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

Looking after all our water needs

Perth Shallow Groundwater Systems Investigation

Lake Mariginiup

Hydrogeological record series

Report no. HG36
July 2010

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Cover photographs: Lake Mariginiup wetland vegetation (Photo courtesy of Edith Cowan University)

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Preface

This report is based on work carried out as part of the Perth shallow groundwater systems investigation. This is a four-year (2007–10) investigation program being 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 is focused on the many wetlands situated on Gnangara and Jandakot groundwater mounds, the most significant sources of groundwater for the Perth metropolitan area. The groundwater mounds also sustain numerous ecosystems that depend on shallow groundwater. Many of these ecosystems are currently 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 and Bourke 2007). This review summarised the current monitoring and management issues facing selected wetlands on Gnangara and Jandakot mounds, and identified the information and data required to address these issues. The report recommended an investigation program that incorporates up to 30 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 Mariginiup is one of the 28 sites in the Perth shallow groundwater system investigation. In June 2007, the monitoring network at the site was upgraded by installing a cluster of groundwater monitoring bores along the western margin of the lake. A comprehensive 12-month sampling program of these and existing bores have improved understanding of the hydrogeological functioning of the lake.

Previous investigations describe Lake Mariginiup as a through flow lake with significant connection with groundwater flow of the Gnangara Mound and interaction with over half of the Superficial aquifer for most of the year. However, since the late 1960s, groundwater and lake levels have declined such that the lake is now dry for more than six months a year and maximum water levels in winter have been reduced. Groundwater flow is now in weak connection with the lake and interacts with less than one-third of the Superficial aquifer.

In the drier months, for around six months of the year, the lake is no longer in hydraulic connection with the groundwater. Historically, groundwater levels on the western (down-gradient) side of the lake have been very similar to the lake level, However, with the decrease in regional groundwater levels there has been an increasing difference between groundwater and lake levels, as well as lag between the peak lake water and groundwater levels. This suggests that the recharging of groundwater by lake water on the western side of the lake is impeded by low permeability organic rich silty sediments.

The increasing difference between groundwater and lake levels at Lake Mariginiup shows that measuring the Ministerial criteria at the staff gauge may become impossible. Alternatively, bore MS10 should be used to measure the Ministerial criteria when the lake is dry. However, because of the increasing detachment of the watertable, a revised level of 41.14 m AHD is recommended. When comparing groundwater levels to vegetation at the transect, newly established bore MGP_c should be used.

The regional decline of the watertable and the changes in the interaction between surface water and groundwater at Lake Mariginiup have affected the chemistry of both groundwater and lake water. These hydrogeochemical changes are associated with several factors.

- The progressive drying of podsolised soils to the east of Lake Mariginiup has increased the solubility of aluminium and acidity stored in the soils. The increased flow of groundwater through these soils, due to pine plantation clearing, is likely to have flushed the aluminium and other metals towards the lake. Groundwater discharging into Lake Mariginiup from the east has the lowest recorded pH of all bores in the sampling program and concentrations of aluminium, zinc and nickel are well above the Department of Environment's freshwater ecosystem trigger levels (DoE 2003). The dilution effect of groundwater with lower metal concentrations discharging into the lake is lost because less of the regional groundwater flow interacts with the lake, compared to historical times.

- The lake bed sediments contain actual and potential acid sulfate soils with little buffering capacity. The net acidity of lake bed sediments at Lake Mariginiup range from an average of over 1000 mol H^+/t at the surface, to 300 – 400 mol H^+/t at depth. These values greatly exceed the Department of Environment and Conservation's action criteria (DEC 2009) of 18.7 mol H^+/t and suggest further oxidation of sediments will produce large quantities of acidity, which will in turn release more metals to the regional groundwater.
- Oxidation of acid sulfate soils identified within the lake basin is caused by the exposure of the lake bed and by elevated concentrations of nitrate. This has led to Lake Mariginiup, once considered being at risk of acidification, now being permanently acidic, with elevated concentrations of numerous metals and nutrients. Ammonium (NH_4^+), total nitrogen (TN) and total phosphorus (TP) exceed trigger levels for freshwater ecosystems and wetlands in south-western Australia.
- The chemistry of shallow groundwater flowing westwards from the lake is mainly influenced by rainfall and has little interaction with lake water. This is presumably due to the low permeability of lake bed sediments. However, high levels of sulfate ($SO_4^{2-)}$ and iron (Fe) and high ratios of sulfate to chloride (SO_4^{2-}/Cl^-) are indicative of acid sulfate soils oxidation in this area.
- The deeper groundwater flowing downwards from Lake Mariginiup is progressively enriched in calcium ($Ca^{2+)}$, magnesium ($Mg^{2+)}$, total dissolved solids and sulphate ($SO_4^{2-)}$ suggesting that base cation depletion is occurring in the sediment profile beneath the lake.

The hydrogeochemical changes at Lake Mariginiup have resulted in deterioration of the health of the ecosystems associated with it. Major changes include the enchroachment of sedge species into the wetland basin, reduced waterbird wading habitat and declining family richness of macroinvertebrates. Poor water quality is probably the most immediate threat to the system, with water quality below many ANZECC (2000) guidelines.

In order to improve the ecological condition at Lake Mariginiup, water levels need to increase. Local scale numerical modelling has shown that this may occur over the next 30 years under a scenario of pine plantation clearing combined with urbanisation. Under this scenario, water levels would be above absolute minimum Ministerial criteria by about 2014 and there may be some improvement to the macroinvertebrate and waterbird communities and the current vegetation structure may persist. However, this will largely depend on whether the system can survive in its current state until water levels improve. It will also depend on whether water quality improves, which is uncertain. Even if the watertable rises, there is a risk of mobilising heavy metals. Modelling using the PHREEQC geochemical modelling program could give a better understanding of these processes.

It is possible that decreased groundwater abstraction (as prescribed in the *Gnangara water allocation plan*) will further improve water levels in the area. However, it is also possible that these gains may be negated by a further decreasing rainfall sequence. Further modelling of alternative allocation and climate scenarios is required.

The following recommendations are made in this report:

- Continue to endorse the Forest Products Commission pine harvesting schedule, but with the inclusion of water chemistry monitoring of the watertable. This is because, to improve the ecological condition of Lake Mariginiup, water levels need to increase, and this is most likely to be achieved under the combined pine plantation clearing and urbanisation scenario.
- Support the development of water sensitive urban design in the East Wanneroo area.
- Measure the Ministerial criteria level at bore MS10 when the lake is dry. The revised level of 41.14 m AHD should be used.
- Measure groundwater levels at the newly installed bore MGP_c when relating the watertable to the ecological condition of the vegetation transect.
- Develop hydrogeochemical triggers and management actions for the next water reform plan and initiate a hydrochemical monitoring program for the bore MGP_c site. It is recommended that quarterly hydrochemical sampling (major ions, metals, nutrients) and analysis should be undertaken at bores MGP_c, MGP_b, MGP_a, and MT1S. Monthly hydrochemical sampling of the lake should be undertaken when surface water is present.
- Review data from the hydrochemical monitoring program every two years to assess whether management objectives set out in this plan are being met and whether trigger levels need improvement.
- Inform irrigators of the potential effects of high concentrations of heavy metals in groundwater around Lake Mariginiup.
- Reduce private abstraction in the area by 20%, as per the *Gnangara groundwater areas allocation plan* (DoW 2009a).
- Undertake further local area modelling and include drier climate and reduced abstraction scenarios. Further chemical modelling of acidification processes is also required.

1 Context and objectives

Lake Mariginiup is a 'conservation category' wetland (Hill et al. 1996) and Ministerial criteria site (EP Act 1986). In 1988 water level criteria were established at the lake to protect its high water quality, rich aquatic fauna and wading waterbird habitat (WAWA 1995). However, due to a combination of land use, abstraction and climate, water levels have been declining at the wetland since the mid 1970s and have been below Ministerial criteria levels since 1995. The lake has also been affected by fire, physical disturbances and invasion of exotic species. These factors have caused a decline in the lake's ecological condition. The most notable ecological impacts have been terrestrialisation and deteriorating water quality. The wetland is also at severe risk of acidification due to declining water levels and the drying of the lake bed. Water levels are now below the recommended ecological water requirement (EWR) for sediment processes (Froend *et. al.* 2004).

The *Management area review of shallow groundwater systems on Gnangara and Jandakot mounds* (McHugh and Bourke 2007) considered that the decline in water levels and ecological condition was severe enough at Lake Mariginiup to warrant a local area hydrogeological investigation. The review also highlighted the need to investigate the current Ministerial criteria bore (MS10) as a suitable representation of the relationship between water level and ecological condition.

The management area review and the most recent *Review of Ministerial conditions on the Gnangara Mound* (DoW 2008) recommended that site-specific data be collected and analysed to determine the current status of the groundwater–surface water connectivity and groundwater quality and flow into and out of the Lake Mariginiup wetland. It was also recommended that the investigation include the installation of a new shallow monitoring bore at the vegetation transect.

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

- upgrade the groundwater monitoring network
- improve the department's understanding of how Lake Mariginiup functions hydrogeologically
- determine the distribution of acid sulfate soils in and around the lake, and their effects on water chemistry
- link the hydrogeological and chemical understanding with ecological water requirements and determine the implications for ecological values of the lake
- outline the implications of change in water and land use based on groundwater flow modelling results
- highlight the water and land-use issues to be addressed in the water management plan for the Gnangara Mound due in 2012.

2 Background

2.1 Location and climate

Lake Mariginiup is located on the Gnangara Groundwater Mound, approximately 25 km north of the Perth CBD, and 3 km north-east of Wanneroo in Western Australia (Figure 1).

The Swan Coastal Plain experiences a Mediterranean type climate with hot, dry summers and mild, wet winters. Rainfall occurs mainly between May and September. The annual rainfall recorded from the closest monitoring station to Lake Mariginiup, Wanneroo, over a 100-year period (1907 to 2007) shows a declining trend (Figure 2). Figure 2 also shows the long-term (819 mm), medium-term (741 mm) and short-term (744 mm) average rainfall.

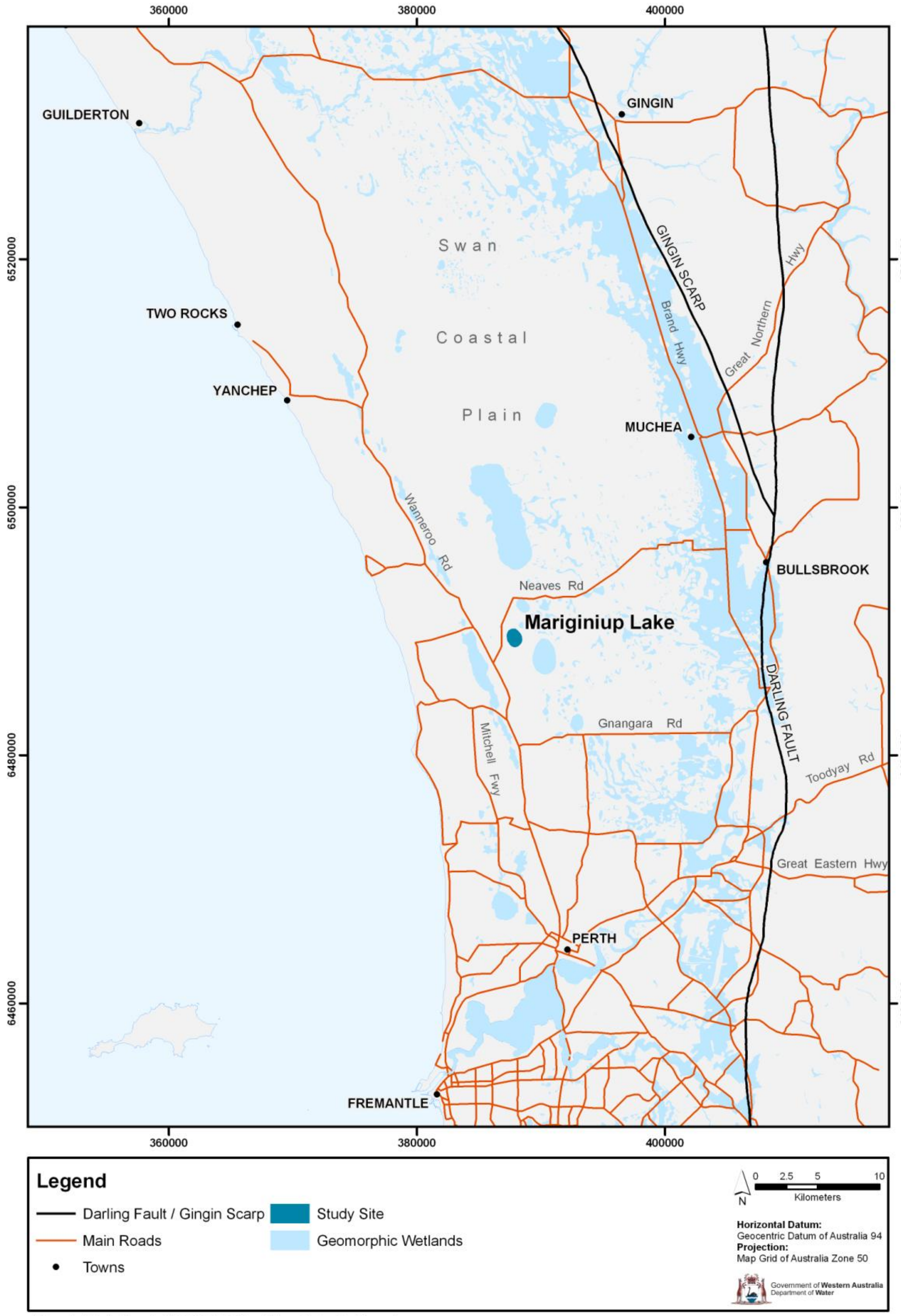
2.2 Geology and geomorphology

2.2.1 Regional geology and geomorphology

Lake Mariginiup is located on the Swan Coastal Plain, within the Perth Basin. The Swan Coastal Plain is bounded to the east by the Darling and Gingin scarps, and by the Indian Ocean to the west (Figure 3). It is composed of a series of sedimentary units termed the superficial formations.

In the Perth region, the superficial formations correspond to four geomorphic units which trend sub-parallel to the present day coast. 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 2007). Lake Mariginiup is situated at the interface between the Spearwood Dunes in the west and Bassendean Dunes in the east (Davidson 1995). It is a circular lake of the Gnangara suite (Hill et al. 1996).

The superficial formations are a collective term for the late Tertiary to Quaternary age sediments which range in thickness from 20 to 100 m (Rockwater 2003). The formations include (in order of deposition) the Ascot Formation, Yoganup Formation, Guildford Clay, Gnangara Sand, Bassendean Sand, Tamala Limestone, Becher Sand and Safety Bay Sand (Davidson 1995). These formations consist of sand, silt, clay and limestone in varying proportions, and are the surficial material over most of the Swan Coastal Plain. Davidson (1995) and Moncrieff and Tuckson (1989) have described the lithology in detail. Lake Mariginiup lies at the interface between the Bassendean Sands and the Tamala Limestone which are both underlain by the Poison Hill Greensand.



J:\gisprojects\Project\A_series\A3003\0081_SGS\mxd\Figure 1 - Location Map.mxd

Figure 1 Location of Lake Mariginiup

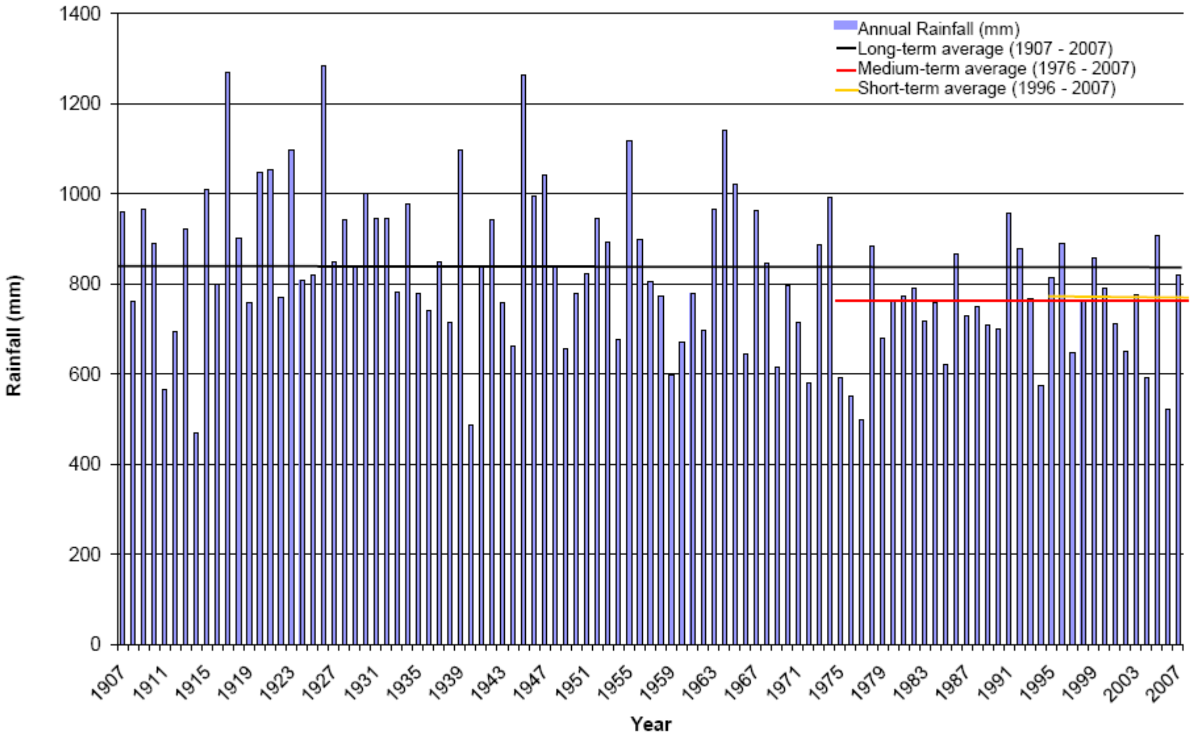


Figure 2 Annual rainfall for Wanneroo showing long-term, medium-term and short-term averages

2.2.2 Acid sulfate soils

Lakes and wetlands on the Swan Coastal Plain are often associated with acid sulfate soils. Acid sulfate soils are naturally occurring soils formed under waterlogged conditions that contain iron sulfide minerals (e.g. pyrite) or their oxidation products. When exposed to air, due to the lowering of the watertable, the sulfides in these soils oxidise generating sulfuric acid and releasing iron and other associated metals into the soil and groundwater (Fältmarsch et al. 2008). The resulting acidity then has the potential to mobilise other metals from the sediment profile into the groundwater flow system.

The term acid sulfate soils includes both potential and actual acidity. Potential acid sulfate soil refers to the sediments which are still waterlogged or unoxidised. Actual acid sulfate soil refers to sediments which have been exposed to air and have produced acidity. Oxidation is commonly caused by lowering of the watertable (Ahern et al. 2004).

Lake Mariginiup is at risk of acidification due to the exposure of acid sulfate soils and declining water levels in the area (McHugh and Bourke 2007; Benier and Horwitz 2003).

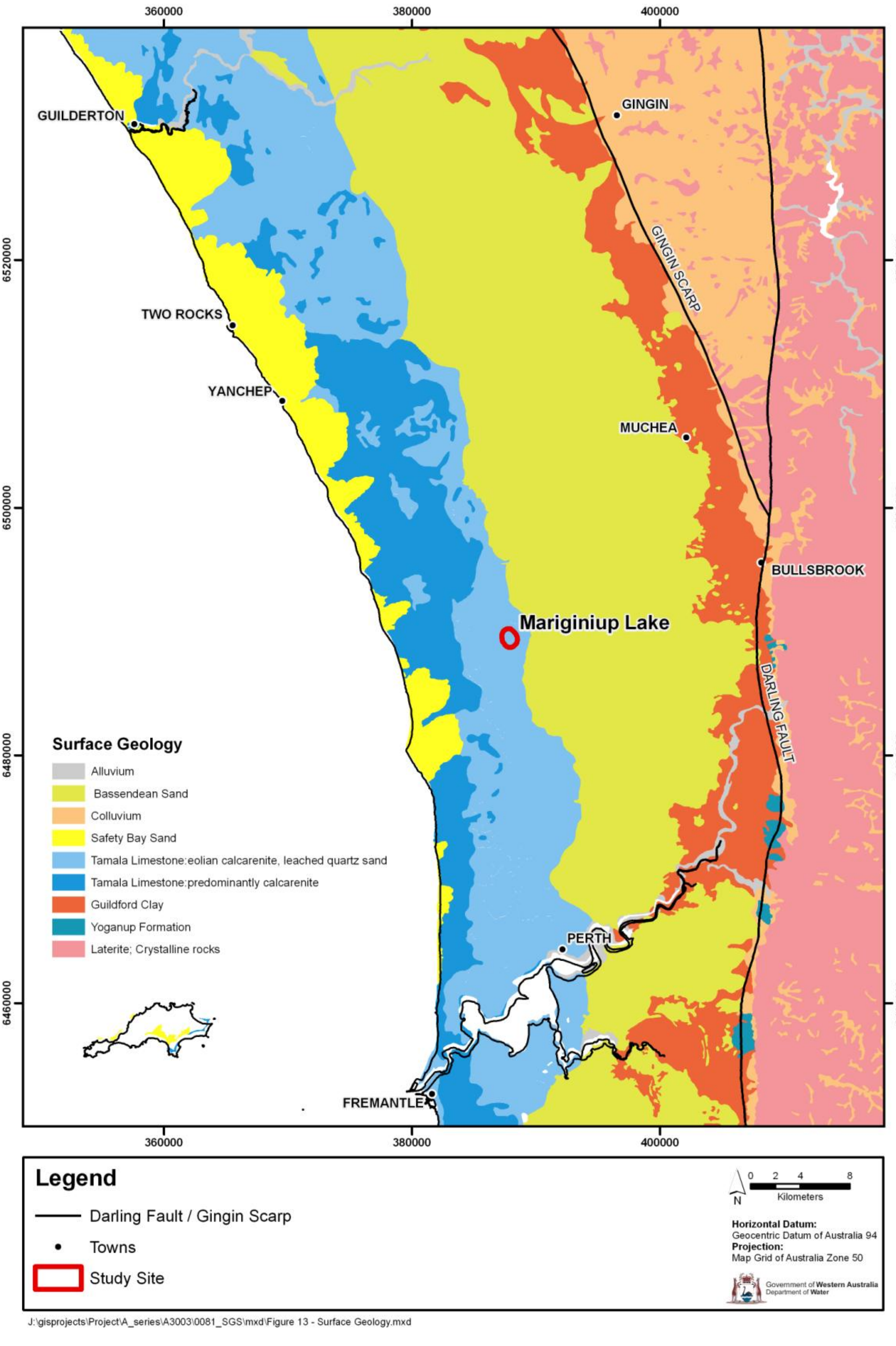


Figure 3 Generalised surface geology in the Lake Mariginiup area

As many of the wetlands on the mounds are progressively drying, including Lake Mariginiup, the exposure of acid sulfate soils is a risk for environmental and groundwater degradation.

2.3 Hydrogeology

2.3.1 Regional hydrogeology

Groundwater occurs in the superficial formations of the Swan Coastal Plain and in the deeper formations of the Perth Basin (Davidson 1995). There are six distinct aquifers separated by major confining layers, but which are locally in hydraulic connection (Davidson 1995). This study focuses on the Superficial aquifer, which is a regional unconfined aquifer made up of the sediments of the superficial formations.

Table 1 outlines the historical physical and chemical properties of the Superficial aquifer.

The Superficial aquifer is mainly composed of porous sands with high permeability (Section 2.2). The hydraulic properties within the Superficial aquifer depend on geology, topography and discharge boundaries and can vary significantly. Hydraulic conductivities range from 0.4 m/day in the clayey sediments of the Guildford clay in the east, are between 10 and 50 m/day, (average of 15 m/day) in the Bassendean and Safety Bay Sands and 8 m/day in the Ascot Formation. Hydraulic conductivity varies widely in the Tamala Limestone in the west, due to solution channels and cavities, and ranges from 100 to 1000 m/day (Yesertener 2009). In the Lake Mariginiup area, the hydraulic conductivities are thought to range from 15 to 18 m/day in the Bassendean Sand, and 10 to 13 m/day in the sands of the Tamala Limestone (Bourke 2009).

Groundwater elevations caused by rainfall draining through the sands of the Superficial aquifer create two substantial groundwater mounds. To the north of Perth is the Gnangara Mound and to the south is the Jandakot Mound (Figure 4). Mounding of the watertable occurs in these locations as the vertical infiltration of rainfall exceeds the ability of the aquifer to horizontally transmit water away from the recharge zone (Davidson 1995). Locally, groundwater is connected between the Superficial aquifer and the underlying Mesozoic formations (Rockwater 2003). A series of permanent and seasonal lakes and wetlands currently occur where the watertable intersects the ground surface.

