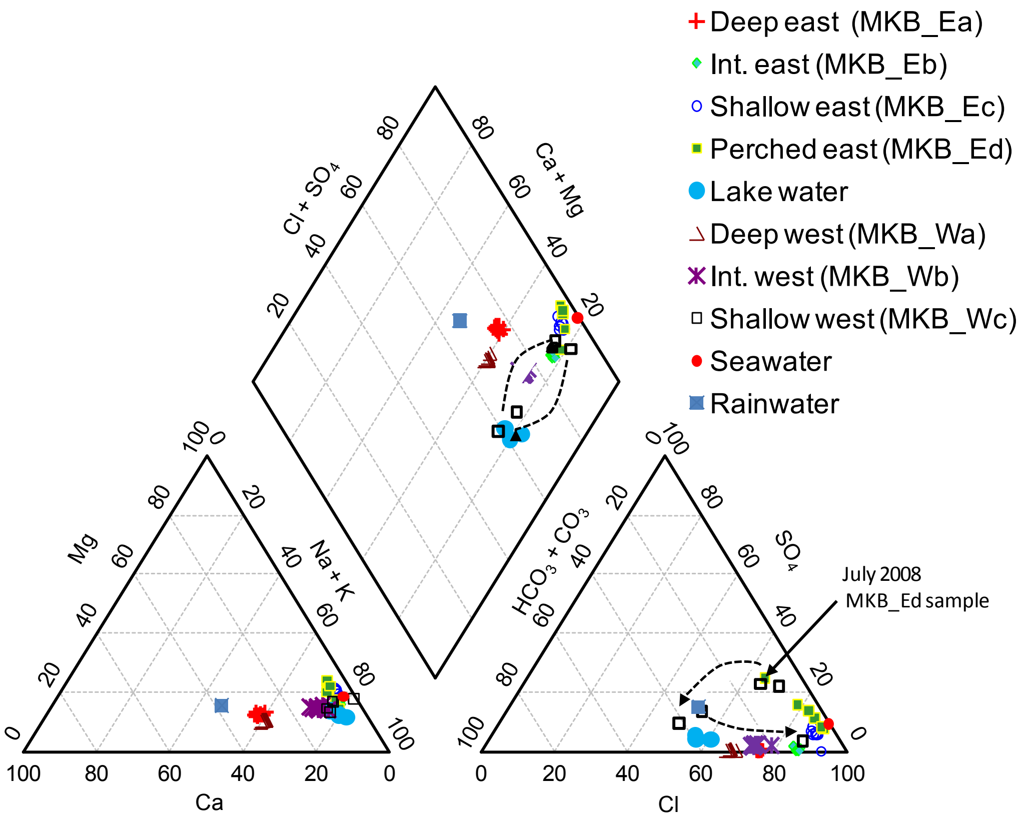
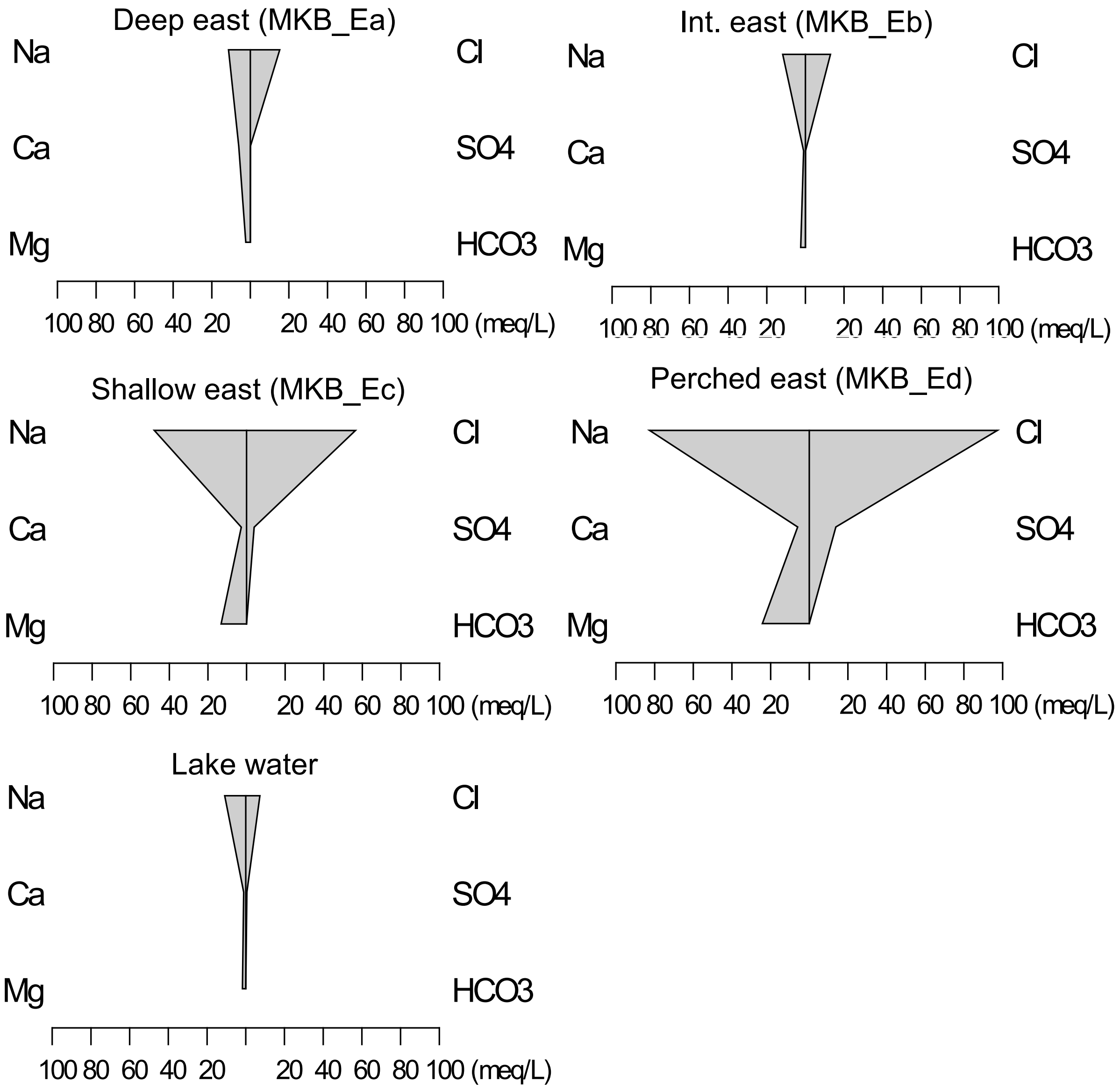


Figure 18 Ternary (Piper) plot of major cations and anions in bores and lake water from Lake Muckenburra (dashed line arrow indicates temporal shift in water type of MKB_Wc while the lake contained water)

In summary, the main of the findings of the hydrogeochemical patterns in relation to groundwater–surface water interaction at Lake Muckenburra are as follows:

- Concentrations of major cations and anions in lake water are less than those of the perched groundwater system and shallow Superficial aquifer and exhibit somewhat different ionic composition, mostly due to variation in anions.

- The water in Lake Muckenburra does not reflect a dominant influence of discharge from the perched groundwater system, but the hydrochemistry indicates that the lake water may be a rainwater diluted form of perched groundwater.
- The groundwater in the perched system and shallow Superficial aquifer was similar on occasion, despite variation in the perched groundwater system.
- Little interaction occurs between the shallow Superficial and deeper Superficial aquifer with very high major ion concentrations occur in groundwater in the perched groundwater system and shallow Superficial aquifer relative to deeper in the aquifer and substantial differences in ionic composition.



Deep east (MKB_Ea)

Int. east (MKB_Eb)

Shallow east (MKB_Ec)

Perched east (MKB_Ed)

Lake water

Figure 19 Representative Stiff diagrams for mean cation and anion concentrations for groundwater from eastern bores compared with lake water

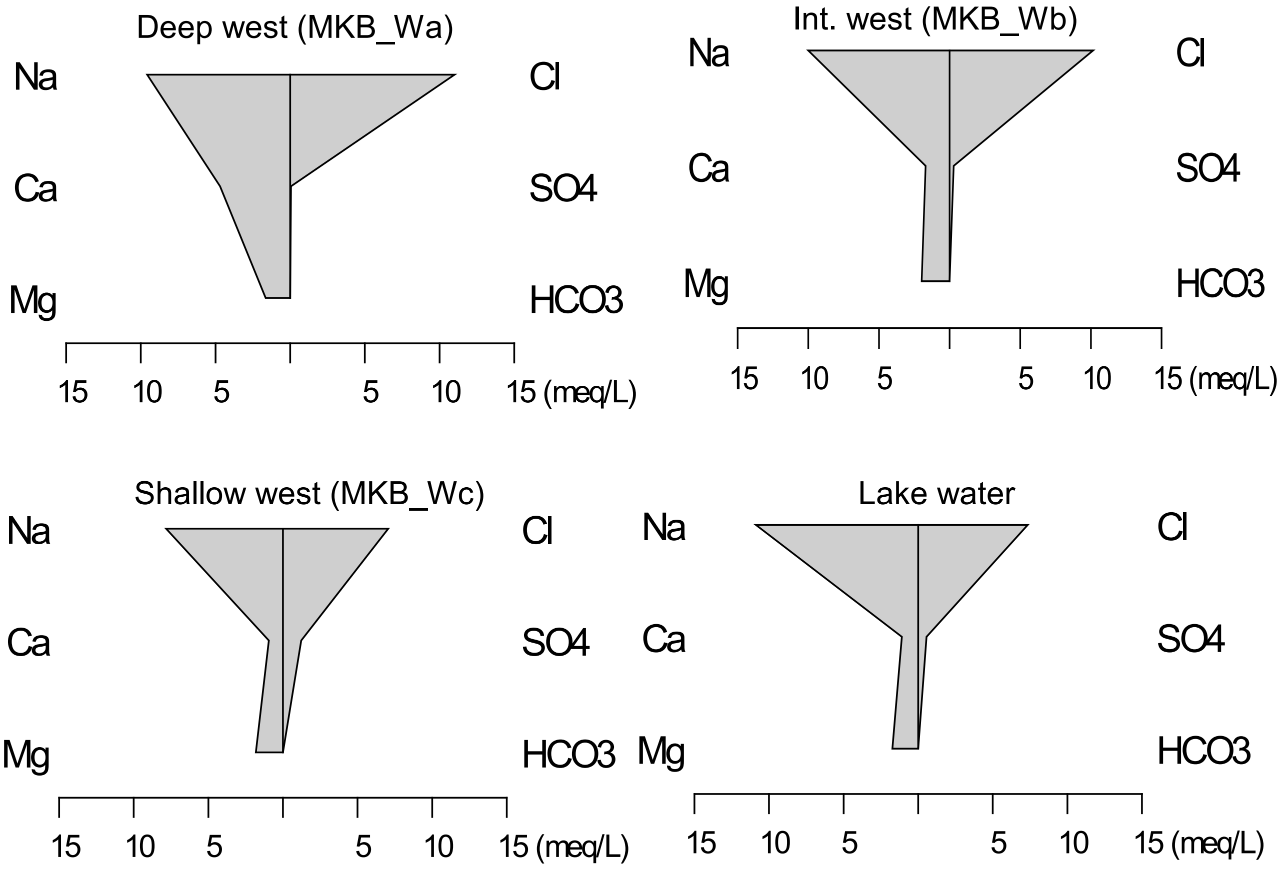


Figure 20 *Representative Stiff diagrams for mean cation and anion concentrations for groundwater from western bores compared with lake water*

6.2.2 Electrical conductivity, total dissolved solids and chloride

There were variations over time and space in electrical conductivity and total dissolved solids in groundwater and lake water at Lake Muckenburra. TDS and EC were strongly correlated and both are presented for general reference.

EC and TDS decreased with depth in the Superficial aquifer with little difference between the mid level and deeper groundwater at both sites (Figure 21 and Figure 22). Groundwater in the perched system and shallow Superficial aquifer was typically brackish (>4000 mg/L TDS) trending to fresh in the deeper Superficial aquifer. Greatest variation in salinity occurred in the perched groundwater system which varied from less than 6000 µS/cm (<3200 mg/L TDS) to almost 12000 µS/cm (>7600 mg/L TDS) between winter and midsummer. The salinity in the perched groundwater system appears to freshen with seasonal recharge and increase during drier periods. This is clear when considering the decrease from 8220 µS/cm at the time of drilling (February 2009; Appendix A) to less than 6000 µS/cm in July 2008, increasing to more than 10 000 µS/cm in December 2008. Although salinity in the deeper Superficial aquifer was less than 2100 µS/cm (<1300 mg/L TDS), groundwater was at least 20% more saline on the eastern side of the lake than the west (Figure 21 and Figure 22). This difference was also apparent in shallow

Superficial groundwater, suggesting a freshening of groundwater with flow from the south-east to the north-west (Figure 16).

Lake water exhibited a salinity that, after filling in July, was initially an order of magnitude less than the salinity of the perched groundwater system and the shallow Superficial aquifer being generally between 630 µS/cm (430 mg/L TDS). Following filling, salinity in lake water increased more than four-fold as water levels decreased, but remained less than the salinity of the perched groundwater system on the up-gradient side of the lake (Figure 21).

The increased salinity of the lake after filling was not consistent with the lake behaving as a closed evaporating waterbody and probably did not occur as a result of additional salt input via groundwater discharge. Decreases in lake depth from 0.86 m in August to 0.55 m in December (see water levels in Section 5.1) would correspond with a water volume decreasing in the order of 60% if the lake basin is assumed to be saucer shaped (i.e. a shape similar to a part-filled sphere). If this volume loss occurred by evaporation the lake salinity would increase by no more than three times, which was less than the more than four-fold increase in salinity that was observed. Increases in the salinity of the water were most likely to have been due to remobilisation of salts contained with the lake bed sediments rather than groundwater discharge from the perched groundwater system. Water levels in the permanent perched groundwater system were less than lake levels and therefore unlikely to be connected with the lake and contributing salts. While capillary rise from the perched groundwater system would enable salts to accumulate above this, these would only be mobilised to the lake as transient through flow following rainfall.

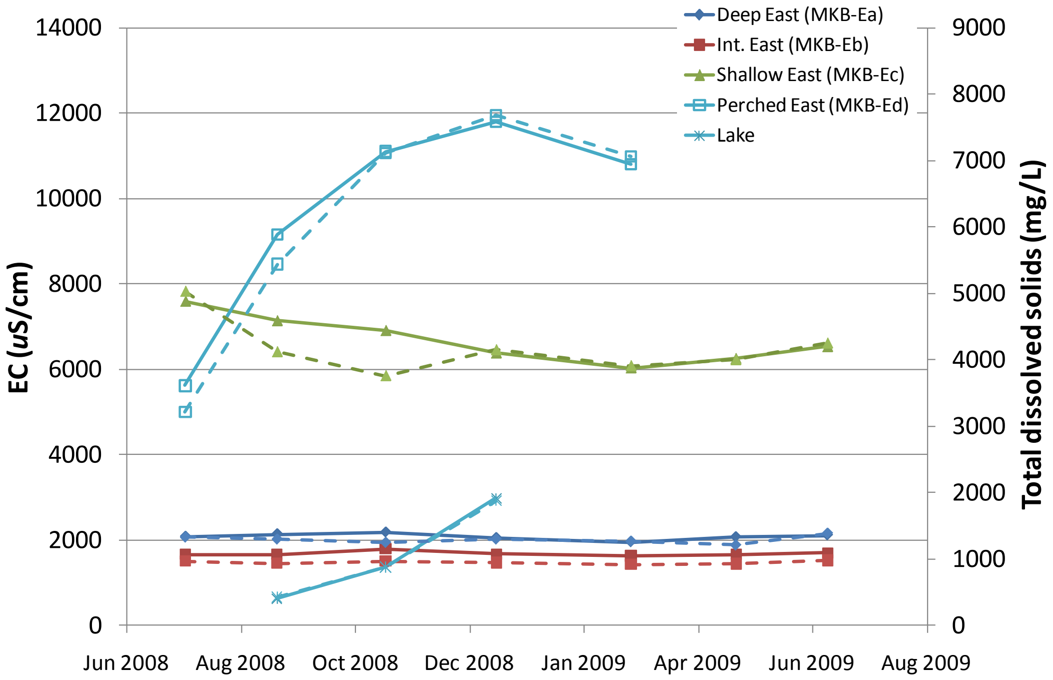


Figure 21 Temporal variation of EC (at 25 °C) and TDS (broken line) in groundwater on the eastern side of Lake Muckenburra and in lake water

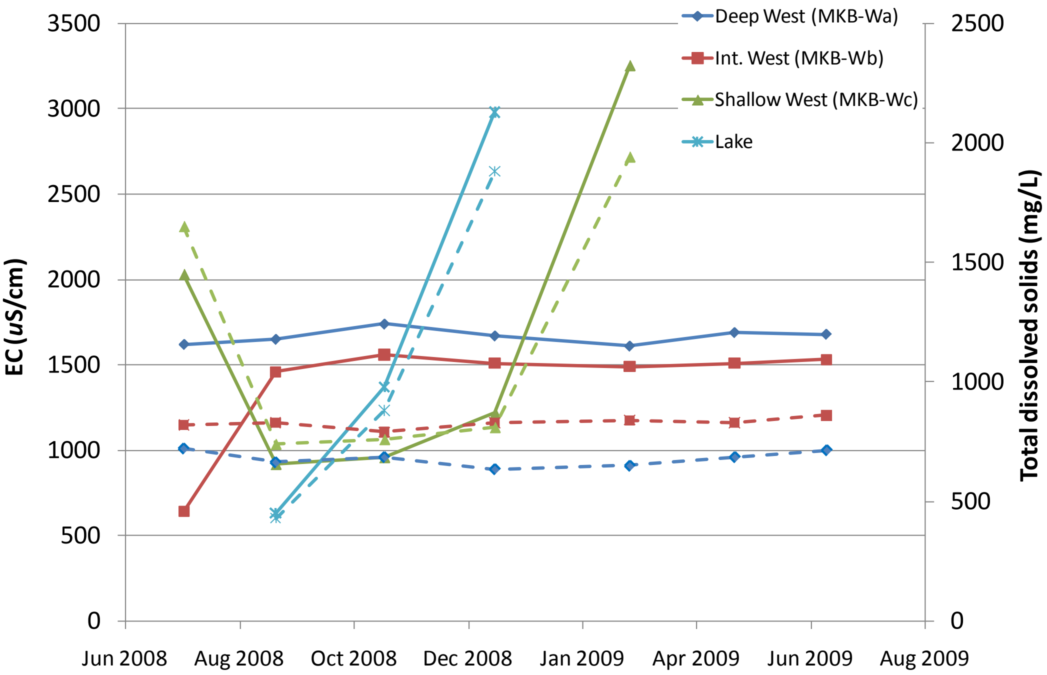


Figure 22 Temporal variation of EC (at 25 °C) and TDS (broken line) in groundwater on the western side of Lake Muckenburra and in lake water

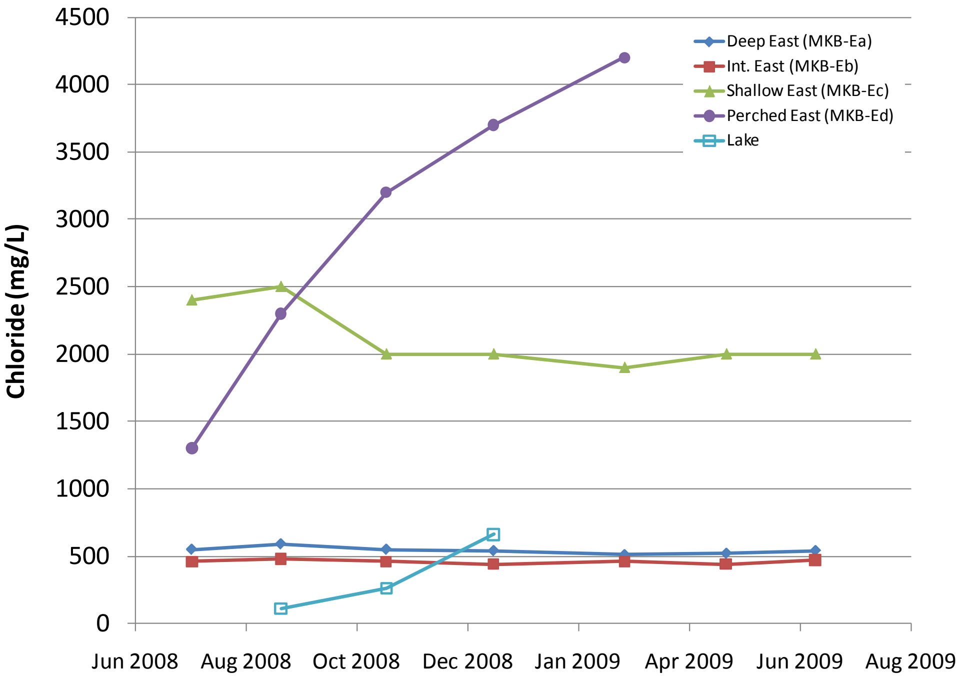


Figure 23 Temporal variation of chloride in groundwater on the eastern side of Lake Muckenburra and in lake water

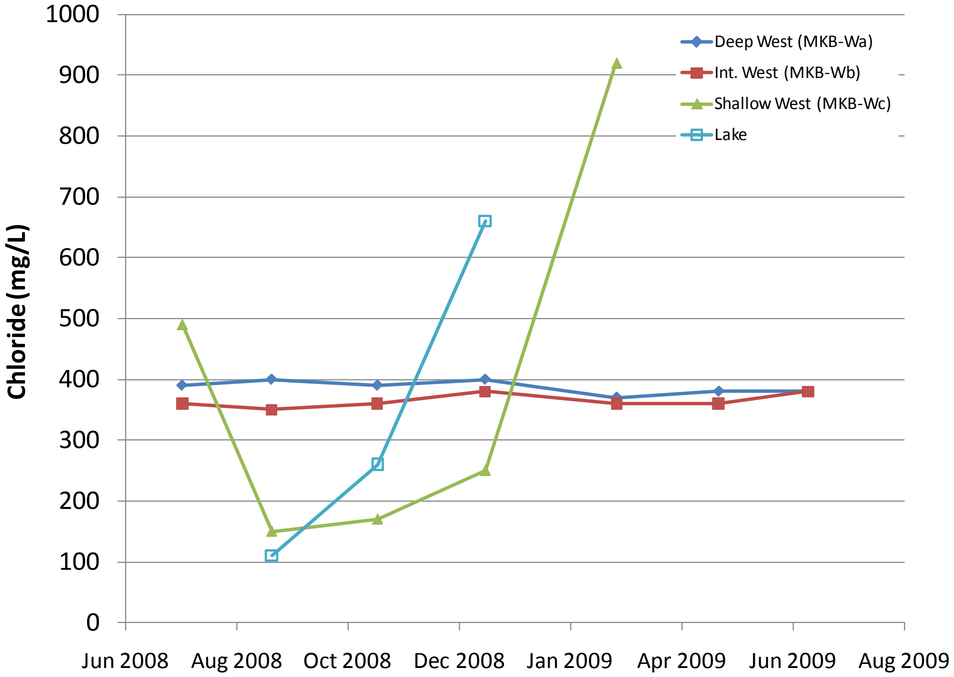


Figure 24 Temporal variation of chloride in groundwater on the western side of Lake Muckenburra and in lake water

Despite the evapo-concentration of salts in the lake during drying, the salinity remained less than in the shallow groundwater. Lake water salinity was consistently less than the perched groundwater system and shallow Superficial aquifer to the east of the lake (MKB_Ec and MKB_Ed in Figure 22), but not to the west. The salinity of the lake late in the drying phase approached that of the shallow Superficial aquifer to the west of the lake (indicated in July 2008 and February 2009, when the MKB_Wc bore was probably not influenced by lake water contamination). This indicates that the lake may have eventually recharged the shallow Superficial aquifer, probably contributing to the freshening of groundwater in this part of the aquifer. However, this process is probably slow given the changes in major ion composition occurring during recharge (see the Tri-Piper diagrams in Section 6.2.1).

Chloride in groundwater to the east of the lake (Figure 23) showed a similar pattern to EC and TDS (Figure 21), with low concentrations in the deep and intermediate Superficial groundwater, much higher concentrations in the shallow Superficial aquifer and perched groundwater system. Chloride concentrations were increased by the same extent as TDS in the perched groundwater system (Figure 23).

6.2.3 Major cations

Concentrations of sodium, magnesium, calcium and potassium were correlated with chloride to varying degrees. Sodium and magnesium had a strong positive correlation with chloride in each level of the Superficial aquifer and perched groundwater system (r^2 >0.9). Calcium and potassium were correlated to varying extents with chloride, generally with a stronger correlation with depth in the

Superficial aquifer (r^2 varying from –0.29 for K in the perched groundwater system to +0.89 for Ca in the deep Superficial aquifer). Temporal changes in the concentrations of the two dominant cations (sodium and calcium) are best illustrated as variation in the mass ratio of the ions with chloride (removing the effects of changes in concentrations due to variations in TDS). Chloride ratios are also useful in assessing geochemical influences on water chemistry, particularly ion exchange.

The ratio of sodium to chloride in the groundwater was less variable with depth, but there were significant differences in ionic ratios between depths in the Superficial aquifer (Figure 25 and Figure 26). The Na:Cl ratio was slightly less than the regional average rainfall (and seawater) deep in the Superficial aquifer on the east side of the lake (e.g. in MKB_Ea), but not the west (Figure 25 and Figure 26). This indicated removal of Na from the groundwater during recharge and transport in the aquifer, which is most commonly due to Na exchange with clays (Hounslow 1995). This typically corresponded with enriched Mg, but not Ca (see below). At intermediate levels, however the Na:Cl ratio was generally slightly greater than rainfall (and seawater; Figure 25 and Figure 26) indicating enrichment with Na, but tended to be similar to rainfall in the shallow Superficial. On the western side the apparent difference to this observation is most likely due to leakage of surface water into the bore.

Significant enrichment in Na was apparent in the lake water (by almost double) for several months of the study. The Na enrichment was possibly due to weathering of clays, particularly albite-plagioclase minerals rather than reverse ion exchange, where Ca exchanges for Na (Hounslow 1995). These clay minerals have been identified in underlying Leederville Formation (Descourvieres et al. 2011) and are likely to be in the superficial formations given the similar provenance**.** There was little evidence of reverse softening of the water (exchange of Ca or Mg for Na) causing enriched Na, since Ca:Cl in most waters was not depleted to a similar magnitude with respect to rainfall (e.g. lake water and perched groundwater) (Figure 25 and Figure 26). Magnesium was enriched, but no more than in the perched groundwater system or the shallow Superficial aquifer.