2.3.2 Lakes and wetlands

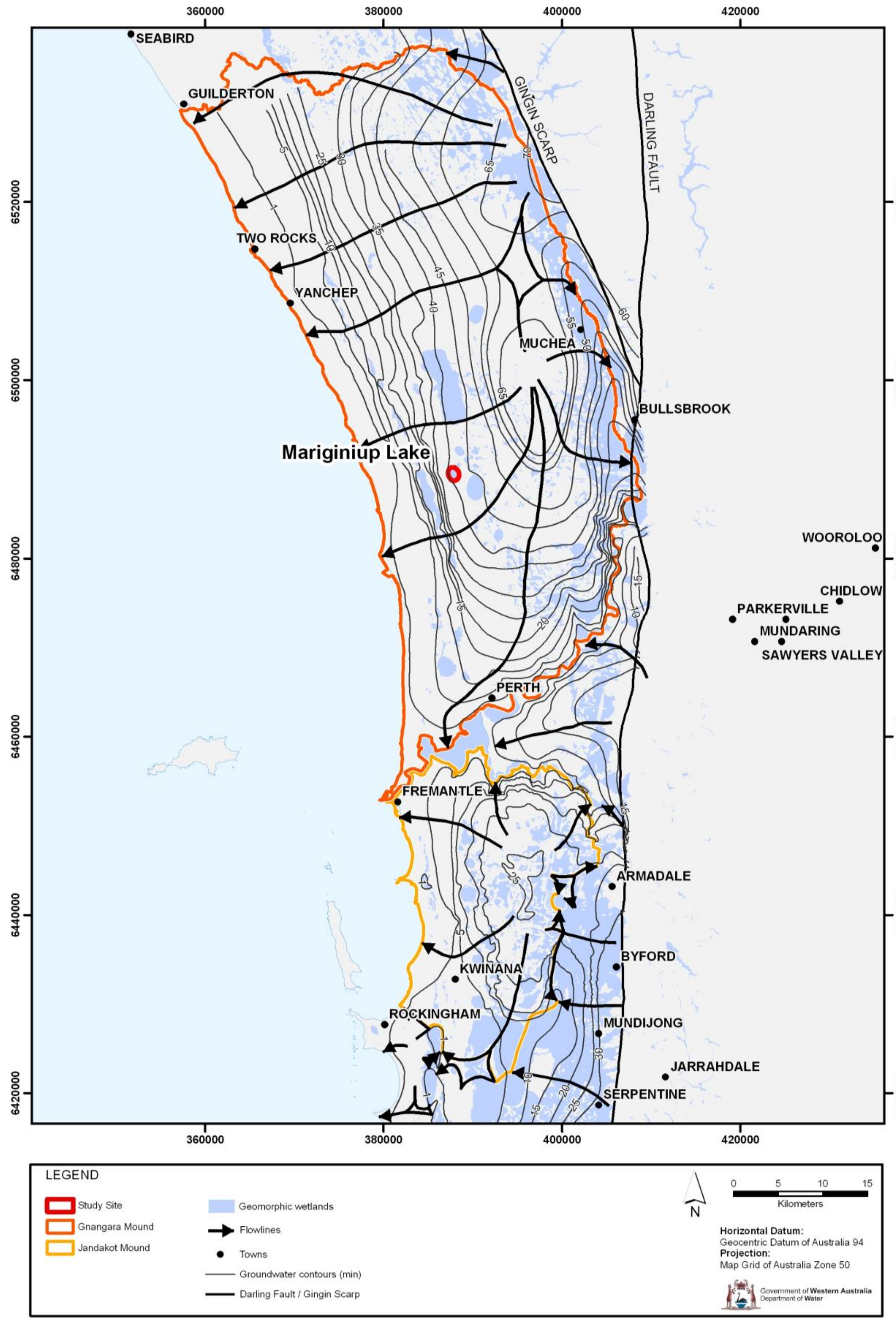
The hydrogeology of Lake Mariginiup is connected to the flow system of the Gnangara Mound. Most lakes and wetlands of the coastal plain are located where the watertable permanently or seasonally intersects the land surface. Surface water fluctuations are generally related to changes in groundwater levels. These lakes and wetlands are often in interdunal swales within the Spearwood and Bassendean Dunes, and at the contact between these geomorphic units. Townley et al. (1993)

reported that most of the wetlands on the Swan Coastal Plain appear to act as flow-through lakes, which capture groundwater on the up-gradient side and discharge lake

Table 1 Historical physical and chemical properties of the Superficial aquifer

Parameter	**Range**		**Reference**
	Low	**High**	
EC	< 25 ms/m only near crest of mound	> 100 ms/m near the coast	Cargeeg et al 1987
TDS	140 mg/L (only near crest of the mounds)	550 mg/L near coast	Cargeeg et al 1987
	130 mg/L	12 000 mg/L but rarely exceeds 1000 mg/L	Davidson 1995
pH	4.5–6.5 away from coast	6.5–7.5 in limestone	Cargeeg et al 1987
	4	8	Davidson 1995
Hardness ($CaCO_3$ mg/L)	< 50 mg/L (Bassendean Sand)	500 mg/L (Tamala Limestone) > 1000 mg/L (coast)	
Eh	No limit	> 0.3 V	Cargeeg et al 1987
NO_3^-	Mostly within drinking water limits	29 mg/L	Cargeeg et al 1987
	0	> 60 mg/L	Davidson 1995
PO_4^{3-}	0	> 0.1 mg/L	Cargeeg et al 1987
	0	0.1 mg/L occasionally 0.2 mg/L	Davidson 1995
SO_4^{2-}	0	200 mg/L	Cargeeg et al 1987
		100 mg/L	Davidson 1995
SO_4^{2-}/Cl^-		> 1	Cargeeg et al 1987
	0.05	0.1	Davidson 1995
Fe (total dissolved)	Generally 1–5 mg/L	> 5 mg/L	Cargeeg et al 1987
	< 1 mg/L	> 50 mg/L	Davidson 1995

Parameter	**Range**		**Reference**
	Low	**High**	
TOC	1 mg/L	> 50 mg/L	Cargeeg et al 1987
Temperature	19° C	23° C	Cargeeg et al 1987
Pesticides	All below potable limits		Cargeeg et al 1987
Cd, Cr, Cu, Pb		Only localised elevated concentrations. No values.	Cargeeg et al 1987



J:\gisprojects\Project\A_series\A3003\0081_SGS\mxd\Mariginiup Lake\Figure 4 - Regional Hydrogeology.mxd

Figure 4 Gnangara and Jandakot Mounds showing flow lines water on the down-gradient side. Rockwater (2003) found that wetlands on the Pinjarra Plain and Bassendean Dunes are usually flow-through lakes, while on the Spearwood Dunes cave systems can influence inflow and outflow.

Lake Mariginiup has previously been classified as a permanently inundated flow-through lake. As Lake Mariginiup is now dry for many months of the year, investigation into the new hydrological regime was required.

2.4 Previous studies

Hall (1985) carried out detailed investigations at Lake Mariginiup. Lithological samples from 24 observation bores were collected every two metres (summary in Table 2). Deep holes were logged with the natural gamma ray method, and bottom samples were collected for palaeontological examination. Several auger holes and trenches were constructed around the shores of the lake. Hall (1985) logged the bore hole lithology but did not separate the superficial formation into its individual units. As part of the shallow groundwater systems investigation, the lithology of the drilling conducted from 1978 to 1979 was interpreted to intersect the Bassendean Sand, Gnangara Sand and Poison Hill Greensand (see full lithological logs in Appendix C).

Table 2 Summary of lithology from Hall, 1985

Formation	Lithology
Bassendean Sand	Sand white, pale brown, light grey and grey. Fine to coarse grained, poorly to moderately sorted, sub-angular to rounded quartz. Clayey intervals around 16–25m. 3–4 m thick iron oxide cemented – limonite stained quartz layer ’coffee rock‘) ranging from 4–14 m. Trace heavy minerals in places.
Gnangara Sand	Sand – gravel grey to white to light grey green. Very fine sand to coarse pebbles, bimodal in places. Commonly poorly sorted, sub-angular to well rounded. Slightly clayey. Trace weathered feldspars.
Poison Hill Greensand	Sand greyish green, dark grey green, dark green and bright green. Fine to very coarse grained. Sub-angular to well rounded. Glauconitic and in places silty and contains fine heavy minerals.

McHugh (2004) performed qualitative energy dispersive spectrometry on sediments at Lake Mariginiup and confirmed the presence of pyrite throughout the lake bed. The inorganic sulfur content (a measure of pyrite concentration) in sediments of Gnangara Mound lakes similar to Lake Mariginiup, ranged from 0.015% to 0.35%, as determined by the standard chromium reducible suite of methods. The upper range of these values exceeds the ‘action criteria’ for acid sulfate soils in Western Australia (McHugh 2004).

Previous work by Hall (1985) determined that lake levels at Mariginiup were maintained by two main processes: rain, and groundwater inflow. The investigation found that groundwater inflow comes from the upper half of the aquifer, through sandy lake deposits on the eastern side of the lake. Recharge to groundwater (on the western margin) is retarded by lake sediments, and evapotranspiration removes around 92% of the water input to the lake. As a result of the evapotranspiration, salinity of Lake Mariginiup is significantly higher than that of the groundwater, and is demonstrated to form a saline plume downstream of the lake. Hall concluded that Lake Mariginiup is a groundwater sink.

McHugh (2004) reconstructed water levels at Lake Mariginiup by applying lithostratigraphy, diatom analysis and groundwater modelling techniques to sediment cores extracted from the lake. The study showed that the evolution and water level history of Lake Mariginiup began sometime in the Pleistocene (more than 20 000 years ago). Since that time the lake has experienced an extended period of aridity and subaerial exposure of the lakebed (20 000 to 15 000 years ago) and wetter periods when lake levels were possibly 2 to 4 m higher than current levels (5900 to 4000 years ago).

Recent local-scale numerical modelling undertaken for the *Gnangara sustainability strategy* (DoW 2009b) suggests that land-use change in the east Wanneroo area has the potential to increase water levels in Lake Mariginiup and the Superficial aquifer (Bourke 2009). Seven modelling scenarios were run, from 2001 to 2031, to investigate the impacts of pine clearing, urbanisation and artificial supplementation on lake levels, under a climate regime similar to 1997 to 2006 (730 mm/yr rainfall). Land-use changes were implemented according to current plans for pine clearing and urban development (WAPC 2007). Water level changes reported under each scenario are at the end of the simulation (December 2030) relative to the base case scenario which assumed land use remained the same as 2005.

The results suggest that clearing pine plantations and replacing them with grassland would not alter minimum water levels (the lake would still dry over summer) but would increase seasonal maximum water levels by 0.2 m. Urbanisation is predicted to increase minimum water levels by 0.2 m and maximum water levels by 0.4 m by 2031. The combined effect of pine clearing plus urbanisation would result in an increase in summer minima of 0.2 m and an increase in maximum water level of 0.6 m by 2031 (Figure 5).

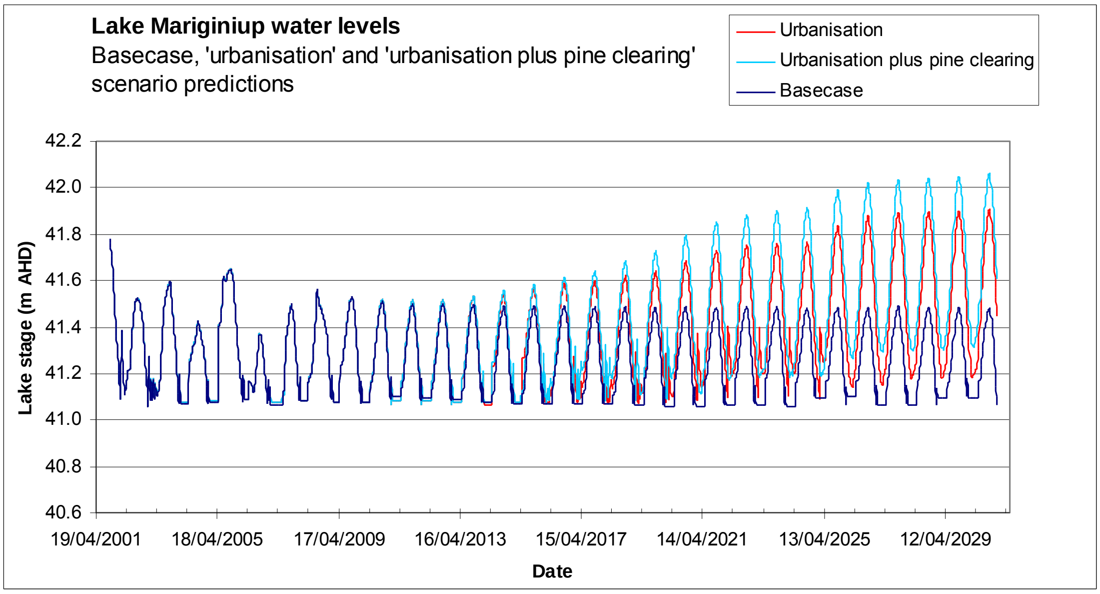


Figure 5 Predicted water levels in Lake Mariginiup under the base case, urbanisation and urbanisation plus pine clearing scenarios (after Bourke 2009)

2.5 Ecological value

Protection of the ecological values at Lake Mariginiup began in the late 1980s by recognising the importance of the lake's high water quality, rich aquatic fauna (including the Swan River goby, *Pseudogobius olorum)* and wading waterbird habitat and by setting water level criteria (WAWA 1995). The department is currently bound to the following ecological and water regime management objectives (WAWA 1995):

- to maintain the existing area of fringing sedge vegetation
- to maintain the wading bird habitat by preserving the extent of the sedge vegetation and exposing the banks in late summer
- to maintain invertebrate diversity through some lake bed drying in summer
- to maintain, and if possible, improve fringing woodland vegetation.

Over the last ten years water levels have been below the Ministerial criteria level that was set to protect the ecological values at Lake Mariginiup. Criteria levels are generally based on ecological water requirements which are the water regimes necessary to maintain a low level of risk to the ecological values (WRC 2000). At Lake Mariginiup, water levels should not fall between 42.1 m AHD and 41.5 m AHD at a rate of more than two in six years, with the absolute minimum criteria being 41.5 m AHD. This is a spring minimum water level that should be measured in spring on staff gauge 6162577 (Figure 6). These criteria levels were set in 1995 and were designed to provide sufficient inundation to the sedge area to prevent sedge encroachment into the basin and reduction in waterbird wading habitat (WAWA 1995).

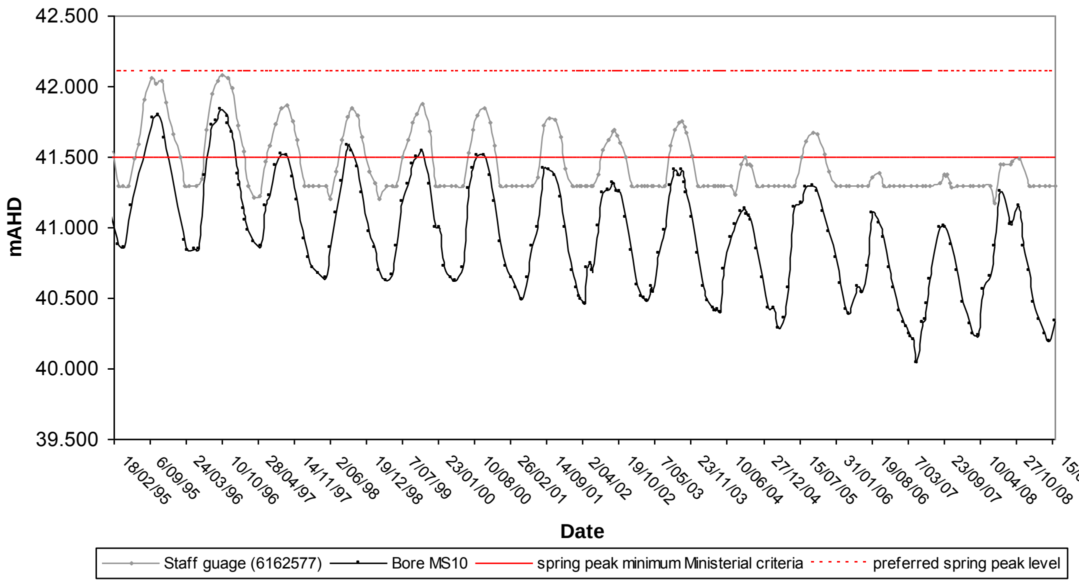


Figure 6 Lake Mariginiup showing current Ministerial criteria

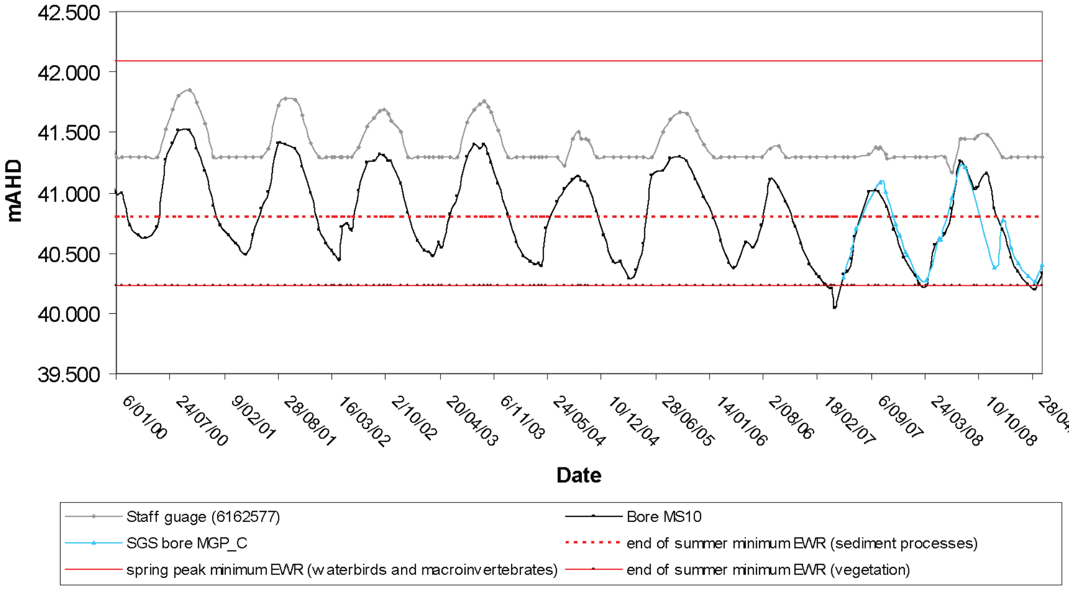


Figure 7 Lake Mariginiup hydrograph showing current ecological water requirements

Ecological monitoring by Edith Cowan University has shown that since water levels stopped meeting the criteria, there has been sedge encroachment into the basin and a reduction in waterbird wading habitat (Froend et al. 2004b). The health of overstorey vegetation has been variable over time, while the understorey is showing signs of stress.

In 2004 the ecological values of Lake Mariginiup were reassessed and new ecological water requirements were proposed (Froend et al. 2004a and b). These have not been adopted as Ministerial criteria, but are used by the department to assess the possible impact of current water levels on current ecological values.

According to Froend et al. (2004b), a groundwater end of summer minimum of 40.8 m AHD and 40.23 m AHD[1] will support sediment processes and groundwater dependent vegetation, respectively. This should be measured at groundwater monitoring bore MS10. To support waterbirds and macroinvertebrates, a minimum spring surface water level of 42.1 m AHD is required (measured on staff gauge 6162577 (Froend et al. 2004b) (Figure 7).

For the past 10 years, summer minimum water levels and spring peaks have been below the ecological water requirements for waterbirds, macroinvertebrates, sediment processes and are close to the those for vegetation. Combined with changing land use near the lake, this has coincided with a general decline in ecological health.

The most notable adverse ecological effect has been the declining quality and increasing acidity of the water in the lake. The pH measured in summer 2006 was the lowest recorded at the lake, and there has been very little seasonal variation since summer 2004 – a trend which has not been recorded previously for this lake. Over the past 13 years, pH values have declined from an average of around 7 to a low of 4.1(see Section 5.4). Increasing acidity has been associated with a change in macroinvertebrate species assemblages and a decline in macroinvertebrate family richness (McKay and Horwitz 2008).

2.6 Cultural significance

Wetlands across the Swan Coastal Plain are spiritually significant to Indigenous groups, and were used extensively in traditional times (Wright 2007). Many lakes and swamps were used as hunting and gathering areas for flora and fauna (Estill 2005). Lake Mariginiup is registered as a site of significance (DIA 3741) and reflects these Indigenous values.

In line with the requirements of the *Aboriginal Heritage Act 1972* and the *Native Title Act 1993,* the Department of Water contracted an anthropologist to undertake an ethnographic survey of the Lake Mariginiup region prior to the start of drilling works. The objectives of the survey were to determine the Indigenous heritage values of the wetland area and then to conduct archaeological and ethnographic surveys as required. During the survey a single scarred tree was recorded but no other artefacts or other archaeological material were identified. The lack of artefacts may reflect the lack of good quality stone in the area for tool making. The high level of ground disturbance in the area caused by grazing and horticultural activity may have also reduced the likelihood of finding archaeological materials (Eureka 2007).

During the consultation process no adverse comments were raised in regard to the proposed groundwater monitoring program, though it was stressed that the

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[1] Froend et al. (2004b) reports an EWR of 40.55 m AHD for vegetation. However, revised ground surface elevations show a lower ground elevation at the lowest extent of *Typha orientalis*. Using the method outlined in Froend et. al. (2004b), a new EWR of 40.23 m AHD is proposed for vegetation at this site.

waterways of Western Australia were important as food sources and spiritual repositories, and that development should not be allowed in the vicinity of them.

Site works and disturbance were kept to a minimum by using smaller direct push drilling methods where possible and infrastructure was installed within existing disturbed areas.

2.7 Land and water management

The *Gnangara groundwater areas allocation plan* (DoW 2009a) sets out the approach for the allocation and licensing of all water users on the Gnangara Mound. The department determines the volume and spatial distribution of water extracted from the mound by assessing proximity to groundwater-dependent ecosystems, ecological condition and rate and magnitude of groundwater level change. For allocation purposes the Gnangara Mound is divided into groundwater areas and subareas. Lake Mariginiup is located in the Wanneroo groundwater area and the Mariginiup subarea (Figure 8).

Prior to 2008, the water allocation limit set for the Mariginiup subarea was 5.4 GL and approximately 90% of this limit was allocated. The allocation limit for the Mariginiup subarea was reduced to 4.0 GL in the groundwater areas allocation plan. The subarea is now over-allocated, no further licenses are being issued and a policy of recouping unused entitlements has been initiated.

Water use in the area is linked to the dominant land use. Lake Mariginiup is surrounded by privately owned land used for rural purposes, residential development and irrigated horticulture (Figure 8). The original planning policy was to promote this area for horticulture but current water resource issues have initiated a review of this land use. Horticulture is highly dependent upon groundwater and this has now become the limiting factor for the local industry (WAPC 2007). Land-use changes currently proposed will see the creation of new urban areas and the phasing out of horticultural activity within the area (WAPC 2007) (Figure 8). It is anticipated that this change will reduce private abstraction and increase runoff into the groundwater system (Bourke 2009).

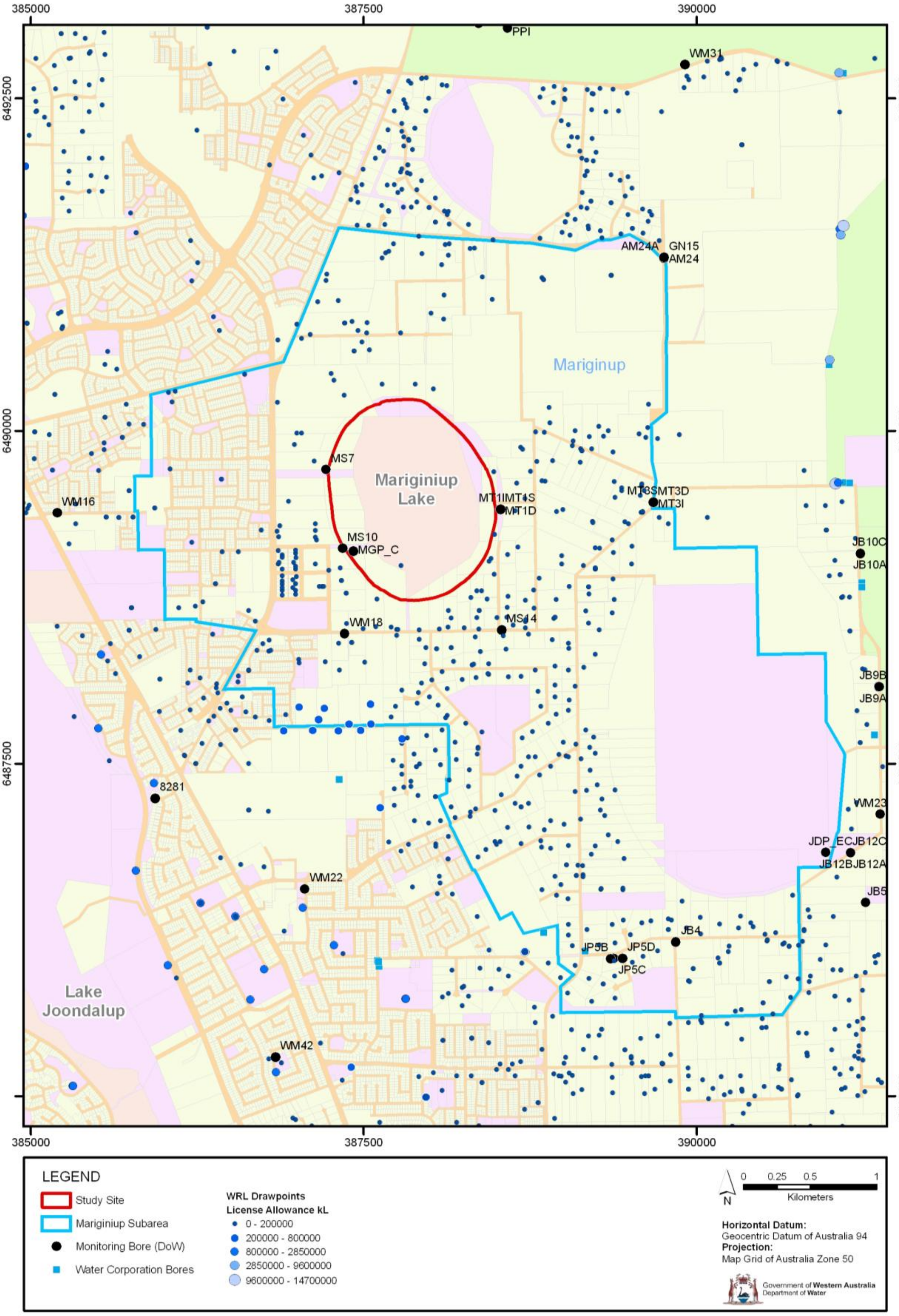

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Figure 8 Water allocation and land use around Lake Mariginiup

3 Investigation program

The management area review of McHugh and Bourke (2007) highlighted the need for site-specific information about wetland function to appropriately manage Lake Mariginiup and the shallow groundwater systems of the Gnangara and Jandakot mounds.

The review recommended that the shallow groundwater systems investigation construct new monitoring bores, and undertake water chemistry sampling and water level measurements at Lake Mariginiup. Investigations of acid sulfate soils were also carried out.

3.1 Bore construction

The management area review recommended upgrading the groundwater monitoring network at Lake Mariginiup to enable hydrogeological and hydrogeochemical investigations. It was recommended that groundwater monitoring bores be installed in clusters of three: shallow (screened at the watertable), intermediate (screened approximately halfway through the Superficial aquifer) and deep (screened at the base of the Superficial aquifer). The clusters should be positioned up hydraulic gradient and down hydraulic gradient of the main lake water body so that both horizontal and vertical groundwater flow could be measured.

The infrastructure upgrade included a cluster of bores on the western (down-gradient) side of the lake (MGP_a, MGP_b and MGP_c). Lithological and construction details are reported in Appendix A, and in Bourke (2008). A cluster of bores on the eastern (up-gradient) side of Lake Mariginiup was installed in 1978, (MT1S, MT1I and MT1D), and used in this investigation. Lithological bore logs are provided in Appendix C.

The two clusters of bores were used for groundwater sampling.

Table 3 gives general details for groundwater monitoring bores used for this investigation. Figure 9 shows the location of all bore clusters used in this investigation.

Table 3 Bores involved in the investigation at Lake Mariginiup

Depth	AWRC name	AWRC number	Drilled depth m below natural surface	Screened interval m below natural surface
Shallow	MGP_c	61611440	8.3	0.95 – 4.95
Intermediate	MGP_b	61611441	30.0	24.81 – 26.81
Deep	MGP_a	61611442	57.0	44.80 – 46.80
Shallow	MT1S	61610736	9.0	2.00 – 9.00
Intermediate	MT1I	61610737	27.0	22.00 – 24.00
Deep	MT1D	61610738	52.0	45.00 – 47.00

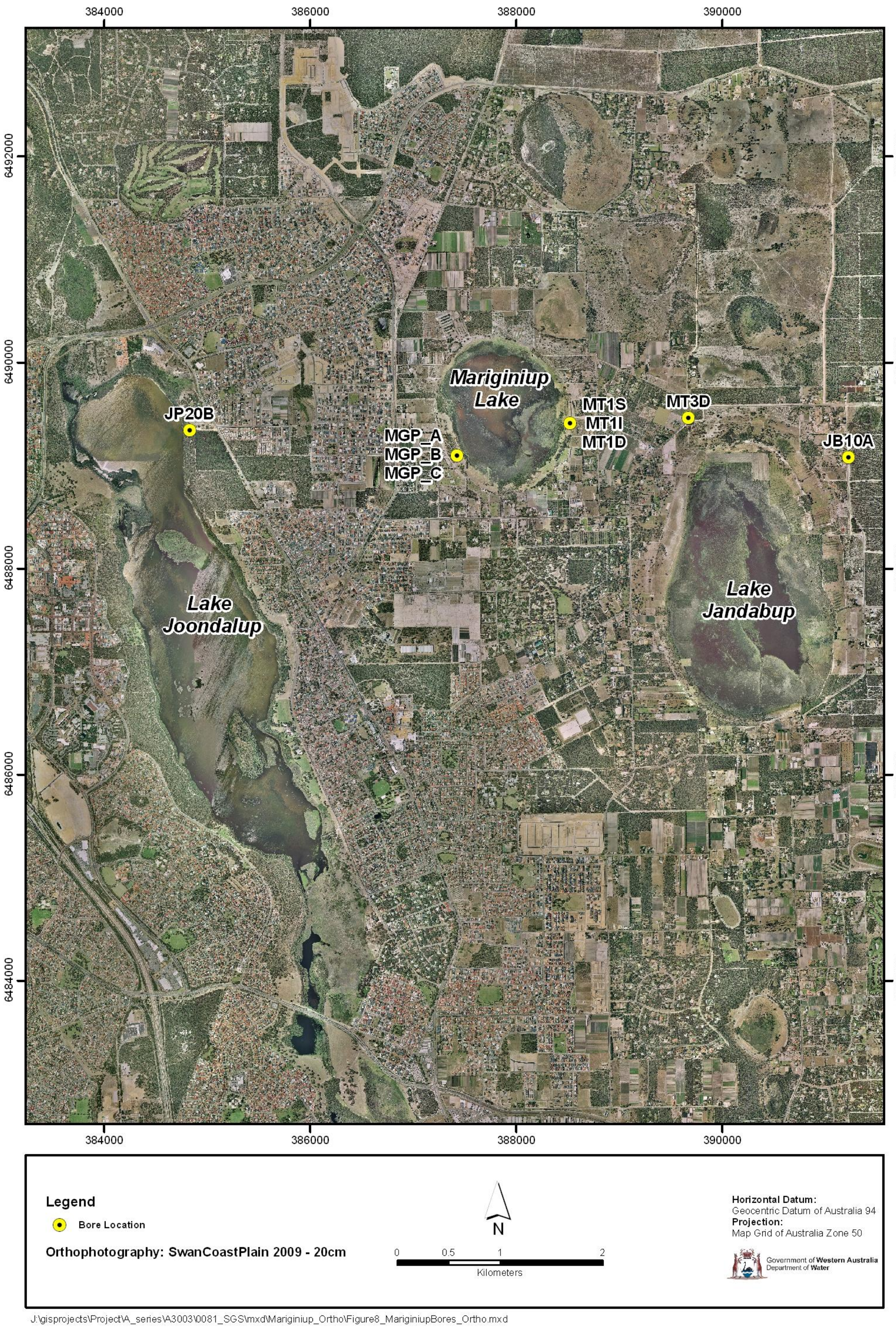

Figure 9 Location of bores used in the investigation at Lake Mariginiup

3.2 Acid sulfate soils testing

To determine the distribution and characteristics of sulfidic sediments in Lake Mariginiup, and the potential of these to affect groundwater quality, a study was conducted as part of the shallow groundwater systems investigation and reported in Turvey (2007). A total of 28 sediment cores of up to 2 m in length were collected across the lake basin (Figure 10). From each core, samples were collected approximately every 25 cm and analysed in the field for potential acid sulfate soils and actual acid sulfate soils according to the Department of Environment's *Draft investigation and identification of acid sulfate soils* guide (2006) (see Appendix B for the full methods used).

Further laboratory testing was conducted for net acidity by the National Measurement Institute. Sediment samples were placed in plastic bags, as much air expelled as possible, and refrigerated until delivery at the institute. Samples were taken to the laboratory either the same day as extracted from the ground, or the following day. The institute used the chromium reducible sulfur suite as well as the SPOCAS suite of analyses to conduct acid base accounting (see Appendix B for laboratory methods). Thin sections were analysed, and chemical testing for metals was carried out on sediments.

Field and laboratory tests were also conducted on sediment from the watertable bore (MGP_c) during bore construction. Analysis followed the same methods.

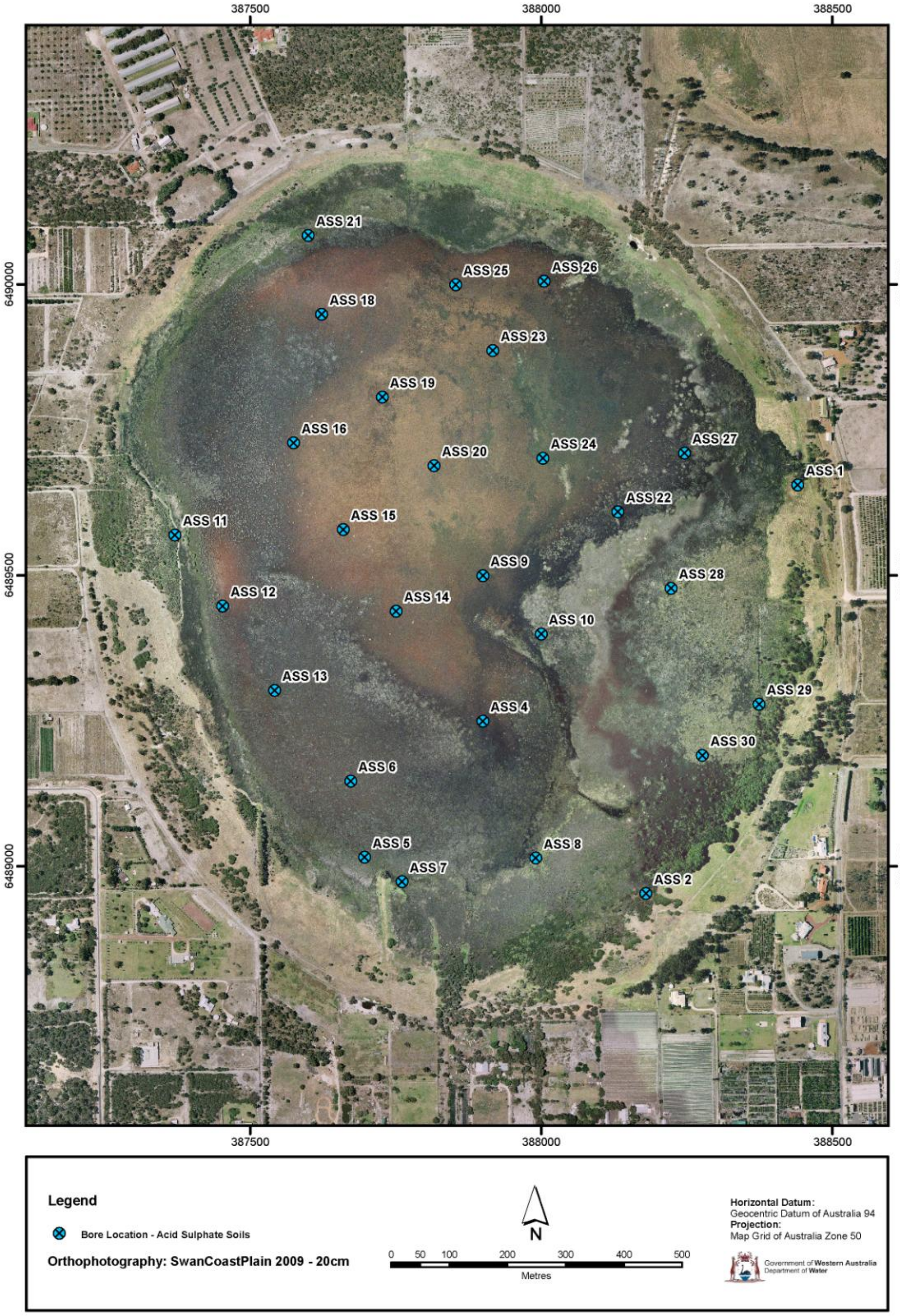

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Figure 10 Location of samples taken for acid sulfate soils investigation

3.3 Water monitoring and sampling program

Lake water and groundwater sampling and analysis was undertaken to determine the hydrochemical characteristics of each site, the distribution and availability of potential pollutants and the interaction between the wetland and the Superficial aquifer.

The sampling regime comprised monthly sampling for both water levels and water quality for the period between June 2007 and July 2008, for the six bores (Figure 11). Monitoring and sampling of the lake water was carried out when surface water was present at the staff gauge. This only happened on three occasions during the sampling program, but as the staff gauge is not located in the deepest part of the lake basin, there were occasions when there was water in small pools but no samples were taken.

Water samples were collected using low flow pumping methods as outlined in Appendix B. The cluster of bores on the eastern side (MT1S, MT1I, MT1D) have been monitored for water levels at least twice a year since 1978. Lake levels have been recorded since 1954, with a frequency ranging from every five years to monthly. Analyses of water samples were conducted for major ions, metals, nutrients and a number of herbicides and pesticides.

Table 4 shows the analytes tested for by the National Measurement Institute for the shallow groundwater systems investigation.

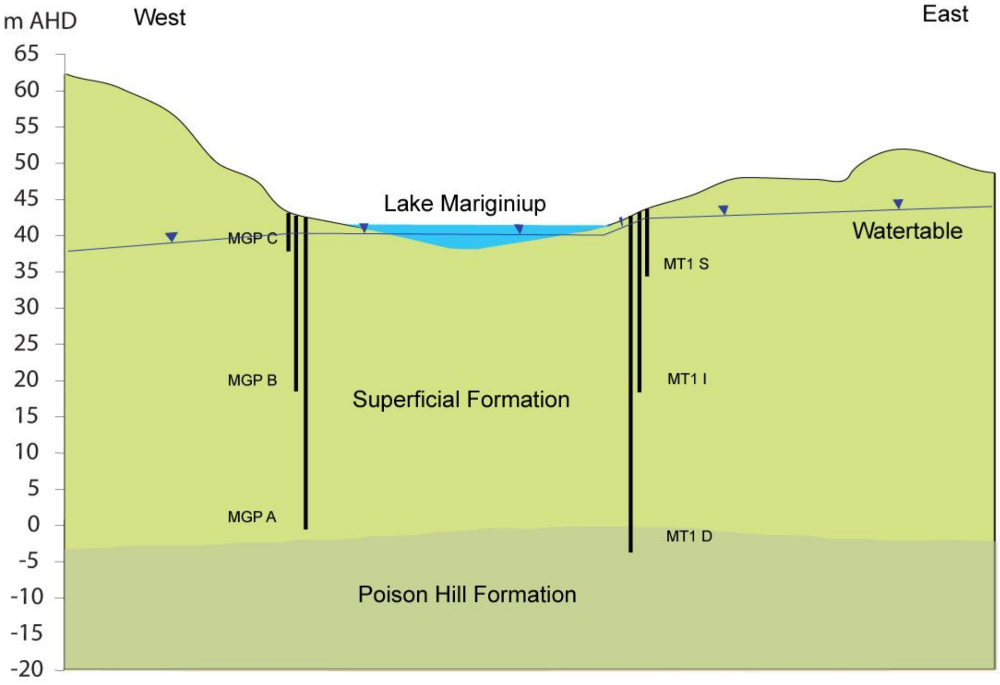

Figure 11 Location of bores used for sampling and monitoring

Field analysis was carried out for electricity conductivity (EC), pH, Eh, dissolved oxygen (DO) and temperature using a Quanta multi parameter probe. This probe adjusts Eh values to the standard H^+ half cell. Readings were taken when values for EC, pH and temperature stabilised. However, Eh and DO values did not stabilise.

Table 4 Water analysis conducted by the National Measurement Institute

Total metals	**Hg, Al, As, Cd, Cr, Fe, Mn, Ni, Se, Zn**
Dissolved metals	Ca, Mg, Na, K, B, Fe, Al
Nutrients	NH_3-N, TN, TP, NOx, FRP
Herbicides and pesticides	Chlordane {Tech; a+g}, DDD-p,p, DDE-p,p, DDT-p,p, Dieldrin, Endosulf sulfate, Endosulf-a, Endosulf-b , Endrin, HCH (BHC) a,b,d, HCH (BHC), Heptachlor, Heptachlor epoxide, Hexachlorobenzene, Methoxychlor, Ocs
Other	EC, TSS, TDS, HCO_3, CO_3, Cl, F, SiO_2, SO_4, pH, Acidity, Alkalinity, DOC, DON

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, or statistical errors, result from random fluctuations in the analytical procedure. Precision can be calculated by performing repeat analysis on the same sample. Seven laboratory duplicates were analysed for this investigation. Results from these indicate that laboratory precision is very good, with most duplicates being within +/- 5% to 10 % of the actual value.

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 and Postma 2007), so the sum of the cations in solution should equal the sum of the anions:

$$\text{electrical balance \%} = \frac{\text{sum cations + sum anions}}{\text{sum cations - sum anions}} \times 100$$

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

Deviations of more than 5 % indicate that sampling and analytical procedures should be examined (Appelo and Postma 2007). For this investigation, if the electrical balance for a sample was greater than 6 %, without satisfactory explanation, then that sample was left out of the analysis.

Comparing the pH measured in the laboratory with that measured in the field immediately after sampling can indicate that a water sample has been altered by the collection, transport or storage processes. There are numerous reasons for a difference in field and laboratory pH reading, including reactions involving oxidation, precipitation and release of dissolved gas. These differences can be an indicator of uncertainty in the reported chemical concentrations. Figure 12 compares the pH values taken in the field and from the laboratory for this investigation. The correlation coefficient between field and laboratory pH values indicates that the laboratory results are reasonably reliable (r = 0.88). More than 85 % of samples show less than 1 pH unit difference between the two pH readings.

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 Mariginiup area:

- re-interpretation of historical lithological logs
- geological cross-sections from historical and Perth shallow groundwater systems investigation data
- analysis of hydrographs
- classification of redox processes
- groundwater contour mapping
- flow nets for both maximum and minimum water levels
- Piper diagrams for major ions
- time series plots for major ions, metals, nutrients, herbicides, pesticides and physical properties.

The chemical data set was filtered by investigation into ion balances as part of a quality assurance and quality control process as described above.

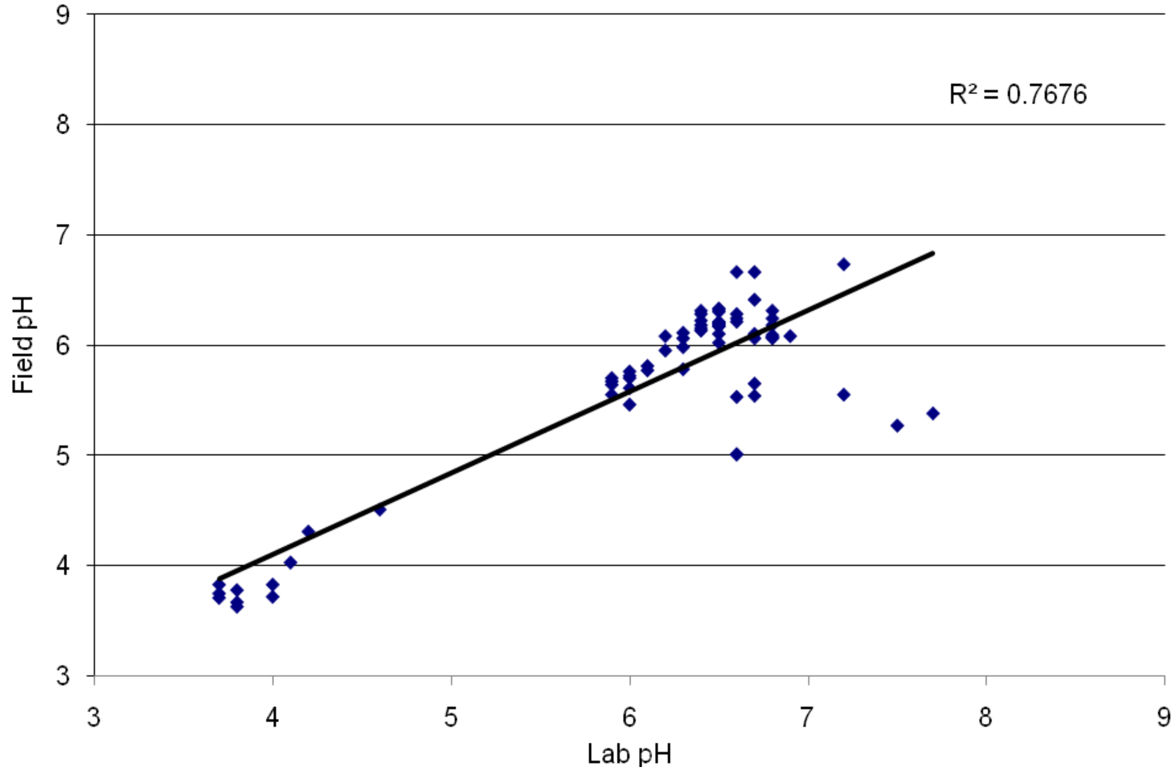

Figure 12 Comparison of field measured pH with laboratory measured pH

4 Geology

4.1 Superficial and Mesozoic formations

Previous mapping of the surficial geology of the Swan Coastal Plain (Figure 3) has placed the contact between the Bassendean Sand and Tamala Limestone more than 1 km east of Lake Mariginiup. Our geological investigations and hydrogeochemical indicators (see Section 5.3) demonstrate that Lake Mariginiup in fact lies on the interface, with the Bassendean Sand to the east and the Tamala Formation on the west (Figure 13). The section also incorporates the lithology recorded by Hall (1985). Table 5 outlines the generalised stratigraphy of the Lake Mariginiup area, using data from the shallow groundwater systems investigation as well as from Hall (1985).

Table 5 Generalised stratigraphy of the Lake Mariginiup area

Age	Unit	Thickness m	Lithology
Quaternary	Tamala Limestone	49	Sand and silty sand
Quaternary	Bassendean Sand	28–45	Sand with clay intervals and ’coffee rock’
Quaternary	Gnangara Sand	3–29	Very fine sand to coarse pebbles, bimodal in places
Cretaceous	Poison Hill Greensand	?	Sand and silty sand

In the Mariginiup area, the Tamala Limestone is about 49 m thick and comprises very dark greyish-brown, light brownish-grey, light grey, pale brown to grey, fine to medium-grained quartz sand and silty quartz sand. It becomes coarser grained at the base with feldspars. The quartz sand is unconsolidated, moderately sorted, sub-angular to sub-rounded, with some coarsening upwards trends.

The Bassendean Sand in this area ranges from 28 to 49 m in thickness and is a white, pale brown, light grey and grey, fine to coarse grained, poorly to moderately sorted, sub-angular to rounded quartz sand with trace heavy minerals. There are clayey intervals at a depth of around 16 to 25 m. An iron oxide cemented, limonite stained quartz layer (‘coffee rock’) ranges from 3 to 4 m in thickness and occurs at a depth ranging from 4 to 14 m.

The Gnangara Sand underlies both the Tamala Limestone and Bassendean Sand and is 3 to 29 m thick. It is a predominantly grey and white to light greyish-green, very fine grained to coarse grained quartz sand and is bimodal in parts. It is commonly poorly sorted, sub-angular to well rounded. It can be slightly clayey and contains trace weathered feldspars.

East of Lake Mariginiup the Poison Hill Greensand is a greyish-green, dark grey green, dark green and bright green, fine to very coarse-grained quartz sand which is sub-angular to well rounded. The formation is glauconitic and in places silty and contains fine heavy minerals. To the west, underlying the Tamala Formation, the Poison Hill Greensand is a greenish grey, silty fine to coarse quartz sand with heavy minerals present.

Figure 13 is a geological cross-section created using data from the shallow groundwater systems investigation as well as the drilling carried out by Hall (1985). The location of bores and features depicted in the cross-section are shown in Figure 9.

4.2 Lake deposits

Within the lake basin, there is a thin sequence, up to 2 m thick, of lacustrine deposits consisting of friable, weakly cemented sandy diatomite (of unknown thickness) overlain by homogenous and laminated organic rich clayey silt (Hall 1985; McHugh 2004). Turvey (2007) further differentiated the lake bed sediments into eight lithologies and mapped their lateral and vertical extent by extracting 28 cores across the lake basin. The study showed that the diatomite is generally restricted to the western part of the lake basin where the lake sequence is thickest. The lake sediments in the eastern part of the lake are underlain by well sorted, pinkish grey sands (Table 6 and Figure 14 and Figure 15).

Table 6 Lithology of the lake deposits (from Turvey, 2007)

Lake deposit	**Lithological description**
Surface silt	Dry, heavily oxidised (red iron mottles and coatings present), fine roots abundant, ~ 10–20 cm thickness, black to red in colour.
Laminated silt	Damp, laminations (mm scale), iron staining along laminations, ~10–20 cm thickness, dark grey in colour.
Massive clay	Moist, sticky, structureless silty clay, ~ 30 cm thick, dark brown in colour
Layered clay	Wet, layers (cm scale), up to 50 cm thick, alternating brown, green and black, occasional sulfurous smell.
Black clay	Wet, sticky clay, spongy texture, up to 30 cm thick, black, strong sulfurous smell.
Diatomite	Wet surface (occasionally dry below surface of unit), crumbly texture, flows when wet, forming hard surface cap, light grey. Max thickness unknown.
Organic sand	Moist to wet, medium grained quartz sand with organic matrix, dark grey in colour, grades to clean sand.
Pink sand	Moist to wet, well sorted, medium to coarse grained quartz sand, pinkish grey in colour.

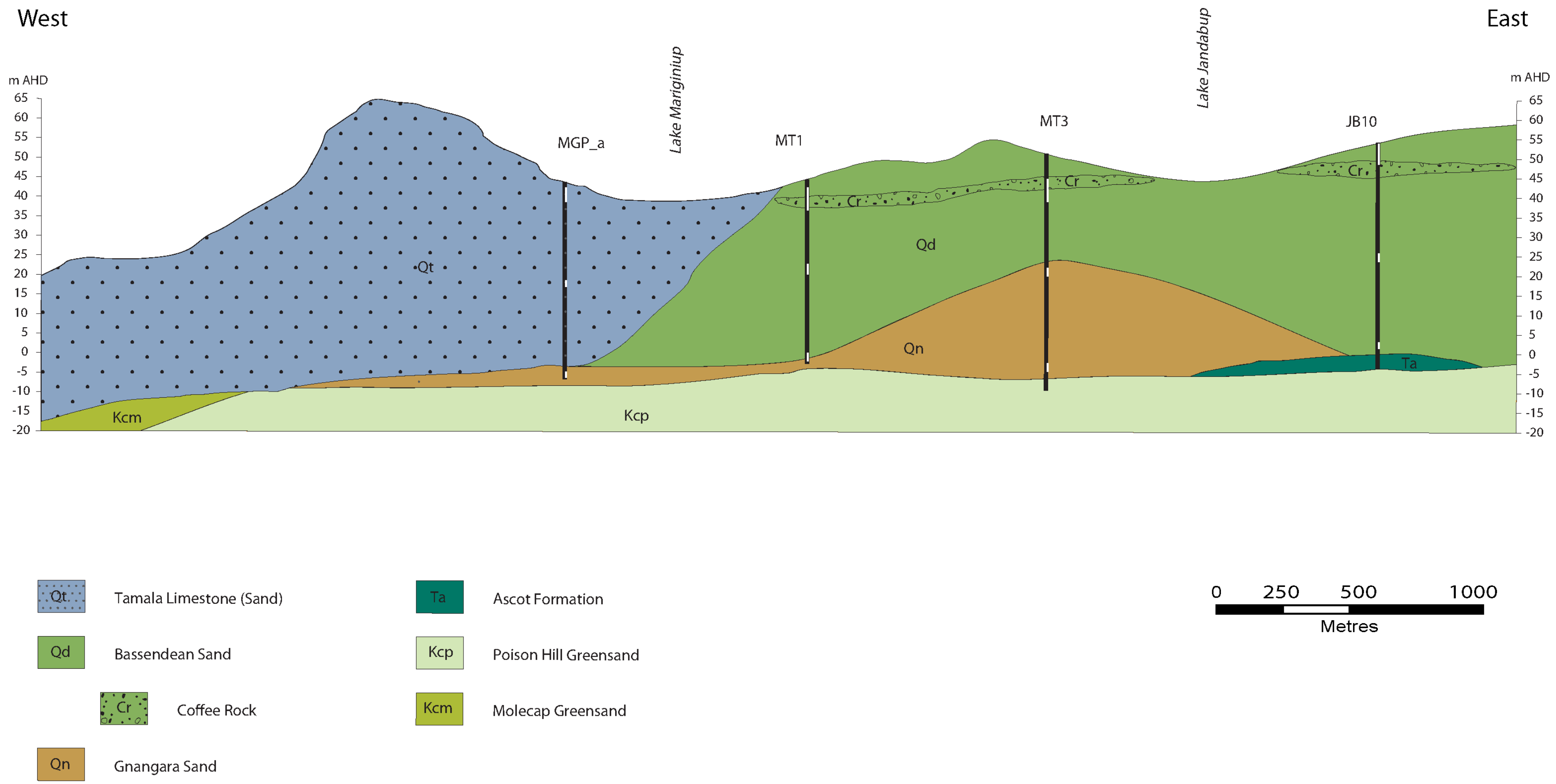

Figure 13 Geological cross-section at Lake Mariginiup

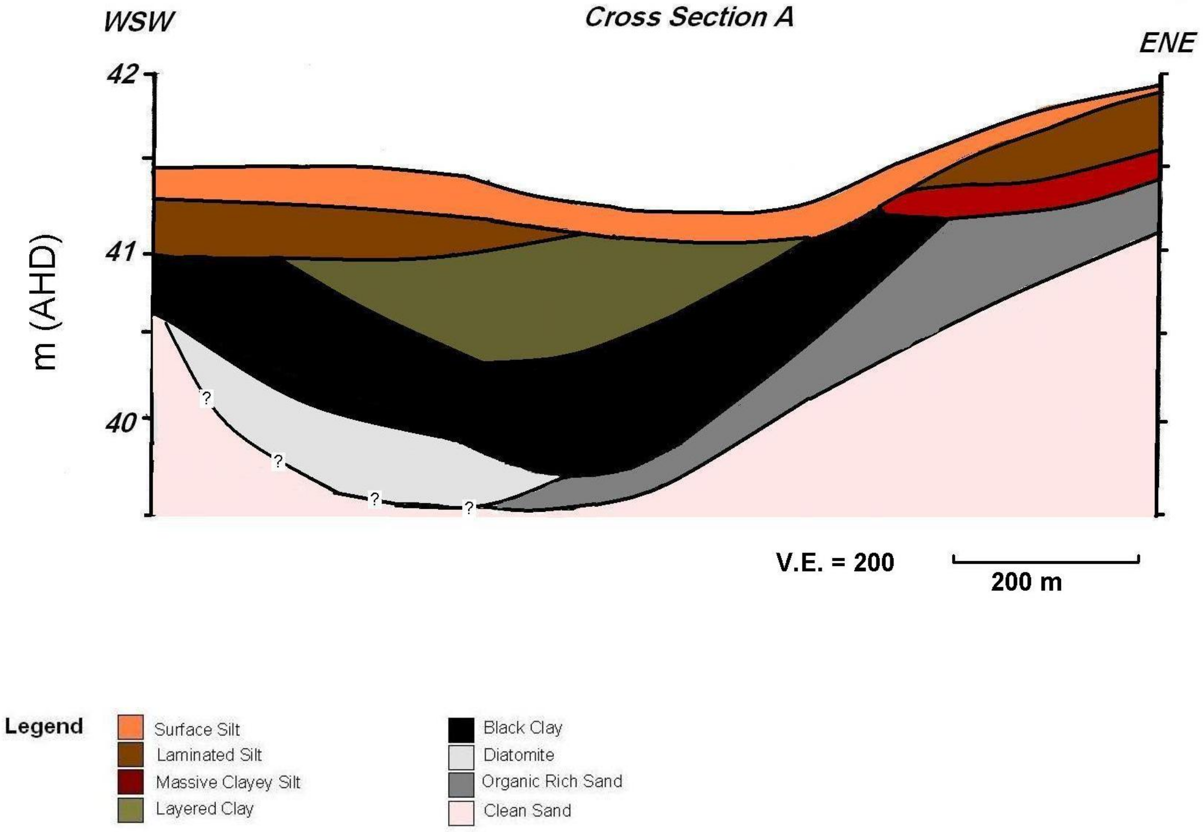

Figure 14 Cross-section of Lake Mariginiup lake bed (from Turvey 2007)

4.3 Acid sulfate soils

In conjunction with this investigation, detailed lake bed geochemical analysis was carried by Turvey (2007) and is discussed here in Section 4.3.1. Samples from the lake perimeter were taken during construction of bore MGP_c. Results are reported and discussed in Section 4.3.2 and in Appendix D.