Temporal variation in the Ca:Cl ratio followed patterns that were different from those of Na:Cl, although it followed a general pattern of increasing with depth in the Superficial aquifer and with generally little temporal variation. The Ca:Cl ratio of deep groundwater was more than double that of regional rainfall reference values (Hingston & Gailitis 1976) whereas other waters were similar or depleted (converging on seawater ratios). Lake water was not dissimilar to rainfall, whereas the perched groundwater system and upper Superficial aquifer were more depleted, but not in any pattern corresponding with the salinity of the waters.

The patterns of Ca enrichment and depletion are broadly reflective of two dominant processes in different parts of the Superficial aquifer. Enrichment of Ca deeper in the Superficial aquifer was probably due to dissolution of carbonates, given that cation exchange seems unlikely (since Na was not enriched to a similar extent to the enrichment in Ca). This was also consistent with Mg being enriched in the deeper groundwater. In contrast, depletion of Ca in the upper parts of the Superficial aquifer

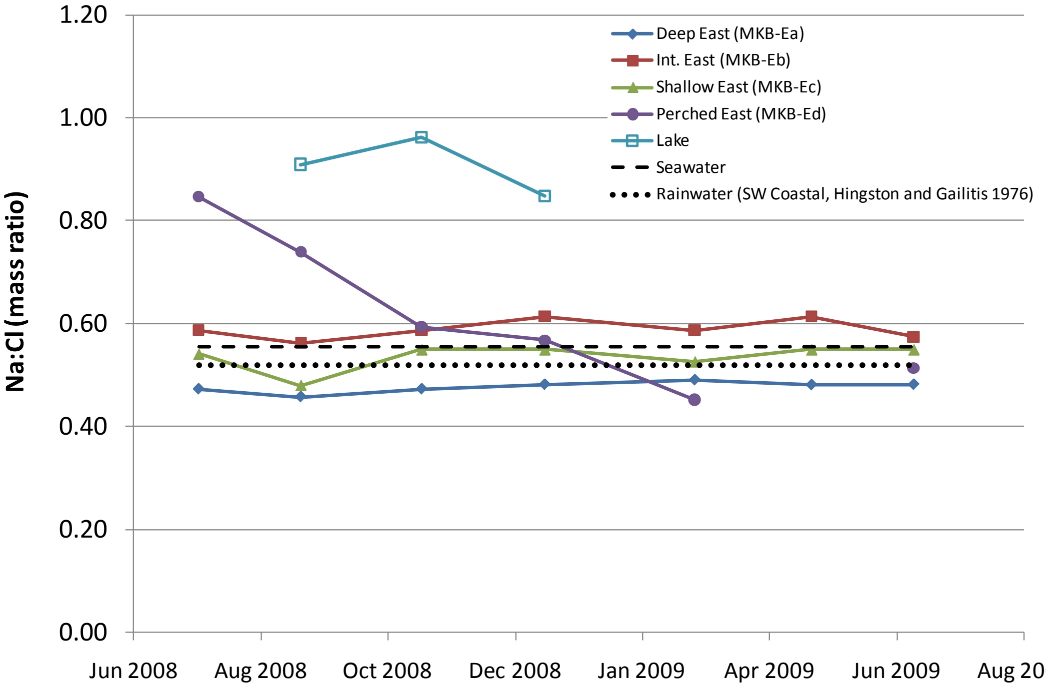


Figure 25 Temporal variation of Na:Cl ratio in lake water and groundwater to the east of Lake Muckenburra in relation to seawater and local reference values

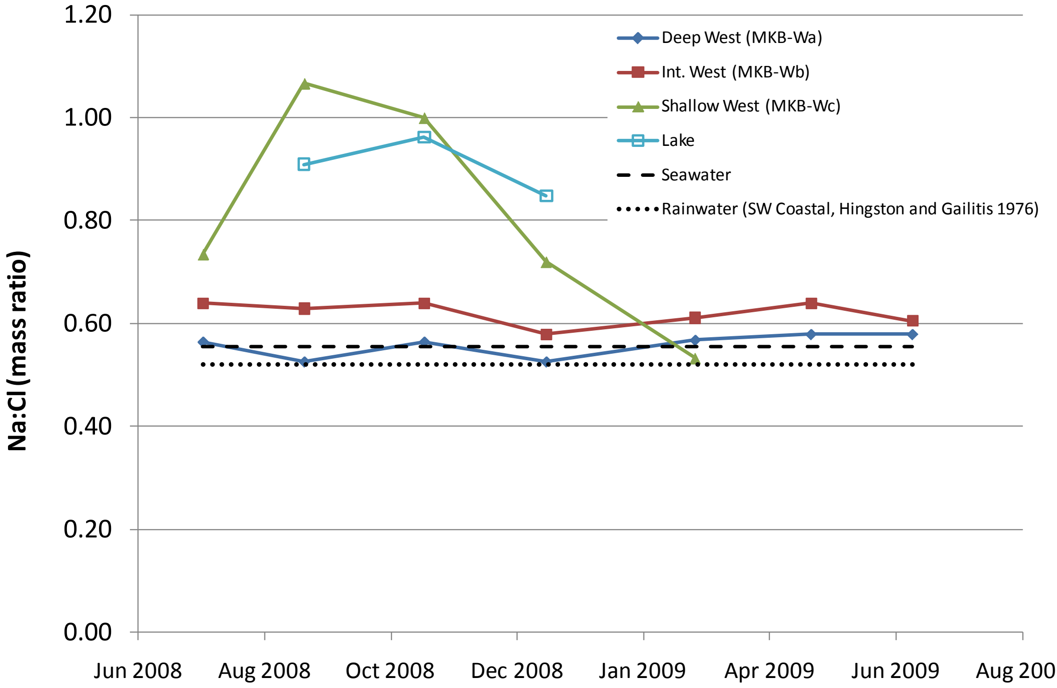


Figure 26 Temporal variation of Na:Cl ratio in lake water and groundwater to the west of Lake Muckenburra in relation to seawater and local reference values

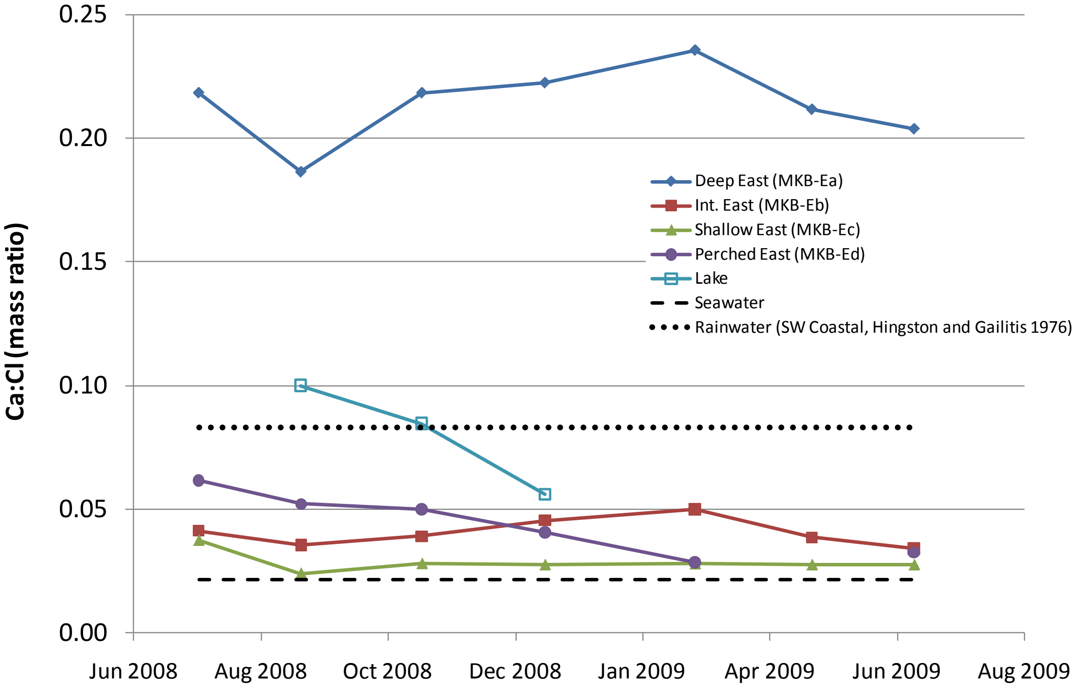


Figure 27 Temporal variation of Ca:Cl ratio in lake water and groundwater to the east of Lake Muckenburra in relation to seawater and local reference values

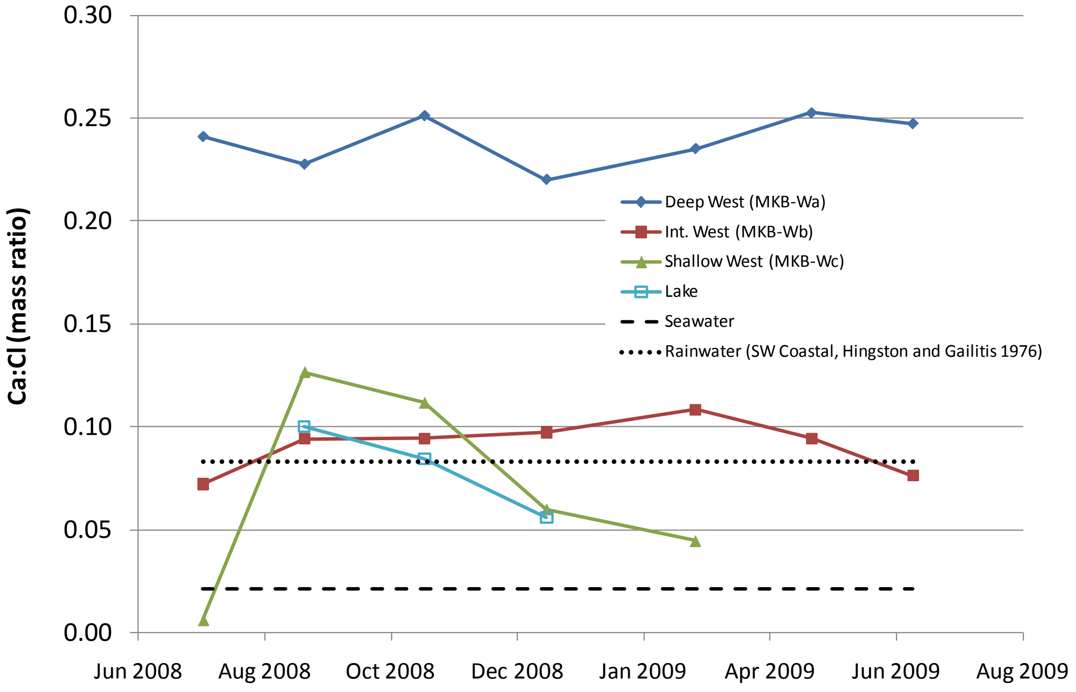


Figure 28 Temporal variation of Ca:Cl ratio in lake water and groundwater to the west of Lake Muckenburra in relation to seawater and local reference values

may be due to cation exchange processes, particularly Ca displacement of Mg, probably during recharge. The similarity of the Ca:Cl ratio in lake water to a regional rainfall reference suggests that the processes influencing groundwater do not influence the shallow through flow groundwater discharging to the lake.

6.2.4 Alkalinity

Groundwater and lake water contained generally moderate levels of alkalinity and typically exceeded 100 mg $CaCO_3$/L. Alkalinity was consistently between 200 and 300 mg $CaCO_3$/L in the perched groundwater system and deep in the Superficial aquifer, but not at shallow and intermediate depths in the Superficial aquifer (Figure 29 and Figure 30). There was little seasonal variation in alkalinity in the intermediate and deeper bores. There was a general spatial trend of increasing alkalinity from east to west.

Alkalinity in the lake water increased from less than 100 mg $CaCO_3$/L to more than 500 mg $CaCO_3$/L over four months. This was similar in magnitude to changes in salinity (see Section 6.2.2), indicating that the increase was due to evapo-concentration rather than biological processes.

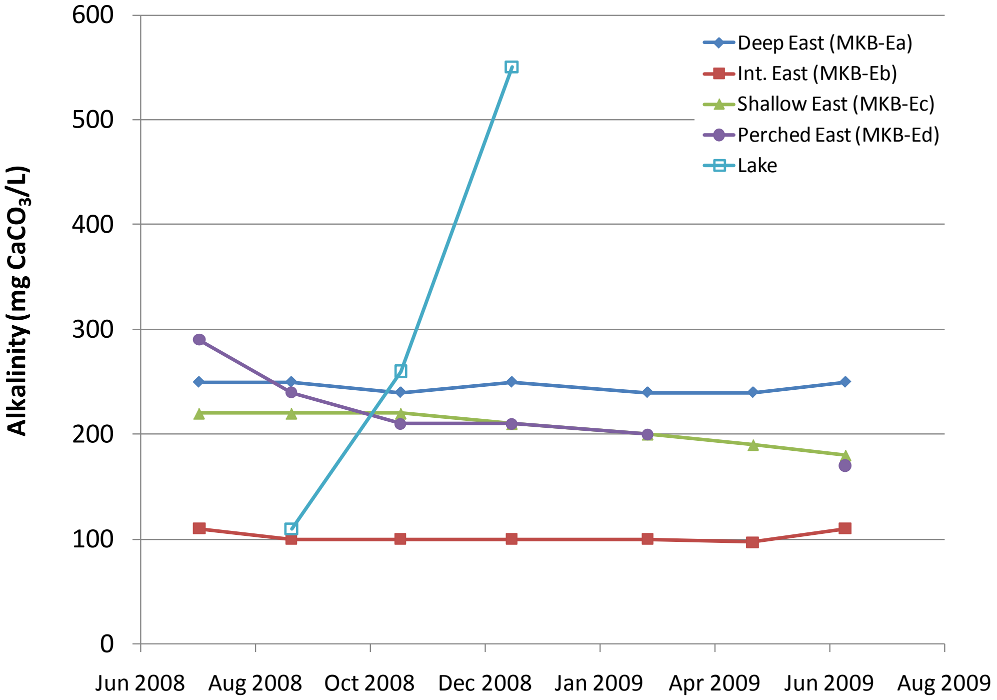


Figure 29 Temporal variation of alkalinity in groundwater on the eastern side of Lake Muckenburra and in lake water

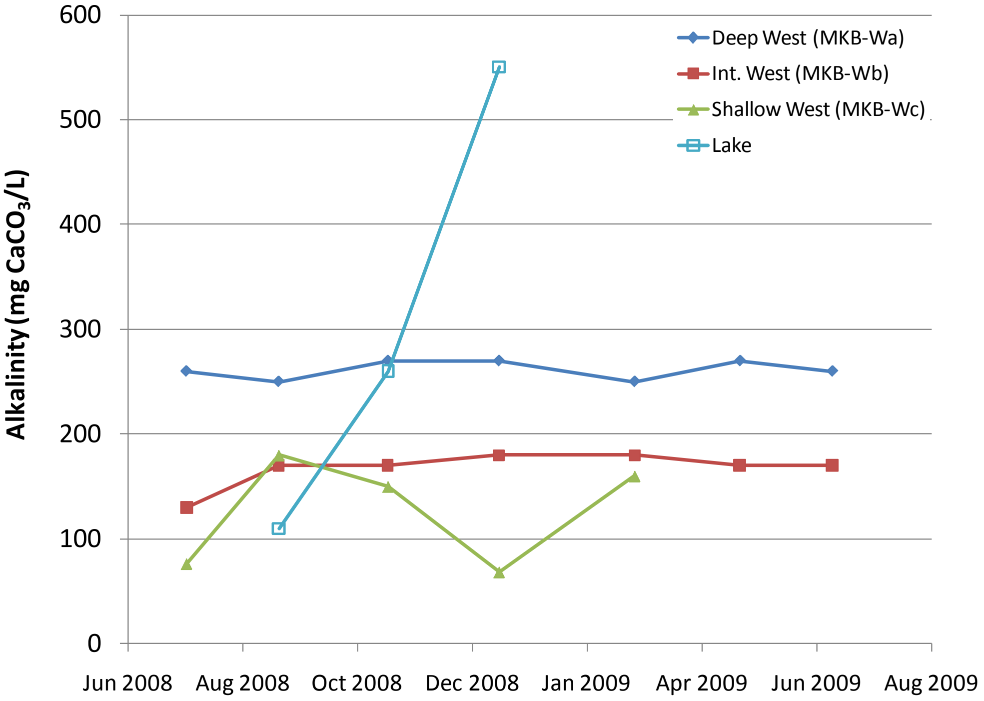


Figure 30 Temporal variation of alkalinity in groundwater on the western side of Lake Muckenburra and in lake water

6.2.5 Sulfate

Sulfate concentrations decreased with depth in the Superficial aquifer and were generally greater on the eastern side of the lake, particularly in the perched groundwater system and shallow Superficial aquifer (Figure 31 and Figure 32). Seasonal variation in sulfate concentrations was minimal for most parts of the aquifer and most pronounced in the perched groundwater system. Due to the leakage at bore MKB_Wc, concentrations of sulfate reflected those of lake water, while it was present. Concentrations of sulfate at intermediate and deep levels in the Superficial aquifer were frequently at or below detection limits.

Ratios of SO_4:Cl were evaluated to determine dominant patterns of sulfur chemistry in the aquifer. The SO_4:Cl ratio of groundwater varied significantly with depth beneath the lake, with much lower values prevailing deeper in the Superficial aquifer and little temporal variation occurring at depth (Figure 33 and Figure 34). Seawater and average rainfall for the south-west coastal region (Hingston & Gailitis 1976) were used as a point of comparison, being representative of the likely sulfate input in rainfall recharge to the area.

Depletion of sulfate was evident deep in the Superficial aquifer on both sides of the lake with the SO_4:Cl ratio being generally significantly less than in the shallow Superficial aquifer or perched groundwater system, seawater and rainfall (Figure 33 and Figure 34). The depletion of sulfate may be due to sulfate reduction, given the low redox potential recorded for the deeper groundwater (see physical characteristics in Section 6.1).

A dynamic pattern of sulfate enrichment and depletion was evident in the perched groundwater system and shallow Superficial aquifer, possibly indicating seasonal sulfide oxidation and re-formation. Water in the perched groundwater system and shallow Superficial aquifer exhibited higher but significantly varying SO_4:Cl ratios beneath both sides of the lake (Figure 33 and Figure 34). Despite enrichment of sulfate being evident in the perched groundwater system as a greatly elevated SO_4:Cl ratio in late 2008, this was not influencing the lake water (Figure 33). As discussed earlier (see Section 5.1), variation in water quality in the shallow bore on the western side of the lake may have been due to leakage of lake-water into the bore annulus, although this was unlikely to have influenced the analyses for July 2008 (before lake filling) to February 2009 (after lake drying).

The general trend for all parts of the Superficial aquifer was one of sulfate removal throughout the 12-month monitoring period. This was consistent with sharp decreases in redox potential and dissolved oxygen in the perched groundwater system, although not reaching levels where sulfate reduction would be expected to dominate (<200 mV) (Appelo & Postma 2005).

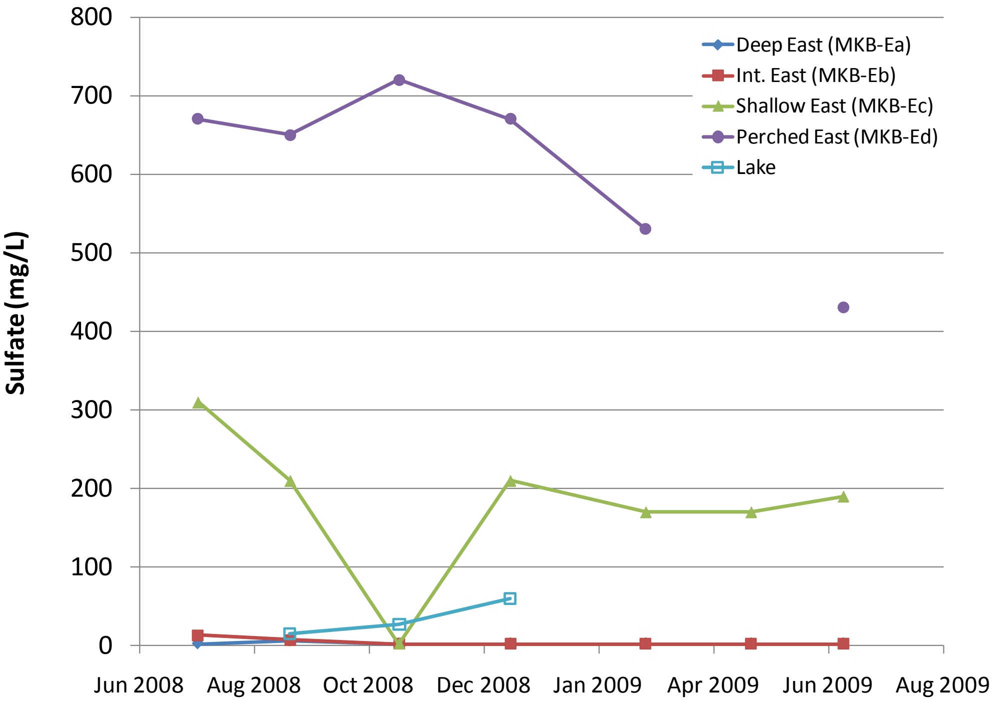


Figure 31 Temporal variation of sulfate concentration in groundwater on the eastern side of Lake Muckenburra and in lake water

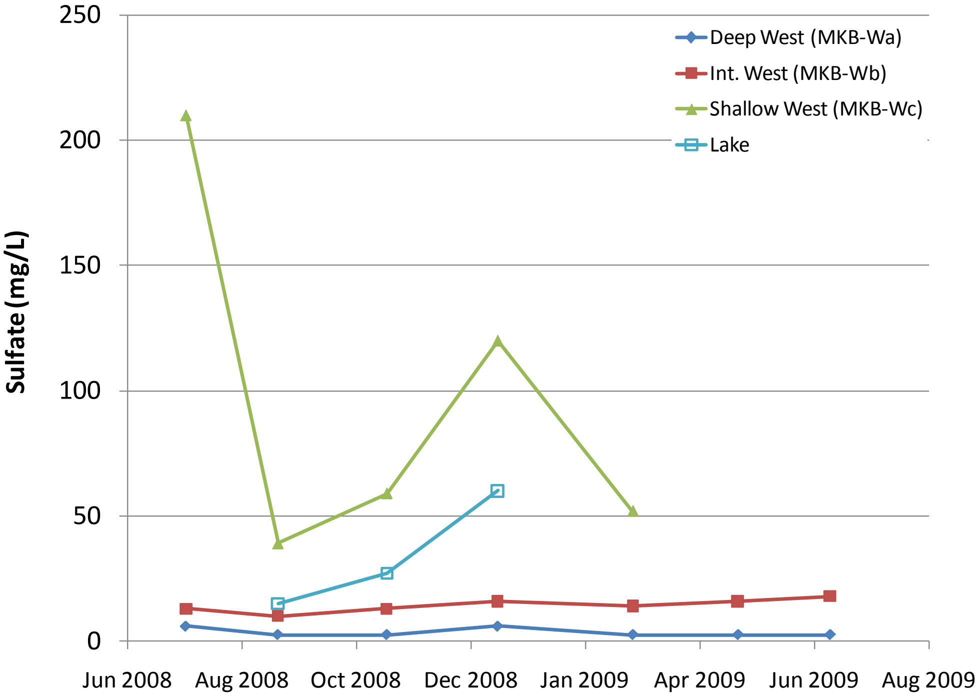


Figure 32 Temporal variation in sulfate concentration in groundwater on the western side of Lake Muckenburra and in lake water

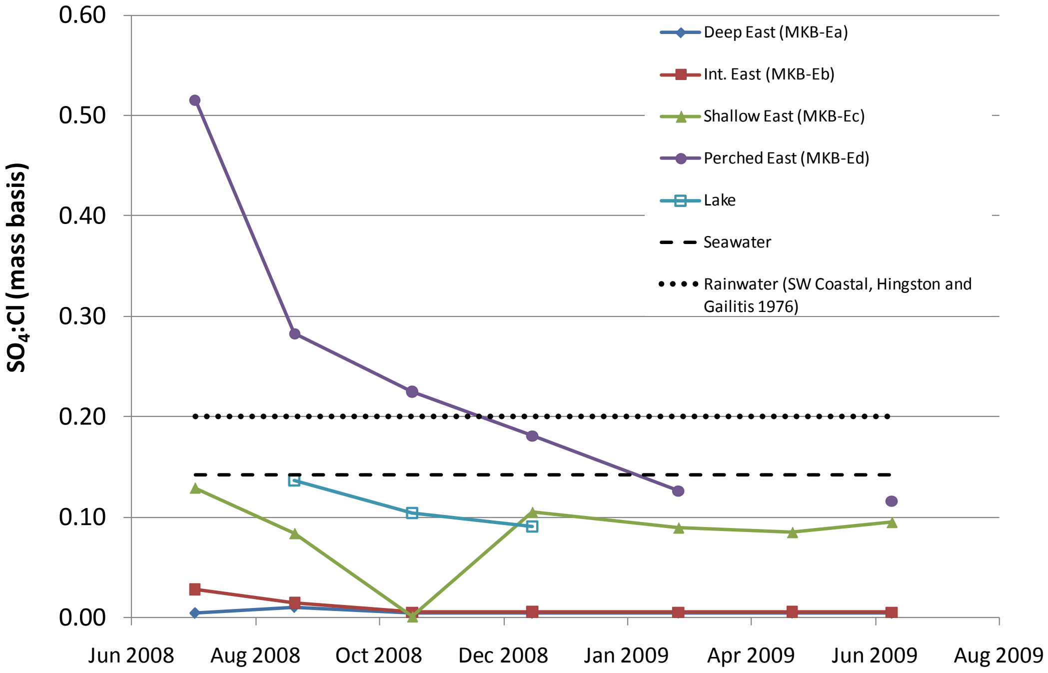


Figure 33 Temporal variation in SO_4:Cl ratio of lake water and groundwater to the east of Lake Muckenburra in relation to seawater and rainfall reference values

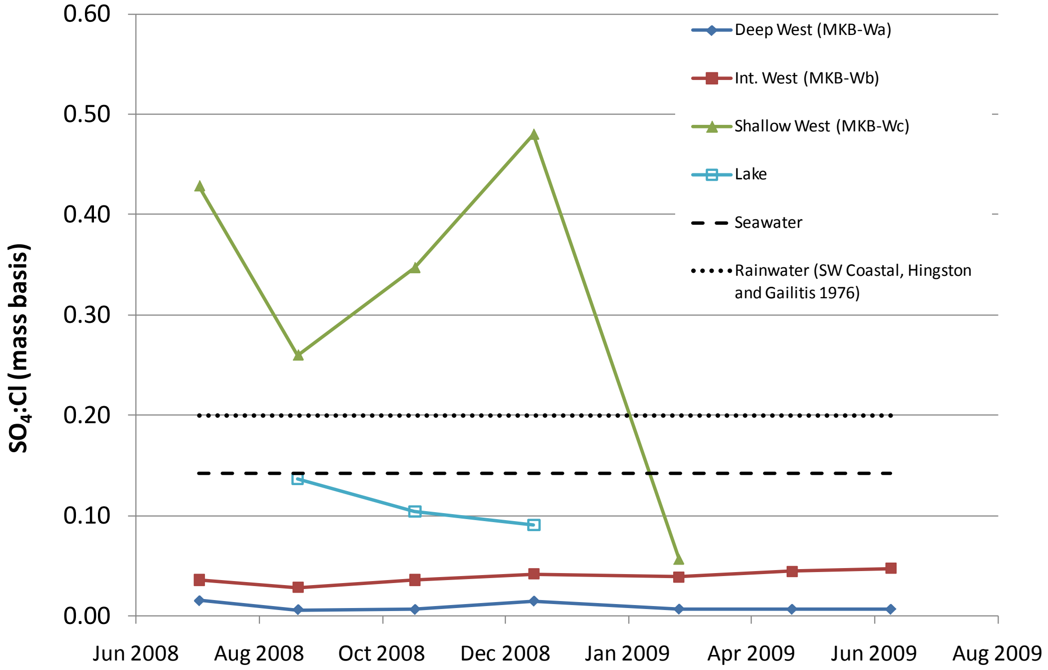


Figure 34 Temporal variation in SO_4:Cl ratio of lake water and groundwater to the west of Lake Muckenburra in relation to seawater and rainfall reference values

6.2.6 Nutrients

Nutrients were present in groundwater and lake water in generally moderate concentrations, with the lake water often containing higher concentrations than in the perched groundwater system or shallow Superficial aquifer.