4.3.1 Lake bed

Turvey collected 28 sediment cores of up to 2 m each from across the lake bed. This sediment was analysed in the field for pH and oxidised pH (pH_f and pH_{fox} respectively), as well as laboratory analysis using both the SPOCAS and chromium suite of methods. The results show that there is considerable risk of acidification from actual acid sulfate soils and potential acid sulfate soils within the lake bed sediments at Lake Mariginiup. The field pH (pH_f) test measures the existing acidity and is useful in identifying actual acid sulfate soils (pH of less than 4). The field pH peroxide test (pH_{fox}) is useful in determining the presence of potential acid sulfate soils, as it oxidises the soil and releases acidity stored in largely insoluble compounds. A substantial decrease in pH (i.e. $pH_{fox} < pH_f$) upon oxidation indicates the presence of potential acid sulfate soils.

The laboratory analysis measured the net acidity of the sediments. This measures the effect of acid generating components of the sediments against neutralising (or basic) components and is commonly known as acid base accounting. The overall equation for this is:

$$\text{Net acidity} = \text{actual acidity} + \text{potential sulfidic acidity} + \text{retained acidity} - \frac{\text{acid neutralising capacity}}{\text{fineness factor}}$$

where any sediments with a net acidity of 0.03% sulfur (18 mol H+/t) or greater are considered an acidification risk, and require careful management to prevent their oxidation or to ameliorate any current acidity.

Defining these terms using Ahern et al. (2004), actual acidity is the soluble and exchangeable acidity already present in the soil. Potential sulfidic acidity is latent acidity that will be released if the sulfide minerals in acid sulfate soils are fully oxidised. Retained acidity is the ‘less available’ fraction of the existing acidity which may be released slowly into the environment. Acid neutralising capacity is a measure of a soil’s ability to buffer acidity and resist the lowering of soil pH. 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.

Three distinct zones were identified in terms of acid producing potential. These zones, relating to lithology and depth, are the surface silts (0–50 cm), the middle organic clays, (layered and black clays at 50–100 cm) and the sands/diatomite (> 100 cm) (Figure 14) (Turvey 2007).

The surface silts had high reducible sulfide content (Figure 16), relatively low pH_f (Figure 15) and a high net acidity when compared to the deeper layers (Figure 17). The uppermost surface silt zone also contained a large amount of oxidisable products which can further lower the pH, even though it is the most commonly oxidised of all the layers. The retained acidity of the surface silts is largely in the form of hydrolysable iron and aluminium compounds, which will continue to produce acidity slowly even when oxygen is not available (Figure 18) (Ahern et al. 2004; Turvey 2007).

The middle organic clays (layered and black clays) are usually saturated and become moist at the edges of the lake. They have a higher pH_f (Figure 15), react more strongly to oxidation, and contain high reducible sulfides and net acidity (Figure 16 and Figure 17) (Turvey 2007).

In the zone below 100 cm the acid producing potential decreases, along with decreasing organic matter. Although potential sulfidic acidity and overall net acidity decrease with depth, the net acidity of the diatomite and sands exceed the management threshold (Turvey 2007).

All samples analysed at the laboratory had a pH_{KCl} of less than 6.5. This indicates that the sediments have little buffering capacity, suggesting that any acidity produced will immediately affect the lake. Around 80 % of samples showed a net acidity well above the management thresholds. The Department of Environment and Conservation have set action criteria (DEC 2009) for net acidity at 18.7 mol H^+/t. The surface sediments of Lake Mariginiup have an average net acidity of over 1000 mol H^+/t, and at depths of 50–100 cm, clays have a net acidity of 300–400 mol H^+/t,. Further oxidation of sediments will produce large quantities of acidity, which will in turn release more metals to the regional groundwater (Turvey 2007).

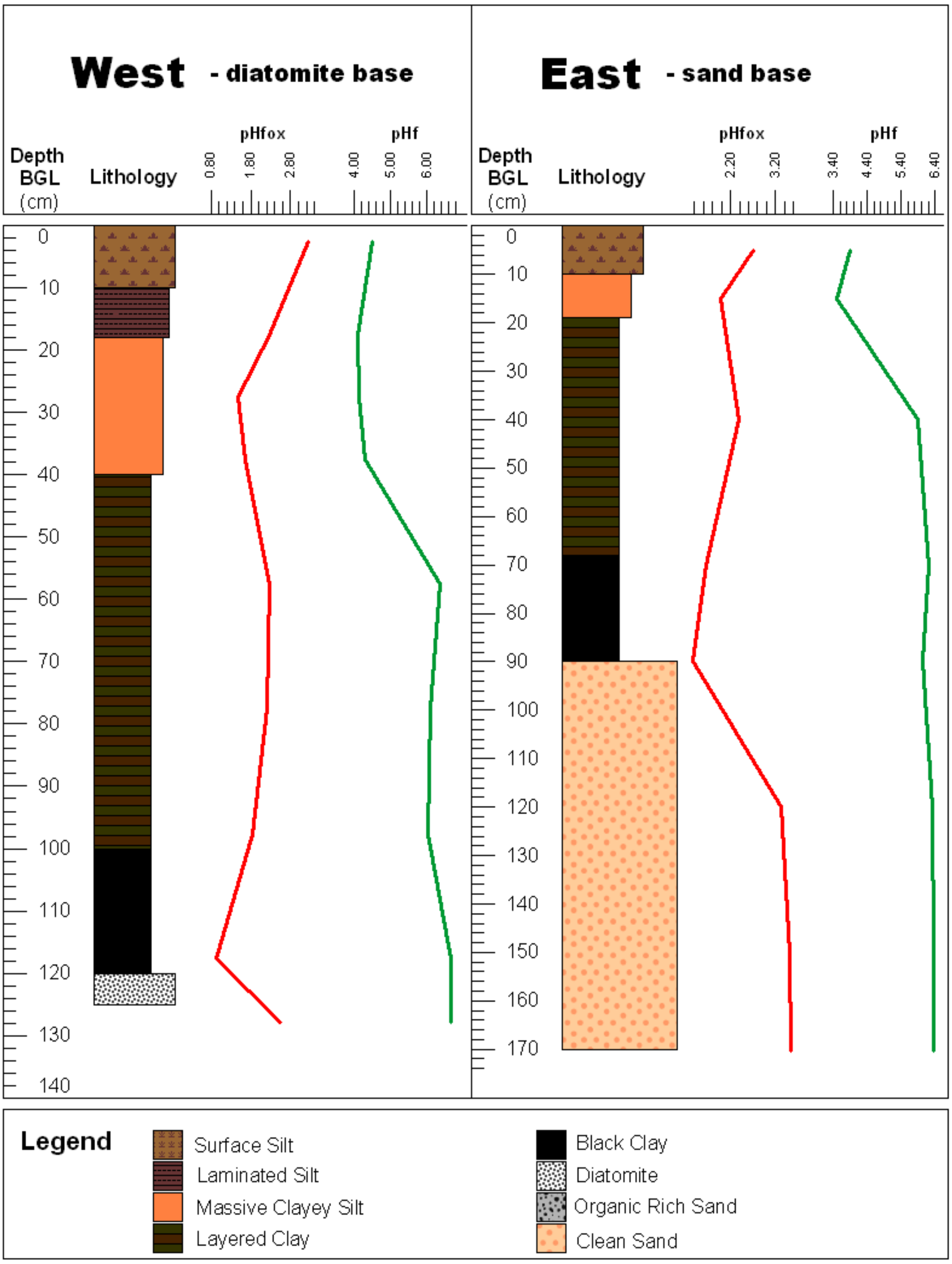

Figure 15 Representative east and west lithological logs showing change in pH_{fox} and pH_f at Lake Mariginiup (modified from Turvey 2007)

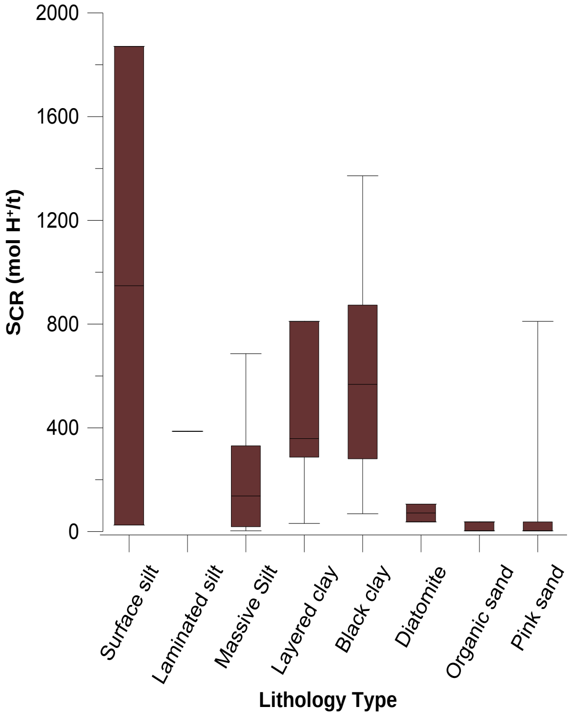

Figure 16 Distribution of reducible sulfides (potential acidity) in relation to lithology (from Turvey 2007)

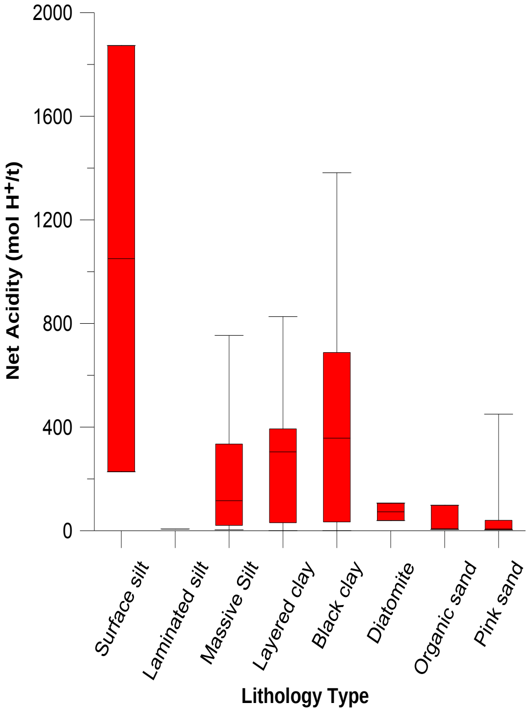

Figure 17 Distribution of overall net acidity in relation to lithology (from Turvey 2007)

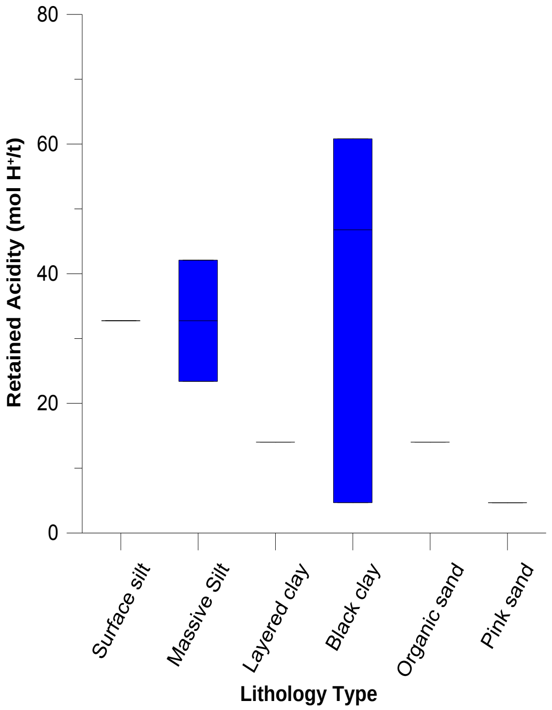

Figure 18 Distribution of retained acidity in relation to lithology (from Turvey 2007)

4.3.2 Lake perimeter

Acid sulfate soil testing was carried out on core samples collected during construction of the watertable bore MGP_c which is west of the lake bed, in sandy sediments. Over the 8 m of sediment core, 23 samples were field tested and 12 samples were sent to the National Measurement Institute for analysis (see Section 3.2 and Table 7 and Table 8).

Values for pH_f measured in the field range between 5.26 and 6.37. These results do not constitute actual acid sulfate soils. However, at depths greater than 2.2 m, field results show a major decrease in pH to very acidic values when the oxidising agent was added. The pH_{fox} of the soil after peroxide oxidation falls into three zones. The average oxidised pH between 0.2 m and 1.9 m is 4.58, between 2.2 m and 5.0 m it is 1.69, and between 5.5 m and 8 m it is 2.44 (Figure 19). These field tests suggest the presence of potential acid sulfate soils.

Laboratory analysis show zero excess acid neutralising capacity, as pH_{KCl} is less than 6.5 for all samples. This indicates that any acidity produced will immediately affect the lake and potentially the groundwater. Contrary to the field tests, laboratory results show that none of the samples are classified as actual acid sulfate soils or potential acid sulfate soils using the currently accepted guidelines of Ahern et al. (2004).

Field conditions were optimal during the testing, and both the field and laboratory methods use the same concentration of peroxide as the oxidising reagent. The discrepancy between lab and field results could have a number of causes:

- loss of volatiles such as hydrogen sulf*ide gas and carbon dioxide gas, during crushing and drying for sample preparation*
- *oxidation during sample preparation*
- acidity could be associated with organic matter.

During field sampling, a hydrogen sulfide smell was detected. This indicates that loss of volatiles is likely to be contributing to the difference between laboratory and field results.

The difference between field pH and oxidised field pH is as great as 4.7, reducing the pH_{fox} to as low as 1.64. As a pH of less than 4.6 is unlikely to result from natural acidification (Appelo and Postma 2007), the low pH_{fox} is not likely to be associated with organic materials.

Table 7 reports the laboratory results of acid base accounting for the core samples retrieved during installation of the MGP_c bore hole. Appendix D has the full results. The chromium reducible sulfur method is not susceptible to contributions from organic acids and so S_{Cr} is used in preference to S_{POS} as a measure of potential acidity. S_{POS} is included in Table 7 for comparison. As the sediments at Lake Mariginiup have no measureable acid neutralising capacity, or retained acidity, the simplified equation becomes:

$$\text{Net acidity} = \text{potential sulfidic acidity } (S_{Cr}) + \text{actual acidity (TAA)}$$

None of the 13 samples showed a net acidity above management thresholds. The SPOCAS method reported a potential acidity of 0.23 % sulfur for the sample taken from the top 10 cm of sediment where as the chromium suite of methods did not detect any sulfur in this sample. While the two methods of acid base accounting are generally well correlated, it is common for the SPOCAS method to show a greater net acidity than the chromium method ($S_{POS} > S_{Cr}$). This is because the SPOCAS method can inadvertently include sulfur from organic matter (Ahern et al. 2004).

Laboratory pH_{KCl} (4.6–5.9 pH units) are slightly lower than field pH_f values (5.26–6.37 pH units). Results for oxidised pH were much lower in the field tests (pH_{fox}: 1.6–5.0) than laboratory results (pH_{ox}: 3 .0–4.2). It is not clear why laboratory analysis did not reflect field results.

Soil samples were also analysed for a range of metals, metalloids and selenium concentrations (Table 8). Aluminium and iron had the greatest concentrations, followed by manganese and zinc. Arsenic, cadmium, chromium, nickel and selenium were generally below detection limits. Most metals (As, Al, Cr, Fe, Ni, Se, Zn) showed a spike in concentration correlating to the sample with the highest net acidity. This indicates these metals are likely to be associated with or incorporated into the sulfides.

Although conventional laboratory methods have not identified the sandy sediments on the eastern shores of Lake Mariginiup to be acid sulfate soils, the lake bed has been identified as containing large amounts of net acidity. The acid sulfate soils are likely to be affecting, and will continue to affect, the water quality within the lake and groundwater.

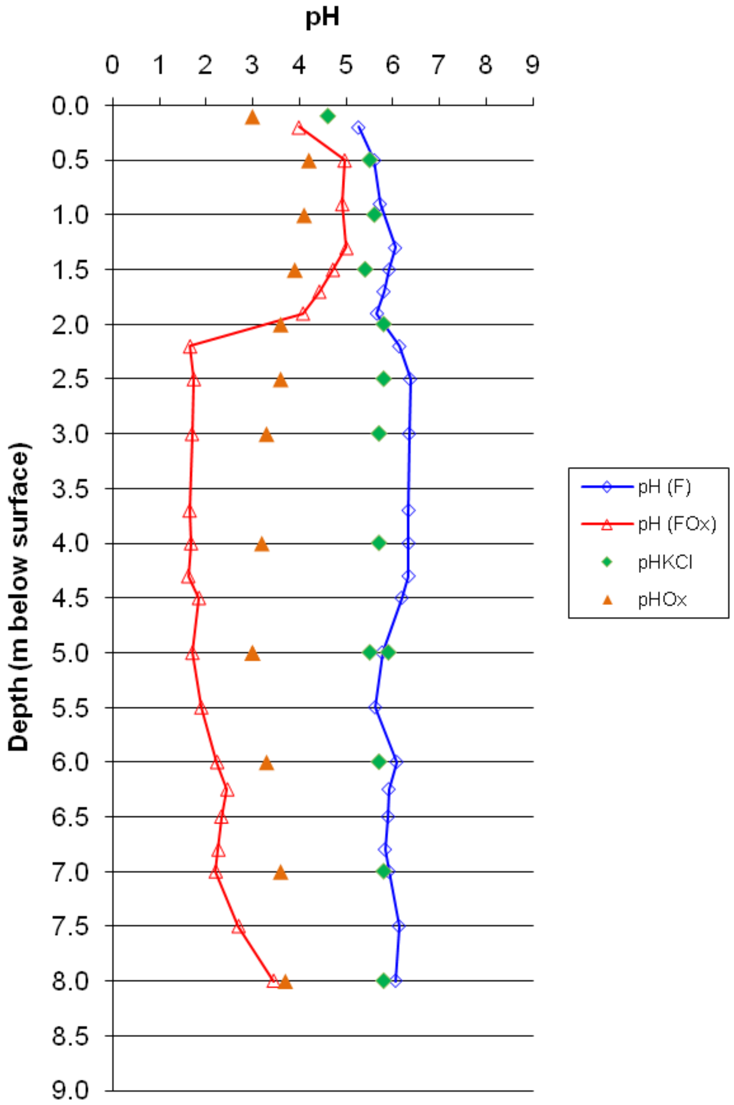

Figure 19 Natural and oxidised field pH measurements at bore MGP_c

Table 7 Summarised acid base accounting for both the SPOCAS and chromium reducible sulfur suite of analyses

Depth m below surface	**Total actual acidity % S**	**S_{POS} % S**	**S_{Cr} % S**	**Net acidity % S**
0.1	0.0176	0.23	< 0.01	0.018
0.5	0.0000	< 0.01	< 0.01	0.000
1.0	0.0000	< 0.01	< 0.01	0.000
1.5	0.0000	< 0.01	< 0.01	0.000
2.0	0.0000	< 0.01	< 0.01	0.000
2.5	0.0000	< 0.01	0.02	0.020
3.0	0.0000	< 0.01	< 0.01	0.000
4.0	0.0000	< 0.01	0.01	0.010
5.0	0.0000	0.01	0.02	0.020
5.0 (duplicate)	0.0000		0.02	0.020
6.0	0.0000	< 0.01	< 0.01	0.000
7.0	0.0000	< 0.01	< 0.01	0.000
8.0	0.0000	< 0.01	< 0.01	0.000

Table 8 Metals and metalloids in soils

Depth m below surface	**Al mg/kg**	**As mg/kg**	**Cd mg/kg**	**Cr mg/kg**	**Fe mg/kg**	**Mn mg/kg**	**Ni mg/kg**	**Se mg/kg**	**Zn mg/kg**
0.1	2710	1.8	< 0.5	5.9	450	2.3	0.5	0.71	3.7
0.5	170	< 0.5	< 0.5	< 0.5	42	0.61	< 0.5	< 0.5	1.1
1.0	120	< 0.5	< 0.5	< 0.5	37	< 0.5	< 0.5	< 0.5	1.1
1.5	130	< 0.5	< 0.5	< 0.5	33	0.64	< 0.5	< 0.5	< 0.5
2.0	94	< 0.5	< 0.5	< 0.5	140	1.3	< 0.5	< 0.5	< 0.5
2.5	75	< 0.5	< 0.5	< 0.5	260	1.5	< 0.5	< 0.5	< 0.5
3.0	79	< 0.5	< 0.5	< 0.5	200	1.7	< 0.5	< 0.5	< 0.5
4.0	270	< 0.5	< 0.5	< 0.5	180	1.2	< 0.5	< 0.5	< 0.5
5.0	290	< 0.5	< 0.5	< 0.5	240	1.6	< 0.5	< 0.5	1.3
6.0	280	< 0.5	< 0.5	< 0.5	150	2.2	< 0.5	< 0.5	< 0.5
7.0	240	< 0.5	< 0.5	< 0.5	130	3.1	< 0.5	< 0.5	< 0.5
8.0	250	< 0.5	< 0.5	0.6	130	4.6	< 0.5	< 0.5	< 0.5

5 Hydrogeology

5.1 Water levels

Analysis of hydrographs from Department of Water monitoring bores around Lake Mariginiup (see Figure 9 for bore locations) show that over the past 20 years, water levels in the Superficial aquifer, both up and down hydraulic gradient from the lake, are declining (Figure 20). Minimum water levels in the MT1 bores series, on the eastern shore of the lake, have dropped by between 1.3 m (MT1D) and 0.86 m (MT1S). Maximum water levels have fallen by between 1.14 m (MT1D) and 0.85 m (MT1S). Water levels in the JP20 bores (2.6 km east of Lake Mariginiup, not shown in Figure 20), the MT3 bores (1.15 km west of MT1) and MS10 (85 m north-east of MGP_a) all show a similar decline.

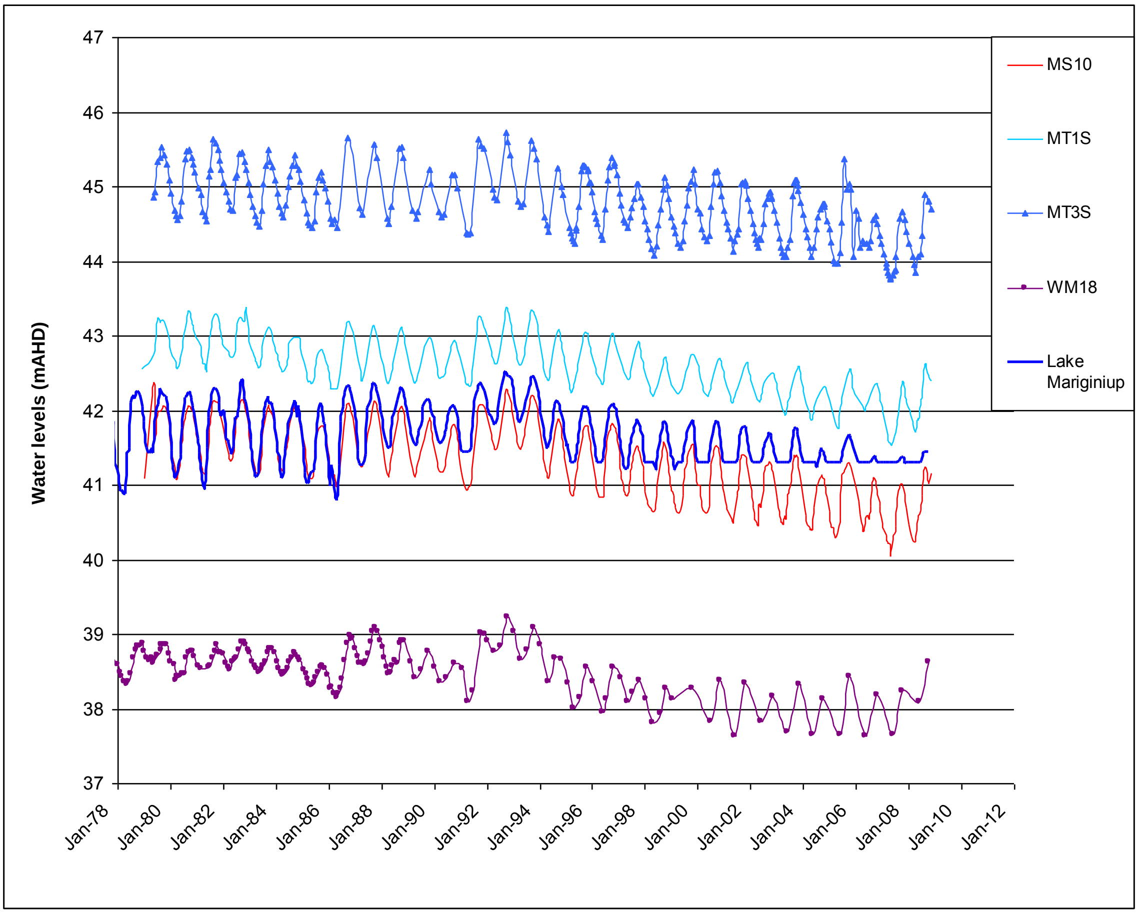

Figure 20 Hydrographs of bores in the Lake Mariginiup area

Lake levels have also been falling and as a consequence, the periods during which the lake actually has water in it have been reduced (Figure 20). When the lake's hydrograph is flat, the lake is dry at 41.3 m AHD. Since 1998, it has been dry for around 6 months of the year, and maximum water levels for this period ranged from 0.08 m to 0.6 m above ground level. From 1978 to 1997 records show that Lake Mariginiup was dry for an average of 2 months each year, and was never recorded as dry from 1968 to 1978. Prior to 1968 records were too infrequent to compare meaningfully. Maximum lake water levels ranged from 0.5 to 1.22 m above ground surface during the period 1979 to 1998, and from 1968 to 1978, water levels were between 0.74 to 2.23 m above ground surface.

Groundwater has been declining more rapidly than the lake levels, presumably due to the perching cause by lake bed sediments. This increases the difference between surface water and groundwater levels (Figure 20). The main cause of water level decline in the Mariginiup region has been linked to groundwater abstraction for private use (Yesertener 2007).

5.2 Groundwater flow

Hall (1985) determined that Lake Mariginiup was a groundwater sink, in hydraulic connection with the groundwater of the Superficial aquifer. Water flows into the lake on the eastern side, from the upper half of the aquifer, where evapotranspiration removes around 92% of this input. Some water, impeded by lake sediments, recharges groundwater on the western side. The outflowing water, as a result of evapotranspiration, is more saline than the regional groundwater, and creates a saline plume downstream of the lake.

Groundwater contours derived from the monitoring program of the shallow groundwater systems investigation, and from nearby monitoring bores, generally confirm Hall's (1985) findings with groundwater flowing from the east-north-east to the west-south-west (Figures Figure 21 and Figure 22).The groundwater gradient is relatively gentle on the eastern side of the lake. On the western side however, the hydraulic gradient is steeper, as a result of solution channels within the Tamala Limestone. Using the technique described by Turner and Townley (2006), the capture zone of Lake Mariginiup is likely to be overlapping the release zone of Lake Jandabup.

Figure 21 shows the configuration of the watertable in April 2008, when water levels are lowest near the end of summer. At the end of winter (around October), watertable contours show a very similar pattern but (Figure 22), there is a about a 1 m increase on either side of the lake, when compared to minimum levels.

Hydrogeological cross-sections from October 2007 and April 2008 are shown in Figure 23 and Figure 24. These sections are approximately parallel to groundwater flow. They represent the maximum and minimum water levels respectively, and include water level measurements for shallow, intermediate and deep bores on either side of the lake.

The October 2007 section (end of winter) shows weak upward heads on the eastern side of the lake, demonstrating that groundwater discharges into the lake from the east. The isopotential lines indicate that flow in the lower two-thirds of the aquifer is horizontal, and it is only the top portion (~10 m) which interacts with the lake.

On the western side, the water levels are lower than the eastern side of the lake, indicating outflow occurs on the western side. However the MGP bore cluster does not show typical downward heads, as the intermediate bore has a greater water level than the shallow bore. It is likely that this is the result of a downward component of

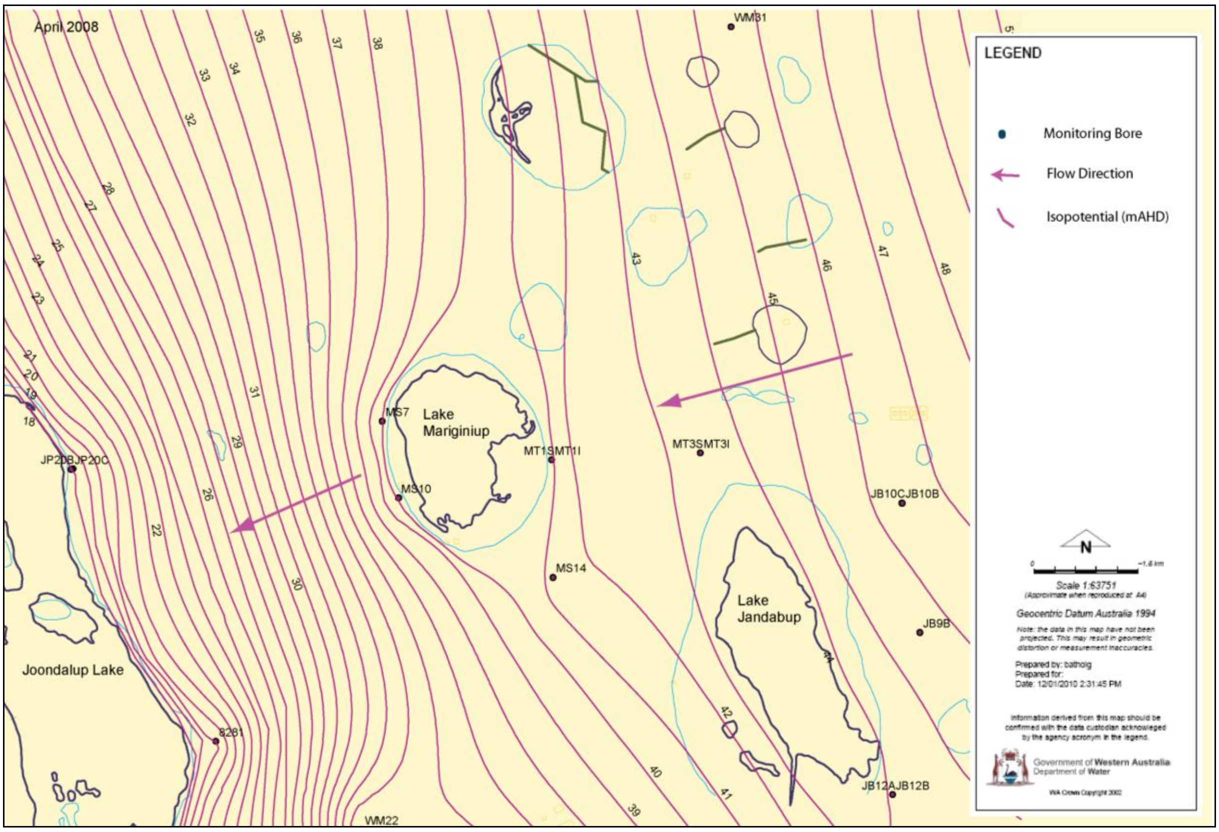

Figure 21 Minimum watertable contours (April 2008)

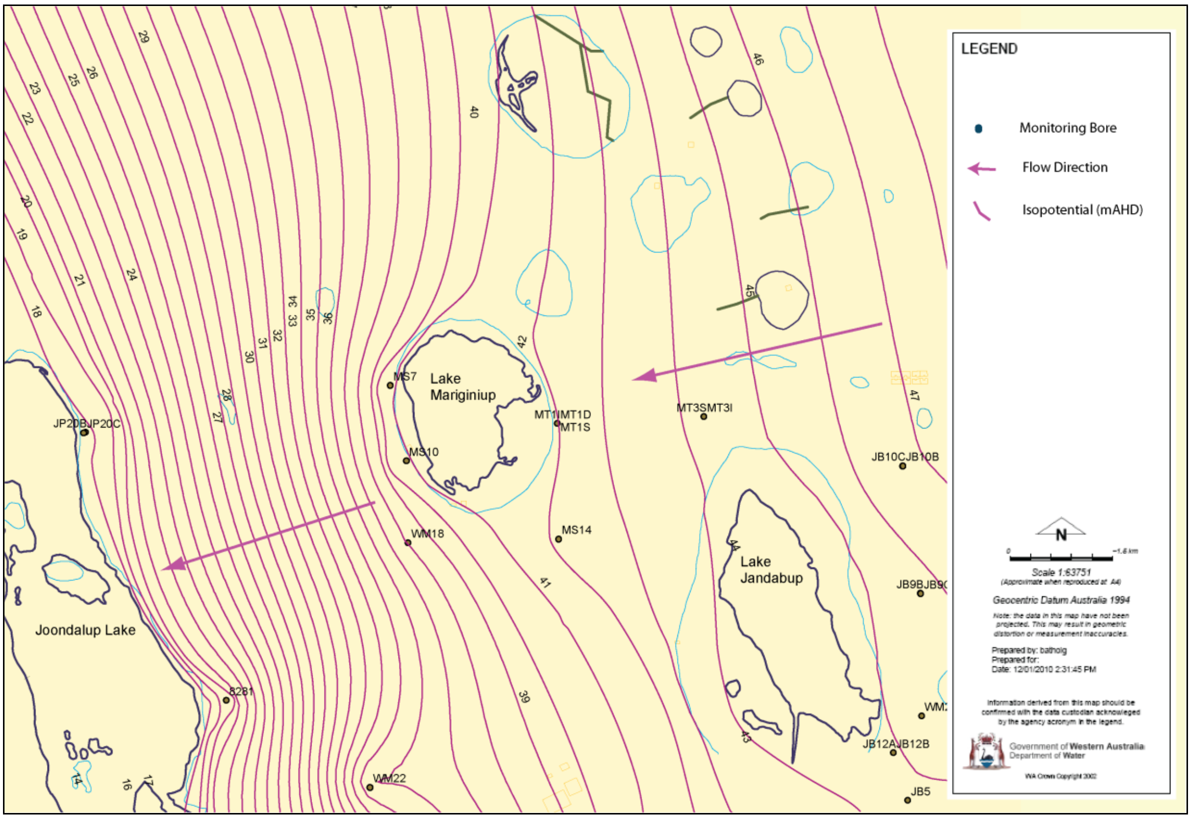

Figure 22 Maximum watertable contours (October 2008)

the flow path, with water leaving the western side of the lake and flowing down toward the intermediate bore, beneath the bottom of the shallow bore. Water chemistry results support this (see Section 5.3).

The cross-section for April (2008) shows the lake is dry and does not show upward heads on the eastern side, indicating the lake is not in hydraulic connection with the groundwater flow system. Furthermore, the isopotential lines suggest that water in the upper half of the aquifer is flowing downwards while the deeper section is flowing slightly up. Again, on the western side, the watertable is lowest, yet the intermediate bore has the greatest head measurement, followed by the shallow then the deep.

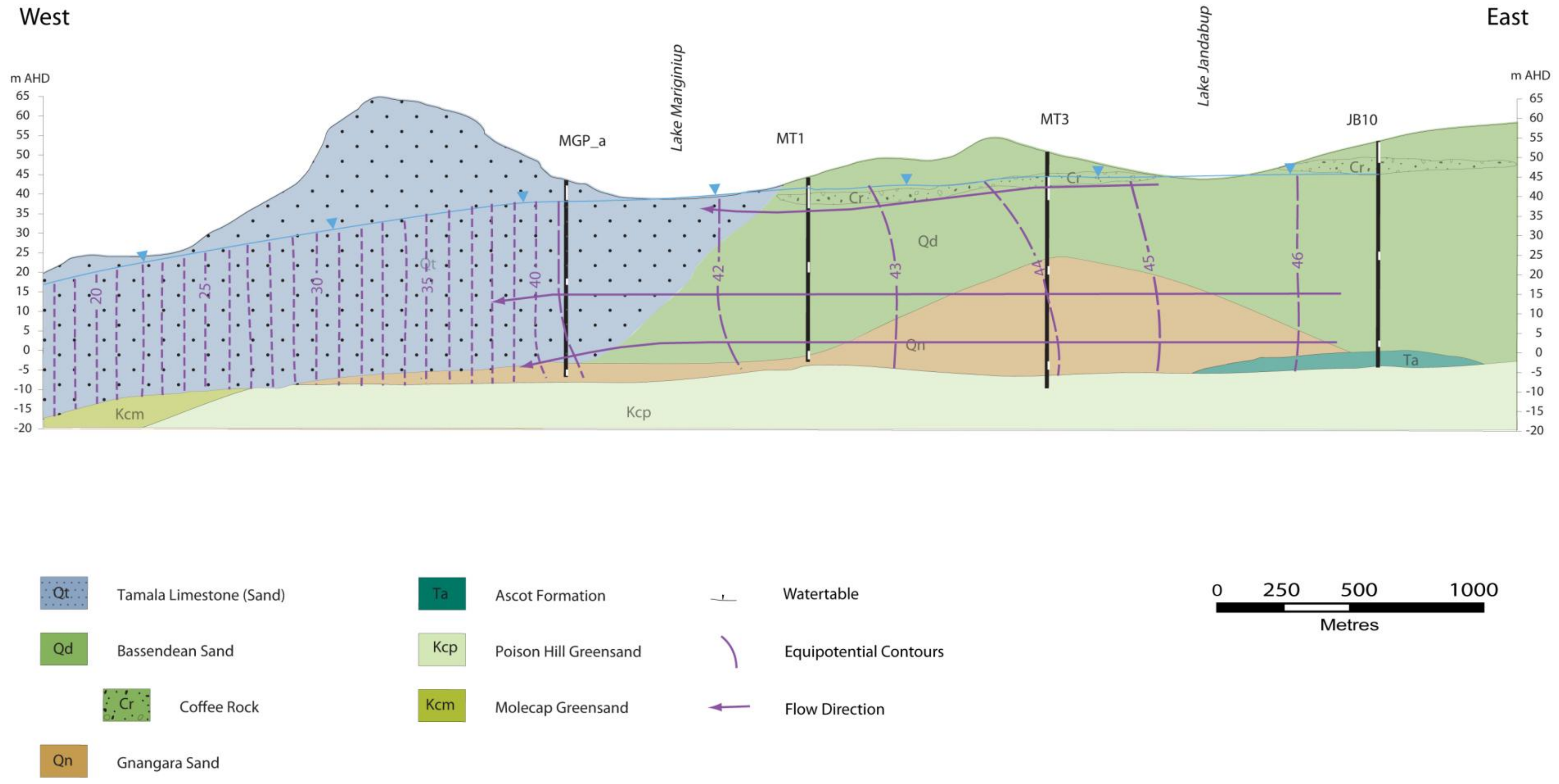

Figure 23 End of winter groundwater flow paths (October 2007)

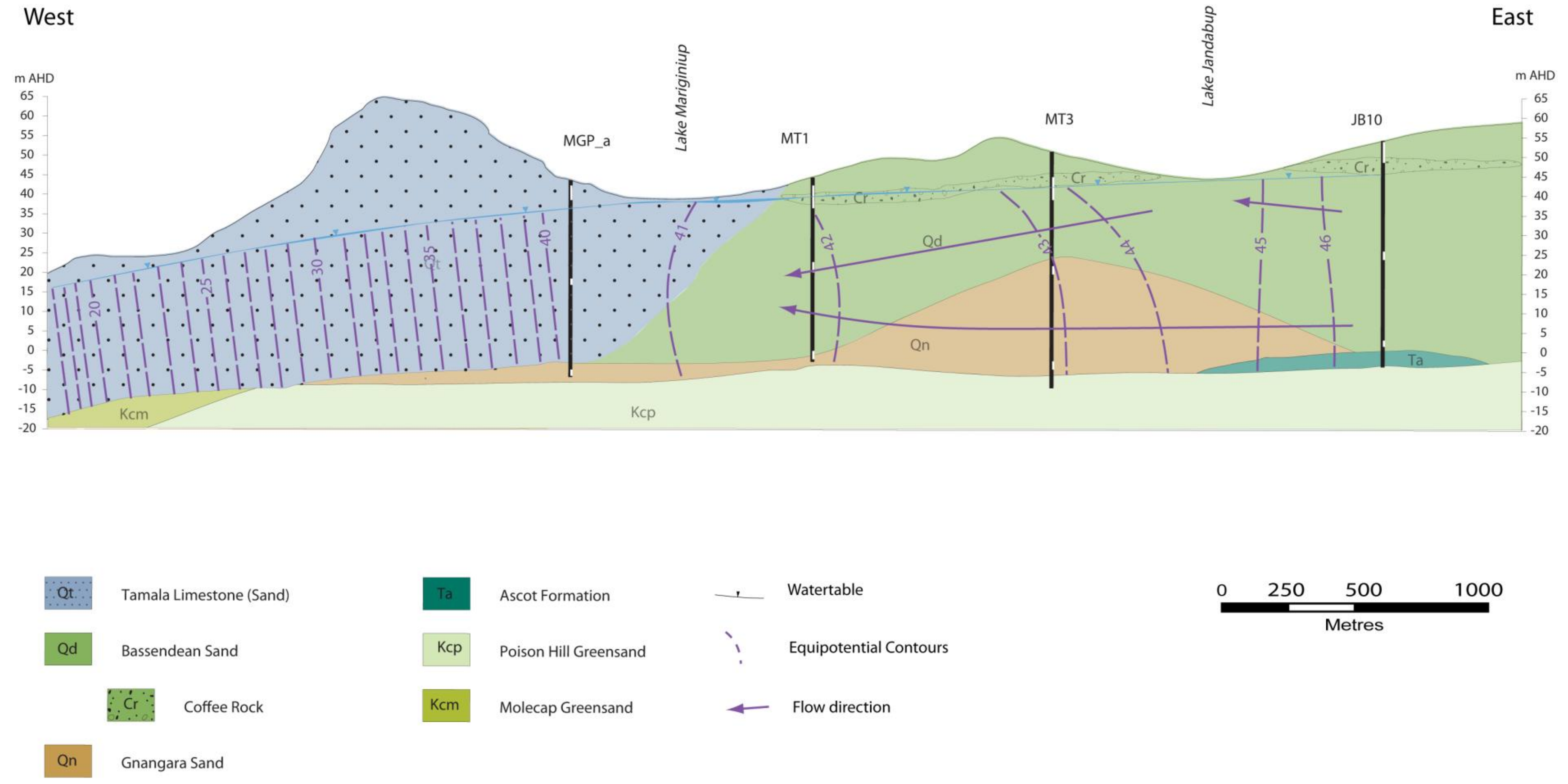

Figure 24 End of summer groundwater flow paths (April 2008)

5.3 Flow budget

Using the equation in Hall (1985), the water balance at Lake Mariginiup can be represented by:

$G_i + R = D + E$

where G_i = groundwater inflow to the lake

R = rainfall on the lake

D = outflow to groundwater from the lake

E = evapotranspiration from the lake.

To evaluate the magnitude of change to the system, average water flow can be used to compare the water balance established for Lake Mariginiup in 1979–1980 (Hall 1985) to the flow budget developed for 2001–06 (RPS 2009) (Table 9).

Table 9 Comparison of flow budgets at Lake Mariginiup

Water balance component	**Average flow m^3/day**	
	1979–1980	***2001–2006***
	3500	*223*
	3013	*39*
	547	*121*
	6027	*142*

Table 9 shows the total volume of water entering and leaving the system has decreased dramatically, as expected from the reduced rainfall and lower groundwater levels. Although simplistic, Table 9 also shows that the relative contributions have changed. Hall's (1985) work showed that rainfall and groundwater contributed almost equally to the lake, and that evapotranspiration removed around 92 % of total input. The recent work by RPS (2009) indicates that groundwater is now the major contributor of water to the lake, at 85 % of inflow, while evapotranspiration and outflow to groundwater are almost equal.

5.4 Hydrogeochemistry

Sampling and analysis of lake water and groundwater were used to determine the hydrochemical characteristics of each site, the presence, distribution and availability of potential pollutants and the interaction between the wetland and the Superficial aquifer.

Chemical data was compared against trigger levels and assessment levels for various water uses and environments. Trigger levels for fresh water, irrigation water and drinking water were taken from and applied in accordance with the Department of Environment's 2003 *Draft assessment levels for soil, sediment and water*. These trigger levels have been amalgamated from a number of sources. The freshwater and irrigation water trigger levels were taken from the *Australian and New Zealand guidelines for fresh and marine water quality* (ANZECC & ARMCANZ 2000). The drinking water assessment levels were taken from the *Australian drinking water guidelines* (NHMRC & ARMCANZ 1996). The trigger levels which are specific to south-western Australia (wetlands and fresh water) also come from the ANZECC 2000 guidelines.

The main use for groundwater around Lake Mariginiup is irrigation, therefore groundwater quality was assessed against the irrigation guidelines. Where there was no irrigation trigger level, drinking water guidelines were used (in accordance with the methods described in the Department of Environment's 2003 guidelines). The assessment levels for freshwater aquatic ecosystems in these guidelines are also relevant for the lake and groundwater discharging into the lake, as are the nutrient and physical property trigger levels for wetlands and freshwater lakes in south-west Australia (ANZECC & ARMCANZ 2000).

5.4.1 Physical and chemical characteristics

Major ions

To characterise the water in the Superficial aquifer and in Lake Mariginiup, a variety of ions and physical properties were measured. Concentrations of major ions (sodium, potassium, calcium, magnesium, chloride, bicarbonate, and sulfate) were used to create 'Piper' and 'Stiff' diagrams. Piper diagrams are a simple but useful method to present information for determining the geochemical nature of individual groundwater samples, and help to compare and contrast samples with different chemical characteristics. Stiff diagrams plot the major chemical components, in milliequivalents per litre, as a polygonal shape created from four parallel horizontal axes extending on either side of a vertical zero axis. Stiff diagrams are useful to visually compare groundwater from different sources and to show how the ionic composition of groundwater changes along a known flow path.

For this investigation, the Piper and Stiff diagrams were used to determine the water type of lake and groundwater samples around Lake Mariginiup, highlight potential chemical outliers, and to confirm lithological classifications. Time-series graphs were used to show seasonal variation in major ion composition.

Piper diagrams plotting all groundwater samples for this investigation are presented below in

Figure 25, and Stiff diagrams in Figure 26. The diagrams show that groundwater near Lake Mariginiup and in the lake was generally of sodium–chloride type, but with some clear differences between groundwater flowing eastwards through and westwards out of Lake Mariginiup. There were also differences between the hydrogeochemistry at the watertable and at depth in the Superficial aquifer. These were:

- Groundwater on the inflow (eastern side) of the lake (MT1D, MT1I and MT1S) was sodium–chloride type and had relatively low ionic concentrations.
- *Groundwater on the outflow (western side) of the lake (MGP_a, MGP_b and MGP_c) had higher major ion concentrations, and the shallow and intermediate bores were also enriched in sulfate, calcium and magnesium*. The intermediate bore (MGP_b) had the highest ion concentrations of all the bores. *Groundwater from the shallow bore was not of sodium–chloride type.*
- Water in the lake was also enriched in *sulfate, calcium and magnesium* and was most similar in composition to the intermediate outflow bore (MGP_b).