Nitrogen in groundwater was mostly present as organic nitrogen, with highest concentrations recorded in the shallow Superficial aquifer (MKB_Ec and MKB_Wc) and in perched groundwater (Table 10). Moderately high concentrations of total nitrogen occurred in most groundwater (frequently exceeding 2 mg/L) and were greatest in the perched groundwater system. Ammonium was present in all groundwater at concentrations generally ranging from 0.4 to 0.5 mg/L, most of which exceed drinking water guidelines (Table 10). These concentrations were generally considered to be due to natural processes and were consistent with the generally anoxic status of the Superficial aquifer, particularly at intermediate and deep levels. There was little inorganic nitrogen present as nitrate or nitrite in the Superficial aquifer and the lake, with concentrations generally being less than 0.5 mg/L. Nitrate and nitrite were frequently not detected at shallow and intermediate depths in the aquifer.

Concentrations of nitrogen fractions did not vary with any specific pattern during the year, with the only notable exception being the increase in total nitrogen and organic nitrogen in the lake water (of no more than double), which is consistent with evapo-concentration of the water rather than mineralisation of N from sediments or inputs by groundwater.

The concentration of total nitrogen and ammonium in lake water for all sample times exceeded south-west wetland guideline values (ANZECC & ARMCANZ 2000) and for nitrate there was an exceedance in one sample (Table 11). While concentrations of total nitrogen and ammonium-N in most groundwater exceeded wetland values, only those in the perched groundwater system were considered for reporting. This choice was based on the likelihood of the water being able to interact with the lake.

Total phosphorus and filterable reactive phosphorus (FRP) in lake water exceeded guidance levels for south-west Australian wetlands (ANZECC & ARMCANZ 2000) and were much higher than concentrations in groundwater (Table 11). Phosphorus is typically strongly adsorbed to alumina-silicate clays, iron oxy-hydroxides and soil organic matter (Appelo & Postma 2005), therefore any leakage of lake water into perched and shallow Superficial groundwater would be coupled with adsorption of dissolved phosphorus. The exception to this would be when short circuiting of recharge occurs via root channels or sand lenses, which is probably not likely if most root exploration is confined to the perched groundwater system at Lake Muckenburra.

Dissolved organic carbon was present in high concentrations in Lake Muckenburra (Table 11) and was closely related to similarly high total nitrogen concentrations. The concentrations were almost 10 times greater than has previously been reported in surface waters draining from predominantly Bassendean Sands (Petrone et al. 2008), although these levels are not unusual in wetlands in the Bassendean Sands, often contributing to the highly coloured nature of waters in wetlands (Davis et al. 1993). On this basis, it was highly likely that the dissolved organic carbon was natural and contributed to the high colouring noted in the lake waters at the time of sampling.

Concentrations in lake water were generally similar to those in perched groundwater and shallow Superficial groundwater (bore MKB_Ec and bore MKB_Wc). DOC in deeper groundwater was an order of magnitude lower and more typical of natural concentrations (10–20 mg/L) found in the Superficial aquifer of the Gnangara groundwater system (Cargeeg et al. 1987; Martin & Harris 1982). The high DOC in the shallow Superficial aquifer and perched groundwater system were similar to that in the lake water. This reflected similar origins for the water in these systems and the influence of perched groundwater recharge on the chemistry of the shallow Superficial aquifer.

Table 10 Summary statistics for nitrogen species in groundwater to the east and west of Lake Muckenburra and in lake water

Site or bore	**TN mg/L**			**Organic N[1] mg/L**			**Ammonium-N mg/L**			**Nitrate-N mg/L**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
Deep east – MKB_Ea	1.3	2.1	1.7	0.2	0.6	0.48	**0.75**	**1.5**	**1.3**	<0.01	0.37	0.01
Int. east – MKB_Eb	0.88	2.3	1.1	0.31	1.52	0.55	0.32	**0.78**	**0.54**	0.01	0.3	0.03
Shallow east – MKB_Ec	2.1	2.8	2.4	1.76	2.25	2.00	**0.48**	**0.61**	**0.52**	<0.01	0.03	<0.01
Perched east – MKB_Ed	3.0	7.9	3.45	2.17	7.37	2.96	0.1	**0.84**	**0.45**	0.02	0.38	0.08
Deep west – MKB_Wa	0.69	0.84	0.76	0.18	0.38	0.32	0.34	**0.56**	**0.49**	<0.01	0.05	<0.01
Int. west – MKB_Wb	0.81	2.1	0.99	0.33	1.39	0.51	0.38	**0.71**	**0.54**	<0.01	0.04	<0.01
Shallow west – MKB_Wc	2.8	16	5.4	2.38	9.29	4.98	0.02	0.32	0.23	0.08	6.4	0.42
Lake water	4.0	7.2	5.3	3.41	6.83	4.59	0.11	**0.49**	0.37	0.03	0.59	0.04
Aquatic guidelines[2]		1.5			N/A			0.04			0.1 (NOx)	
Drinking water guidelines[3]		N/A			N/A			0.4*			50	

[1] *Organic N calculated as total Kjeldahl nitrogen – ammonium-N and consists of all dissolved and particulate organic N.*

[2] *Aquatic ecosystem guidelines value for south-west Australian wetlands (ANZECC & ARMCANZ 2000); exceedances in lake water and up-gradient bores highlighted in blue.*

[3] *Drinking water guidelines maximum concentrations from NHMRC & NRMMC (2004), exceedances of guideline values for down-gradient bores in **bold**.*

** Guideline value is for aesthetic rather than health reasons.*

N/A – not applicable

Table 11 Summary statistics for total and filterable phosphate and dissolved organic carbon in groundwater to the east and west of Lake Muckenburra and in lake water

Site or bore		**Total P mg/L**			**FRP mg/L**			**DOC mg/L**	
	Min.	**Max.**	**Med.**	**Min.**	**Max.**	**Med.**	**Min.**	**Max.**	**Med**
Deep east – MKB_Ea	0.060	0.140	0.110	<0.005	0.040	0.020	5	27	14
Int. east – MKB_Eb	0.050	0.140	0.080	0.007	0.047	0.020	15	22	18
Shallow east – MKB_Ec	0.013	0.017	0.014	0.005	0.012	0.008	68	110	93
Perched east – MKB_Ed	0.033	0.230	0.042	0.005	0.035	0.019	78	210	110
Deep west – MKB_Wa	0.037	0.056	0.040	0.014	0.038	0.021	9	21	14
Int. west – MKB_Wb	0.034	0.120	0.048	0.016	0.040	0.034	15	22	17
Shallow west – MKB_Wc	0.087	0.19	0.130	0.028	0.047	0.039	51	280	140
Lake water	0.61	1.10	0.98	0.4	0.74	0.59	70	150	130
Guideline value[1]		0.06			0.03			N/A	

[1] *Aquatic ecosystem guideline value for south-west Australian wetlands (ANZECC & ARMCANZ 2000); exceedances in lake water and up-gradient bores highlighted in blue. Note: there are no drinking water guidelines for these nutrients (NHMRC & NRMMC 2004)*

N/A – not applicable

6.2.7 Minor and trace elements

Concentrations of most minor and trace elements in lake water (for the three sampling events) were below aquatic ecosystem guideline values except for iron, aluminium, chromium and occasionally boron (Table 12). For chromium and boron, the concentrations were within the limits for achieving at least a 90% confidence of species protection, but for aluminium the level of protection was less than 80%. The high concentrations of aluminium were most likely due to retention of aluminium as a colloidal suspension (e.g. organic colloids or clays) since at the pH of the lake water (median of 7.87, Table 9) the solubility of Al(III) is generally at a minimum (Nordstrom & Ball 1986). Interestingly, across all results for groundwater, soluble aluminium was somewhat correlated with dissolved organic C ($r^2 = 0.57$) which may be indicative of the aluminium being associated with dissolved organic complexes. Previous sampling of surface waters across the state have also found that aluminium is present in similarly high concentrations, sometimes irrespective of whether acidification is evident (Kilminster & Cartwright 2011).

Soluble iron in the lake waters was also likely to be due to colloidal materials, since it was unlikely that iron remained present as either ferrous (Fe(II)) or ferric (Fe(III)) iron given the moderate to high pH and high redox status of the lake waters. Chromium was similarly probably associated with suspended materials collected with the samples (some >0.2 g/L), although with the alumino-silicate mineral component rather than any suspended iron minerals. This conclusion was based on total Cr being strongly correlated with total Al (r^2 = 0.77), but not total Fe (r^2 = 0.08) across all samples. The copper-chromium-arsenic (CCA) treated fence posts on the margin of the lake may be a source of some chromium.

Although the concentrations of aluminium, iron, chromium and boron exceed levels that would achieve high levels of aquatic ecosystem protection, this does not mean that impacts on the ecology of the lake are occurring, particularly since the form of the trace elements was in doubt. This investigation was designed to provide a broad level of assessment of the risk that components pose to aquatic organisms and broad direction for constituents that should be considered in future investigations.

Concentrations of boron, cadmium, nickel and zinc in groundwater beneath Lake Muckenburra were generally less than drinking water guideline limits, with iron, aluminium, manganese and arsenic exceeding these in some parts of the Superficial aquifer. Iron, aluminium and manganese present a problem for the aesthetic qualities of groundwater (if untreated), whereas arsenic may be a concern for human health if the water is consumed untreated. This must be considered in context of the salt (and chloride) concentrations of the groundwater also posing constraints on potable use. As with the lake waters, concentrations of elements such as chromium, nickel and zinc were probably greatly influenced by suspended colloidal mineral material collected with samples, as indicated by the evidence of correlations (r^2 >0.4) between the metals and total aluminium across all samples.

High concentrations of soluble aluminium in groundwater were probably due to the presence of colloidal material, similar to that occurring in the lake water (as discussed above). Unlike the guidelines for aquatic organisms, the concentration limits of aluminium for drinking water are generally of aesthetic rather than health concern. Previous regional level hydrochemical investigations of the Superficial aquifer have found soluble aluminium concentrations exceeding 2000 µg Al/L in groundwater towards the north-eastern part of the Gnangara groundwater mound (Yesertener 2010) with over 50% of all sites containing groundwater with >280 µg Al/L.

Iron and manganese are also present in high concentrations in the Superficial aquifer, with median concentrations exceeding drinking water guideline levels. The iron concentrations are typical of anoxic groundwater present in Bassendean Sands (Davidson 1995; Yesertener 2010) with the dominant pattern of decreasing concentrations with depth (Davidson 1995). The high median concentrations of manganese were probably a result of anoxic conditions in the Superficial aquifer, promoting reductive dissolution of Mn oxides. Guidelines for iron and manganese are set for aesthetic reasons and given the elevated levels are probably due to natural processes in the Superficial aquifer, which are not relevant to groundwater management in the region of Lake Muckenburra.

Table 12 Summary statistics for trace elements in groundwater and lake water at Lake Muckenburra

Site or bore	**Al (soluble) µg/L**			**As µg/L**			**B µg/L**			**Cd µg/L**			**Cr µg/L**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
Deep east – MKB_Ea	7	24	9	3	6	5	25	65	39	<0.1	<0.1	<0.1	3	26	9
Int. east – MKB_Eb	49	81	75	**16**	**100**	**51**	11	47	33	<0.1	<0.1	<0.1	7	49	11
Shallow east – MKB_Ec	22	37	30	6	**13**	**8**	47	76	59	<0.1	<0.1	<0.1	2	3	3
Perched east – MKB_Ed	72	**2100**	160	2	**10**	4	110	230	170	<0.1	0.2	0.15	7	**51**	1
Deep west – MKB_Wa	7	32	9	7	**10**	**9**	13	73	40	<0.1	<0.1	<0.1	<1	2	<1
Int. west – MKB_Wb	59	**1100**	**240**	17	**30**	**21**	36	71	39	<0.1	<0.1	<0.1	4	**97**	6
Shallow west – MKB_Wc	180	**4500**	**2500**	3	**9**	4	83	190	130	<0.1	<0.1	<0.1	6	32	11
Lake water	210	840	410	2	12	7	150	510	350	<0.1	<0.1	<0.1	3	7	6
Aquatic ecosystem guidelines*	55			13 (for As(V))			370			0.2			1 (for Cr(VI))		
Drinking water guidelines**	200***			7			400			2			50 (for Cr(VI))		

** Aquatic ecosystem guideline values are for a high species protection level (95% confidence) suitable for slightly to moderately disturbed freshwater aquatic ecosystems (ANZECC & ARMCANZ (2000). Exceedances in lake water and the groundwater likely to discharge to the lake (perched groundwater system indicated by MKB_Ed) are highlighted in blue.*

*** Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004) applied to groundwater analyses with exceedance highlighted in* ***bold****.*

**** Guideline value is for aesthetic rather than health reasons.*

Table 12 (continued)

Site or bore	**Fe (soluble) µg/L**			**Mn µg/L**			**Ni µg/L**			**Zn µg/L**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
Deep east – MKB_Ea	**1 100**	**2 100**	**2 000**	**390**	**1 100**	**810**	3	7	4	5	190	32
Int. east – MKB_Eb	**750**	**1 900**	**1 300**	18	61	23	9	20	13	5	520	100
Shallow east – MKB_Ec	**7 500**	**14 000**	**10 500**	**110**	**250**	**120**	9	20	13	8	17	28
Perched east – MKB_Ed	**900**	**9 900**	**2 300**	**180**	**570**	**360**	8	**26**	15	100	1 000	270
Deep west – MKB_Wa	**1 000**	**1 600**	**1 300**	**410**	**680**	**610**	3	17	3	6	120	23
Int. west – MKB_Wb	**640**	**1 300**	**0.850**	51	69	56	3	18	5	7	42	11
Shallow west – MKB_Wc	**490**	**12 000**	**2 100**	32	81	53	4	14	6	80	450	260
Lake water	750	1 100	890	18	57	32	3	4	3	5	8	6
Aquatic ecosystem guidelines*	300			1900			11			8		
Drinking water guidelines**	300***			500 (100 for aesthetics)			20			3000***		

** Aquatic ecosystem guideline values are for a high species protection level (95% confidence) suitable for slightly to moderately disturbed freshwater aquatic ecosystems (ANZECC & ARMCANZ (2000). Exceedances in lake water and the groundwater likely to discharge to the lake (perched groundwater system indicated by MKB_Ed) are highlighted in blue.*

*** Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004) applied to groundwater analyses with exceedance highlighted in **bold**.*

**** Guideline value is for aesthetic rather than health reasons.*

Median concentrations of arsenic were greater than drinking water guideline levels at intermediate depths in the Superficial aquifer as well as deeper on the west side of the lake, in MKB_Wa (Table 12), and shallow levels on the east side in MKB_Ec (Table 12). All concentrations were below levels for non-potable use of the water, which are arbitrarily set at 10 times that of drinking water guideline levels (Department of Health 2006). Concentrations in the perched groundwater system that may on occasion interact with the lake were not considered to pose a risk to aquatic organisms in the lake.

The arsenic in the groundwater is most likely derived from within the superficial formations, although the concentrations are up to an order of magnitude greater than has been previously reported in regional surveys of the Superficial aquifer (generally <5 µg/L in the Bassendean Sands; Yesertener 2010). The source of arsenic is likely to be arsenic adsorbed on iron oxyhydroxide minerals in the Bassendean Sands mobilised into solution as these undergo reductive dissolution under generally anoxic or mildly anoxic conditions. The presence of dissolved iron in the groundwater is general evidence that iron oxyhydroxides may be undergoing reductive dissolution in the aquifer, although further investigation would be required to verify this. It was unlikely that the arsenic in the groundwater was derived from sulfide containing minerals, contrary to reporting in previous regional investigations of Superficial aquifer hydrochemistry (Yesertener 2010). This conclusion was based on the absence of any sulfide (ASS) driven acidification processes in the Superficial aquifer and the generally very low concentrations of arsenic in any PASS materials. Furthermore, unlike other trace elements, concentrations of arsenic do not appear to be linked with the presence of colloidal minerals in the samples, based on there being no correlation with total aluminium across all samples.

6.2.8 Pesticides

Sampling for pesticides in groundwater on three occasions did not find any pesticides above analytical reporting limits, which were below health guideline limits (NHMRC & NRMMC 2004). Although lake waters were not sampled, similar results were likely.

6.3 Summary of guideline level breaches

Table 13 Summary of water quality comparison with guideline levels (nutrients and trace elements)

	South-west Australia – wetlands guideline levels ANZECC & ARMCANZ (2000)	**Drinking water guidelines* NHMRC & NRMMC (2004)**
pH	All pH values in Lake Muckenburra were within guidance values and ranged from 7.52 to 8.59 (September to December 2008). There was no evidence of acidification of lake water or perched groundwater adjoining the lake.	All groundwater was within recommended pH ranges for drinking water (6.5 to 8.5).
TN	Lake water TN concentrations were above the guideline levels (1.5 mg/L). Most TN was organic. High concentrations also occurred in the perched groundwater system likely to interact with the lake and shallow Superficial aquifer.	No assessment limits (possibly contributes to exceeding aesthetic guidance levels for colouration).
NH_4-N	Ammonium is above the guideline level of 0.04 mg/L in all samples from the lake (range 0.11 mg/L to 0.49 mg/L). Perched groundwater exceeded ecosystem guidance levels on several occasions.	Concentrations in groundwater throughout the Superficial aquifer generally exceeded aesthetic guidance values for drinking water guidelines (0.4 mg/L). These concentrations are considered to be naturally derived.
NO_x	Lake Muckenburra showed concentrations of oxidised nitrogen above the guideline level of 0.1 mg/L in the lake sample and on some occasions in the perched groundwater system.	All groundwater was within guideline limits for drinking water (50 mg/L).
TP	Concentrations of TP in lake water (range 0.61 to 1.1 mg/L) were above the guideline level of 0.06 mg/L. On some occasions the perched groundwater was also above this level.	No assessment limits (possibly contributes to exceeding aesthetic guidance levels for colouration).
FRP	FRP in lake water (range 0.4 to 0.74 mg/L) and was above the guideline level of 0.03 mg/L. On some occasions the perched groundwater was also above this level.	No assessment limits.
DOC	DOC was present in high concentrations within the lake (70 to 150 mg/L) and was probably natural, contributing to the highly coloured nature of the water.	No assessment limits (possibly contributes to exceeding aesthetic guidance levels for colouration).

** Assessments only for groundwater*

Table 13 (continued)

	South-west Australia – wetlands guideline levels ANZECC & ARMCANZ (2000)	**Drinking water guidelines* NHMRC & NRMMC (2004)**
Al (soluble)#	Concentrations in the lake were above the guideline level in all cases, although it is considered this may be due to colloidal suspensions in samples. Exceedances in groundwater of relevance to the lake were also observed in the perched groundwater system (MKB_Ed).	Concentrations in groundwater were above the drinking water guideline value (aesthetic) of 0.2 mg/L particularly in the perched groundwater system. This was attributed to colloidal suspensions in samples.
As (total)	Lake water concentrations were below the guideline values. There were no exceedances in groundwater likely to interact with the lake.	Concentrations in groundwater were above the drinking water guideline of 7 µg/L in most groundwater in the Superficial aquifer, with median concentrations varying from 5 µg/L to 21 µg/L. Natural sources of arsenic in anoxic groundwater are considered to be the cause of these exceedances.
B (total)	Lake waters contained concentrations (0.37 mg/L) that exceeded the wetlands guideline on one occasion. All groundwater concentrations were below guideline level.	All groundwater concentrations were below the drinking water guideline level.
Cd (total)	All lake and perched groundwater concentrations were below the guideline level.	All the groundwater samples were below the drinking water guideline level of 2 µg/L.
Cr (total)	Lake water concentrations were regularly above the guideline level of 1 µg/L, along with concentrations in the perched groundwater system likely to interact with the lake. Cr is likely to be associated with suspended colloidal material.	Groundwater was occasionally above the drinking water guideline (50 µg/L). These levels were attributed to association with suspended colloidal material.
Fe (soluble) #	Lake and perched groundwater consistently exceeded soluble Fe guideline limits, most likely due to colloidal mineral or organic suspensions in samples.	Concentrations in the Superficial aquifer at all levels significantly exceed drinking water guideline value (aesthetic), but were typical of Bassendean Sands
Mn (total)	All lake and perched groundwater concentrations were below the guideline level.	Most samples from the Superficial aquifer were above the drinking water guideline value (aesthetic) of 100 µg/L.
Ni (total)	Concentrations in lake water were below guideline level, but some exceedances occurred in the perched groundwater system.	Generally below drinking water guideline limits, with only one incidence in the perched groundwater system where this was marginally exceeded.

	South-west Australia – wetlands guideline levels ANZECC & ARMCANZ (2000)	**Drinking water guidelines* NHMRC & NRMMC (2004)**
Zn (total)	Lake water concentrations were below the guideline level (11 µg/L), but consistently exceeded it in the perched groundwater system. This was attributed to association with suspended materials in samples.	All the groundwater samples were below the drinking water guideline level of 3000 µg/L.

** Assessments only for groundwater*

 # Soluble metals refer to analysis after filtration (see Table 5)

7 Processes and interactions between surface water and groundwater

This study has identified that Lake Muckenburra is disconnected from the Superficial aquifer, although there is evidence of the lake being intermittently maintained by a localised perched groundwater system. The perched groundwater system that interacts with the lake has formed above sequences of sandy clays and clayey sands in the Bassendean Sand Formation that behave as a semi-confining layer. These sequences appear to extend to the east and the west of Lake Muckenburra (based on the lithology of nearby non-SGS bores). It is likely that the perched groundwater system is locally recharged but does not seasonally discharge to the lake. Groundwater inflows most likely occur as intermittent shallow through flow above the perched groundwater system. These findings represent a significant improvement in the previous understanding of the hydrology of the lake, which was limited to knowledge that the lake was periodically inundated.

The dominant hydrogeological interaction between the lake and groundwater can be represented by a simple conceptual model (Figure 35 and Figure 36). This illustrates the disconnection of the lake from the Superficial aquifer, where there is a dominant south-east to north-west flow gradient.

The localised perched groundwater system is interpreted to have an east to west flow gradient, consistent with the upper surface of the shallowest series of sandy clay and clayey sand sequences grading downwards from east to west. Groundwater in the perched system contacts with the base of the lake and most likely promotes the formation of a transient watertable that enables seasonal through flow of water to the lake. This is only evident as a seasonal decrease in the salinity of the water in the perched groundwater system, with little hydrochemical evidence that the perched groundwater influences lake water chemistry. Water levels indicate that the lake may recharge the perched groundwater system down-gradient of the lake, but monitoring on the western side of the lake would be required to confirm this.

Groundwater levels in the perched groundwater system were likely to have been higher in the past and have decreased progressively over time, as a result of decreasing rainfall. These levels may have maintained greater periods of inundation in the lake in the past with increased likelihood of through flow from the perched groundwater system to the lake.

The lake does not behave as a closed basin once filled and probably contributes recharge to the shallow Superficial aquifer via the perched groundwater system (Figure 35). A lack of corresponding changes in water level pressures in the shallow Superficial aquifer when the lake is filled indicated that there is poor hydraulic connectivity between these systems, probably due to sequences of sandy clays and clayey sands. However, hydrochemical evidence suggests that the lake may recharge the Superficial aquifer, at least on the western side of the lake. The decrease in salinity in the shallow Superficial aquifer with groundwater flow south-east to north-west indicated that water quality is influenced by the lake, but the differences in ionic composition of the lake water and the down-gradient Superficial groundwater suggest that this may be limited.

Interaction between the perched groundwater system and the Superficial aquifer at Lake Muckenburra is limited to intermittent subdued recharge through the semi-confining layer in the upper Bassendean Sand Formation. This is possibly increased by root channels through these sequences, although it is unlikely that plants would explore to the depth of the shallow Superficial aquifer when shallower permanent water is available.

The rate of recharge from the perched groundwater system to the shallow Superficial aquifer may be influenced by the depth of the Superficial watertable. At present, the regional watertable in the Superficial aquifer contacts the approximate base of the semi-confining sequences of sandy clays and clayey sands in the Bassendean Sand Formation. This is likely to influence recharge rates from the lake and the perched groundwater system, at least while the Superficial aquifer is within several metres of levels in the perched groundwater system, as has been found in interactions between streams and shallow groundwater systems (Brunner et al. 2010).

There is minimal groundwater flow occurring vertically at intermediate and deeper levels in the Superficial aquifer beneath and up-gradient of the lake although there is a gentle horizontal flow direction from the south-east to the north-west. The absence of vertical gradients appears localised around the lake, with downward flow of groundwater (recharge) likely in the deeper Superficial aquifer 2 km to the south-west of Lake Muckenburra and upward flow likely 1.5 km to the north-west.