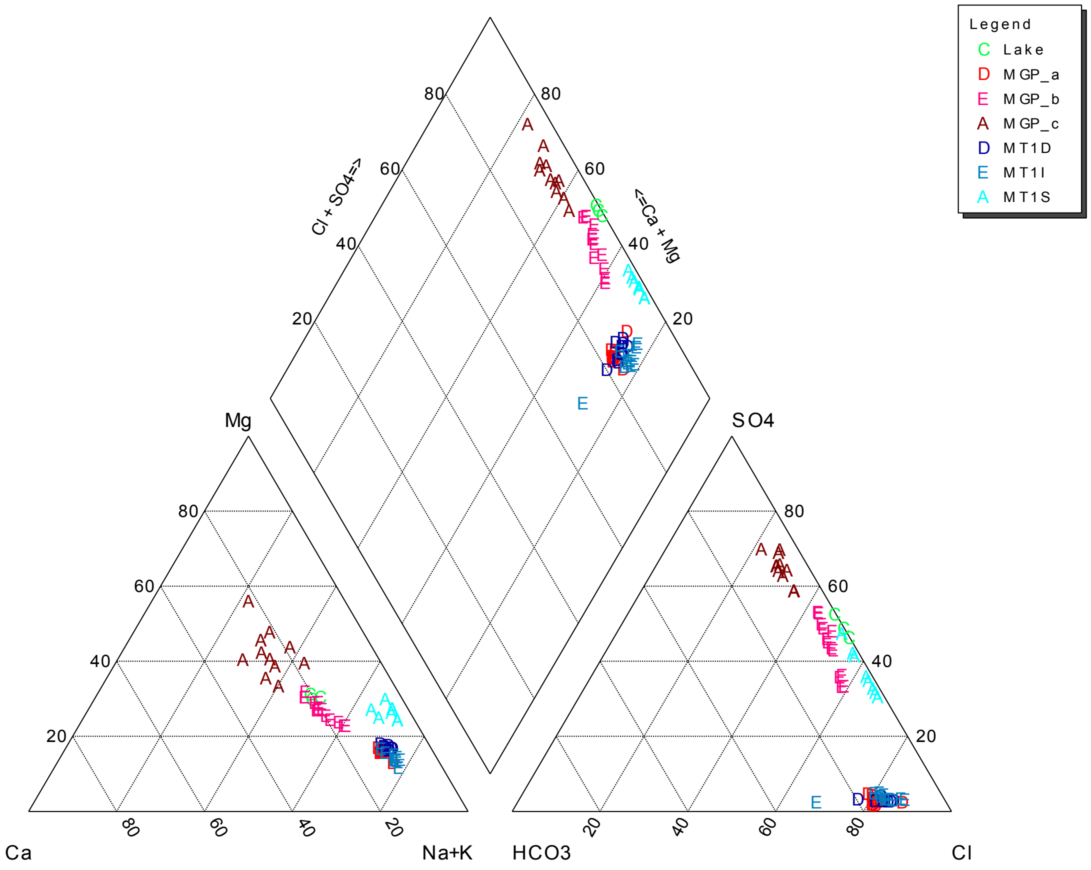

Figure 25 Piper plot of lake and groundwater from Lake Mariginiup monitoring bores sampled June 2007 to July 2008

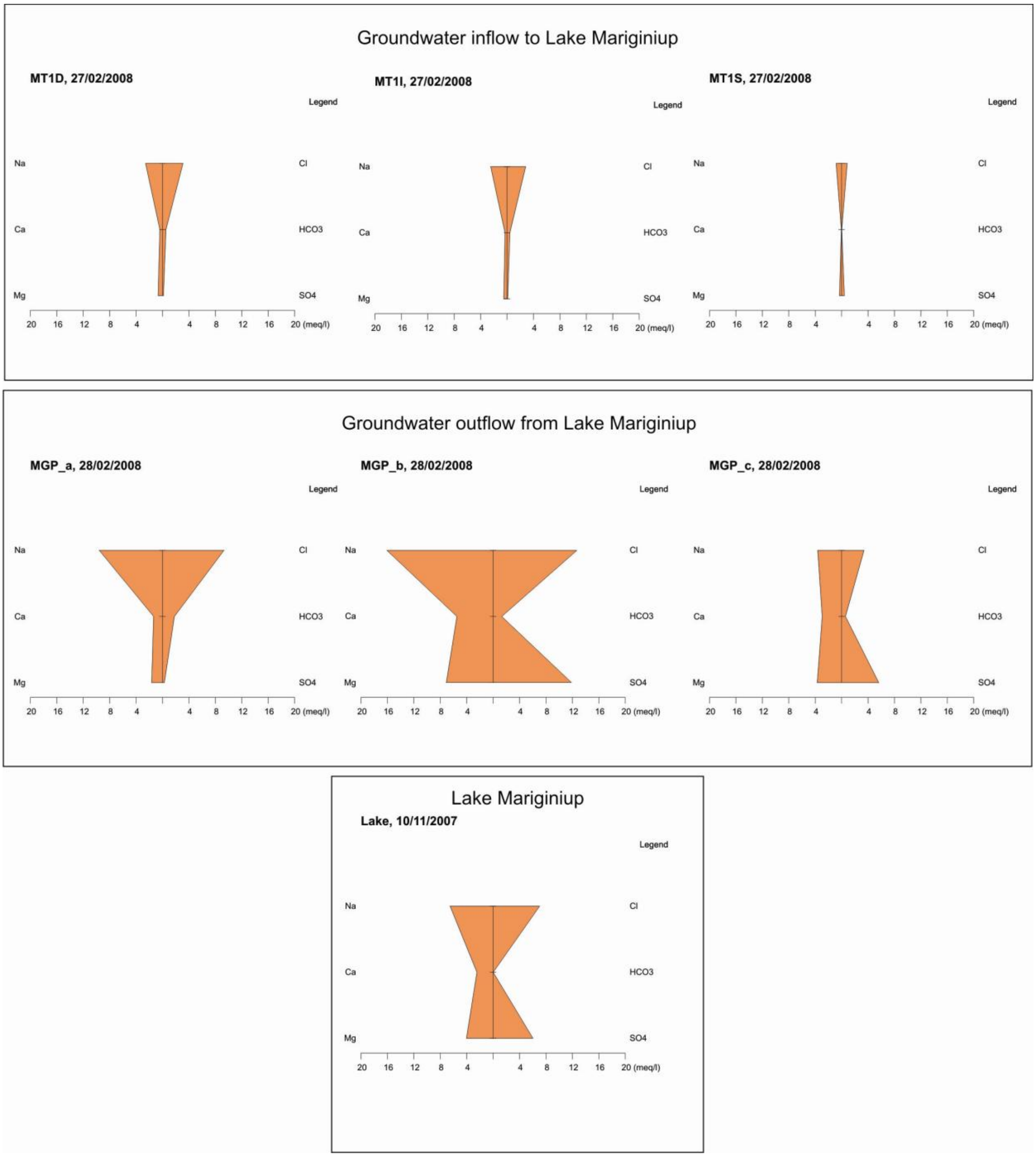

Figure 26 Representative Stiff diagrams of lake water from Lake Mariginiup and from MT series and MGP series monitoring bores

In general there was little seasonal variation in major ion composition, as shown in the time-series graphs in Figure 27 and Figure 28 for chloride (Cl^-) and sodium (Na^+). Chloride concentrations at the watertable have only increased slightly since the late 1970s and 1980s and are still below 500 mg/L. The highest concentrations are in the deep and intermediate outflow bores. The lake has lower concentrations than the intermediate outflow bore. This could be an artefact of the sampling location – lake samples are collected at the edge of the lake, near the staff gauge, which is not the deepest part of the lake. This means when the staff gauge is dry, and no sample is collected, there could still be water, in small pools, elsewhere in the lake bed.

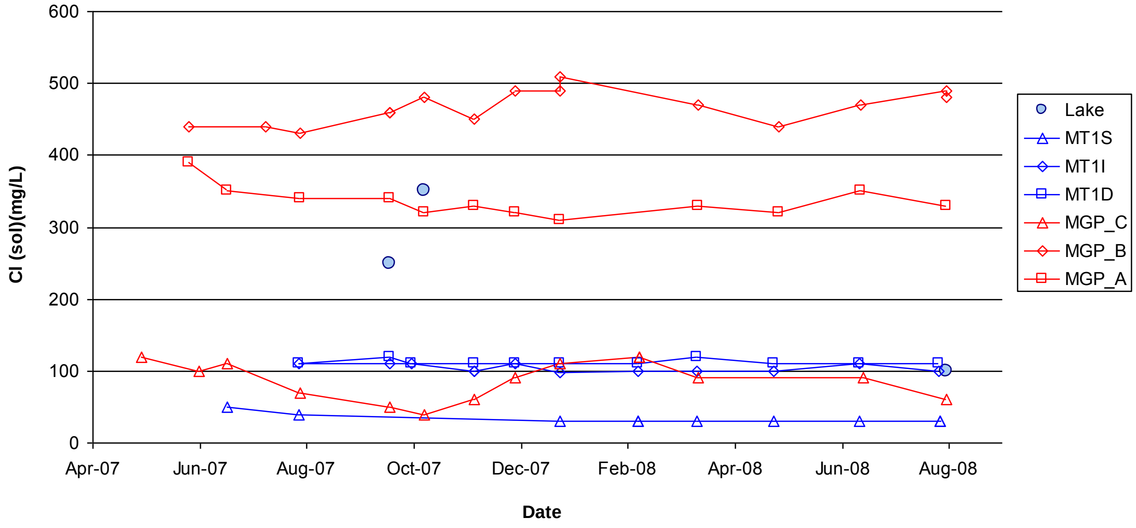

Figure 27 Chloride concentrations in lake and groundwater at Lake Mariginiup

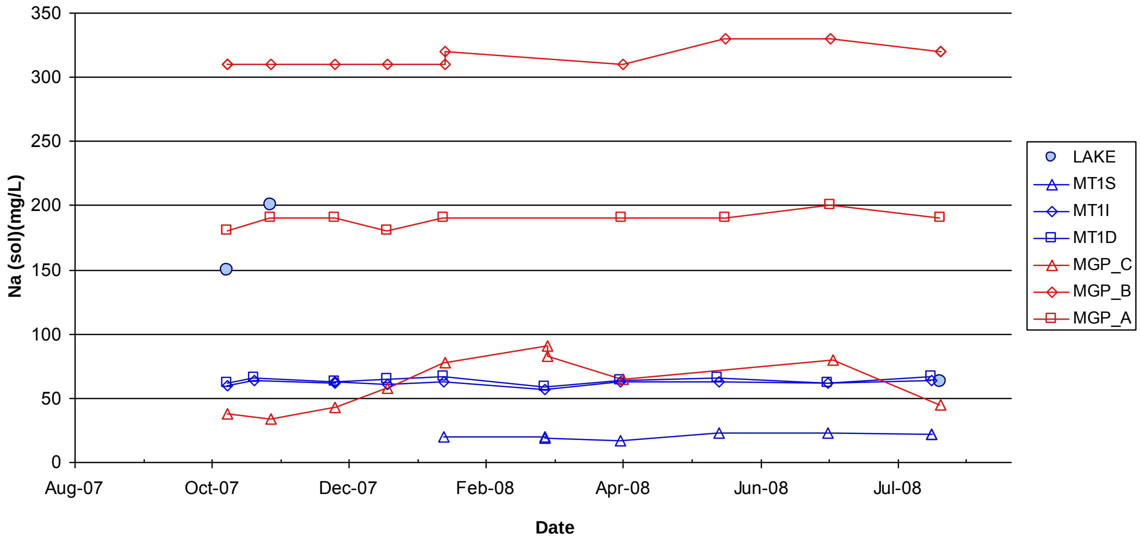

Figure 28 Sodium concentrations in lake and groundwater at Lake Mariginiup

Ionic concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) were highest on the outflow (west) side of Lake Mariginiup. Groundwater from the watertable outflow bore (MGP_c) showed seasonal variation, with Ca^{2+} and Mg^{2+} concentrations highest at the end of summer, and lowest at the end of winter (Figure 29 and Figure 30). The intermediate outflow bore (MGP_b) had the greatest concentrations throughout the year, and concentrations increased steadily throughout the sampling period. The intermediate outflow bore (MGP_b) also has greater concentrations than the lake.

The eastern bores and deep western bore showed no seasonal variation in Ca^{2+} or Mg^{2+} concentrations.

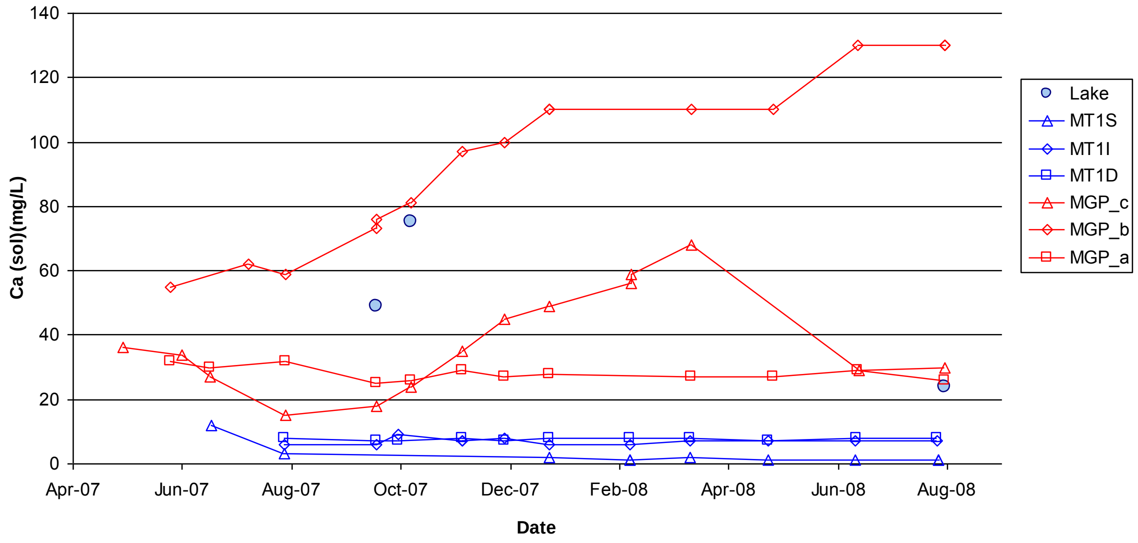

Figure 29 Calcium concentrations in lake and groundwater at Lake Mariginiup

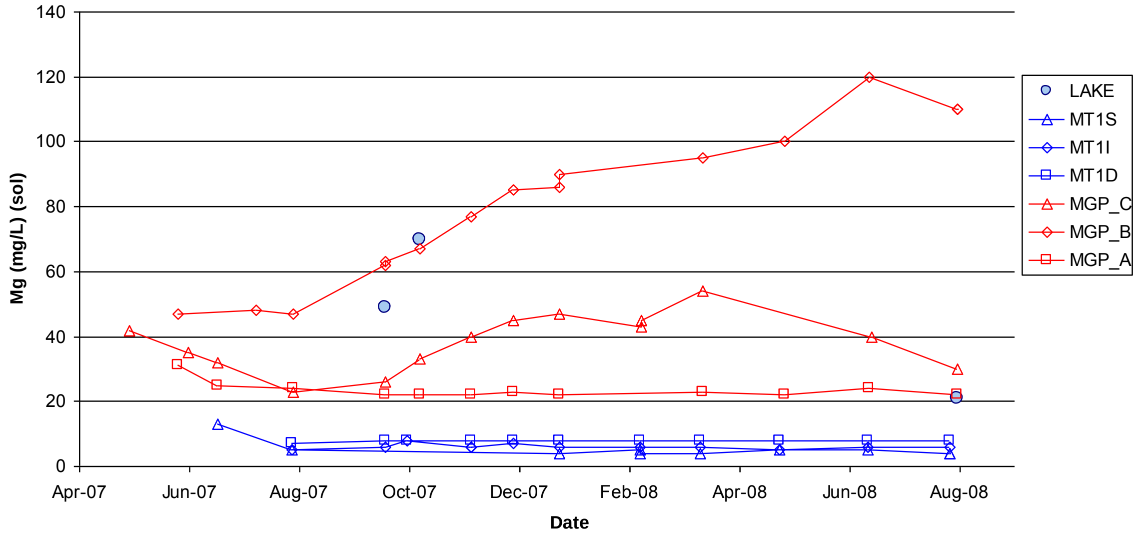

Figure 30 Magnesium concentrations in lake and groundwater at Lake Mariginiup

Historically, sulfate ion (SO_4^{2-}) concentrations are generally less than 100 mg/L in the Superficial aquifer (Davidson 1995). As seen in Figure 31, the SO_4^{2-} concentrations were far greater in the lake and the shallow and intermediate outflow bores compared to the other bores. Sulfate concentrations have increased by up to 28 times on the western side compared to Hall's (1985) work, which reported SO_4^{2-} values in the area of MGP_c to range from 11 to 40 mg/L. On the eastern side there were also increases, but to a lesser extent. Hall (1985) reported values ranging from 16 to 21 mg/L for MT1S.

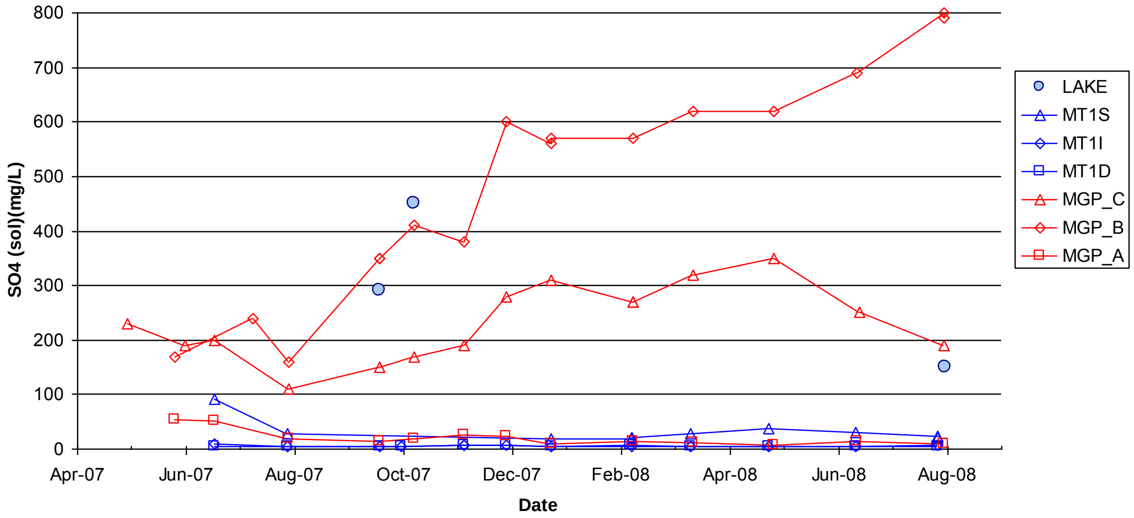

Figure 31 Sulfate concentrations in lake and groundwater at Lake Mariginiup

Acidity and alkalinity

Generally, groundwater from the outflow side of the lake (western) had higher pH values than on the inflow (eastern) side (Figure 32). The three western, outflow bores (MGP_a, MGP_b and MGP_c), had pH values ranging from 6.1 to 7.7. In contrast, the pH of the deep and intermediate eastern bores (MT1I and MT1D) was slightly lower, between 5.9 and 7.2. Water from the lake and the shallow eastern bore (MT1S) was acidic (pH range 4.7 to 3.6).

The Department of Environment's 2003 guidelines set out a pH range of 6.5 to 8.5 for fresh and drinking water, and a lower limit of 7.0 pH units for wetlands in south-west Australia (ANZECC 2000). Commonly pH values are below fresh and drinking water limits, and most samples fall below the lower limit for wetlands (Figure 32).

The results of the shallow groundwater systems investigation show the groundwater to be slightly more acidic than historic pH values reported in Davidson (1995). Davidson (1995) reports that pH values from the Tamala Limestone were generally between 7 and 8. However, our investigation found pH values were between 6.1 and 7.7 (bores MGP_a, MGP_b and MGP_c). Historical pH values for the Bassendean sand were as low as 4.0 at the watertable ranging to 7.5 at depth (Davidson 1995). Our results ranged from 3.7 to 4.0 at the watertable (MT1S) and averaged 6.3 in the deeper bores (MT1I and MT1D).

During the shallow groundwater systems sampling the lake water pH values ranged between 4.1 and 4.6 which was considerably lower than historical values. Twice yearly water quality sampling shows a declining trend in lake pH over the past 13 years (Judd and Horwitz 2009) (Figure 33).

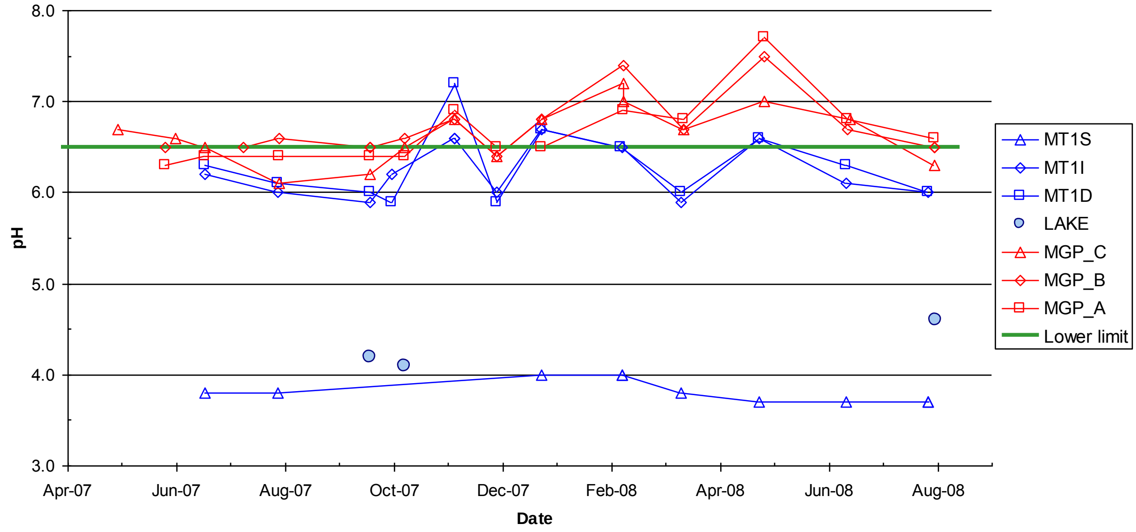

Figure 32 pH values in lake and groundwater at Lake Mariginiup

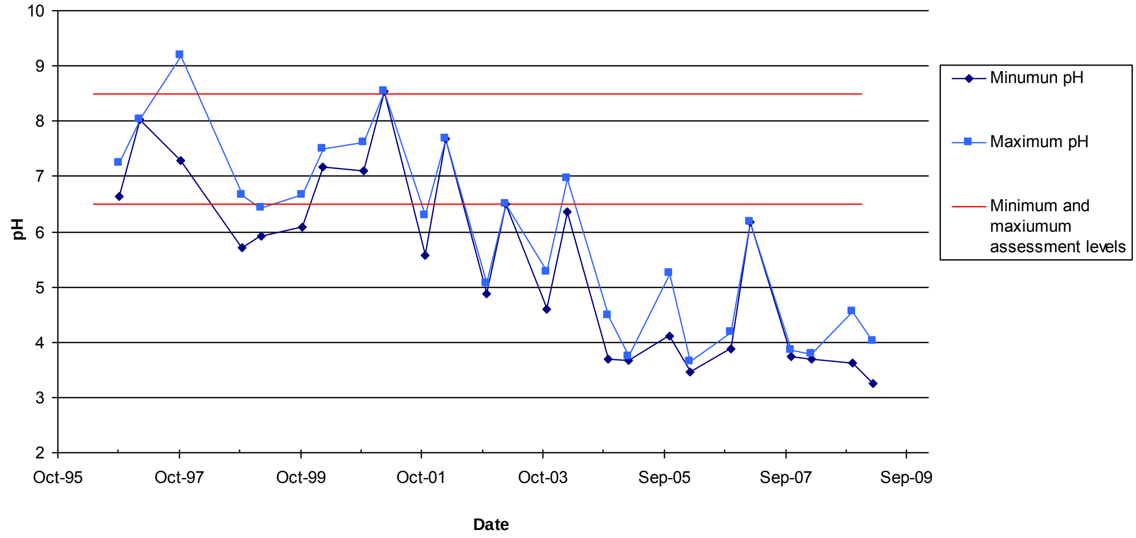

Figure 33 pH values for Lake Mariginiup 1996–2009

The alkalinity of water is its acid neutralising capacity. Analysis of alkalinity can give greater insight into the characteristics of water and its possible behaviours than pH measurements alone, which only measure H^+ activity. As previously mentioned, pH values indicate that only the shallow zone of the aquifer on the eastern side of the lake (MT1S) and the lake itself were acidic. Analysis of the alkalinity however highlights that the intermediate and deep zones on the eastern side, as well as the shallow zone on the western side were vulnerable to acidification, as the groundwater in these locations had only limited acid neutralising capacity (Figure 34).

The high pH values in water samples from MGP_b and MGP_a correspond to high alkalinities, and the low pH values for MT1S and the lake correspond to low alkalinities. High concentrations of Ca^{2+} and Mg^{2+} in MGP_b, which is within the release zone of the lake, could suggest ongoing neutralisation of acidity within the lake.

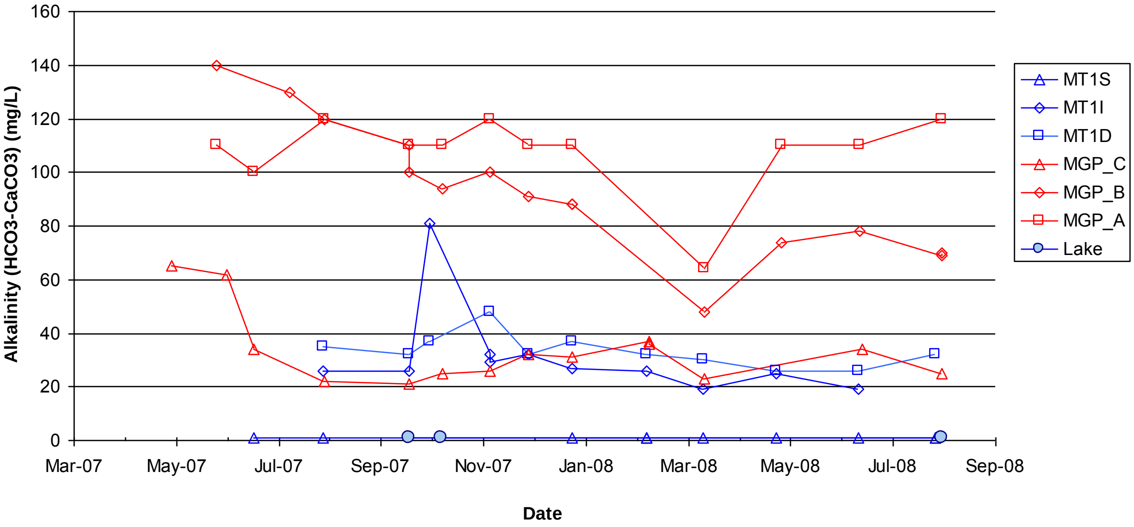

Figure 34 Alkalinity in lake and groundwater at Lake Mariginiup

Salinity as total dissolved solids

Historical values of total dissolved solids (TDS) range from 130 to 12 000 mg/L in the Superficial aquifer, but they are generally not above 1000 mg/L (Davidson 1995). Hall (1985) found that groundwater flowing into the lake was fresh (less than 200 mg/L TDS). However, evapotranspiration had caused the lake water and outflowing groundwater to be more saline (up to 1200 mg/L). He also noted that due to the downward flow component on the outflow side of the lake, the watertable bore was slightly less saline than the deeper bores (up to 700 mg/L). The shallow groundwater systems investigation confirmed this trend, however, measured TDS levels were higher than historic levels (Figure 35). Groundwater samples from the inflow side of the lake averaged 262 mg/L. In June 2007 the intermediate outflow bore (MGP_b) had a TDS of 1200 mg/L which continued to increase over the sampling period to 2090 mg/L in August 2008, reflecting the trend in Ca^{2+} and Mg^{2+} concentrations. The watertable bore and deep bore on the outflow side (MGP_c and MGP_a) ranged from 310 to 920 mg/L TDS.

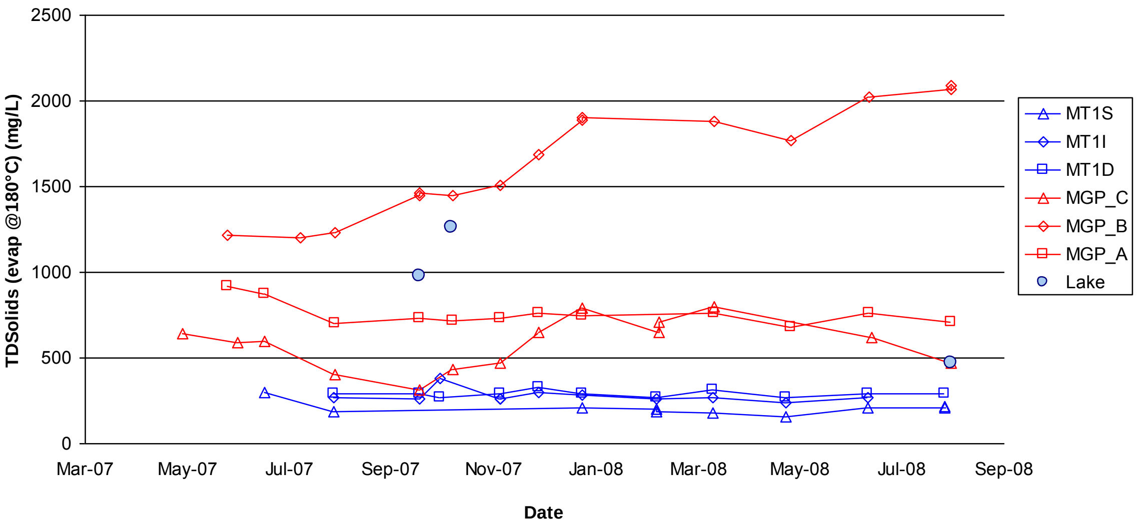

Figure 35 Total dissolved solids in lake and groundwater at Lake Mariginiup

Dissolved oxygen

Dissolved oxygen saturation in lake and groundwater can indicate whether an environment is generally oxic or anoxic. However, during this study field measurements were recorded before dissolved oxygen stabilised, and hence they can only be considered as broadly indicative. Both the lake water and groundwater were low oxygen environments. Only one water sample had dissolved oxygen content above the minimum criteria of 90% saturation set by ANZECC (2000). The shallow inflow bore (MT1S) represents the most oxygen rich part of the aquifer, with a range of 3.6 to 98.4%. Lake water ranged from 52.6 to 75.1%. Over 75% of samples reported dissolved oxygen less than 10 %.

Redox conditions

Eh measurements are useful to give a qualitative indication of redox condition (Yesertener 2009). As with dissolved oxygen, the lake water and the shallow inflow bore (MT1S) had the highest Eh readings, ranging between 100 and 400 mV. All other groundwater samples had negative readings, between -20 and -320 mV. This indicates that much of the aquifer around Lake Mariginiup was a reducing environment.

Using the framework devised by Jurgens et al. (2009), dissolved oxygen, nitrate, manganese, iron, sulfate and sulfide concentrations are used to classify the redox state of groundwater, and to identify the dominant oxidation/reduction processes. Using only water samples which had at least five of these parameters, two different redox categories were observed, each with its own dominant redox process:

- Mixed (anoxic) conditions were dominated by nitrate reduction, as well as iron and/or sulfate reduction. This comprised 67% of samples. All groundwater bores exhibited these characteristics except the shallow inflow bore (MT1S).

- Mixed (oxic–anoxic) conditions were dominated by oxygen reduction, as well as iron and/or sulfate reduction. This comprised 33% of samples. Samples from all bores displayed this redox condition.

The term 'mixed' (above) indicates that two processes are taking place. That is, either both anoxic (mixed (anoxic)), or one oxic and the other anoxic (mixed (oxic–anoxic)).

5.4.2 Water quality

Nitrogen compounds

Total nitrogen concentrations (TN) ranged from 870 to 5100 µg/L (*Figure 36*). All samples were greater than the 350 µg/L trigger level for freshwater lakes, and almost 70% of samples had TN concentrations which exceeded the trigger level of 1500 µg/L for wetlands in the south-west of Australia (ANZECC, 2000). Generally, TN concentrations were greater on the western side of the lake than on the eastern side.

Nitrate and nitrite concentrations (NO_x) were highest in the shallow bores, exceeding trigger levels for wetlands by up to six times. These have not been shown here.

All samples from all bores and lake water exceeded the trigger levels for ammonium and ammonia for wetlands in the south-west of Australia (40 µg/L NH_3-N/NH_4-N (sol)), as well as the trigger for freshwater lakes (10 µg/L) (*Figure 37*). Deep and intermediate down gradient (western) bores are depleted in NO_x and enriched in ammonia and ammonium (ranging from 2300 to 4000 µg/L NH_3-N/NH_4-N (sol)).

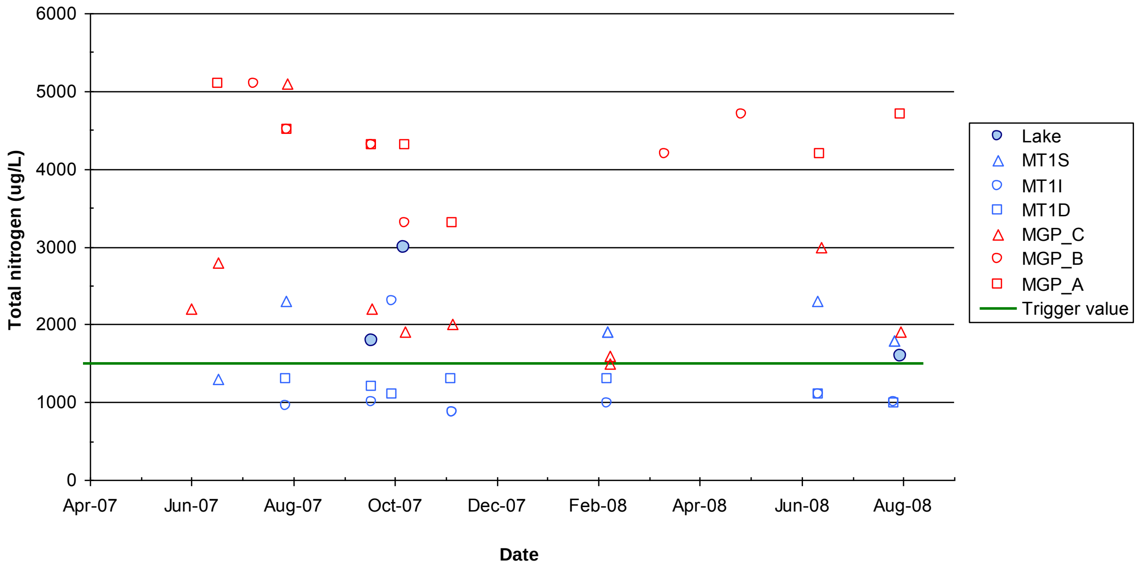

Figure 36 Total nitrogen concentrations in lake and groundwater at Lake Mariginiup

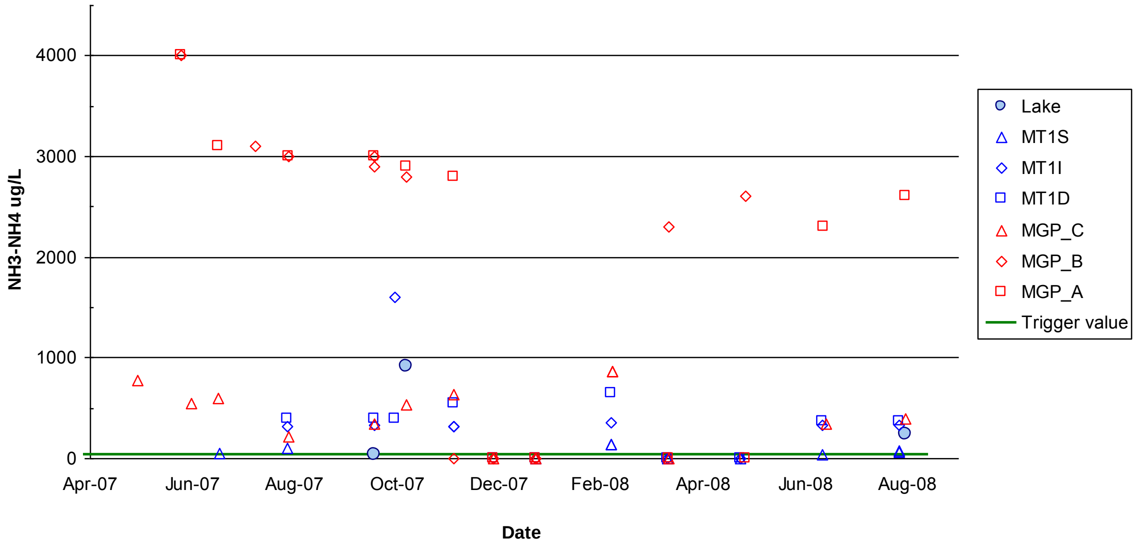

Figure 37 Ammonia /ammonium concentrations in lake and groundwater at Lake Mariginiup

Phosphorus

Total phosphorus (TP) concentrations ranged from 5 to 180 µg/L (Figure 38). Around a quarter of samples had TP concentrations which exceed the ANZECC wetland trigger level (60 µg/L) and were from both the eastern (MT1S, MT1I, and MT1D) and western (MGP_c, MGP_a) bores. Only one lake sample exceeded the wetland trigger level. All but one sample exceeded the freshwater trigger level of 10 µg/L. This sample is not shown on Figure 38.

Concentrations of soluble reactive phosphorus (SRP/FRP) range from 5 to 140 µg/L (Figure 39). Phosphate concentrations for all bore water and lake samples were at or exceeded the freshwater trigger level of 5 µg/L, and some samples from the deep and shallow eastern bores exceeded the trigger level for south-western Australian wetlands (30 µg/L).

Lake Mariginiup was enriched in both nitrogen and phosphorus, and is under eutrophic pressure. Basic statistical analysis was carried out on nutrient concentrations using Primer software. Principal component analysis and multi dimensional scaling showed there was no significant relationship between nutrient concentrations and depth, nutrient concentrations and season, or nutrient concentrations and either side of the lake. Samples from individual bores, however, were related to other samples from the same bore (Figure 40).

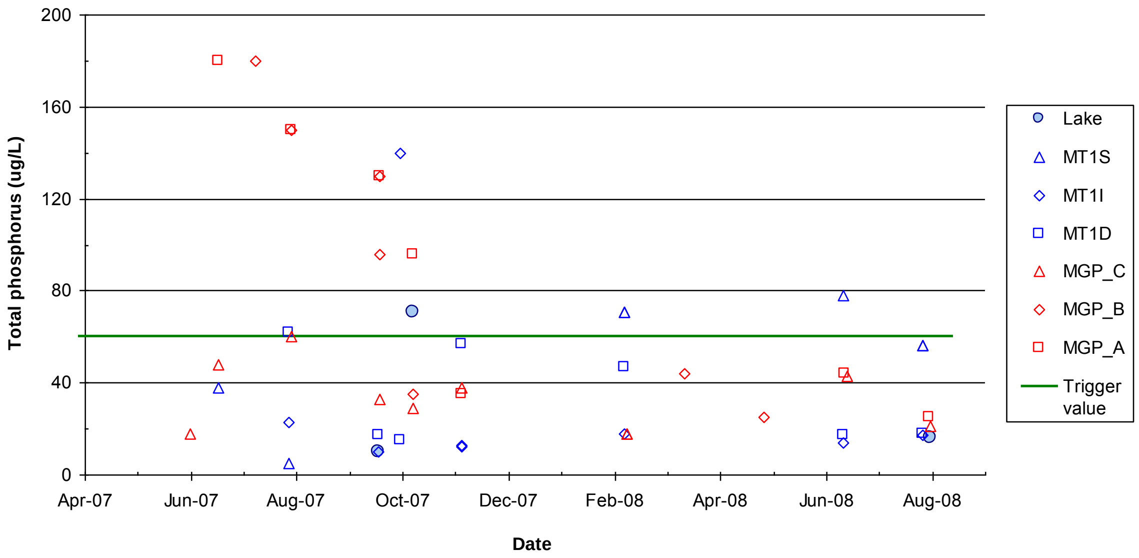

Figure 38 Total phosphorus concentrations in lake and groundwater at Lake Mariginiup

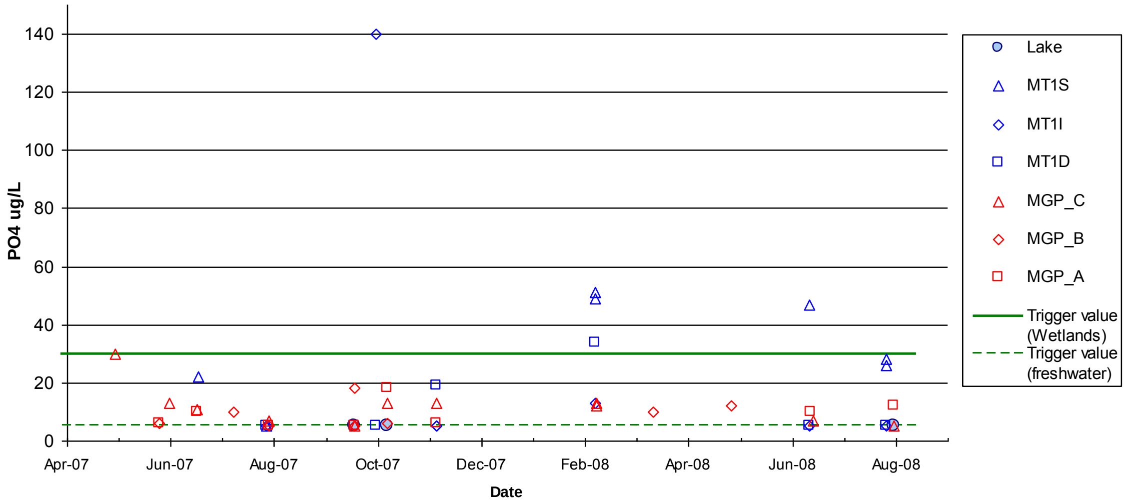

Figure 39 Soluble reactive phosphorus concentrations in lake and groundwater at Lake Mariginiup

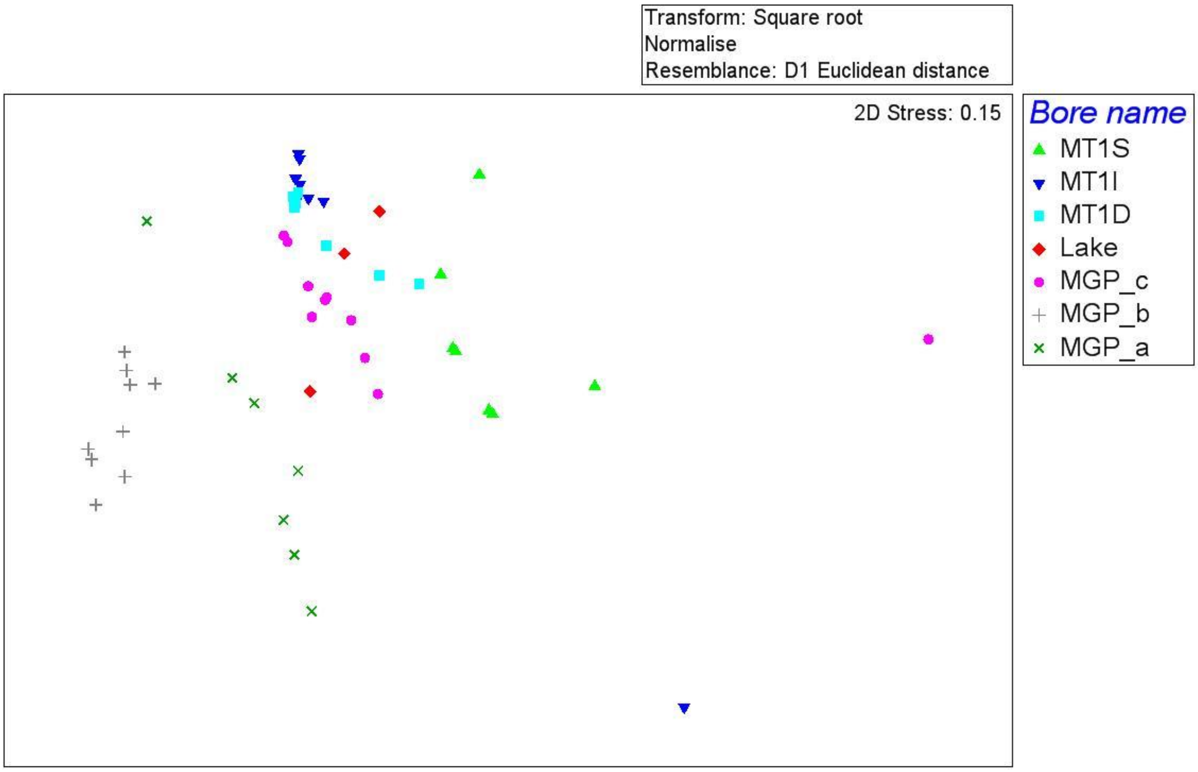

Figure 40 Multi dimensional scaling of nutrient concentration at Lake Mariginiup

Herbicides and pesticides

Samples were analysed for 41 herbicides and pesticides, once in winter 2007 and once in winter 2008. Results were all below detection limits of the laboratory methods. There could still be contamination at concentrations of concern, as some of the trigger levels are below the laboratory method detection levels.

Metals

Aluminium

Soluble aluminium concentrations ranged from 0.007 mg/L (MGP_b) to 2.2 mg/L (MT1S) (Figure 41). The vast majority of aluminium values, including those for the lake, well exceeded the guidelines for freshwater ecosystems (0.055 mg/L) but were below the irrigation water assessment level (5 mg/L) (Department of Environment 2003). There was only a weak seasonal trend to indicate that aluminium concentrations increase on the outflow side of the lake during winter. The shallow bore on the inflow side of the lake (MT1S) has noticeably higher aluminium concentrations than other bores.

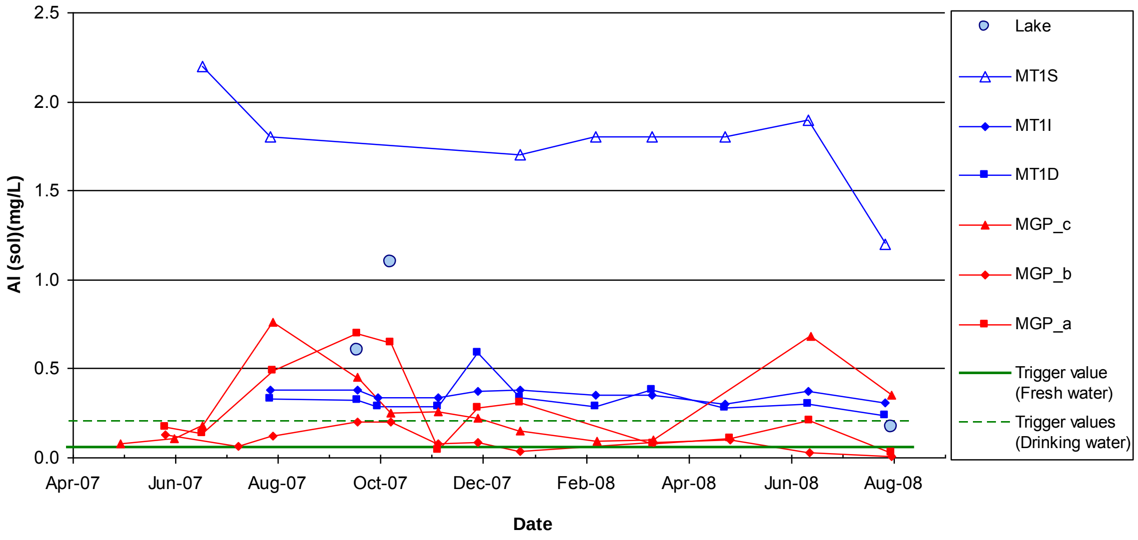

Figure 41 Aluminium concentrations in lake and groundwater at Lake Mariginiup

Chromium

Total chromium concentrations ranged from 0.0001 mg/L to 0.69 mg/L (Figure 42). Generally the outflow side of the lake had the highest concentrations. A few samples (from MGP_a) exceeded the irrigation and drinking water assessment levels of 0.1 mg/L and 0.05 mg/L respectively, while several samples from MGP_a and MGP_b and one from MT1D exceeded the freshwater trigger level of 0.01 mg/L. Generally water samples from the eastern (inflow) bores and the lake had chromium concentrations below all trigger levels.

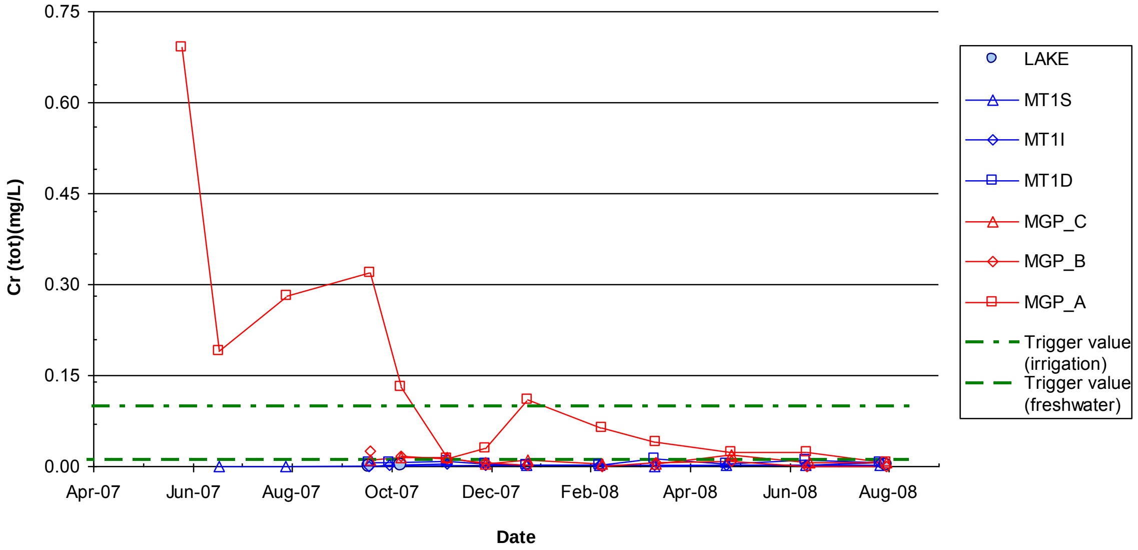

Figure 42 Chromium concentrations in lake and groundwater at Lake Mariginiup

Cadmium

Total cadmium concentrations were relatively low, and have not been shown here. The guidelines use the dissolved concentration as a trigger level, whereas this investigation reports the total concentration. Although not interchangeable, comparison to the guidelines was still carried out to provide a reference. No samples exceeded irrigation or drinking water trigger levels, and no up-gradient samples exceeded the freshwater trigger level.

Zinc

Most of the zinc concentrations for bore and lake water exceeded the freshwater trigger level of 0.008 mg/L. However, all were below the irrigation water limit (2 mg/L) (Figure 43). Values ranged from 0.001 mg/L to 0.086 mg/L. Zinc concentrations show large fluctuations over time. Water from each bore experienced three to four peak and trough cycles, which were generally out of phase with each other and did not show a seasonal trend. Notably, the MGP_a (deep outflow bore) had the highest concentrations and greatest amplitude from June 2007 to April 2008. MT1S had the highest concentrations and amplitude later in the year.

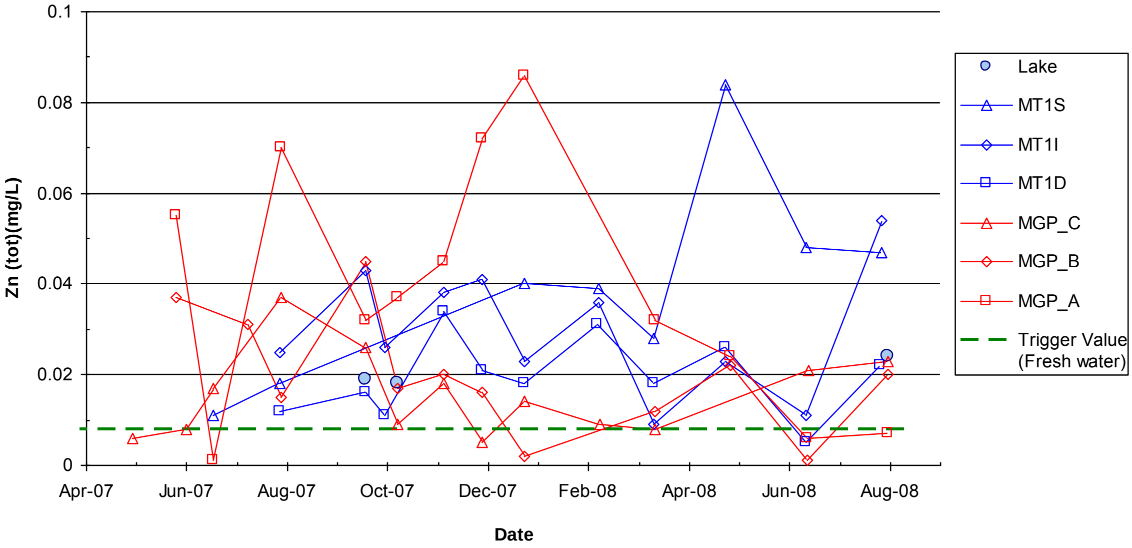

Figure 43 Zinc concentrations in lake and groundwater at Lake Mariginiup

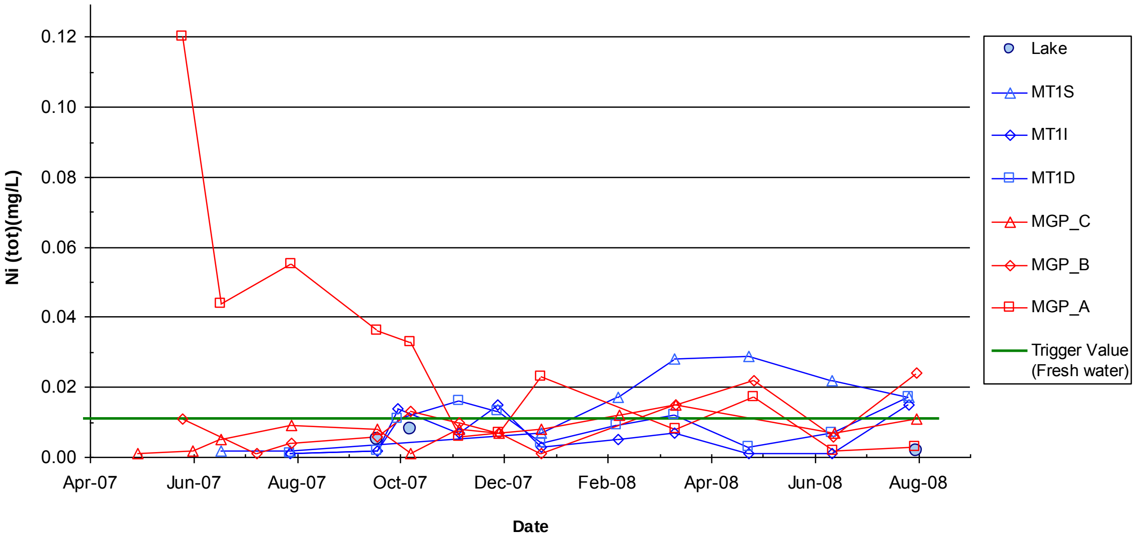

Figure 44 Nickel concentrations in lake and groundwater at Lake Mariginiup

Nickel

A similar trend is evident with the total nickel concentrations. Bore MGP_a (deep outflow bore) had concentrations well above the other samples until February 2008, after which, MT1S (shallow inflow bore) concentrations increased to the highest in the group. One-third of samples had nickel concentrations above the freshwater trigger levels (0.011 mg/L). Only the deep western bore (MGP_a) and shallow eastern bore (MT1S) had concentrations greater than drinking water assessment levels (0.02 mg/L). All samples had nickel concentrations below the irrigation water assessment level (0.2 mg/L).