There is significant vertical zonation of water quality in the Superficial aquifer that reflects the pattern of groundwater flow in it. The perched groundwater system was typically saline and sub-oxic. The shallow Superficial aquifer had somewhat similar characteristics. These waters were also broadly similar in ionic composition providing supporting evidence that the perched groundwater system probably recharges the shallow Superficial aquifer. In contrast, groundwater deeper in the Superficial aquifer (at mid and base levels) was typically brackish to fresh and more anoxic. Groundwater in the perched and shallow Superficial aquifer also contained elevated concentrations of soluble aluminium and iron along with high concentrations of dissolved organic carbon and organic nitrogen, whereas these were generally lower deeper in the Superficial aquifer.

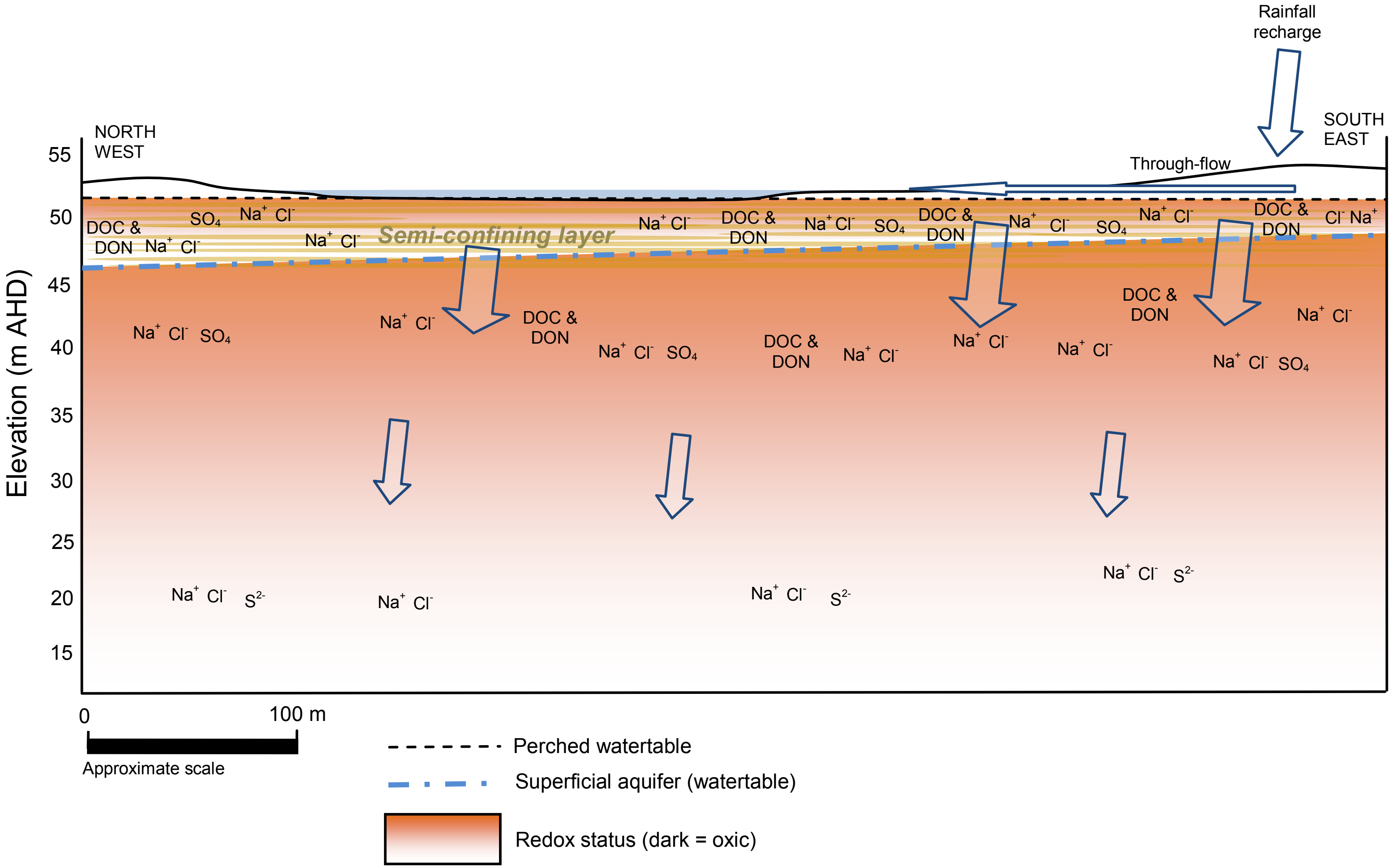


Figure 35 Conceptual model of surface water–groundwater interaction at Lake Muckenburra when the lake is inundated

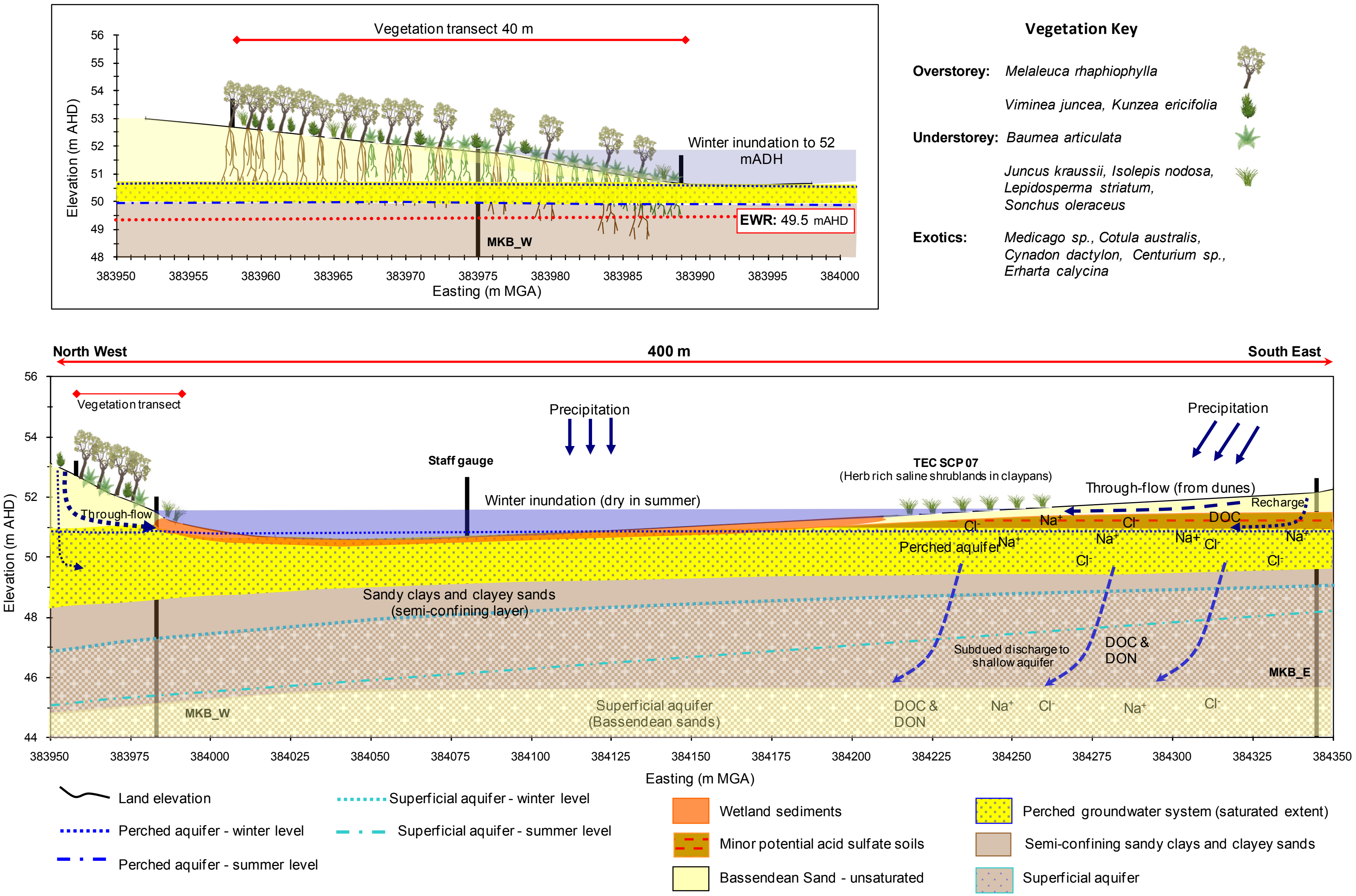


Figure 36 Ecological conceptual model

7.1 Summary

Lake Muckenburra is a seasonally inundated basin wetland where groundwater-dependent ecosystems are likely to rely on a localised perched groundwater system and not the regional Superficial aquifer. Ponding of water in the lake is dependent on an intermittent connection with upper parts of a perched groundwater system, with occasional reliance on surface inflows. Hence, the health of the lake and associated ecosystems can be regarded as being independent of the regional groundwater system.

The perched groundwater system at Lake Muckenburra has formed on sequences of sandy clays and clayey sands in the Bassendean Sand Formation. These impede vertical groundwater movement and promote shallow lateral flow (that allow the lake to fill) and occasional overland flows (where artificial channels have been constructed). The lake and perched groundwater system are not in direct hydraulic connection with the Superficial aquifer. However, there is hydrological and hydrochemical evidence of subdued recharge from the localised perched groundwater system to the shallow Superficial aquifer. This results in a tendency for salts to concentrate in the perched system, along with nutrients and dissolved organic carbon. Groundwater gradients and spatial and seasonal patterns in groundwater quality beneath the lake indicated that there was only limited flow within the Superficial aquifer in the vicinity of the lake.

Groundwater levels in a perched groundwater system to the east of the lake have decreased over the last 30 years. It is likely that levels in the localised perched system at Lake Muckenburra have also declined over this time. This trend is probably due to declining annual rainfall rather than any impacts associated with abstraction from the Superficial aquifer.

Management of drainage and vegetative water use in the landscape surrounding the lake is likely to be important in maintaining water levels and quality in the perched groundwater system.

8 Implications for ecological values and management recommendations

8.1 Monitoring infrastructure

The groundwater monitoring bores and staff gauge at Lake Muckenburra have only been in operation since February 2008. Consequently, there is insufficient data available to assess the suitability of this infrastructure or to identify further requirements. However, this study has identified the need to gain a better understanding of long-term patterns of interaction between the perched groundwater system and the shallow Superficial aquifer. It is therefore recommended that an additional monitoring bore be installed in the perched groundwater system near the wetland vegetation monitoring site on the western side of the lake and that the western bore in the shallow Superficial aquifer (MKB_Wc) be replaced. Given the variability in the perched groundwater system, an additional shallow bore is also recommended to monitor the perched groundwater system near the threatened ecological community to the south of the lake.

The wetland vegetation community at Lake Muckenburra is most likely drawing on groundwater from the perched groundwater system, rather than the Superficial aquifer. However, the only bore currently measuring groundwater levels in the perched groundwater system is MKB_Ed, on the eastern shore of the lake. To address this, the perched groundwater system bore proposed for the western shore of Lake Muckenburra should be adopted as the wetland vegetation monitoring bore.

As the data associated with the new SGS bores is limited, it is recommended that monitoring be maintained at these and the adjacent bore GB9 for a minimum of five years, using data loggers. This period of time is sufficient to determine whether hydrological patterns identified in this study occur over the long term, to identify if any further infrastructure is required and to decide whether the monitoring frequency of the bores is appropriate.

It is recommended that the suitability of the SGS monitoring bores be reviewed after the five years of data collection to ensure that they provide the data necessary to assess ecological changes.

8.2 Ecological implications

The ecological values of Lake Muckenburra, including the threatened ecological community of herb-rich saline shrubland, waterbirds and other wetland-dependent vertebrates, are not affected by groundwater levels in the regional Superficial aquifer. The hydrogeology of Lake Muckenburra indicates that the surrounding wetland vegetation and the threatened ecological community to the south of the lake would be drawing on groundwater from a perched groundwater system rather than directly from the Superficial aquifer. Groundwater levels in the perched system are likely to be controlled at local scales by the balance between local recharge from rainfall, local recharge to the underlying Superficial aquifer and summer water use by local remnant vegetation. These eco-hydrological relationships are illustrated in a conceptual model (Figure 36).

Data is available over a period that is too short to detect any clear trends in lake inundation frequency or trends in water levels in the local perched groundwater system. During the investigation period, water levels in the perched groundwater system were close to the minimum water requirement for *Baumea articulata* of 49.44 m AHD identified as part of this investigation (see ‘

Ecological water requirements’ in Section 2.4.1). If perched groundwater levels fall below this, some wetland vegetation species, including *B. articulata*, will start to experience water stress, triggering a decline in vegetation condition. Protection of the environmental values of Lake Muckenburra requires:

- a minimum water level of 49.5 m AHD within the perched groundwater system (measured at bore MKB_Ed)
- a minimum annual wetland inundation period of three months for at least two out of three years.

Decreasing groundwater levels of approximately 0.3 m in the perched groundwater system over the last 30 years (indicated in nearby bore GB9; Figure 15) represent a threat to the ecology of the lake and adjacent groundwater-dependent vegetation. These declines are likely to be due to decreasing rainfall on the Swan Coastal Plain, evident since the mid 1970s. A consequence of these changes is that there are likely to be shorter periods of inundation at Lake Muckenburra. This suggests that the lake is now a sump wetland rather than a permanently inundated lake.

The declining groundwater levels due to decreasing rainfall are likely to have been buffered by historic land clearing. Removal of native vegetation from the landscape surrounding the lake for agricultural development is likely to have reduced evapotranspiration losses and increased recharge to the perched groundwater system. In similar landscapes of the Swan Coastal Plain to the south of Perth, modelling has found that removal of native vegetation for urban development results in significant increases in the watertable, resulting in increased discharge to surface drainage (Hall et al. 2010). The clearing of native vegetation around Lake Muckenburra would have resulted in a similarly higher water levels being sustained each winter (at least in the decades following land clearing) and was probably the reason behind the construction of drainage channels to the east and south-east of the lake.

Continued decline in rainfall will alter the hydrological regime of Lake Muckenburra, reducing the frequency and duration of inundation events. These changes will affect the ecological values of the lake. For example, the threatened ecological community requires seasonal inundation (Horwitz & Judd 2009b; Froend et al. 2004b), and declines in plant condition are anticipated in response to significant reductions in inundation duration and frequency. This may lead to declines in phreatophytic vegetation condition and distribution, as well as the encroachment of xerophytic vegetation species.

Changes to the lake's hydrological regime will also reduce the availability of suitable habitat for waterbirds and other wetland vertebrates, potentially reducing the richness of vertebrate fauna at Lake Muckenburra.

There is negligible risk of lake or groundwater acidification by acid sulfate soils at Lake Muckenburra should there be changes in groundwater levels that result in exposure and drying of sediments in the perched groundwater system. This means there is minimal risk of acid-driven trace metal contamination of groundwater by metals contained within the soil materials. In addition, the concentrations of these were generally not significant. Coring of the lake bed and adjacent shallow sediments indicated that although low level potential ASS materials exist, there is a low risk that these would develop into actual acid sulfate soils and acidify the lake or groundwater. This is based on the infrequent potential ASS that was found in predominantly sandy clay and clayey sand lithology. These materials exhibited field pH generally exceeding 6.0, which indicates that there is a low to moderate capacity to buffer pH that is likely to provide partial buffering in pH at 6.5 (with additional capacity likely at between pH 5.0 and 6.5). Although the pH buffering capacity of the Bassendean Sand Formation on the crest of the Gnangara Groundwater Mound is typically very low (Appleyard & Cook 2008), the pH buffering capacity at Lake Muckenburra is likely to be greater because of the greater clay content at this site.

Additional protection against acidification at Lake Muckenburra is also likely to be provided by the generally high levels of alkalinity in the perched groundwater system and shallow Superficial aquifer. Such high levels of alkalinity are regarded as providing significant protection against any unforseen acidification (Department of Environment and Conservation 2009b; Swedish Environmental Protection Agency 2007). Further mitigation of any moderate acidification is also highly likely with bacterial sulfate reduction that results in sulfide reformation with concurrent generation of alkalinity (Neculita et al. 2007). Sulfate reduction is favoured by the high dissolved organic carbon concentrations found in the perched groundwater system and low redox potentials that form seasonally.

While there was indication of actual ASS at a depth of 6 m in the Superficial aquifer, this appeared restricted in extent with no hydrochemical evidence of acidification in the shallow Superficial aquifer beneath this (in bore MKB_Ec). There is also minimal risk of trace metal contamination associated with the metals contained within the soil materials.

Groundwater in the perched groundwater system and shallow Superficial aquifer at Lake Muckenburra contains concentrations of trace elements such as aluminium, iron, chromium, zinc and boron that may pose a risk to aquatic organisms, but it is not clear whether these pose a risk to the vegetation (including the threatened ecological community) surrounding the lake. The risk to aquatic organisms is likely to be low given that the elements were probably mostly associated with colloidal organic or mineral materials rather than present as dissolved species. In relation to vegetation, increasing concentrations of aluminium and boron are widely reported to be toxic to many plants (Bell 1999; Slattery et al. 1999). Aluminium can be toxic to roots across a range of concentrations (for monomeric Al), with many plant species being generally sensitive at concentrations above 0.1 mg Al/L (Corrales and Barceló 2008). However, the toxicity of Al is generally highly sensitive to pH and is moderated by concentrations of dissolved organic species, Ca and Mg (Slattery et al. 1999; Corrales and Barceló 2008). The high concentrations of dissolved organic carbon in the groundwater at Lake Muckenburra are likely to have a significant mitigating effect on the plant toxicity of aluminium by forming complexes.

The elevated nutrient concentrations within Lake Muckenburra are likely to persist, with further increases likely due to decreasing rainfall (leading to increased nutrient concentrations by evaporation). High nutrient levels generally stimulate excessive algal growth when wetlands are inundated (Davis et al. 1993), reducing the extent of habitat available for aquatic macroinvertebrates and waterbirds. However, the high DOC and colouration of the water may reduce light penetration and limit the likelihood of this occurring.

Although there are significant threats to the ecological values of Lake Muckenburra, these threats are not related to regional groundwater management but to declines in local rainfall and subsequent declines in runoff and recharge to the perched groundwater system.

8.3 Land and water use

Abstraction from the Superficial or deeper aquifers does not affect the lake since the hydrology and ecology of Lake Muckenburra are not affected by groundwater levels in the Superficial aquifer. This has implications for the extent to which recommended reductions in private licensed use (by 2020) might need to be applied on this sub-area of the Gnangara Sustainability Strategy (Department of Water 2009a). However, the ecological condition of the wetland is directly influenced by trends in rainfall and management of the local water balance within the catchment to the south-east, east and north-east.

Lake Muckenburra is surrounded by a reserve of crown land encircled by freehold land (Figure 7) which is predominantly cleared rural landholdings (Wilson et al. 2009). Maintenance of the water balance in the cleared freehold land is likely to benefit maintenance of water levels in the lake.

Land use within the wetland catchment is likely to influence the lake's ecological condition by modifying the quantity and quality of recharge into the perched groundwater system and runoff occasionally flowing into the lake (via constructed drains). Increasing recharge to the perched groundwater system would reduce the rate of groundwater decline and may help to maintain perched groundwater levels that meet the vegetation ecological water requirements. This effect is likely to be influenced by any change in local drainage of the area or water balance induced by changes to vegetation. The area to the south-east and east of the lake is likely to be where the perched groundwater system is recharged and is currently largely cleared.

Any replanting of this with perennial or high water use vegetation or increased drainage of water to the north-west would be likely to reduce groundwater levels in the perched groundwater system.

Management of the extensive series of shallow drains in the catchment to the lake (including surface drainage into the lake) will need to be considered as part of future land management. These drains may locally divert water to the north that could otherwise recharge the perched groundwater system. Increasing runoff into the lake via the artificial channel would also help to increase the duration and extent of lake inundation, partially offsetting rainfall related changes to the hydrology of the system. However, the benefits of this would need to be assessed against likely increased transport of nutrients from the semi-rural and agricultural catchment to the lake.

Management of the crown reserve to increase rainfall recharge may also provide benefits to the lake, although these are likely to be limited. The reserve includes an area of native bushland where the native vegetation management strategy proposed by the Department of Environment and Conservation (2009c) could be implemented to reduce water uptake by vegetation. This strategy suggests that by reducing vegetation density using prescribed burning of native vegetation can increase recharge. However, given that the total area of native vegetation at Lake Muckenburra amenable to such management is approximately 100 ha, only minor improvements in recharge and runoff are likely to be achieved through changed burning practices. These management strategies may also conflict with protection of the threatened ecological community to the south of the lake.

In summary, the ecological values of Lake Muckenburra are supported by rainfall runoff and a perched, brackish aquifer beneath the wetland. Although the ecological values are currently in good condition, risks to the values are mainly due to declining local rainfall levels.

8.4 Recommendations

These recommendations are the result of this study and aim to build-on the outcomes. Their implementation will depend on the normal process of prioritising within the available resources.

Management actions

- Ecological water requirements have been identified for Lake Muckenburra but are not suitable for adoption as Ministerial criteria due to the reliance of the lake’s ecology on the localised perched groundwater system, rather than the regional Superficial aquifer.
    - Implementation and responsibility: Department of Water to apply recommended vegetation based ecological water requirements in assessing water levels in the perched groundwater system (bore MKB_Ed).

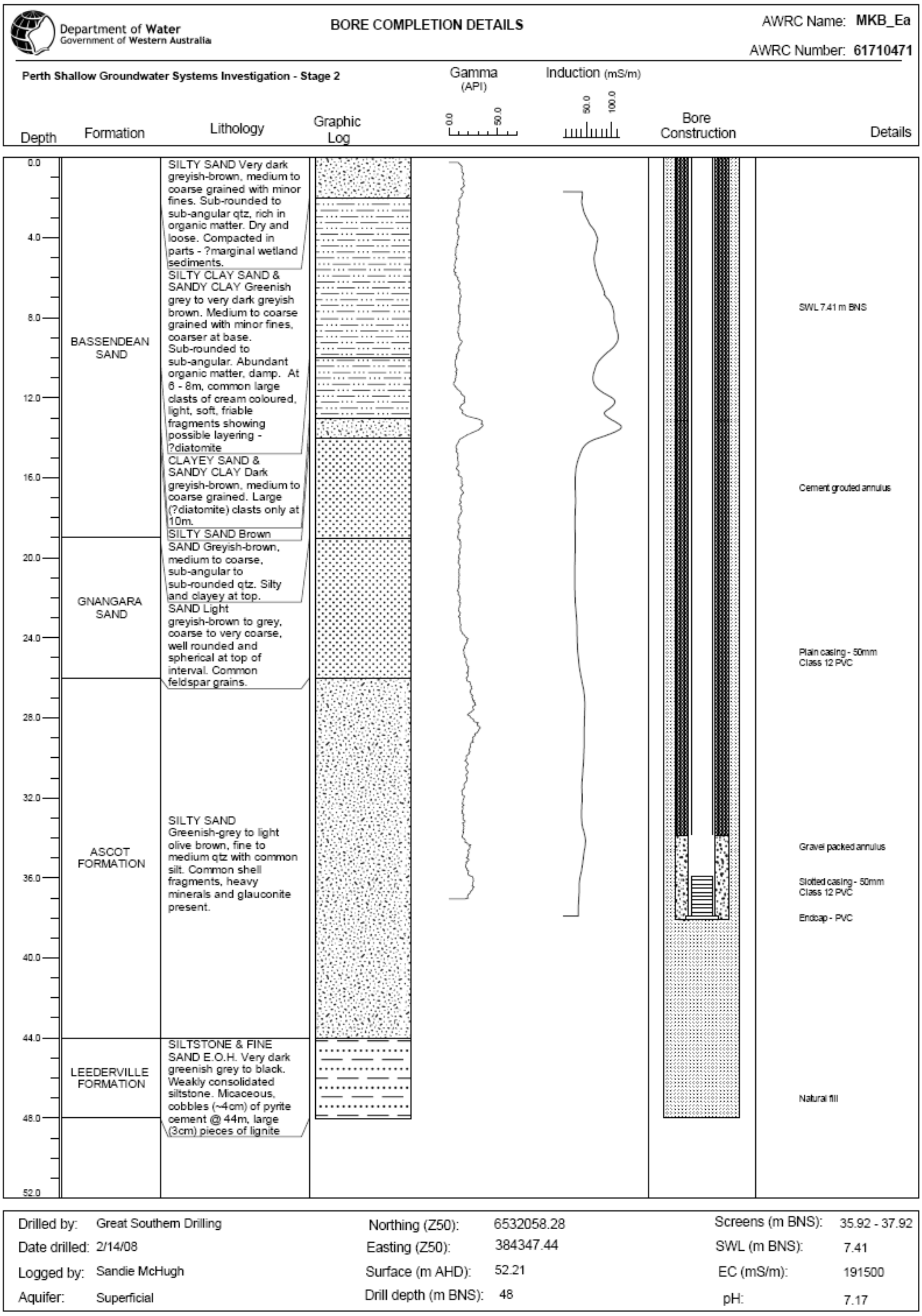
- Design a local area model that incorporates the new hydrogeological understanding gained from this study, and includes scenarios that model changes in recharge to the perched groundwater system through rainfall variability, managing the density of vegetation and managing changes in drainage.
    - Implementation and responsibility: Department of Water to design the north Gnangara local area model and evaluation of various scenarios. Results to be related to similar perched systems and inform the next Gnangara water allocation plan.

Future monitoring

- As the data associated with the MKB series bores is limited, it is recommended that monitoring be maintained at bore GB9 for a minimum of five years, concurrent with the MKB series bores.
    - Implementation and responsibility: Department of Water to ensure monitoring at GB9 continues for a minimum of five years concurrent with the MKB bores.
- Installation of two additional monitoring bores is recommended when the opportunity arises. These should include a shallow bore on the western side of the lake in close proximity to the vegetation transect and a shallow bore near the threatened ecological community to the south of the lake. These bores to be screened in the perched groundwater system (upper Bassendean Sand Formation) above the semi-confining sandy clays and clayey sands (~1 to 2 mbgl). Removal and redrilling of the bore screened in the shallow Superficial aquifer (MKB_Wc) is also recommended.
    - Implementation and responsibility: Department of Water to install these bores as part of bore construction works in any future shallow groundwater systems investigations.

Appendices

Appendix A — Bore construction diagrams and lithology



BORE COMPLETION DETAILS

AWRC Name: **MKB_Ea**
AWRC Number: **61710471**

Perth Shallow Groundwater Systems Investigation - Stage 2

Formation	Lithology
BASSENDEAN SAND	SILTY SAND Very dark greyish-brown, medium to coarse grained with minor fines. Sub-rounded to sub-angular qtz, rich in organic matter. Dry and loose. Compacted in parts - ?marginal wetland sediments.
	SILTY CLAY SAND & SANDY CLAY Greenish grey to very dark greyish brown. Medium to coarse grained with minor fines, coarser at base. Sub-rounded to sub-angular. Abundant organic matter, damp. At 6 - 8m, common large clasts of cream coloured, light, soft, friable fragments showing possible layering - ?diatomite
	CLAYEY SAND & SANDY CLAY Dark greyish-brown, medium to coarse grained. Large (?diatomite) clasts only at 10m.
	SILTY SAND Brown
GNANGARA SAND	SAND Greyish-brown, medium to coarse, sub-angular to sub-rounded qtz. Silty and clayey at top.
	SAND Light greyish-brown to grey, coarse to very coarse, well rounded and spherical at top of interval. Common feldspar grains.
ASCOT FORMATION	SILTY SAND Greenish-grey to light olive brown, fine to medium qtz with common silt. Common shell fragments, heavy minerals and glauconite present.
LEEDERVILLE FORMATION	SILTSTONE & FINE SAND E.O.H. Very dark greenish grey to black. Weakly consolidated siltstone. Micaceous, cobbles (~4cm) of pyrite cement @ 44m, large (3cm) pieces of lignite

Drilled by:	Great Southern Drilling	Northing (Z50):	6532058.28	Screens (m BNS):	35.92 - 37.92
Date drilled:	2/14/08	Easting (Z50):	384347.44	SWL (m BNS):	7.41
Logged by:	Sandie McHugh	Surface (m AHD):	52.21	EC (mS/m):	191500
Aquifer:	Superficial	Drill depth (m BNS):	48	pH:	7.17

Depth m	Summary texture	Lithological description (MKB_Ea)
0–2	Silty sand	Very dark greyish-brown, medium to coarse grained with minor fines. Sub-rounded to sub-angular quartz rich in organic matter. Dry and loose. Compacted in parts–?marginal wetland sediments.
2–4	Silty clayey sand	Greenish grey, medium to coarse grained with minor fines. Sub-rounded to sub-angular. Abundant organic matter, damp.
4–6	Silty clay sand and sandy clay	Greenish black, medium to coarse grained, plastic, stiff, cohesive.
6–8	Silty clay sand and sandy clay	As above but including common large clasts of cream coloured, light, soft, friable fragments showing possible layering–?diatomite
8–10	Silty clay sand and sandy clay	Very dark greyish-brown, medium to coarse grained with minor fines. Sub-rounded to sub-angular quartz. Clasts as above, but smaller. Coarser grained overall.
10–13	Clayey sand and sandy clay	Dark greyish-brown, medium to coarse grained. Large (?diatomite) clasts only at 10 m.
13–14	Silty sand	Brown
14–19	Sand	Greyish-brown, medium to coarse grained, sub-angular to sub-rounded quartz. Clay in top metre.
19–26	Sand	Light greyish-brown to grey, coarse to very coarse, well rounded and spherical at top of interval. Common feldspar grains.
26–27	Silty sand	Greenish-grey, fine to medium grained quartz with common silt.
27–30	Silty sand	Greenish-grey, fine to medium grained quartz with common silt. Common shell fragments, heavy minerals and glauconite nodules. Very wet and loose.
30–33	Silty sand	As above but coarser grained–fine to coarse quartz sand.
33–34	Silty sand	Greenish-grey, fine to medium grained, abundant shell fragments. Heavy minerals present, wet, loose.
34–39	Silty sand	Light olive brown to greyish brown to grey. Fine to medium grained, abundant shell fragments. Heavy minerals present, wet, loose.
39–43	Silty sand	Greenish-grey, fine to medium grained, getting finer. Abundant shell fragments. Heavy minerals present, wet, loose.
43–44	Silty sand	Dark grey fine to medium grained with abundant shell fragments. Heavy minerals present, wet, loose.
44–48	Siltstone and fine sand	E.O.H. Very dark greenish grey to black. Weakly consolidated siltstone. Micaceous, cobbles (~4 cm) of pyrite cement at 44 m, large (3 cm) pieces of lignite

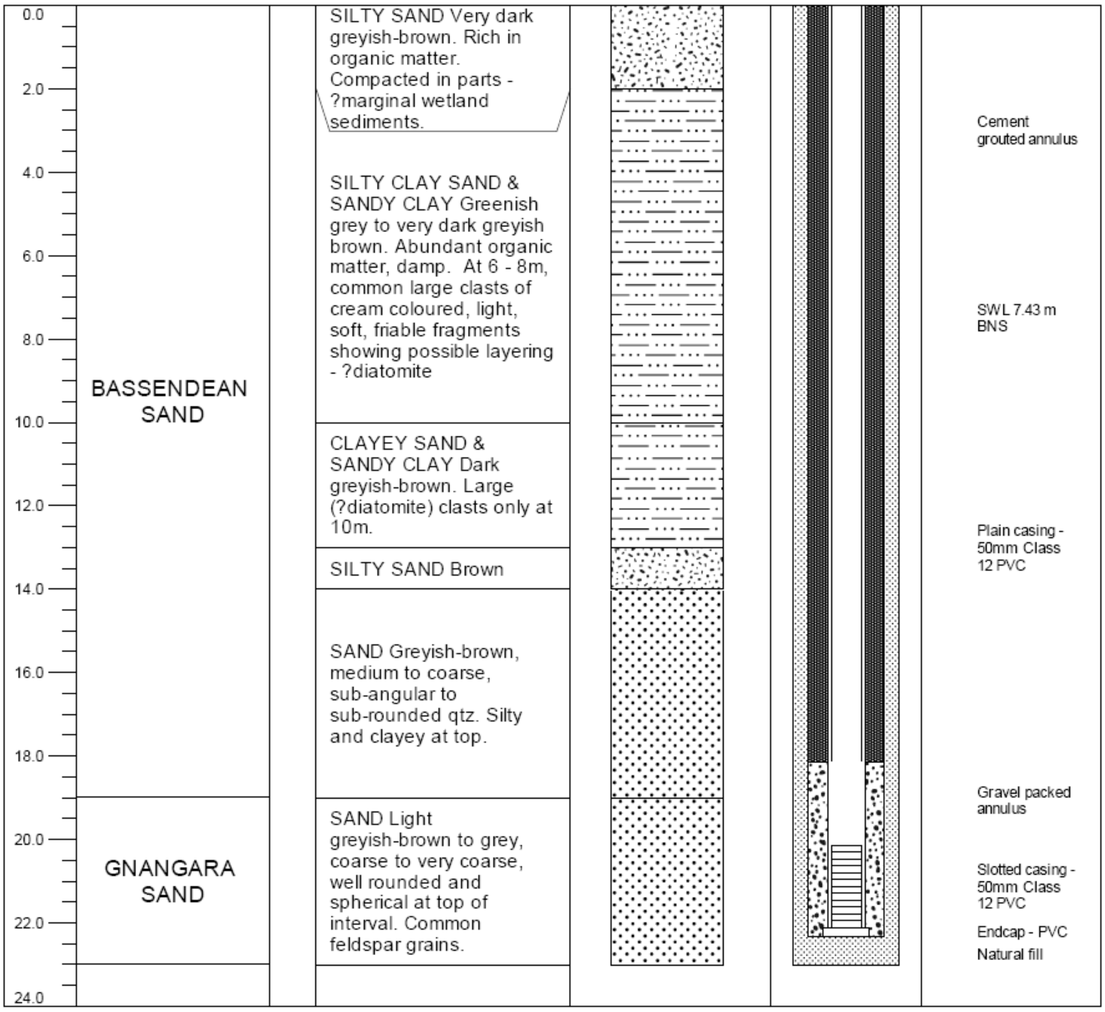
Department of **Water**
Government of **Western Australia**

BORE COMPLETION DETAILS

AWRC Name:	**MKB_Eb**
AWRC Number:	**61710472**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth	Formation	Lithology
0.0	BASSENDEAN SAND	SILTY SAND Very dark greyish-brown. Rich in organic matter. Compacted in parts - ?marginal wetland sediments.
		SILTY CLAY SAND & SANDY CLAY Greenish grey to very dark greyish brown. Abundant organic matter, damp. At 6 - 8m, common large clasts of cream coloured, light, soft, friable fragments showing possible layering - ?diatomite
10.0		CLAYEY SAND & SANDY CLAY Dark greyish-brown. Large (?diatomite) clasts only at 10m.
		SILTY SAND Brown
14.0		SAND Greyish-brown, medium to coarse, sub-angular to sub-rounded qtz. Silty and clayey at top.
	GNANGARA SAND	SAND Light greyish-brown to grey, coarse to very coarse, well rounded and spherical at top of interval. Common feldspar grains.
24.0		



Drilled by:	Great Southern Drilling	Northing (Z50):	6532059.79	Screens (m BNS):	20.13 - 22.13
Date drilled:	2/14/08	Easting (Z50):	384346.74	SWL (m BNS):	7.43
Logged by:	Sandie McHugh	Surface (m AHD):	52.19	EC (uS/m):	155800
Aquifer:	Superficial	Drill depth (m BNS):	23	pH:	6.17

Depth m	Summary texture	Lithological description (MKB_Eb)
0–2	Silty sand	Very dark greyish-brown, medium to coarse grained with minor fines. Sub-rounded to sub-angular quartz rich in organic matter. Dry and loose. Compacted in parts – ?marginal wetland sediments.
2–4	Silty clayey sand	Greenish grey, medium to coarse grained with minor fines. Sub-rounded to sub-angular. Abundant organic matter, damp.
4–6	Silty clay Sand and sandy clay	Greenish black, medium to coarse grained, plastic, stiff, cohesive.
6–8	Silty clay sand and sandy clay	As above but including common large clasts of cream coloured, light, soft, friable fragments showing possible layering – ?diatomite
8–10	Silty clay sand and sandy clay	Very dark greyish-brown, medium to coarse grained with minor fines. Sub-rounded to sub-angular quartz. Clasts as above, but smaller. Coarser grained overall.
10–13	Clayey sand and sandy clay	Dark greyish-brown, medium to coarse grained. Large (?diatomite) clasts only at 10 m.
13–14	Silty sand	Brown
14–19	Sand	Greyish-brown, medium to coarse grained, sub-angular to sub-rounded quartz. Clay in top metre.
19–23	Sand	Light greyish-brown to grey, coarse to very coarse, well rounded and spherical at top of interval. Common feldspar grains.

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

[redacted]

[redacted]

Drilled by:	Great Southern Drilling	Northing (Z50):	6532061.07	Screens (m BNS):	4.96 - 9.96
Date drilled:	2/7/08	Easting (Z50):	384346.15	SWL (m BNS):	3.65
Logged by:	Sarah Bourke	Surface (m AHD):	52.16	EC (uS/m):	669000
Aquifer:	Superficial	Drill depth (m BNS):	10	pH:	6.11

Depth (m)	Summary texture	Lithological description (MKB_Ec)
0.00–0.02	Topsoil	
0.02–0.22	Sand	Light grey, fine to coarse, sub-rounded to sub-angular quartz. Minor heavy minerals and organic matter.
0.22–0.95	Clayey sand	Brown to grey, medium to fine grained, sub-rounded to sub-angular. compacted, consolidated, friable, (?)organic mottling in parts, minor heavy minerals and organic matter.
0.95–1.1	Sandy clay	Dark brown, fine to coarse grained, minor iron staining.
1.1–2.3	Sandy clay	Dark yellowish-brown to dark brown, fine to coarse grained. Rare (?)organic matter.
2.3–3.5	Clayey silty sand	Dark yellowish-brown, fine to coarse grained, iron staining.
3.5–3.6	Sandy clay	Dark yellowish-brown, fine to medium grained.
3.6–4.35	silty clayey sand	Light yellowish brown to light grey, fine to coarse grained quartz.
4.35–4.6	clay	Olive brown. Sandy in parts.
4.6–5.3	Silty clayey sand	Olive brown, fine to medium grained quartz.
5.3–5.5	Sandy clay	Light olive brown, fine to medium grained quartz sand.
5.5–5.7	Clayey silty sand	Light yellowish brown, fine to coarse grained quartz sand.
5.7–5.9	Sand	Light grey, fine to coarse grained quartz sand with minor silt.
5.9–6.3	Sand	White, fine to medium grained quartz sand.
6.3–6.8	Silty clayey sand	Brown to dark brown, fine to coarse grained quartz sand.
6.8–6.87	Sand	Light brown, fine to medium grained quartz sand.
6.87–6.9	Silty clayey sand	Brown to dark brown, fine to coarse grained quartz sand.
6.9–7.1	sand and clay	Pale brown to brown, fine to medium grained quartz sand with minor silt. Clay at 7 m.
7.1–7.25	Sand	White, fine to medium grained quartz sand with dark grey laminae. laminae become closer spaced at 7.25 m.
7.25–10	Silty sand	E.O.H. greyish brown, fine to coarse grained quartz. Wet.

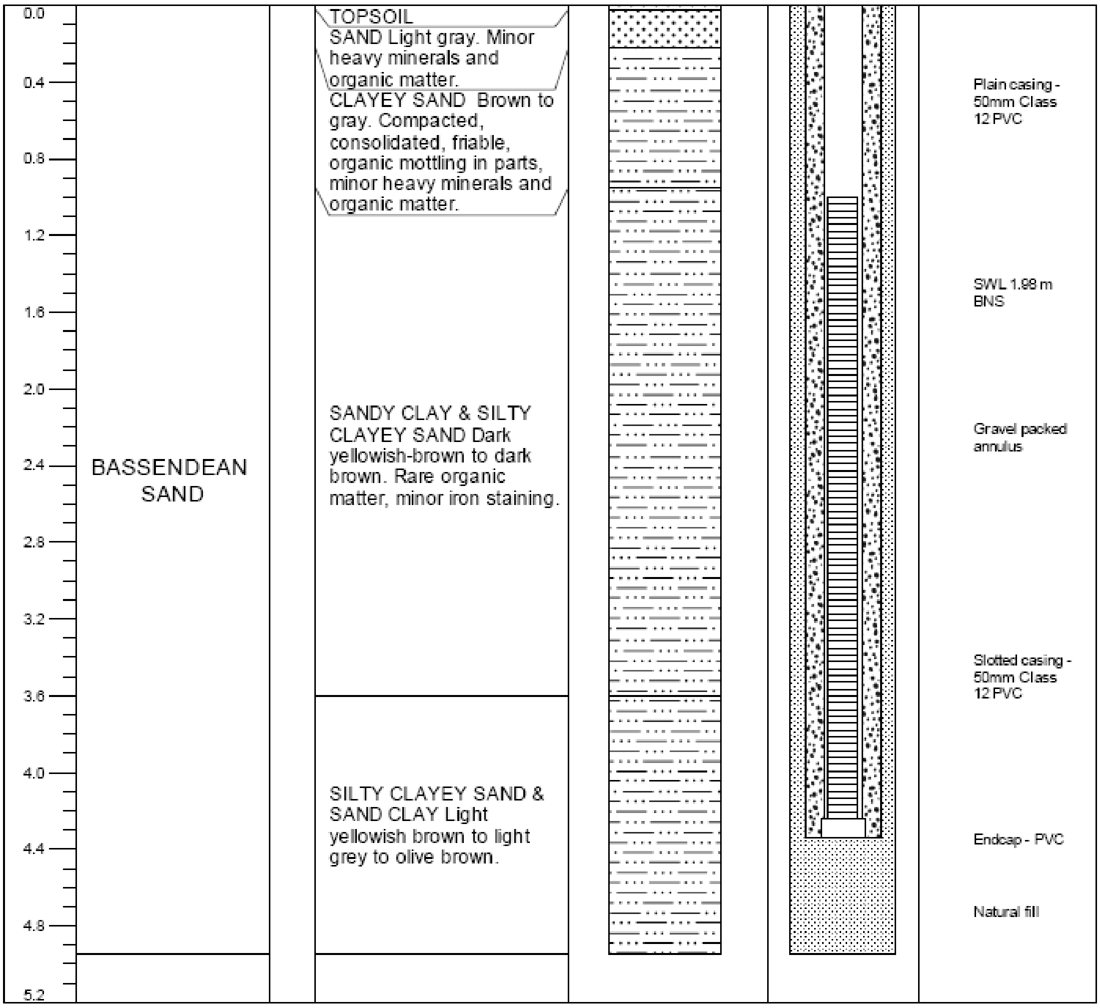
Department of Water
Government of **Western Australia**

BORE COMPLETION DETAILS

AWRC Name:	**MKB_Ed**
AWRC Number:	**61710474**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth	Lithology	Formation	Graphic Log	Bore Construction	Details



TOPSOIL

SAND Light gray. Minor heavy minerals and organic matter.

CLAYEY SAND Brown to gray. Compacted, consolidated, friable, organic mottling in parts, minor heavy minerals and organic matter.

SANDY CLAY & SILTY CLAYEY SAND Dark yellowish-brown to dark brown. Rare organic matter, minor iron staining.

SILTY CLAYEY SAND & SAND CLAY Light yellowish brown to light grey to olive brown.

Drilled by:	Great Southern Drilling	Northing (Z50):	6532062.51	Screens (m BNS):	1 - 4.24
Date drilled:	2/20/08	Easting (Z50):	384345.55	SWL (m BNS):	1.98
Logged by:	Sarah Bourke	Surface (m AHD):	52.14	EC (uS/m):	822000
Aquifer:	Superficial	Drill depth (m BNS):	5	pH:	8.19

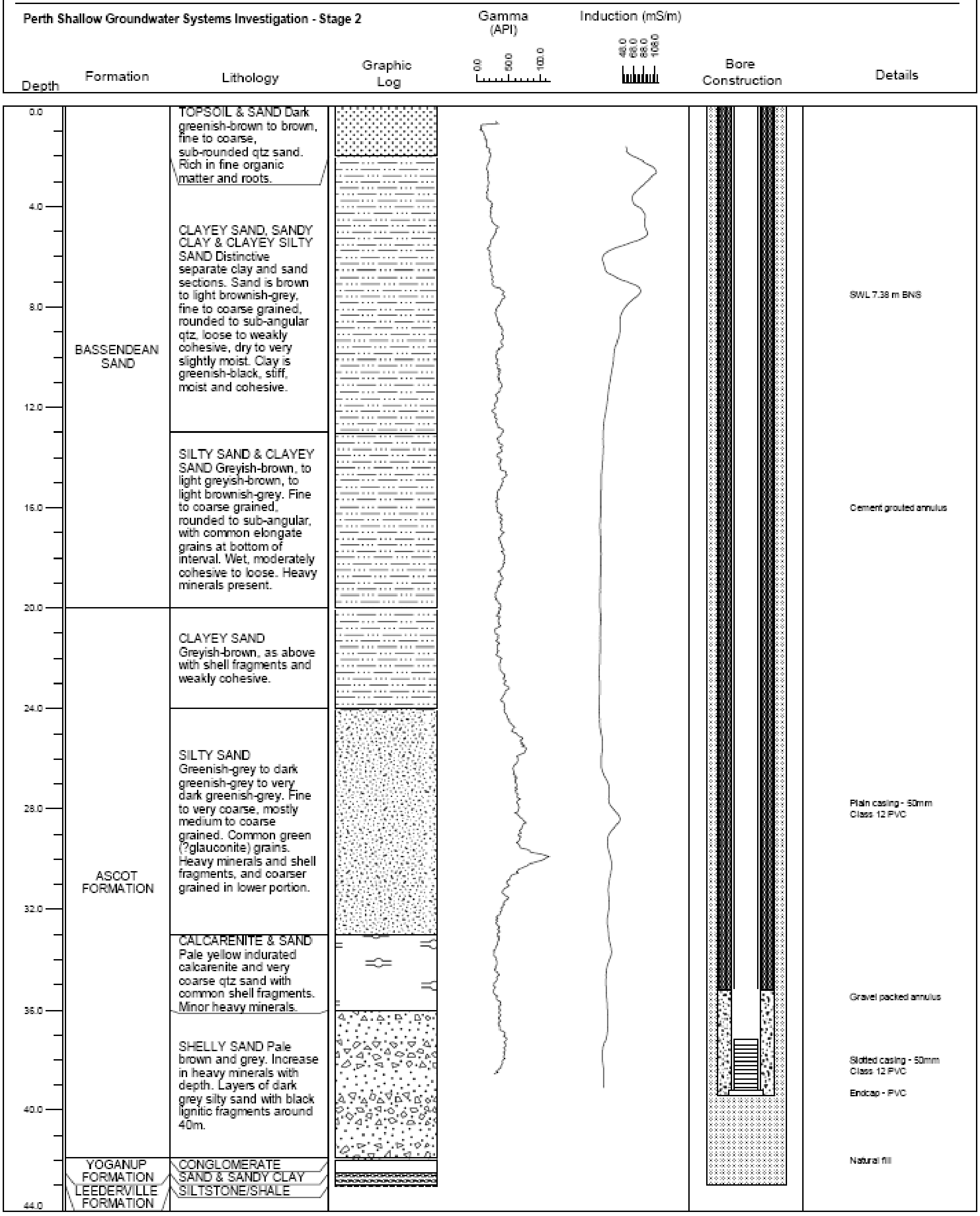
Depth m	Summary texture	Lithological description (MKB_Ed)
0.0–2.0	Sand	Very dark greyish-brown, medium to coarse grained with minor fines. Sub-rounded to sub-angular quartz, rich in organic matter. Dry and loose. Compacted in parts – ?marginal wetland sediments.
2–4.92	Silty clayey sand	Greenish grey, medium to coarse grained with minor fines. Sub-rounded to sub-angular. Abundant organic matter, damp.

Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **MKB_Wa**
AWRC Number: **61710476**

Perth Shallow Groundwater Systems Investigation - Stage 2



Formation	Lithology
BASSENDEAN SAND	TOPSOIL & SAND Dark greenish-brown to brown, fine to coarse, sub-rounded qtz sand. Rich in fine organic matter and roots.
	CLAYEY SAND, SANDY CLAY & CLAYEY SILTY SAND Distinctive separate clay and sand sections. Sand is brown to light brownish-grey, fine to coarse grained, rounded to sub-angular qtz, loose to weakly cohesive, dry to very slightly moist. Clay is greenish-black, stiff, moist and cohesive.
	SILTY SAND & CLAYEY SAND Greyish-brown, to light greyish-brown, to light brownish-grey. Fine to coarse grained, rounded to sub-angular, with common elongate grains at bottom of interval. Wet, moderately cohesive to loose. Heavy minerals present.
ASCOT FORMATION	CLAYEY SAND Greyish-brown, as above with shell fragments and weakly cohesive.
	SILTY SAND Greenish-grey to dark greenish-grey to very dark greenish-grey. Fine to very coarse, mostly medium to coarse grained. Common green (?glauconite) grains. Heavy minerals and shell fragments, and coarser grained in lower portion.
	CALCARENITE & SAND Pale yellow indurated calcarenite and very coarse qtz sand with common shell fragments. Minor heavy minerals.
	SHELLY SAND Pale brown and grey. Increase in heavy minerals with depth. Layers of dark grey silty sand with black lignitic fragments around 40m.
YOGANUP FORMATION	CONGLOMERATE
	SAND & SANDY CLAY
LEEDERVILLE FORMATION	SILTSTONE/SHALE

Drilled by:	Great Southern Drilling	Northing (Z50):	6532235.87	Screens (m BNS):	37.15 - 39.15
Date drilled:	2/19/08	Easting (Z50):	383952.71	SWL (m BNS):	7.38
Logged by:	Josephine Searle	Surface (m AHD):	52.18	EC (mS/m):	148700
Aquifer:	Superficial	Drill depth (m BNS):	43	pH:	7.22

Depth m	**Summary texture**	**Lithological description (MKB_Wa)**
0–1	Topsoil	Dark greenish-brown, fine to coarse grained, sub-rounded quartz sand rich in organic matter and roots. Loose and dry.
1–2	Silty sand	Brown, fine to coarse, sub-rounded quartz sand rich in fine organic matter and roots. Loose and dry.
2–3	Clayey sand and sandy clay	Distinctive separate clay and sand sections. Clay is greenish-black, stiff, moist and cohesive. Sand is brown, and as above but slightly moist and weakly cohesive.
3–6	Clayey sand and clayey silty sand	Greenish-grey to dark greenish-grey, fine to coarse, sub-rounded to sub-angular. Slightly moist, weakly cohesive, becoming drier and looser towards bottom.
6–13	Silty sand and clay	Sand is brown to light brownish-grey, fine to coarse grained, rounded to sub-angular quartz, loose to weakly cohesive, dry to very slightly moist. Clay is present in discrete intervals, less common at bottom of interval. It is light olive-brown and cohesive.
13–20	Silty sand and clayey sand	Greyish-brown, to light greyish-brown, to light brownish-grey. Fine to coarse grained, rounded to sub-angular, with common elongate grains at bottom of interval. Wet, moderately cohesive to loose. Heavy minerals present.
20–24	Clayey sand	Greyish-brown, as above with shell fragments and weakly cohesive.
24–29	Silty sand	Greenish-grey, fine to coarse but mostly medium grained, sub-rounded to sub-angular quartz. Wet and weakly cohesive. Common green (glauconite) nodules.
29–33	Silty sand	Dark greenish-grey to very dark greenish-grey, fine to very coarse grained, mostly coarse grained. Saturated, common green (glauconite) nodules, heavy minerals and shell fragments.
33–36	Calcarenite and sand	Pale yellow indurated calcarenite and very coarse grained quartz sand. Sand is angular to rounded, moderately sorted with common shell fragments. Minor heavy minerals, wet and loose.
36–41.9	Shelly sand	Pale brown and grey, very coarse grained quartz sand, abundant shells. Sub-angular to sub-rounded, poorly sorted. Wet and loose, increase in heavy minerals with depth. Layers of dark grey silty sand with black lignitic fragments around 40 m.
41.9–42	Conglomerate	Yellowish brown, indurated and cemented. Angular quartz pebbles and shell fragments.
42–42.5	Sand and sandy clay	Yellow, medium to coarse grained quartz sand.
42.5–43	Siltstone and shale	Grey, stiff, suggestions of lamination.

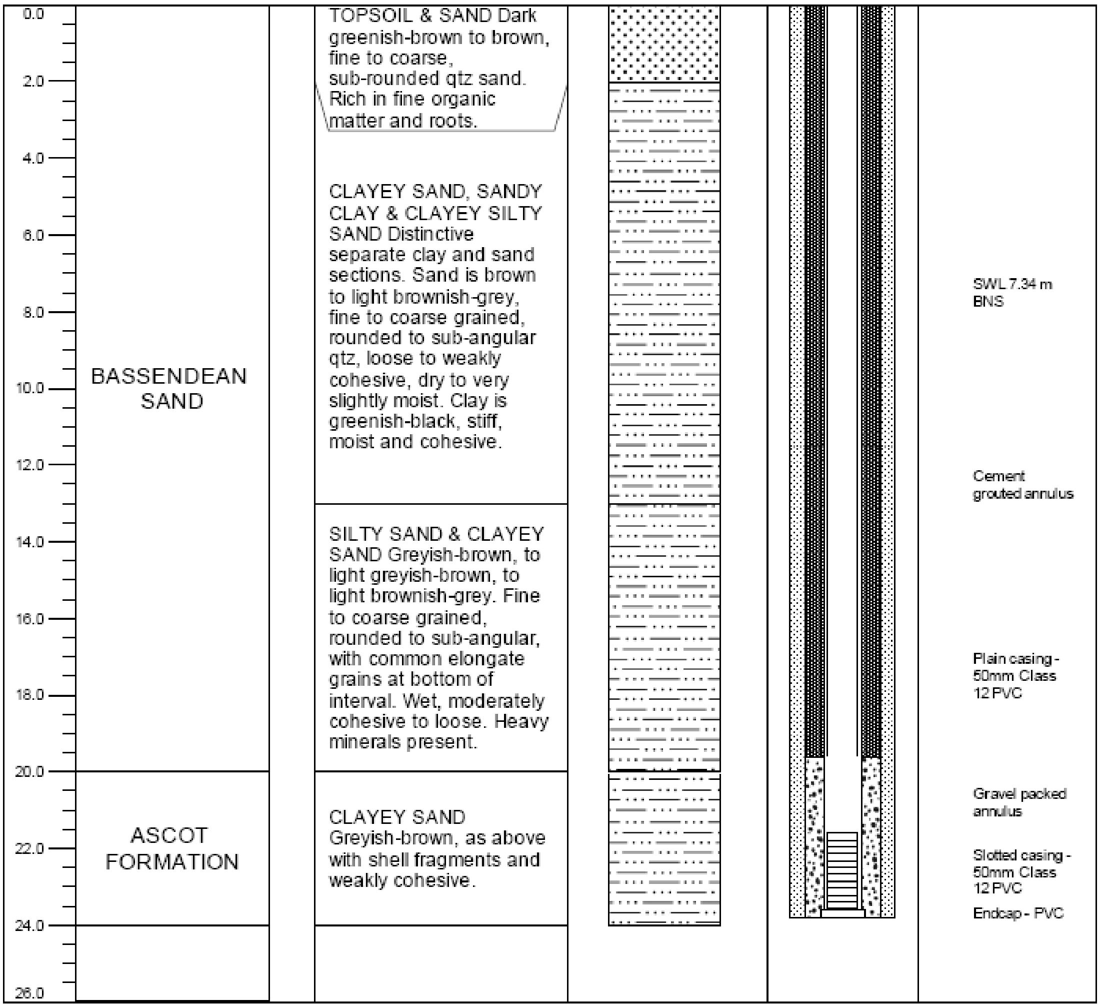
Department of **Water**
Government of **Western Australia**

BORE COMPLETION DETAILS

AWRC Name:	**MKB_Wb**
AWRC Number:	**61710477**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth | Formation | Lithology | Graphic Log | Bore Construction | Details



TOPSOIL & SAND Dark greenish-brown to brown, fine to coarse, sub-rounded qtz sand. Rich in fine organic matter and roots.

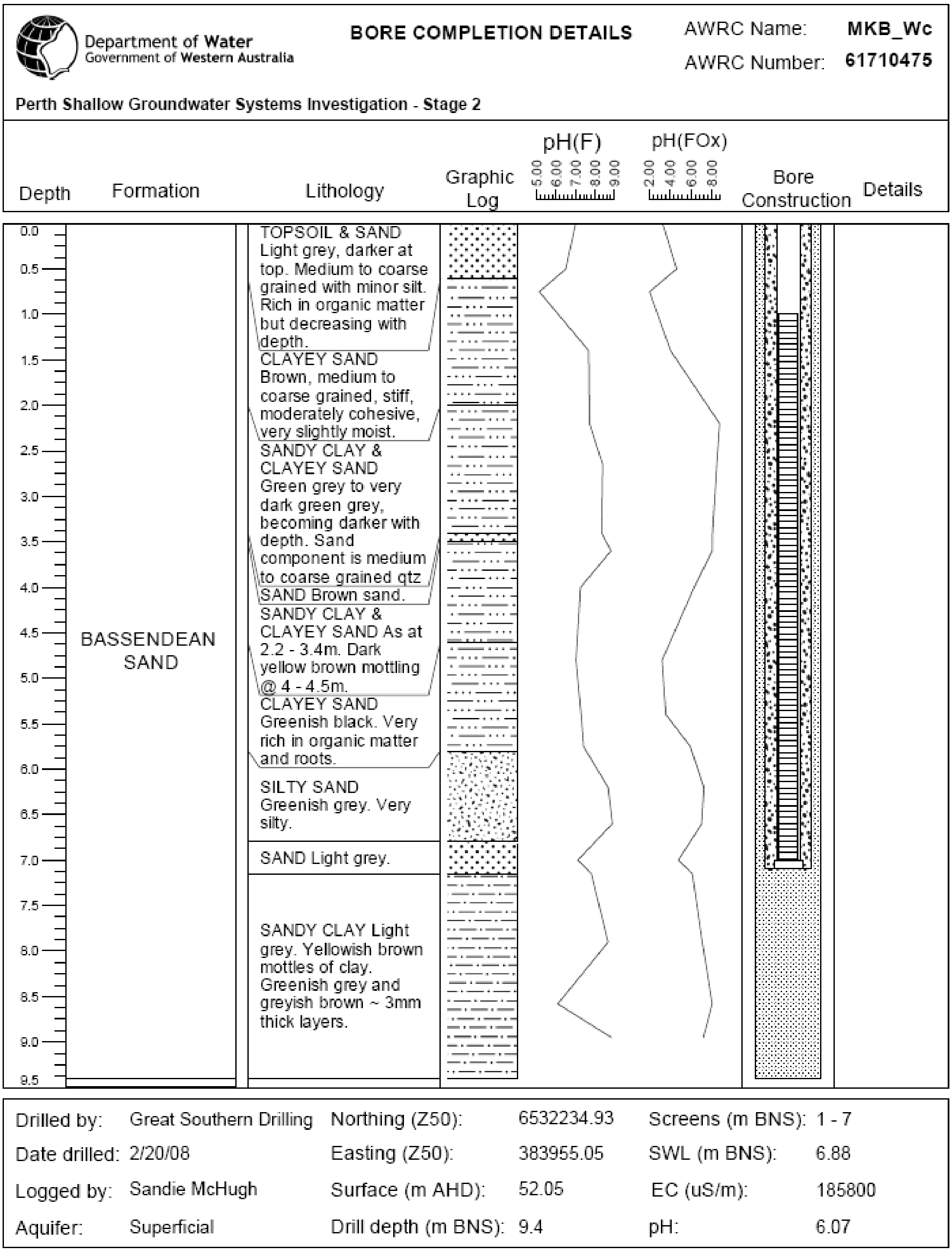
CLAYEY SAND, SANDY CLAY & CLAYEY SILTY SAND Distinctive separate clay and sand sections. Sand is brown to light brownish-grey, fine to coarse grained, rounded to sub-angular qtz, loose to weakly cohesive, dry to very slightly moist. Clay is greenish-black, stiff, moist and cohesive.

SILTY SAND & CLAYEY SAND Greyish-brown, to light greyish-brown, to light brownish-grey. Fine to coarse grained, rounded to sub-angular, with common elongate grains at bottom of interval. Wet, moderately cohesive to loose. Heavy minerals present.

CLAYEY SAND Greyish-brown, as above with shell fragments and weakly cohesive.

Drilled by:	Great Southern Drilling	Northing (Z50):	6532235.38	Screens (m BNS):	21.56 - 23.56
Date drilled:	2/21/08	Easting (Z50):	383953.97	SWL (m BNS):	7.34
Logged by:	Josephine Searle	Surface (m AHD):	52.12	EC (uS/m):	129200
Aquifer:	Superficial	Drill depth (m BNS):	23.56	pH:	7.04

Depth m	Summary texture	Lithological description (MKB_Wb)
0–1	Topsoil	Dark greenish-brown, fine to coarse grained, sub-rounded quartz sand rich in organic matter and roots. Loose and dry.
1–2	Silty sand	Brown, fine to coarse grained, sub-rounded quartz sand rich in fine organic matter and roots. Loose and dry.
2–3	Clayey sand and sandy clay	Distinctive separate clay and sand sections. Clay is greenish-black, stiff, moist and cohesive. Sand is brown, and as above but slightly moist and weakly cohesive.
3–6	Clayey sand and clayey silty sand	Greenish-grey to dark greenish-grey, fine to coarse grained, sub-rounded to sub-angular. Slightly moist, weakly cohesive, becoming drier and looser towards bottom.
6–13	Silty sand and clay	Sand is brown to light brownish-grey, fine to coarse grained, rounded to sub-angular quartz, loose to weakly cohesive, dry to very slightly moist. Clay is present in discrete intervals, less common at bottom of interval. It is light olive-brown and cohesive.
13–20	Silty sand and clayey sand	Greyish-brown, to light greyish-brown, to light brownish-grey. Fine to coarse grained, rounded to sub-angular, with common elongate grains at bottom of interval. Wet, moderately cohesive to loose. Heavy minerals present.
20–23.56	Clayey sand	Greyish-brown, as above with shell fragments and weakly cohesive.



Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **MKB_Wc**
AWRC Number: **61710475**

Perth Shallow Groundwater Systems Investigation - Stage 2

TOPSOIL & SAND Light grey, darker at top. Medium to coarse grained with minor silt. Rich in organic matter but decreasing with depth.

CLAYEY SAND Brown, medium to coarse grained, stiff, moderately cohesive, very slightly moist.

SANDY CLAY & CLAYEY SAND Green grey to very dark green grey, becoming darker with depth. Sand component is medium to coarse grained qtz

SAND Brown sand.

SANDY CLAY & CLAYEY SAND As at 2.2 - 3.4m. Dark yellow brown mottling @ 4 - 4.5m.

CLAYEY SAND Greenish black. Very rich in organic matter and roots.

SILTY SAND Greenish grey. Very silty.

SAND Light grey.

SANDY CLAY Light grey. Yellowish brown mottles of clay. Greenish grey and greyish brown ~ 3mm thick layers.

Drilled by:	Great Southern Drilling	Northing (Z50):	6532234.93	Screens (m BNS):	1 - 7
Date drilled:	2/20/08	Easting (Z50):	383955.05	SWL (m BNS):	6.88
Logged by:	Sandie McHugh	Surface (m AHD):	52.05	EC (uS/m):	185800
Aquifer:	Superficial	Drill depth (m BNS):	9.4	pH:	6.07

Depth m	**Summary texture**	**Lithological description (MKB_Wc)**
0–0.1	Topsoil	Very dark grey, medium to coarse grained, sub-rounded to sub-angular quartz sand rich in organic matter. Dry and loose.
0.1–0.6	Sand	Light grey, medium to coarse grained with minor silt. Rich in organic matter but decreasing with depth.
0.6–2	Clayey sand	Brown, medium to coarse grained, stiff, moderately cohesive, very slightly moist.
2–2.2	Sandy clay	Black sandy clay
2.2–3.4	Sandy clay and clayey sand	Green grey to very dark green grey, becoming darker with depth. Sand component is medium to coarse grained quartz
3.4–3.5	Sand	Brown sand
3.5–4.6	Sandy clay and clayey sand	As at 2.2–3.4 m. Dark yellow brown mottling at 4–4.5 m.
4.6–5.8	Clayey sand	Greenish black. Medium to coarse grained quartz sand. Very rich in organic matter and roots. Very sloppy.
5.8–6.8	Silty sand	Greenish grey, medium to coarse grained, sub-rounded. Very silty.
6.8–7.15	Sand	Light grey, medium to coarse grained with minor silt. Rounded to sub-rounded grains.
7.15–9.4	Sandy clay	Light grey, fine to coarse grained. Sub-angular to sub-rounded. Yellowish brown mottles of clay at 7.15–7.25 m. Greenish grey and greyish brown ~ 3 mm thick layers.

Appendix B — Local groundwater bore summary information

Site name: GB9
Aquifer: Superficial
Formation: Bassendean Sand
Screen interval (mbgl): 2.3 to 4.3 (bottom of bore)
Screen interval (m AHD): 55.4 to 53.4 (bottom of bore)
Easting : 386104
Northing: 6532765

Depth mbgl	**Lithology (from hand augering adjacent to bore to 3.7 mbgl, April 2011)**
0-0.2	Sand : Grey, medium, moderately sorted, rounded to sub-rounded, abundant roots
0.2–0.65	Sand : Grey, medium, moderately sorted, rounded to sub-rounded, moist
0.65–1.3	Sand : White, medium, moderately sorted, rounded to sub-rounded, moist
1.3–1.9	Sand : Light brownish grey, medium, moderately sorted, rounded to sub-rounded, occasional roots, saturated
1.9–3.0	Sand : Pale brown, minor brown mottles, medium, moderately sorted, rounded to sub-rounded, saturated
3.0–3.4	Sand : Pale brown, abundant dark brown mottles, medium, moderately sorted, rounded to sub-rounded, occasional roots, saturated
3.4–3.7	Silty sand : Dark brown, medium, moderately sorted, rounded to sub-rounded

Site name: NG5B
Aquifer: Upper Leederville
Formation: Leederville (Warnboro Group)
Screen interval (mbgl): 82 to 88
Screen interval (m AHD): –27 to –33
Easting : 382169
Northing: 6530739

Depth mbgl	Lithology
0–4	Sand : Light grey to white; fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz with trace very fine- to fine heavy minerals. Grades into brown clayey sand from 3-4 m. Thin layer of dark brown; moderately consolidated ferrugenised sand (coffee rock) at 3-4 m.
4–10	Sandy clay : Brown with black and orange mottles; firm with fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz.
10–13	Clayey sand : Light brown; more than 80% sand (no plasticity); fine- to very coarse-grained; very poorly sorted; sub-angular to rounded quartz with trace fine heavy minerals.
13–27	Sand : White to light grey; fine- to very coarse-grained; very poorly sorted; sub-angular to rounded quartz with minor black; fine heavy minerals and trace white; sub-rounded to rounded pebbles 0.5-3 cm diameter (quartzite?).
27–32	Weathered limestone : Yellowish orange grey with major fine- to very coarse-grained; very poorly sorted; sub-angular to rounded; unconsolidated quartz.
32–41	Limestone : Yellowish grey (buff); pulverised from drilling with clayey sand; fine- to coarse grained (mostly fine); sub-rounded to rounded quartz and minor heavy minerals and root casts.
41–44	Clayey sand : Grey; fine- to coarse-grained; poorly sorted; angular to rounded quartz with white to grey feldspar. Trace shell fragments; fine mica and heavy minerals. Trace black; well rounded; polished oblate-spherical pebbles 0.5-1 cm (sandstone?).
44–47	Sand : Grey; very fine- to very coarse-grained (with trace cobbles to 5 cm of conglomerate of well rounded black pebbles; quartz; feldspar and shell fragments); very poorly sorted; angular to well rounded; with minor grey feldspar and trace pyritised charcoal.
47–50	Sand : Grey; fine- to very coarse-grained; very poorly sorted; angular to well rounded quartz with minor feldspar; trace bivalve fragments; trace conglomerate (containing black; well rounded pebbles); trace pyritised charcoal; fining to 50 m becoming clayey sand. There are thin bands of grey firm clay at 47 and 49 m.
50–55	Sandy CLAY : Black and firm with fine- to very coarse-grained; sub-angular to sub-rounded quartz sand with minor feldspar and trace charcoal and mica.
55–58	Clay : Black; soft to firm and micaceous with minor sand as below.
58–65	Sand : Light grey; fine-grained to granule-sized; very poorly sort; sub-angular to sub-rounded quartz and feldspar.
65–74	Clay : Dark grey to black; soft to firm and micaceous.
74–80	Sand : Light grey; fine-grained to granule-sized; very poorly sorted; sub-angular to sub-rounded quartz and feldspar with minor; black; soft and micaceous clay bands.
80–82	Sandy clay : Black; soft to firm and micaceous with light grey; fine-grained to granule-sized; very poorly sorted; sub-angular to sub-rounded quartz and feldspar sand.

82–91	Sand : Light grey; fine-grained to granule-sized; very poorly sorted; sub-angular to sub-rounded quartz and feldspar with minor; black; soft and thin clay bands.

Site name: NG5C
Aquifer: Superficial
Formation: Ascot
Screen interval (mbgl): 42 to 48
Screen interval (m AHD): 12.55 to 6.55
Easting : 382167
Northing: 6530743

Depth mbgl	Lithology
0–4	Sand : Light grey to white; fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz with trace very fine- to fine heavy minerals. Grades into brown clayey sand from 3-4 m. Thin layer of dark brown; moderately consolidated ferrugenised sand (coffee rock) at 3-4 m.
4–10	Sandy clay : Brown with black and orange mottles; firm with fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz.
10–14	Clayey sand : Light brown; more than 80% sand (no plasticity); fine- to very coarse-grained; very poorly sorted; sub-angular to rounded quartz with trace fine heavy minerals.
14–27	Sand : White to light grey; fine- to very coarse-grained; very poorly sorted; sub-angular to rounded quartz with minor black; fine heavy minerals and trace white; sub-rounded to rounded pebbles 0.5-3 cm diameter (quartzite?).
27–32	Weathered limestone : Yellowish orange grey with major fine- to very coarse-grained; very poorly sorted; sub-angular to rounded; unconsolidated quartz.
32–41	Limestone : Yellowish grey (buff); pulverised from drilling with clayey sand; fine- to coarse grained (mostly fine); sub-rounded to rounded quartz and minor heavy minerals and root casts.
41–44	Clayey sand : Grey; fine- to coarse-grained; poorly sorted; angular to rounded quartz with white to grey feldspar. Trace shell fragments; fine mica and heavy minerals. Trace black; well rounded; polished oblate-spherical pebbles 0.5-1 cm (sandstone?).
44–47	Sand : Grey; very fine- to very coarse-grained (with trace cobbles to 5 cm of conglomerate of well rounded black pebbles; quartz; feldspar and shell fragments); very poorly sorted; angular to well rounded; with minor grey feldspar and trace pyritised charcoal.
47–50	Sand : Grey; fine- to very coarse-grained; very poorly sorted; angular to well rounded quartz with minor feldspar; trace bivalve fragments; trace conglomerate (containing black; well rounded pebbles); trace pyritised charcoal; fining to 50 m becoming clayey sand. There are thin bands of grey firm clay at 47 and 49 m.

Site name: NG5D
Aquifer: Superficial
Formation: Ascot
Screen interval (mbgl): 14 to 17
Screen interval (m AHD): 40.48 to 37.48
Easting : 382165
Northing: 6530747

Depth mbgl	Lithology
0–4	Sand : Light grey to white; fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz with trace very fine- to fine heavy minerals. Grades into brown clayey sand from 3-4 m. Thin layer of dark brown; moderately consolidated ferrugenised sand (coffee rock) at 3-4 m.
4–10	Sandy clay : Brown with black and orange mottles; firm with fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz.
10–14	Clayey sand : Light brown; more than 80% sand (no plasticity); fine- to very coarse-grained; very poorly sorted; sub-angular to rounded quartz with trace fine heavy minerals.
14–19	Sand : White to light grey; fine- to very coarse-grained; very poorly sorted; sub-angular to rounded quartz with minor black; fine heavy minerals and trace white; sub-rounded to rounded pebbles 0.5-3 cm diameter (quartzite?).

Site name: NG6B
Aquifer: Upper Leederville
Formation: Leederville (Warnboro Group)
Screen interval (mbgl): 115 to 121
Screen interval (m AHD): –58.39 to –64.39
Easting : 385431
Northing: 6533209

Depth mbgl	**Lithology**
0–3	Sand : White; fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz with trace very fine- to fine heavy minerals.
3–13	Sandy clay : Brown with dark brown; black and orange mottles; firm with fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz.
13–14	Clayey sand : Greenish brown; fine- to very coarse-grained; very poorly sorted; angular to rounded quartz with pebbles to 5 mm of weathered limestone.
14–16	Weathered limestone : White at 14-15 m; yellowish orange grey and friable with major fine- to very coarse-grained; very poorly sorted; sub-angular to rounded; unconsolidated quartz.
16–42	Silty sand : Pale yellowish brown; buff coloured; very fine- to very coarse-grained (mostly very fine- to medium-grained); poorly sorted; sub-angular to rounded; calcareous quartz with trace shell fragments to 4 mm.
42–45	Sand : Grey; fine- to very coarse-grained; very poorly sorted; angular to sub-rounded; with minor white to grey feldspar.
45–48	Clay : Dark grey; firm with minor medium- to very coarse-grained; poorly sorted quartz with feldspar.
48–55	Clayey sand : Dark grey; medium- to very coarse-grained; poorly sorted quartz with feldspar.
55–67	Clay/shale : Black; firm and micaceous.
67–71	Sandy clay : Black; firm and micaceous with medium- to very coarse-grained; sub-angular to sub-rounded; poorly sorted quartz and feldspar.
71–73	Clay/shale : Black; firm and micaceous.
73–84	Sand : Grey; medium- to very coarse-grained (to 3 mm diameter); sub-angular to sub-rounded; poorly sorted quartz and feldspar with minor angular pyrite cementation.
84–89	Sandy clay : Black and grey bands interbedded with grey; medium- to very coarse-grained; sub-angular to sub-rounded; poorly sorted quartz and feldspar sand.
89–103	Sand : Grey; medium- to very coarse-grained (to 3 mm diameter); angular to sub-rounded; poorly sorted quartz with white to grey feldspar.
103–109	Clayey sand : Grey; medium- to very coarse-grained (to 3 mm diameter); angular to sub-rounded; poorly sorted quartz with white to grey feldspar with centimetre-scale bands of grey and black; firm clay.
109–123	Sand : Grey; medium- to very coarse-grained; sub-angular to sub-rounded; poorly sorted quartz and white to grey feldspar.

Site name: NG6C
Aquifer: Superficial
Formation: Ascot
Screen interval (mbgl): 35 to 41
Screen interval (m AHD): 21.55 to 15.55
Easting : 385431
Northing: 6533214

Depth mbgl	**Lithology**
0–3	Sand : White; fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz with trace very fine- to fine heavy minerals.
3–13	Sandy clay : Brown with dark brown; black and orange mottles; firm with fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz.
13–14	Clayey sand : Greenish brown; fine- to very coarse-grained; very poorly sorted; angular to rounded quartz with pebbles to 5 mm of weathered limestone.
14–16	Weathered limestone : White at 14-15 m; yellowish orange grey and friable with major fine- to very coarse-grained; very poorly sorted; sub-angular to rounded; unconsolidated quartz.
16–42	Silty sand : Pale yellowish brown; buff coloured; very fine- to very coarse-grained (mostly very fine- to medium-grained); poorly sorted; sub-angular to rounded; calcareous quartz with trace shell fragments to 4 mm.
42–43	Sand : Grey; fine- to very coarse-grained; very poorly sorted; angular to sub-rounded; with minor white to grey feldspar.

Site name: NG6D
Aquifer: Superficial
Formation: Ascot
Screen interval (mbgl): 16 to 19
Screen interval (m AHD): 40.51 to 37.51
Easting : 385431
Northing: 6533220

Depth mbgl	**Lithology**
0–3	Sand : White; fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz with trace very fine- to fine heavy minerals.
3–13	Sandy clay : Brown with dark brown; black and orange mottles; firm with fine- to coarse-grained; poorly sorted; sub-angular to rounded quartz.
13–14	Clayey sand : Greenish brown; fine- to very coarse-grained; very poorly sorted; angular to rounded quartz with pebbles to 5 mm of weathered limestone.
14–16	Weathered limestone : White at 14–15 m; yellowish orange grey and friable with major fine- to very coarse-grained; very poorly sorted; sub-angular to rounded; unconsolidated quartz.
16–21	Silty sand : Pale yellowish brown; buff coloured; very fine- to very coarse-grained (mostly very fine- to medium-grained); poorly sorted; sub-angular to rounded; calcareous quartz with trace shell fragments to 4 mm.

Site name: NG13C
Aquifer: Superficial
Formation: Ascot
Screen interval (mbgl): 40.5 to 46.5
Screen interval (m AHD): 9.69 to 3.69
Easting : 383029
Northing: 6534943

Depth mbgl	**Lithology**
0–2	Sand : Light grey; medium- to coarse-grained; poorly sorted; sub-rounded to rounded quartz grains; trace white feldspar.
2–13	Sandy clay : Brown to greenish brown; minor silt to coarse-grained; poorly sorted; sub-rounded to rounded quartz grains; trace white feldspar and trace heavy minerals. Gravel sized chert clasts present at 9 m. Thin band of black clay at 12 m.
13–18	Sand : Light grey to white; predominantly fine- to coarse-grained; poorly sorted; sub-angular to sub-rounded quartz grains; trace white feldspar.
18–24	Clay : Black to light brown; mottled; trace very coarse to fine-grained; sub-rounded quartz grains. Trace white feldspar and fine iron oxides. Thin layers of very coarse-grained; rounded; poorly sorted quartz grains at 21 and 23 m.
24–31	Sand : Light brown; fine- to very coarse-grained; sub-angular to sub-rounded quartz grains; common gastropods and bivalves at 27 and 30 m; minor clay content and finer grained sand between 24 and 26 m.
31–35	Sandy clay : Light brown; minor very coarse to fine-grained; poorly sorted; sub-angular to sub-rounded quartz grains; minor shell fragments.
35–36	Clay : Light brown; minor silt to very fine quartz sand grains.
36–37	Sand : Light brown to light grey; fine- to medium-grained; moderately sorted; sub-rounded to rounded quartz grains; trace white; yellow and orange feldspar.
37–42	Sandy silt : Light yellowish brown to light grey; iron stained; yellow to orange mottle at 40 m; quartz grains with feldspar and heavy minerals (salt and pepper look) and minor medium- to coarse-grained quartz sand; trace shell fragments.
42–45	Sandy clay : Grey; soft; minor fine- to medium-grained; sub-angular to sub-rounded quartz grains.
45–47	Sand : Grey; fine- to coarse-grained; moderately to poorly sorted; sub-angular to sub-rounded quartz grains; more clayey at 47 m; trace feldspar.
47–49.5	Clay : Black; soft; minor silt to fine quartz grains. No sample collected at 49 to 50 m.

Site name: NG13D
Aquifer: Superficial
Formation: Gnangara sand
Screen interval (mbgl): 12 to 18
Screen interval (m AHD): 38.19 to 32.19
Easting : 383031
Northing: 6534943

Depth mbgl	**Lithology**
0–2	Sand : Light grey; medium- to coarse-grained; poorly sorted; sub-rounded to rounded quartz grains; trace white feldspar.
2–13	Sandy clay : Brown to greenish brown; minor silt to coarse-grained; poorly sorted; sub-rounded to rounded quartz grains; trace white feldspar and trace heavy minerals. Gravel sized chert clasts present at 9 m. Thin band of black clay at 12 m.
13–18	Sand : Light grey to white; predominantly fine- to coarse-grained; poorly sorted; sub-angular to sub-rounded quartz grains; trace white feldspar.
18–20	Clay : Black to light brown; mottled; trace very coarse to fine-grained; sub-rounded quartz grains. Trace white feldspar and fine iron oxides.

Appendix C — Sampling methods and analysis

Groundwater sampling methodology

Water samples were collected using low-flow pumping methods. The low-flow sampling technique provides a low stress, low impact, minimal drawdown purging method of groundwater sampling. The pump is lowered to the screened interval of the bore and purged until the water quality parameters of pH, EC and temperature have stabilised. Once stabilised, in situ readings can be recorded and samples collected for further laboratory analysis. The method requires smaller volumes of water to be withdrawn than conventional techniques and possibly reduces the aeration or degassing of samples collected. It also minimises the disturbance of water and sediments within the water column, reducing turbidity. This is particularly important when sampling for in situ physical water quality and total nutrient concentrations or metallic based contaminants in groundwater. The unit used for this investigation project was a Geotech Stainless Steel bladder pump.

Low-flow bladder pump and water quality procedures

- All equipment was checked for cleanliness and washed and decontaminated before use
- All instrumentation and equipment (pumping equipment, hoses, and standing water level recorders) were decontaminated prior to and after sampling at each site location. Decontamination was conducted by firstly rinsing with a mixture of Decon-910® and scheme water. A second thorough rinse was performed using just scheme water, and then a final very thorough rinse was conducted using the standard laboratory purchased deionised water.
- New (disposable) air and water tubing were used for each sampling event.
- Water quality meters were calibrated before each period of sampling.
- Groundwater levels were dipped and recorded before sampling.
- The screen depth was identified from bore construction records and the low-flow bladder pump was lowered to midway between screened interval. When sampling a shallow bore (full length screen) the pump was lowered to 0.5 m below groundwater level.
- The air supply was connected and the water outlet tubing was connected to the instrument flow cell (Hydrolab Quanta).
- Air was applied to the pump to start pumping, with adjustments made to the air supply to achieve the desired pumping rate.
- Groundwater quality was measured for the in situ field parameters: pH, conductivity, temperature, redox and dissolved oxygen using multiprobe sensors installed in a flow cell (Hydrolab test equipment – Quanta and

multiprobe sensors). Measurements were recorded every five minutes until the parameters stabilised, then a final reading was recorded.

- Field observations of the waters were recorded during pumping, such as interesting sample colour, presence of large quantities of particulate matter, and smell.
- These results were recorded on a field observation form for submission to the Department of Water database.
- Once physical in situ field parameters had stabilised and recorded, samples were collected for laboratory analysis. All sample bottles were filled to the shoulder of the bottle leaving a small airspace at the top of the bottle.

Acid sulfate soil field test methods

Before sampling:

1. Clean, dry beakers were set up in rack designed to measure pH_F on the right and pH_{FOX} on the left.
2. pH measuring equipment was calibrated using appropriate solutions.
3. The pH was adjusted for approximately 1 L of 30% hydrogen peroxide (suitable for a day's worth of measurements) to between pH 4.5 and 5.5 using drop-wise addition of 1M NaOH.
4. Sediment cores were collected and returned to the 'field laboratory' setup to perform field tests before oxidation of sediments occurred.

Field pH_F and pH_{FOX} testing

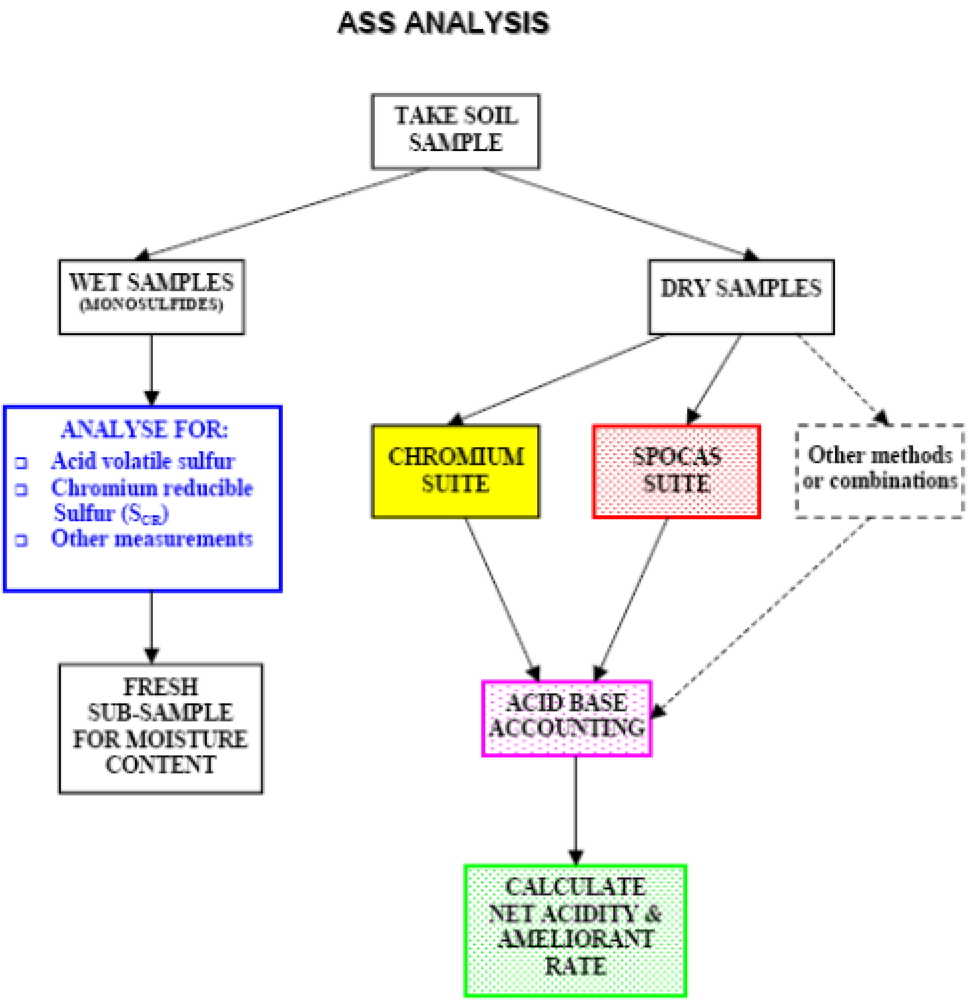
1. A ½ teaspoon sized sample of sediment was sampled approximately every 0.25 m or when a lithology change was noted (whichever was lesser), noting the depth of the sample.
2. The sample was placed into a beaker used for pH_F tests and 12 ml of water added from a clean syringe (marked pH_F) to make a 1:5 soil:water solution. This was mixed well using a clean plastic spoon.
3. A second ½ teaspoon sample of sediment was taken from the same place in the core as the previous sample and used for the pH_F measurement. This was placed into a beaker used for measuring pH_{FOX}.
4. Approximately 12 ml of pH-adjusted 30% hydrogen peroxide was added to the second beaker (marked pH_{FOX}) to make a 1:5 soil:peroxide solution, and mixed well using a clean plastic spoon.
5. The above steps where repeated until entire core had been sampled.
6. All beakers were left for approximately 1 hour (during which time logging of cores was carried out).
7. The beakers were regularly stirred (i.e. every 5 to 10 minutes) to ensure maximum amount of sediment remained mixed with the solutions.

8. After 1 hour pH_F and pH_{FOX} readings were recorded, with all pH_F measurements recorded first (to ensure no contamination with peroxide and also to allow maximum time for peroxide to react with the sediments). The pH probe was cleaned with distilled water between each reading.
9. All solutions were disposed into an appropriate container (although hydrogen peroxide rapidly decomposes to water and oxygen so was not harmful to the environment) and the beakers and other equipment thoroughly cleaned using Decon (detergent) and water.

Laboratory methods

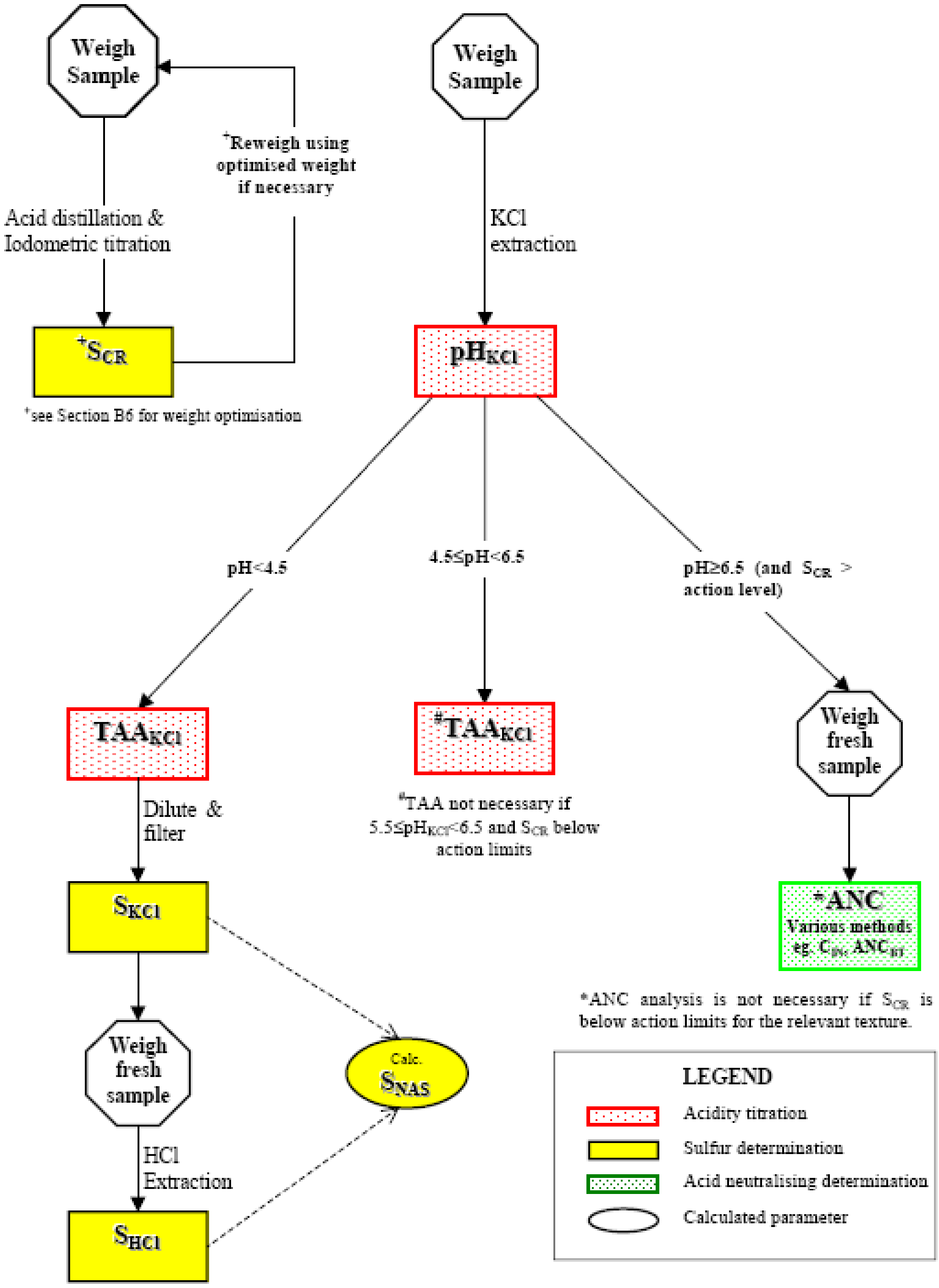
(After Ahern et al. 2004)

Flow diagram representation of overall methods followed in the quantitative analysis of acid sulfate soils. For the full method description, refer to Ahern et al. (2004).

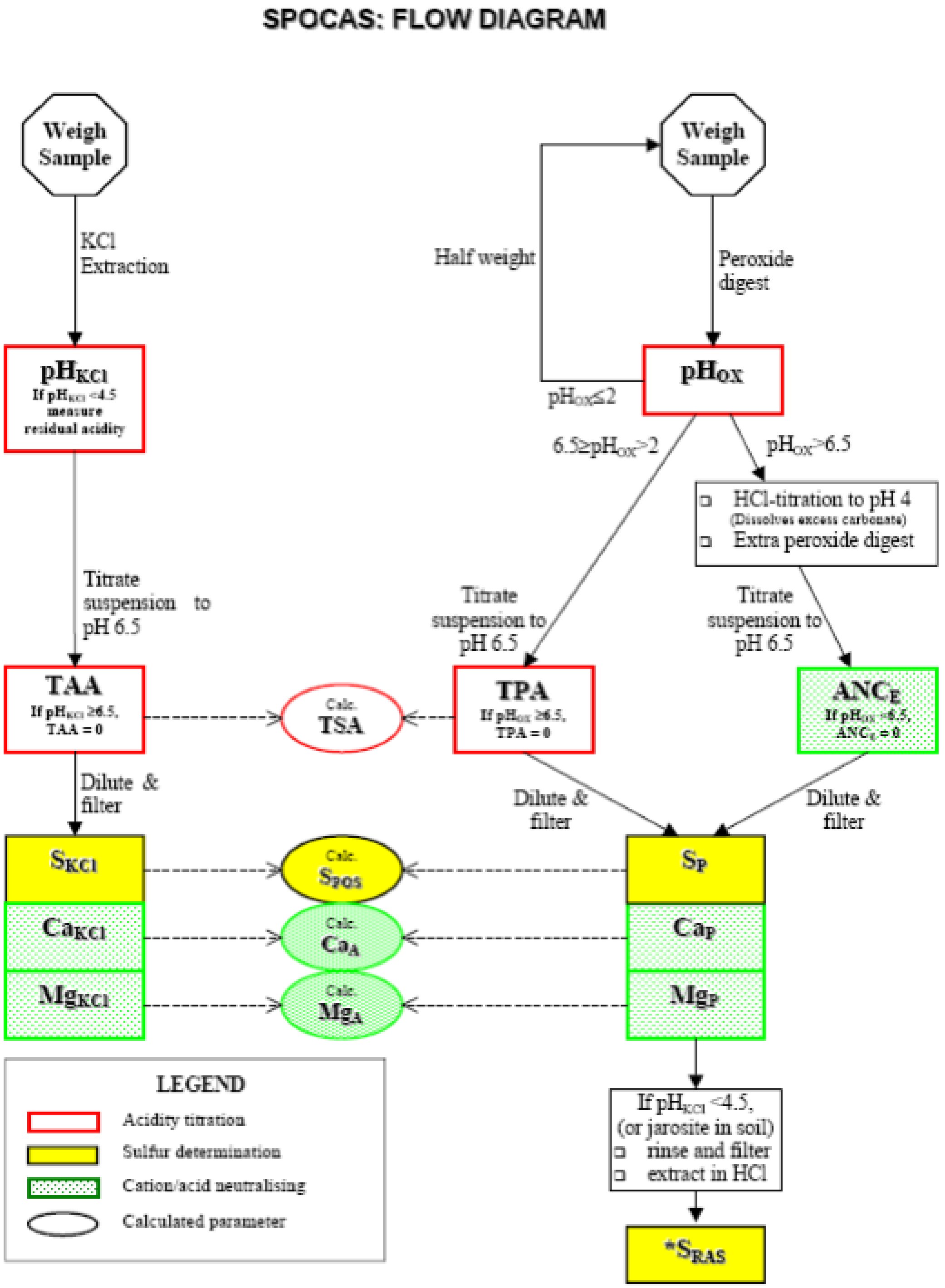


Flow diagram representation of steps followed in the chromium suite applied to the analysis of acid sulfate soils. For the full method description, refer to Ahern et al. (2004).

CHROMIUM SUITE



Flow diagram representation of steps followed in the SPOCAS method applied to the analysis of acid sulfate soils. For the full method description, refer to Ahern et al. (2004).



Appendix D — Acid sulfate soils lab and field results

Bore ID	**Soil texture**	**Field pH**			
		Depth m	**pH_F**	**pH_{FOX}**	**Δ pH**
MKB_Ec	See lithology logs in Appendix A	0.10	5.38	4.47	–0.91
		0.59	6.00	4.11	–1.89
		1.00	6.64	5.05	–1.59
		1.50	7.22	6.55	–0.67
		2.00	7.34	6.70	–0.64
		2.50	7.11	5.92	–1.19
		3.00	7.34	5.22	–2.12
		3.50	6.84	5.04	–1.80
		4.10	8.72	5.81	–2.91
		4.70	7.05	6.17	–0.88
		5.00	7.34	5.34	–2.00
		5.50	8.74	5.62	–3.12
		6.00	3.11	3.36	0.25
		6.80	7.95	8.04	0.09
		7.10	7.70	5.09	–2.61
		7.25	7.22	5.09	–2.13
		7.50	8.27	8.25	–0.02
		8.00	8.78	7.56	–1.22
		8.50	8.73	8.07	–0.66
		9.00	8.80	7.63	–1.17
		9.50	7.68	7.39	–0.29
MKB_Wc	Top soil, OM	0.00	6.40	4.60	–1.80
	Qtz sand	0.28	6.97	4.85	–2.12
	Brown silt	0.75	7.68	3.46	–4.22
	Silty, clayey sand	1.10	7.66	3.94	–3.72
	As above	1.60	7.98	2.75	–5.23
	As above	2.10	8.05	5.80	–2.25
	Sandy silty clay	2.25	7.46	8.00	0.54
	Silty clayey sand	2.45	7.66	7.21	–0.45
	As above	2.85	8.48	8.48	0.00
	As above	3.35	7.42	8.61	1.19
	Mottled silty clayey sand	3.85	9.19	8.26	–0.93
	V Dk Green / brown silty sand	4.40	6.59	2.67	–3.92
	Green grey clayey sand	4.70	8.97	8.68	–0.29
	V Dk Green / brown sand	4.90	7.74	3.89	–3.85

Bore ID	**Soil texture**	**Field pH**			
		Depth m	**pH_F**	**pH_{FOX}**	**Δ pH**
	D green grey sandy clay	5.30	8.82	8.38	–0.44
	Light brown grey M to C Qtz sand	5.80	8.64	6.23	–2.41
	as above	6.10	8.23	6.11	–2.12
	Yellow brown silty M to C Qtz sand	6.65	8.11	5.97	–2.14
	Olive silty sand	7.00	8.71	6.38	–2.33

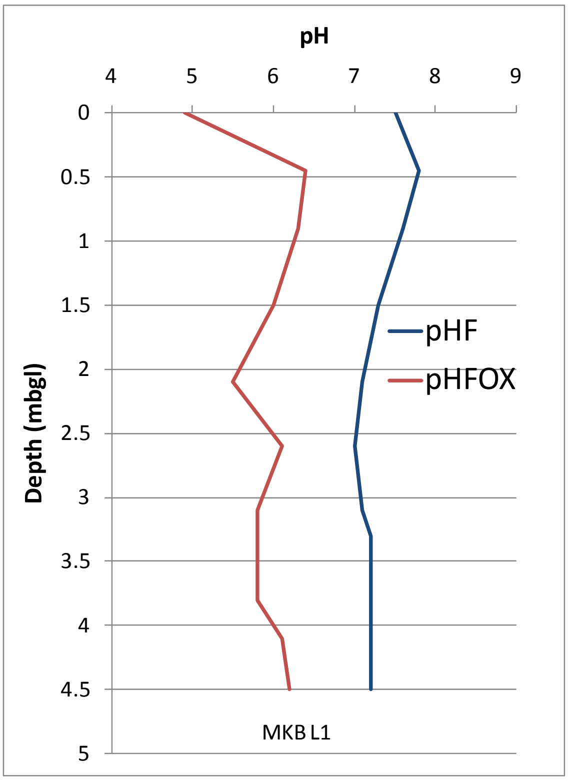
Appendix E — Water sample analysis details

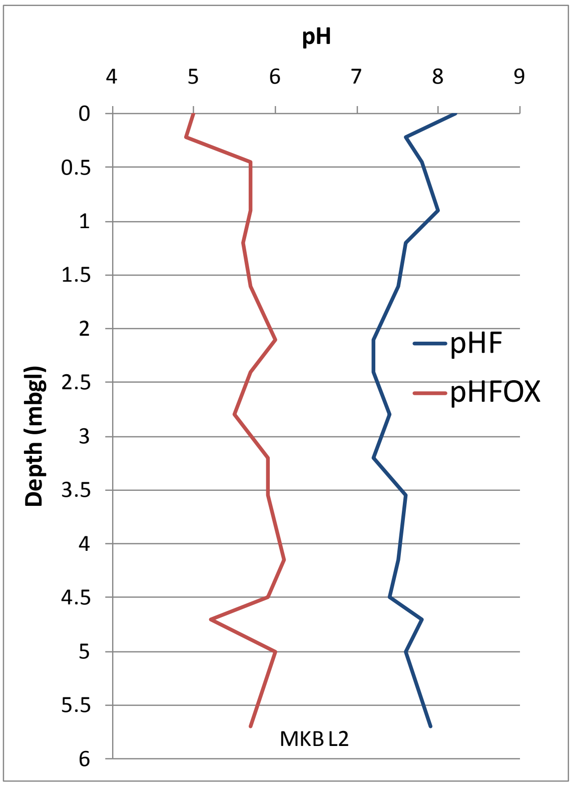
Description	**Element/ compound**	**Collection**	**Analysis method reference**	**Reporting limits**
Total metals	Hg	Direct collection	USEPA 2007, 2008	0.0001 mg/L
	Al		USEPA 2007, 2008	0.005 mg/L
	As		USEPA 2007, 2008 with hydride generation	0.001 mg/L
	Cd		USEPA 2007, 2008	0.0001 mg/L
	Cr		USEPA 2007, 2008	0.005 mg/L
	Fe		USEPA 2007, 2008	0.005 mg/L
	Mn		USEPA 2007, 2008	0.001 mg/L
	Ni		USEPA 2007, 2008	0.001 mg/L
	Se		USEPA 2007, 2008 with hydride generation	0.005 mg/L
	Zn		USEPA 2007, 2008	0.005 mg/L
Dissolved metals	Ca	On-site 0.45 µm filtration	AAS, APHA 17th Ed 3111B, D	1 mg/L
	Mg		AAS, APHA 17th Ed 3111B, D	1 mg/L
	Na		AAS, APHA 17th Ed 3111B, D	10 mg/L
	K		AAS, APHA 17th Ed 3111B, D	1 mg/L
	B		USEPA 2007, 2008	0.005 mg/L
	Fe		USEPA 2007, 2008	0.005 mg/L
	Al		USEPA 2007, 2008	0.005 mg/L
Nutrients	NH3-N	Direct collection	Autoanalyser APHA 20th Ed 4500G	0.01 mg/L
	NOx		Autoanalyser, APHA 20th Ed 4500F	0.01 mg/L
	DON		Autoanalyser, APHA 20th Ed 4500F	0.025 mg/L
	TN		Autoclave digestion and autoanalyser	0.025 mg/L
	FRP		Autoanalyser, APHA 4500-P B	0.005 mg/L
	TP		Autoanalyser, APHA 4500-P B	0.005 mg/L
Other inorganic constituents	EC	Direct collection	Conductivity meter, APHA 17th Ed 2510A, 2510B	1 mS/cm
	TDS		Gravimetry, based on APHA 2540C	10 mg/L
	TSS		Gravimetry, based on APHA 2540C	1 mg/L
	HCO3		Titration, APHA, 20th Ed 2320B	1 mg/L
	CO3,		Titration, APHA, 20th Ed 2320B	1 mg/L
	Cl		Ion chromatography APHA 4110 B	10 mg/L
	F		Ion selective electrode, APHA 19th Ed 4500-F-C	0.2 mg/L
	SO4		Ion chromatography APHA 4110 B	5 mg/L
	SiO2		Autoanalyser APHA 4500E	0.002 mg/L
	pH		pH meter, APHA 17th Ed 4500	0.1

Description	Element/ compound	Collection	Analysis method reference	Reporting limits
	Acidity		Titration, APHA, 20th Ed 2310B	1 mg/L
	Alkalinity		Titration, APHA, 20th Ed 2320B	1 mg/L
	DOC		APHA 18th Ed 5310	1 mg/L
Herbicides and pesticides	Aldrin (total)	**Direct collection**	Extraction by liquid-liquid separating funnel with dichloromethane, concentration and cleanup with GPC if required. Analysis by GC with various detectors USEPA8081, USEPA8141A, USEPA8082	0.01 µg/L
	Atrazine			0.1 µg/L
	Azinphos-ethyl (tot)			0.1 µg/L
	Azinphos-methyl (tot)			0.1 µg/L
	Bromophos-ethyl (tot)			0.1 µg/L
	Chlordane {Tech; a+g}			0.01 µg/L
	Chlordane-a (cis)			0.01 µg/L
	Chlordane-g (trans)			0.1 µg/L
	Chlorfenvinfos (Z) (tot)			0.1 µg/L
	Chlorfenvinfos (tot)			0.1 µg/L
	Chlorpyrifos (tot)			0.1 µg/L
	Chlorpyrifos-methy (tot)			0.1 µg/L
	DDD-p,p			0.01 µg/L
	DDE-p,p,			0.01 µg/L
	DDT-p,p,			0.01 µg/L
	Diazinon			0.1 µg/L
	Dimethoate			0.1 µg/L
	Dieldrin,			0.01 µg/L
	Diuron			0.1 µg/L
	Endosulf sulfate			0.01 µg/L
	Endosulf-a			0.01 µg/L
	Endosulf-b			0.01 µg/L
	Endrin aldehyde			0.01 µg/L
	Endrin ketone			0.01 µg/L

Description	**Element/ compound**	**Collection**	**Analysis method reference**	**Reporting limits**
	Enthion			0.1 µg/L
	Fenchlorphos			0.1 µg/L
	Fenitrothion			0.1 µg/L
	Fenthion			0.1 µg/L
	HCH (BHC) a,b,d,			0.01 µg/L
	HCH (BHC)			0.01 µg/L
	Heptachlor			0.01 µg/L
	Heptachlor epoxide			0.01 µg/L
	Hexachlorobenzene			0.01 µg/L
	Hexazinone			0.1 µg/L
	Linuron			0.1 µg/L
	Malathion			0.1 µg/L
	Methoxychlor			0.01 µg/L
	Metolachlor			0.1 µg/L
	Mevinphos			0.1 µg/L
	Molinate			0.1 µg/L
	Oxychlordane			0.01 µg/L
	Oxyfluorofen			0.1 µg/L
	Parathion {Ethyl par.}			0.1 µg/L
	Parathion-methyl			0.1 µg/L
	Pendimethalin			0.1 µg/L
	Pirimiphos-ethyl			0.1 µg/L
	Pirimiphos-methyl			0.1 µg/L
	Simazine			0.1 µg/L
	Tetrachlorvinphos			0.1 µg/L
	Trifluralin			0.1 µg/L

Appendix F — Lithology and field ASS test results for Lake Muckenburra lake-bed cores



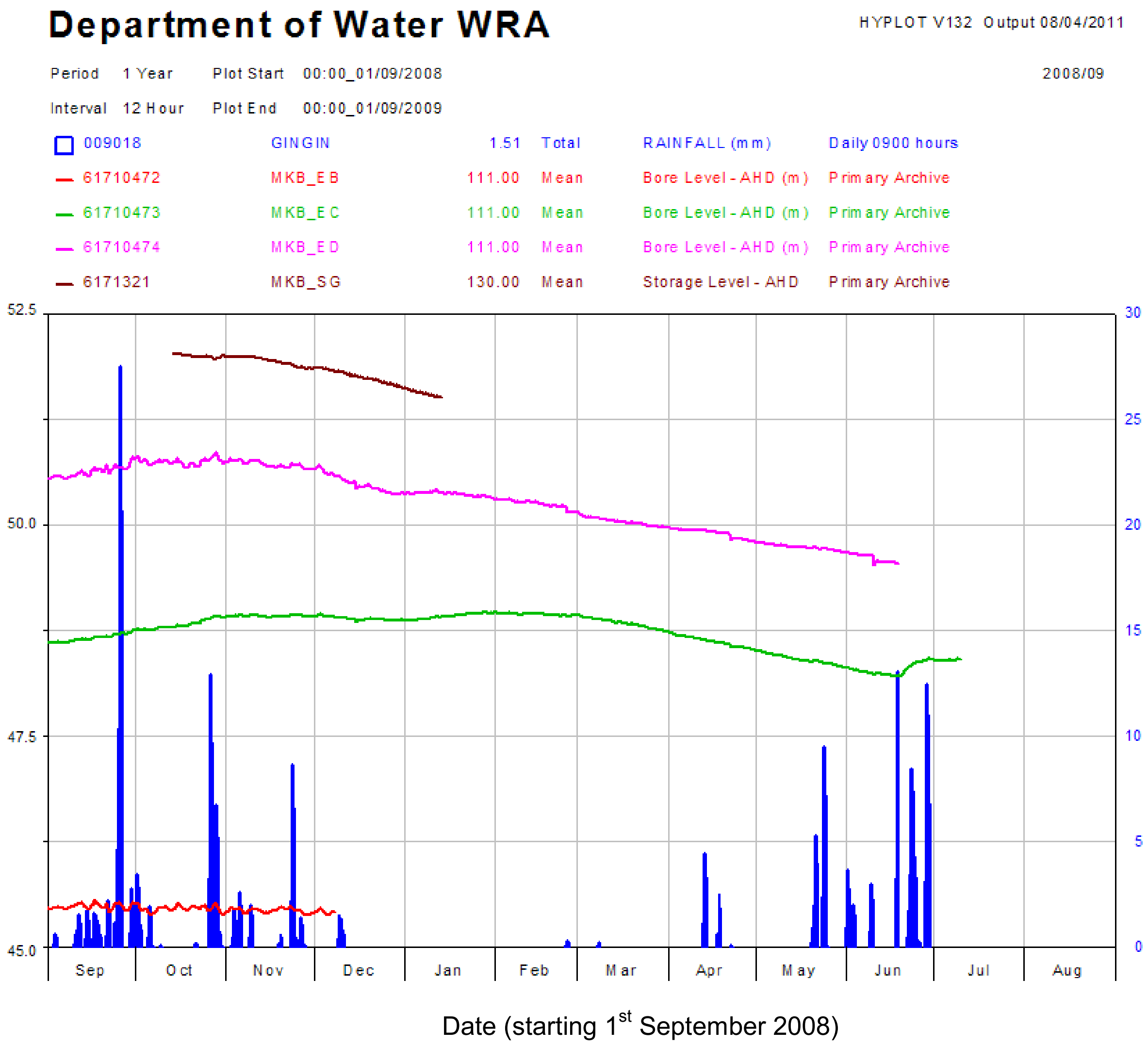


Depth m	**Summary texture**	**Lithological description (MKBL_1)**
0–0.95	Silt and silty sandy clay	Black, organic rich silt, slightly moist and very weakly consolidated transitioning to very dark grey (10YR 3/1) silty sandy clay, soft and cohesive. Laminations indicated from 0.2 to 0.35 m. Olive brown (10YR 5/4) mottles throughout sandy clay.
0.95–1.0	Silt	Black, organic rich silt with sharp boundary
1.0–2.15	Silty sandy clay	Very dark grey (10YR 3/1) silty sandy clay, soft and cohesive. Strong olive yellow (2.5Y 6/8) and olive brown (10YR 5/4) mottles.
2.15–2.20	Silt	Black, organic rich silt with sharp boundary
2.2–3.0	Silty sandy clay	Very dark grey (10YR 3/1) silty sandy clay, soft and cohesive. Strong olive yellow (2.5Y 6/8) and olive brown (10YR 5/4) mottles.
3.0–3.15	Clay	Grey (1 6/N) clay, cohesive and plastic
3.15–3.50	Silty sandy clay	Very dark grey (10YR 3/1) silty sandy clay, soft and cohesive. Strong olive yellow (2.5Y 6/8) and olive brown (10YR 5/4) mottles.
3.50–3.55	Silt	Black, organic rich silt with sharp boundary
3.55–4.5	Silty sandy clay	Very dark grey (10YR 3/1) silty sandy clay, soft and cohesive, slightly sandy, crumbly and dry in parts. Strong olive yellow (2.5Y 6/8) and olive brown (10YR 5/4) mottles intensified at 4.1 to 4.2 m.

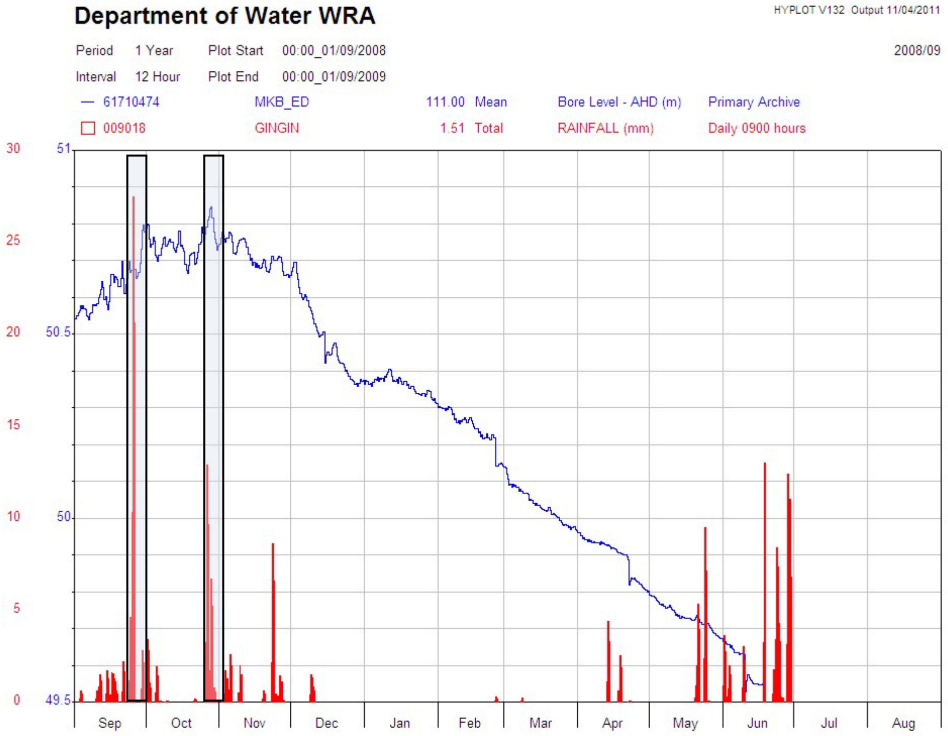
Depth **m**	**Summary texture**	**Lithological description (MKBL_2)**
0–0.4	Silt	Black (10YR 2/1), organic rich silt, very slightly moist, crumbly with fibrous roots. Minor sand component.
0.4–1.1	Silty clayey sand	Black (10YR 2/1) grading to dark grey brown (2.5 Y 4/2) and olive yellow (2.5 Y 6/6) silty, clayey sand, medium to course quartz. Gradual transition from overlying silt at 0.4 m. Thin lenses (<0.05 m) of sandy clays throughout.
1.1–1.2	Sand	Dark grey (2.5 Y 4/1) medium to course quartz sand.
1.2–2.4	Silty clayey sand	Dark grey brown (2.5 Y 4/2) and olive yellow (2.5 Y 6/6) silty, clayey sand, medium to course quartz sand. Thin lenses (<0.05 m) of sandy clays throughout.
2.4–3.0	Clay and silty sand	Clay grading to silty sand. Very slightly moist to dry. Crumbly, very weakly cohesive. Strong olive yellow (2.5 Y 6/8) mottles from 3.0 to 3.2 m.
3.0–3.8	Silty sand	Yellowish brown (10YR 5/6) silty sand more clayey in parts.
3.8–5.0	Silty sand and silty clayey sand	Dark grey (2.5 Y 4/1) silty sand and silty clayey sand. Medium to course quartz sand. Stiff, crumbly, slightly moist to dry. Strong yellow mottling at 4.0 m.
5.0–5.7	Silty sand and silty clayey sand	Grey brown (2.5 Y 5/2) silty sand and silty clayey sand. Very stiff and cohesive. Crumbly in parts where less clayey. Strong brown (2.5 Y 5/6) mottling throughout.

Appendix G — Continuous water levels for selected groundwater bores at Lake Muckenburra, lake water levels and rainfall (recorded at Gingin)

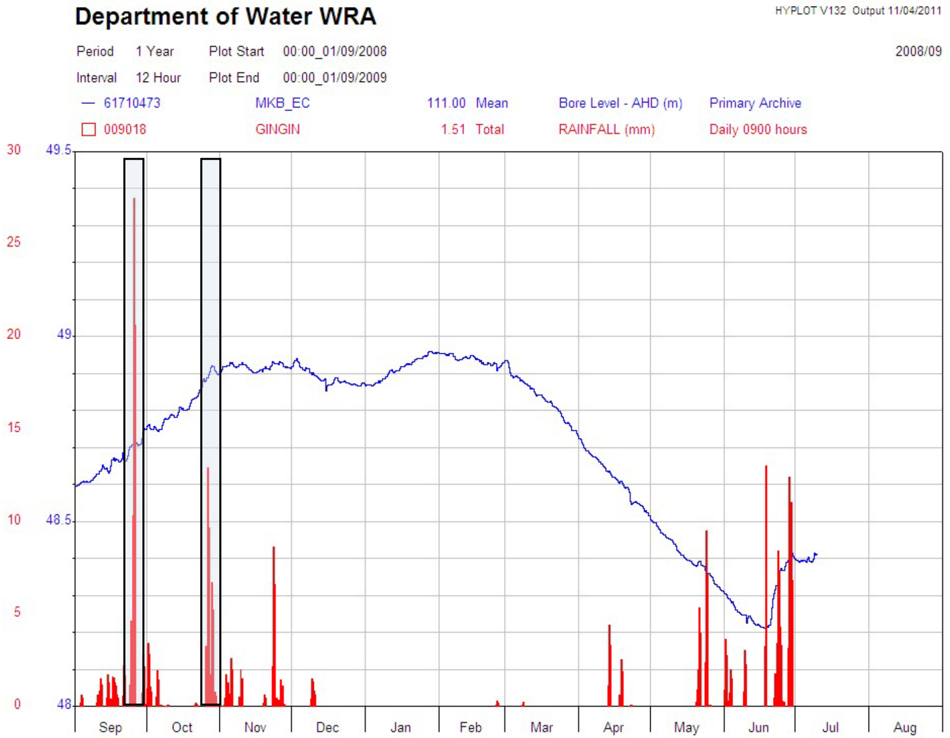
Full monitoring period



Groundwater responses of perched groundwater and shallow Superficial in relation to selected rainfall events (at Gingin)



Date (starting 1st September 2008)



Date (starting 1st September 2008)

Shortened forms

AASS	Actual acid sulfate soil
ABA	Acid-base accounting
ANC	Acid neutralising capacity
ASS	Acid sulfate soil
AWRC	Australian Water Resources Commission
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
EC	Electrical conductivity
Eh	Redox potential
EIL	Ecological investigation limit
EPP	Environmental protection policy
FRP	Filterable reactive phosphorus
GDE	Groundwater-dependent ecosystem
GSS	Gnangara Sustainability Strategy
mbgl	Metres below ground level
NH_4-N	Nitrogen present as ammonia
NOx	Nitrogen present as oxidised inorganic forms (nitrate and nitrite)
ORP	Oxidation–reduction potential
PASS	Potential acid sulfate soil
SGS	Shallow groundwater systems (investigation)
TAA	Titratable actual acidity
TDS	Total dissolved salts

TEC	Threatened ecological community
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids

References

Ahern, CR, McElnea, AE & Sullivan, AE 2004, *Acid sulfate soils laboratory methods guidelines*, Queensland Department of Natural Resources, Mines and Energy, Indooroopilly, Queensland, Australia.

ANZECC & ARMCANZ 2000, *Australia and New Zealand guidelines for fresh and marine water quality,* Australia and New Zealand Environment and Conservation Council and Agricultural and Resource Management Council of Australia and New Zealand.

Appelo, CAJ. & Postma, D 2005, *Geochemistry, groundwater and pollution*, 2nd edition, AA Balkema Publishers, Leiden, The Netherlands.

Appleyard, S & Cook, T 2008, 'Reassessing the management of groundwater use from sandy aquifers with climate change and population increase: acidification and calcium depletion exacerbated by drought, groundwater withdrawal and land use practices on the Gnangara Mound, Western Australia', *Hydrogeology journal*, vol. 17, pp. 579–88.

Appleyard, SJ, Angeloni, J & Watkins, R 2006, 'Arsenic-rich groundwater in an urban area experiencing drought and increasing population density, Perth, Australia', *Applied geochemistry,* vol. 21, pp. 83–97.

Bell, RW 1999, 'Boron', in: KI Peverill, LA Sparrow & DJ Reuter (eds), *Soil analysis: an interpretation manual,* CSIRO Publishing, Collingwood, Victoria, pp. 309 – 17.

Brunner, P, Cook, PG & Simmons, C T 2010, 'Disconnected surface water and groundwater: from theory to practice', *Groundwater*, vol. 49, DOI: 10.1111/j.1745-6584.2010.00752.x.

Bureau of Meteorology 2011, *Climate data online for Gingin townsite station 009018,* Bureau of Meteorology, viewed January 2011, <www.bom.gov.au/climate/data>.

Cargeeg, GC, Boughton, GN, Townley, LR, Smith, GR, Appleyard, SJ & Smith, RA 1987, *Perth urban water balance study,* Water Authority of Western Australia publication, Volume 1, Water Authority of Western Australia, Perth.

Corrales, I & Barceló, J 2008, 'A glance into aluminium toxicity and resistance in plants', *Science of the total environment*, vol. 400, pp. 356–68.

Davidson, WA 1995, *Hydrogeology and groundwater resources of the Perth Region,* Western Australia, Bulletin 142, Geological Survey of Western Australia, Perth.

Davis, JA, Rosich, RS, Bradley, JS, Growns, JE, Schmidt, LG & Cheal, F 1993, *Wetland classification on the basis of water quality and invertebrate community data,* Wetlands of the Swan Coastal Plain series, vol. 6, Water and Rivers Commission. Perth.

De Silva, J 2009, *Perth region aquifer modelling system (PRAMS) scenario modelling for the Gnangara Sustainability Strategy,* Hydrogeological record series report no. HG39, Department of Water, Perth.

Degens, BP 2006, *Metadata statement for 1:50 000 acid sulfate soil risk map – Swan Coastal Plain*, Department of Environment, Perth.

Department of Environment and Conservation 2009a, *Identification and investigation of acid sulfate soils and acidic landscapes,* Acid sulfate soils guideline series, Department of Environment and Conservation, Perth.

—— 2009b, *Treatment and management of soils and water in acid sulfate soil landscapes,* Acid sulfate soils guideline series, Department of Environment and Conservation, Department of Environment and Conservation, Perth.

—— 2009c, Gnangara Sustainability Strategy, Biodiversity Values and threatening Processes of the Gnangara Groundwater System, Department of Environment and Conservation, Department of Environment and Conservation, Perth.

—— 2010, *Assessment levels for soil, sediment and water,* Contaminated sites management series, version 4, revision 1, Department of Environment and Conservation, Perth.

Department of Health 2006, *Contaminated sites reporting guideline for chemicals in groundwater,* viewed March 2011, <www.public.health.wa.gov.au/cproot/1368/2/Contaminated%20sites%20Ground%20Water%20Guideline%20%20FinalSep06%20(2).pdf>.

Department of Water 2008, *Review of the Ministerial conditions on the groundwater resources of the Gnangara Mound*, Department of Water, Perth.

—— 2009a, *Gnangara sustainability strategy Appendix 1 – Gnangara groundwater system zone plans,* Department of Water, Perth.

—— 2009b, *Gnangara groundwater areas allocation plan,* Water resource allocation and planning series, report no. 30, Department of Water, Perth.

Descourvieres, C, Douglas, G, Leyland, L, Hartog, N & Prommer, H 2011, Geochemical reconstruction of the provenance, weathering and deposition of detrital-dominated sediments in the Perth Basin: The Cretaceous Leederville Formation, south-west Australia, *Sedimentary geology*, vol. 236, pp. 62–76.

Fältmarsch, RM; Åström, ME & Vuori, KM 2008, ‘Environmental risks of metals mobilised from acid sulfate soils in Finland: A Literature Review’, *Boreal environmental research,* vol. 13, pp. 444–56.

Froend, R & Loomes, R 2004, *Approach to determination of ecological water requirements of groundwater-dependent ecosystems in Western Australia,* report to the Department of Environment, Edith Cowan University, Joondalup.

—— Loomes, R, Horwitz, P, Rogan, R, Lavery, P, How, J, Storey, A, Bamford, M & Metcalf, B 2004a, *Study of ecological water requirement on the Gnangara and Jandakot mounds under section 46 of the Environmental Protection Act – Task 1: identification and re-evaluation of ecological values,* report to the Water and Rivers Commission, Centre for Ecosystem Management, Edith Cowan University, Joondalup.

—— Loomes, R, Horwitz, P, Bertuch, M, Storey, A & Bamford, M 2004b, *Study of ecological water requirement on the Gnangara and Jandakot mounds under section 46 of the Environmental Protection Act – Task 2: determination of ecological water requirements,* report to the Water and Rivers Commission, Centre for Ecosystem Management, Edith Cowan University, Joondalup.

—— Rogan, R, Loomes, R, Horwitz, P, Bamford, M & Storey, A 2004c, *Study of ecological water requirements on the Gnangara and Jandakot mounds under section 46 of the Environmental Protection Act – Tasks 3 & 5: parameter identification and monitoring program review,* report to the Water and Rivers Commission, Centre for Ecosystem Management, Edith Cowan University, Joondalup.

Gibson, N, Keighery, BJ, Keighery, G J. Burbidge, AH & Lyons, MN 1994, *A floristic survey of the Southern Swan Coastal Plain,* unpublished report for the Australian Heritage Commission, CALM and Conservation Council of Western Australia, Perth.

Gozzard, JR 2007, *Geology and landforms of the Perth Region,* Geological Survey of Western Australia, Perth.

Hall, J, Kretschmer, P, Quinton, B & Marillier, B 2010, *Murray hydrological studies: surface water, groundwater and environmental water – land development, drainage and climate scenario report,* Water science technical series, report no. 26, Department of Water, Perth.

Hill, AL, Semeniuk, CA, Semeniuk, V, & Del Marco, A 1996, *Wetland mapping, classification and evaluation – Wetland atlas,* Wetlands of the Swan Coastal Plain series, volume 2b, Water and Rivers Commission, Perth.

Hingston FJ & Gailitis V 1976, 'The geographic variation of salt precipitated over Western Australia', *Australian journal of soil research,* vol. 14, pp. 319–35.

Horwitz, P & Judd, S 2009b, *Annual report for the Wetland Macroinvertebrate Monitoring Program of the Gnangara Mound Environmental Monitoring Project Spring 2008 to Summer 2009,* Centre for Ecosystem Management, Edith Cowan University, Joondalup.

—— Sommer, B & Froend, R 2009a, 'Chapter Four: Wetland and Groundwater-Dependent Ecosystems' in BA Wilson & L Valentine (eds), *Biodiversity Values and Threatening Processes of the Gnangara Groundwater Syst*ems, Department of Environment and Conservation, Government of Western Australia, Perth.

Hounslow, AR 1995, *Water quality data: analysis and interpretation,* CRC Press, Boca Raton, Florida.

Judd, S & Horwitz, P 2010, *Annual report for the Wetland Macroinvertebrate Monitoring Program of the Gnangara Mound Environmental Monitoring Project Spring 2009 to Summer 2010,* Centre for Ecosystem Management, Edith Cowan University, Joondalup.

Jurgens, BC, McMahon, PB, Chapelle, FH & Eberts, SM 2009, *An Excel® workbook for identifying redox processes in ground water*, USGS Open-File Report 2009-1004, U.S. Geological Survey, Reston, Virginia, viewed November 2011, <http://pubs.usgs.gov/of/2009/1004>.

Kilminster, K & Cartwright, I 2011, 'A sulfur-stable-isotope-based screening tool for assessing impact of acid sulfate soils on waterways', *Marine and freshwater research*, vol. 62, pp. 152–161.

Martin, RE & Harris, PG 1982, *Hydrogeochemical study of groundwater from an unconfined aquifer in the vicinity of Perth, W.A.,* Technical paper no. 67, Australian Water Resources Council, Canberra.

McArthur, WM & Bettenay, E 1960, *The development and distribution of the soils of the Swan Coastal Plain, Western Australia*, CSIRO Australian Soils, Publication no. 16.

McDonald, E, Coldrick, B, & Villiers, L 2005, *Study of groundwater-related Aboriginal cultural values on the Gnangara Mound, Western Australia*, report for the Department of Environment, Perth.

McHugh, SL & Bourke, SA 2007, *Management area review: shallow groundwater systems on Gnangara and Jandakot mounds,* Hydrogeological record series report no. HG25, Department of Water, Perth.

Moncrieff, JS & Tuckson, M, 1989, *Hydrogeology of the superficial formations between Lancelin and Guilderton*, Western Australia Geological Survey, Professional papers, report 25, pp. 39–57.

Neculita, CM, Zagury, GJ, & Bussiere, B 2007, 'Passive treatment of acid mine drainage in bioreactors using sulfate-reducing bacteria: critical review and research needs', *Journal of environmental quality*, vol. 36, pp. 1–16.

NHMRC &NRMMC 2004, *Australian drinking water guidelines,* National Health and Medical Research Council and Natural Resource Management Ministerial Council, Canberra.

Nordstrom, DK & Ball, JW 1986, 'The geochemical behaviour of aluminium in acidified surface waters', *Science*, vol. 232, pp. 54–6.

Petrone, KC, Richards, JS, & Grierson, PF 2008, 'Bioavailability and composition of dissolved organic carbon and nitrogen in a near coastal catchment of south-western Australia', *Biogeochemistry*, vol. 92, pp. 27–40.

Pigois, JP 2011, *Geology of the North Gnangara Mound,* Hydrogeological record series report no. HG55, Department of Water, Perth.

Searle, J 2009, *Bore completion report for the Shallow Groundwater System Investigation Stage 2,* Hydrogeological record series, report no. HR276, Department of Water, Perth.

Slattery, WJ, Conyers, MK & Aiken, RL 1999, 'Soil pH, aluminium, manganese and lime requirement', in: Peverill, KI, Sparrow, LA and Reuter, DJ. (eds.), *Soil* *analysis: an interpretation manual,* CSIRO Publishing, Collingwood, Victoria, pp. 103–28.

Sommer, B & Horwitz, P 2009, 'Macroinvertebrate cycles of decline and recovery in Swan Coastal Plain (Western Australia) wetlands affected by drought-induced acidification', *Hydrobiologia*, vol. 624, pp. 191–9.

Sullivan, LA, Fitzpatrick, RW, Bush, RT, Burton, ED, Shand, P & Ward, NJ 2010, *Modifications to the classification of acid sulfate soil materials*, Southern Cross GeoScience technical report no. 309, Southern Cross University, Lismore, New South Wales.

Swedish Environmental Protection Agency 2007, *Environmental quality criteria for groundwater*. Swedish EPA report no. 5051, viewed November 2011, <www.naturvardsverket.se/en/In-English/Start/State-of-the-environment/Environmental-quality-criteria/Publications-on-environmental-quality-criteria>.

Townley, LR & Trefry, MG 2000, 'Surface water–groundwater interaction near shallow circular lakes: flow geometry in three dimensions', *Water resources research*, vol. 36, pp. 935–49.

—— Turner, JV, Trefry, MG & Barr, AD 1991, 'Groundwater flow patterns near lakes and wetlands: modelling and field validation', in *Proceedings of the International Hydrology and Water Resources Symposium 1991*, Perth.

Wilson, J, Cullinane, T & Froend, R 2009, *Wetland vegetation monitoring 2008 – survey of Gnangara wetlands*, *CEM report no. 2009-08,* report for the Department of Water, Centre for Ecosystem Management, Edith Cowan University, Joondalup.

Wright, G 2007a, *Scoping report – Indigenous heritage,* Perth Shallow Groundwater Systems Project, Department of Water, Perth.

—— 2007b, *Ethnographic report - – Indigenous heritage survey – Yued native title claim* group, Perth Shallow Groundwater Systems Project, Department of Water, Perth.

Yesertener, C 2008, *Assessment of the declining groundwater levels in the Gnangara Groundwater Mound,* Hydrogeological record series report no. HG14, Department of Water, Perth.

—— C 2010, *Hydrogeochemical assessment of the Superficial aquifer: Perth metropolitan area,* Hydrogeological record series report no. HG37, Department of Water, Perth.

Department of **Water**
168 St Georges Terrace, Perth, Western Australia
PO Box K822 Perth Western Australia 6842
Phone: 08 6364 7600
Fax: 08 6364 7601
www.water.wa.gov.au

7405 17 0112