Arsenic

The guidelines use the dissolved concentration of arsenic as a trigger level, whereas the this investigation reports the total concentration. Although not interchangeable, comparison to the guidelines was still carried out to provide a reference. Arsenic, although a concern over much of the Swan Coastal Plain, was below irrigation and fresh water trigger levels for all bores and lake water at Lake Mariginiup. Because the levels were so low, they have not been shown here. Values ranged from 0.001 mg/L to 0.019 mg/L. However, the deep and intermediate outflow bores (MGP_a and MGP_b) had some samples which exceeded the drinking water guidelines of 0.007 mg/L.

Iron

Soluble iron concentrations ranged from 0.032 mg/L (MGP_c) to 12 mg/L (MGP_a) (Figure 45). Many of the samples had concentrations which greatly exceeded both the irrigation and drinking water guidelines of 0.2 mg/L and 0.3 mg/L respectively. The watertable bores (MGP_c and MT1S) and lake water had the greatest concentrations of iron. The shallow inflow bore (MT1S) increases in iron concentration over the summer. The eastern watertable bore (MT1S) had an average iron concentration of 1.85 mg/L, almost 10 times the irrigation assessment level, and western watertable bore (MGP_c) had an average concentration over 25 times the irrigation water assessment level (5.18 mg/L).

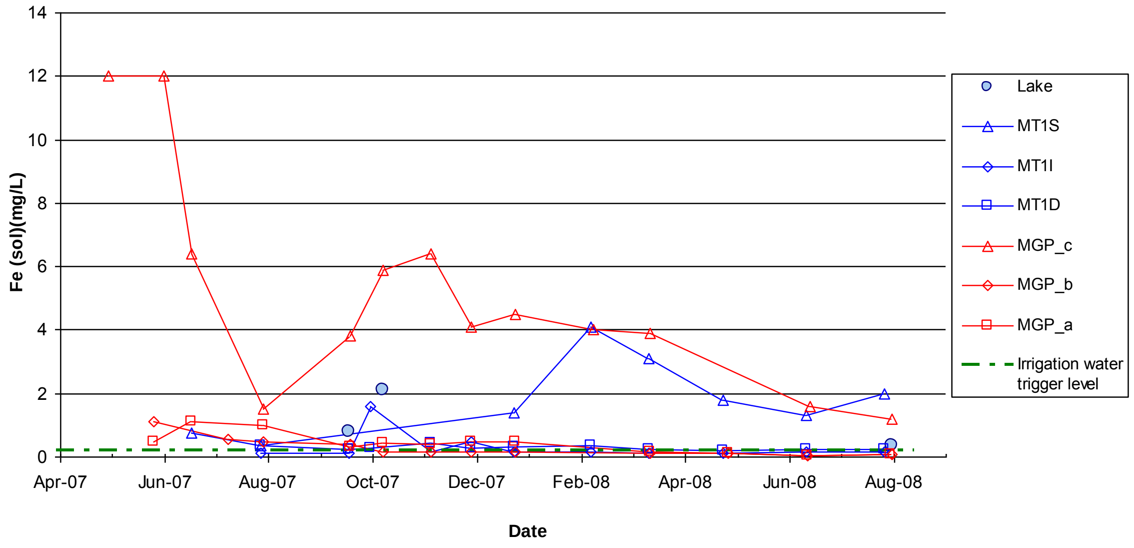

Figure 45 Iron concentrations in lake and groundwater at Lake Mariginiup

Selenium

There were only three samples, all from the deep outflow bore (MGP_a), in which selenium concentrations exceeded the freshwater trigger level of 0.005 mg/L. These have not been shown here. Total selenium concentrations of water samples from MGP_a ranged from 0.001 to 0.019 mg/L.

Manganese

Five samples, from the shallow down-gradient bore (MGP_c) had total manganese concentrations greater than the irrigation assessment level (0.2 mg/L). These samples have not been shown here. Manganese concentrations of water samples from MGP_c ranged between 0.027 – 1.5 mg/L.

Boron

Boron concentrations were below all trigger levels.

5.4.3 Summary of assessment and trigger level breaches

As outlined at the beginning of section 5.3, trigger levels for fresh water, irrigation water and drinking water were taken from and applied in accordance with the Department of Environment's 2003 *Draft assessment levels for soil, sediment and water,* and the trigger levels which are specific to south-western Australia (wetlands and fresh water) were taken from the ANZECC (2000) guidelines. Table 10 summarises those parameters found to be in breach of the various trigger levels. The most significant breaches of assessment and trigger levels based on beneficial end use of water are outlined below.

Fresh water and wetlands

Samples from lake water and groundwater up hydraulic gradient of the lake, were compared against the freshwater and wetland guidelines. This showed that:

- pH in the lake and groundwater breached the trigger levels
- lake water samples exceeded the freshwater assessment levels for Al (sol) and Zn (tot)
- TN, NO_x, $NH_3/_4$ and TP concentrations exceed trigger levels for fresh water and wetlands in south-west Australia in samples from the lake and groundwater
- PO_4^{3-} freshwater trigger levels were exceeded by both groundwater and surface water, while only shallow groundwater samples exceeded PO_4^{3-} wetland trigger levels
- the freshwater guidelines were breached by groundwater samples for a number of metals including Al (sol), Zn (tot), Ni (tot), and As (tot).

Irrigation water

All groundwater samples were compared against the irrigation guidelines, as irrigated horticulture is a major user of water in the area. This showed that:

- irrigation water assessment levels for Fe (sol) and Cr (tot) were breached by groundwater samples from various bores.

Drinking water

There is no abstraction for public water supply in the Mariginiup groundwater subarea. The department considers that untreated waters taken from the environment are unsafe for human drinking (DoW 2006). Data from this study supports this view.

- Drinking water guidelines were exceeded in the deep, down-gradient zone of the aquifer (MGP_a) for total concentrations of As, Cr and Ni, while all zones of the aquifer and lake exceed limits for soluble Al and Fe at various times.

Table 10 Summary of trigger level breaches

	Australia wide trigger levels			Specific trigger levels for south-west Australia	
	Fresh water	**Irrigation water**	**Drinking water**	**Wetlands**	**Fresh water**
pH	Samples from the lake and shallow inflow bore (MT1S) are always below the lower limit of 6.5. Other inflow bores (MT1I and MT1D) are commonly below, while outflow bores (MGP_a, MGP_b, MGP_c are only sometimes below the lower limit.	not applicable	As for Australian fresh water	Nearly all samples, from all bores and lake, are below the lower limit of 7 pH units	As for Australian fresh water
TN	not applicable	not applicable	No samples exceed	All lake samples, most samples from outflow bores, and some samples from inflow bores exceed	All samples exceed
NOx	not applicable	not applicable	not applicable	Some samples from both shallow bores, and one lake sample exceed	Most samples are at or above the trigger level
$NH^{3/4}$	not applicable	not applicable	not applicable	Most samples are at or above trigger level	Most samples are at or above trigger level
TP	not applicable	not applicable	not applicable	One lake sample, some samples from MGP_a, MGP_b, MT1S and one from MT1I exceed	All but one sample at or above
PO_4^{3-}	not applicable	not applicable	not applicable	Some inflow shallow and intermediate samples exceed	All at or above
Al	Nearly all samples, and all lake samples, exceed	below	All bores commonly exceed, two lake water samples	not applicable	not applicable

Fe	not applicable	All samples but most from MT1I & half from MGP_b	All samples but most from MT1I, MT1D and half from MGP_b	not applicable	not applicable
Cd	MGP_a commonly exceeds (reported values are total concentrations while trigger levels are dissolved concentrations)	below	below	not applicable	not applicable
Zn	Nearly all samples, and all lake samples, exceed	below	below	not applicable	not applicable
Ni	No lake samples exceed, some from some bores do exceed	below	Most samples from MGP_a	not applicable	not applicable
Cr (total)	Deep and intermediate and some shallow outflow bores and 1 MT1D, but no lake samples, exceed.	Only MGP_a	Only MGP_a	not applicable	not applicable
As	MGP_a and MGP_b exceed (reported values are total concentrations while trigger levels are dissolved concentrations)	below	Only some from MGP_a (reported values are total concentrations while trigger levels are dissolved concentrations)	not applicable	not applicable

5.5 Processes and interactions between surface water and groundwater

Analysis of the local hydrogeology at Lake Mariginiup allows an interpretation of hydrogeochemical processes and surface water-groundwater interactions to be made. This is shown conceptually in

Figure 47.

The findings of this investigation generally agree with previous work that Lake Mariginiup is a flow-through lake, and has a connection to the regional groundwater flow system of the Gnangara mound. However, since Hall's (1985) study there have been some fundamental changes to the surface water–groundwater interactions and the hydrogeochemistry of the lake and its surroundings.

The chemical composition of groundwater on the inflow side of Lake Mariginiup agrees with the findings of Yesertener (2009). Groundwater recharging the lake flowing through Bassendean Sand is of the Na–Cl type and is recharged primarily from rainfall. Our results show that during winter, groundwater is only in weak connection with the lake. The data indicates that vertical hydraulic gradients east of the lake have decreased, and the shape of the isopotential lines have straightened, suggesting that the thickness of the aquifer which interacts with the lake has also reduced. Weak upward heads on the eastern side during this time indicates mainly horizontal flow into and below the lake, whereas previous work showed upward flow from the upper half of the aquifer (Hall, 1985).

When the lake holds water during winter, it recharges groundwater along a downward flow path, towards the middle of the aquifer. This flow path is suggested by comparison of water levels and hydrogeochemistry of samples from the intermediate outflow bore (MGP_b) to those of the other zones. This bore has consistently higher water levels than the shallow or deep bores on the western side, indicating greater water pressure and possibly preferential flow. Concentrations of TDS, Na^+ and Cl^- are greatest in samples from this bore, suggesting the water has undergone evaporative concentration. The Piper plot (Figure 25) illustrates that water in the lake is most similar in composition to the intermediate outflow bore (MGP_b).

In the drier months, currently around six months of the year, the lake is no longer in hydraulic connection with the groundwater (Figure 47). Historically, groundwater levels on the western (down-gradient) side of the lake (e.g. MS10 in Figure 20) have been very similar to the lake level, and other monitoring bores in the area shared water level trends with the lake. With the decrease in regional groundwater levels however, there has been an increasing difference between groundwater and lake levels, as well as an offset between the peak water levels (Figure 20). Although the major ion chemistry shows that at certain times of the year water leaves the lake basin and flows down towards the intermediate western bore, the water levels suggest impedance of water flowing out of the lake basin, and possibly de-coupling of the lake and aquifer.

The regional decline of the watertable and the changes in surface water–groundwater interaction at Lake Mariginiup have affected the chemistry of both groundwater and lake water. These changes are due to several hydrogeochemical processes which are also shown in the conceptual diagram at

Figure 47 and are discussed in detail below.

The regional watertable decline has lead to stored acidity in the soil. The podsolised sediments to the east of Lake Mariginiup are known to have high concentrations of Al, among other metals (Cook et. al. 2006). The progressive drying of these sediments, considerably increases the solubility of Al (Simonsson et. al. 1999). The recent (2005 and 2006) removal of pine plantation areas up hydraulic gradient from Lake Mariginiup is likely to have increased water movement through the sediment, which has probably flushed the newly mobilised Al, and possibly Zn and Ni, towards the lake. Groundwater elevated in Al, Zn and Ni flows from the pines towards Lake Mariginiup, which is evidenced by the elevated concentrations of these metals in the shallow inflow bore (MT1S). Appleyard and Cook (2008) have also reported high Al, Zn and Ni concentrations from groundwater samples between Lake Mariginiup and the pine plantations, which is comparable to the high concentrations of these metals observed in MT1S. More locally, water released from Lake Jandabup, along with any natural or anthropogenic contaminants, is likely to affect water within the capture zone of Lake Mariginiup. The low pH values in the shallow inflow bore (MT1S), which range from 3.6 to 4.7 would also contribute to the high Al levels.

The low pH groundwater observed in the shallow inflow bore (MT1S) could be attributed to three major processes. Natural acidification is caused by decomposition of vegetation, creating organic acids through CO_2 production and root respiration. However, this process is unlikely to produce pH values below 4.6, as observed on the eastern inflow side of Lake Mariginiup (Appelo and Postma 2007).

A second major acidification process is nitrification. The high concentrations of NO_x, positive Eh values and acidic conditions observed in the shallow eastern zone of the Superficial aquifer is suggestive of nitrification. Figure 48 shows the way in which excess NO_x, presumably from fertiliser use in the market gardens up hydraulic gradient from Lake Mariginiup, undergoes nitrification, releasing H^+, and lowering the pH. Oxidation of organic rich sediments within the lake basin could also be contributing to nutrient enrichment in the Lake Mariginiup area, through a process known as internal eutrophication. Water level decline can lead to the progressive oxidation of organic rich sediments near wetlands, which can release both nitrogen and phosphorus into the groundwater (Smolders et al. 2006).

The third possible source of high acidity in groundwater is pyrite oxidation, for example by the exposure of acid sulfate soils. Our investigation showed that the lake bed sediments contain actual and potential acid sulfate soils and little buffering capacity. The net acidity of lake bed sediments at Lake Mariginiup ranges from an average of over 1000 mol H^+/t at the surface to 300 – 400 mol H^+/t at depth. These values greatly exceed the Department of Environment and Conservation's action criteria (DEC 2009) of 18.7 mol H^+/t and indicate high potential for further acid production should oxidation persist. Although there is some evidence of perching in the lake, the duration of open water has reduced from permanently (prior to 1978), to around 6 months per year. Due to the saucer shaped lake basin, a large area of the lake bed is exposed, and the open water reduced to small pools near the centre of the lake allowing the pyrite stored in acid sulfate soils to be oxidised.

Indicators of acid sulfate soil oxidation are high concentrations of SO_4^{2-}, Fe, low pH values and high SO_4^{2-}/Cl^- ratios. The SO_4^{2-}/Cl^- ratio of natural groundwater is around 0.03 – 0.05 (Hirschberg 1984), seawater is 0.15 and rainwater in the Lake Mariginiup area has an SO_4^{2-}/Cl^- ratio of 0.25 (Yesertener 2009). Ratios higher than 0.5 can indicate sulfide oxidation and values greater than 0.9 indicate significant sulfide oxidation (Vogwill et al. 2005). SO_4^{2-}/Cl^- ratios for the lake, both shallow bores (MT1S and MGP_c), and the intermediate outflow bore (MGP_b) are all well above the natural groundwater range (

Figure 46).

The high Fe concentrations observed in watertable bores (MGP_c and MT1S) and in the lake is another indicator of acid sulfate soil oxidation. The shallow inflow bore (MT1S) increases in Fe concentration over the summer, possibly as a result of the lowered watertable facilitating the oxidation of acid sulfate soils, and subsequent release of Fe bound to sulfides. The eastern watertable bore (MT1S) has an average Fe concentration of 1.85 mg/L, which is almost 10 times the irrigation assessment level, and MGP_c has an average concentration which is over 25 times the irrigation water assessment level (5.18 mg/L).

In low oxygen environments, as observed around Lake Mariginiup, the oxidising potential of nitrate is nearly as strong as oxygen (Smolders et al. 2006), whereby nitrate reduction can couple to pyrite oxidation and accelerate groundwater acidification. This process can create similar water quality problems to those caused by oxidation of acid sulfate soil, but without needing falling water levels to trigger the process. Elevated concentrations of SO_4^{2-} produced by pyrite oxidation can out-compete PO_4^{3-} for anion adsorption sites and cause an increase in PO_4^{3-} in anoxic conditions (Smolders et al. 2006; Beltman et al. 2000). The high levels of nitrogen and phosphorus observed in Lake Mariginiup suggest it is under eutrophic pressure.

Nitrate which is not used in pyrite oxidation either undergoes denitrification and is lost to the system as a gas, or undergoes partial denitrification to ammonia (dissimilatory nitrate reduction to ammonium). Partial reduction of nitrate towards the base of the aquifer is thought to be responsible for the elevated concentrations of ammonia/ammonium. This is indicated by the physical and chemical properties of samples from the deep and intermediate down-gradient (western) bores. The samples were reducing and anoxic, and were depleted in nitrate and were being enriched in ammonia and ammonium. Figure 48 show the process by which ammonia applied to the surface as fertiliser undergoes nitrification, as seen in MT1S, and can then undergo partial denitrification resulting in the high ammonia concentrations seen at the base of the aquifer.

The groundwater that discharges into Lake Mariginiup from the east is acidic and high in metals and nutrients due to the hydrogeochemical processes discussed above. The dilution effect of groundwater with lower metal concentrations discharging into the lake is lost because less of the regional groundwater flow interacts with the lake, compared to historical times. As a result, when the lake holds water it is acidic and also has high metal concentrations.

The downward flow of groundwater that is recharged by the lake (

Figure 47) is enriched in Ca^{2+}, Mg^{2+}, TDS and SO_4^{2-}. This suggests that the high acidity of the water is causing base cation depletion of the sediment profile beneath the lake. This leads to a progressive enrichment in the groundwater down gradient of the lake as evidence by the consistent increase of these ions over the sampling period (Figure 49). As water flows from the eastern side of the lake, into the lake basin then downwards into the aquifer, concentrations of Al^{3+} decrease as pH increases. Cation exchange between Al^{3+} and H^+ with Ca^{2+} and Mg^{2+} could be taking place and explains why a decrease in Al^{3+} and H^+ corresponds to an increase in Ca^{2+} and Mg^{2+}. Although the lake bed sediments have pH_{KCl} < 6.5 (usually considered to mean there is no acid neutralising capacity), the increasing concentrations of Ca^{2+} and Mg^{2+} in the groundwater suggest that some buffering of acidity is taking place.

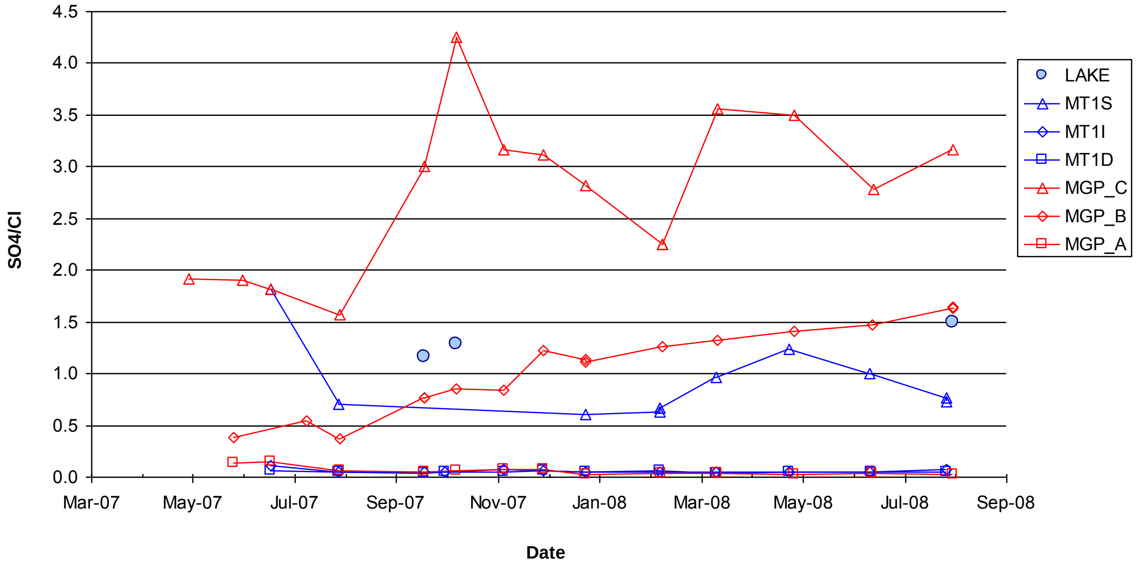

Figure 46 SO_4^{2-}/Cl^- ratios in lake and groundwater at Lake Mariginiup

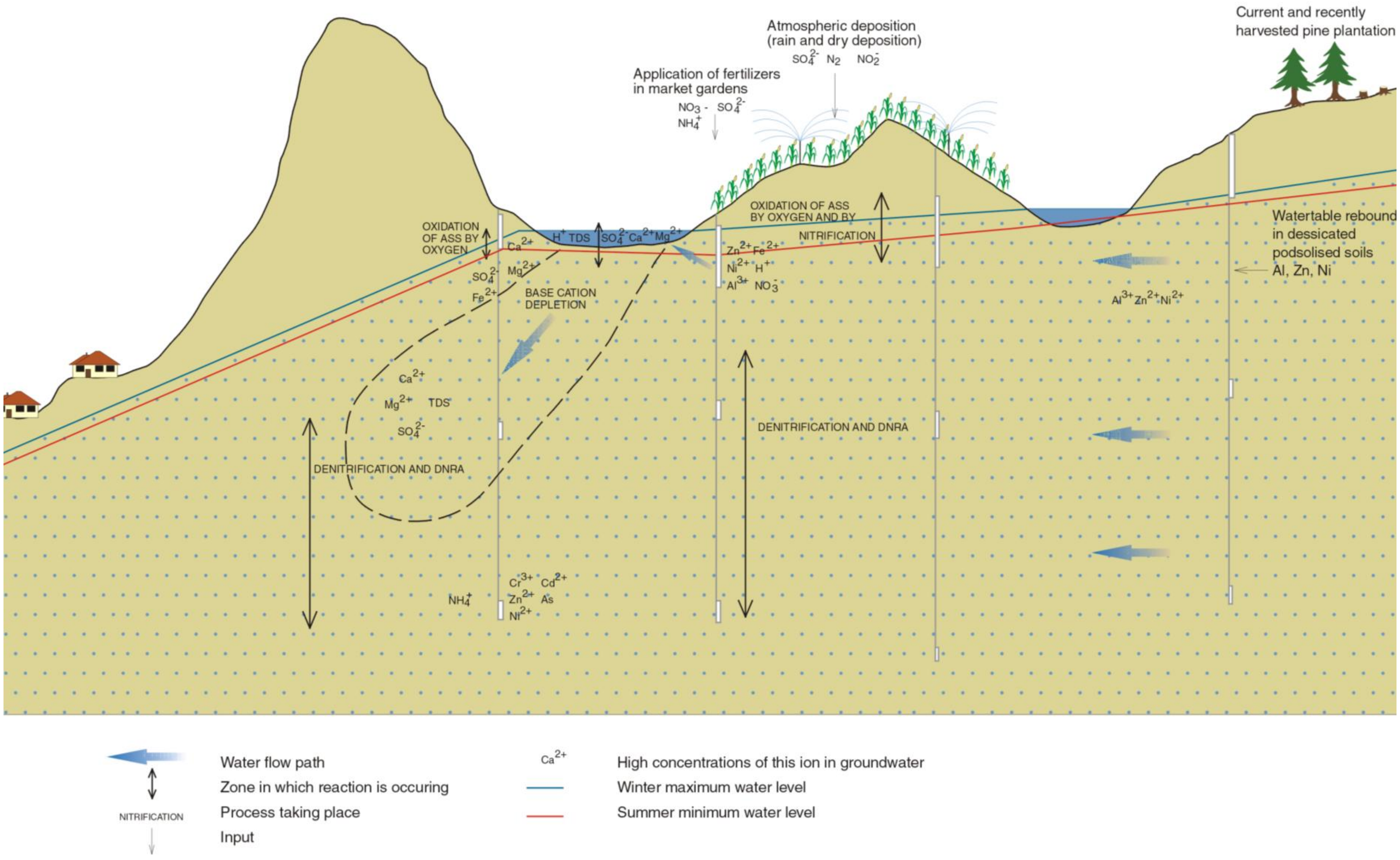

Figure 47 Conceptual diagram of geochemical processes in the Lake Mariginiup area

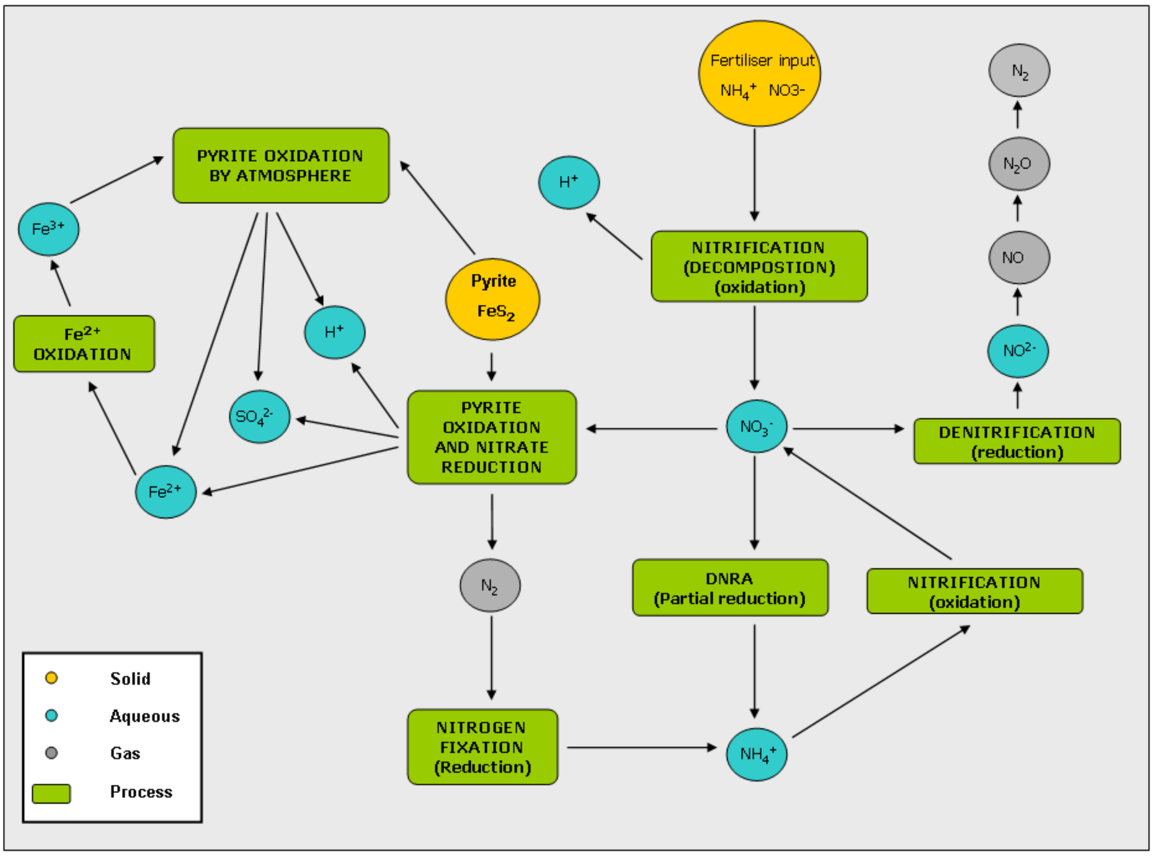

Figure 48 Interaction of the nitrogen and sulfur cycles at Lake Mariginiup

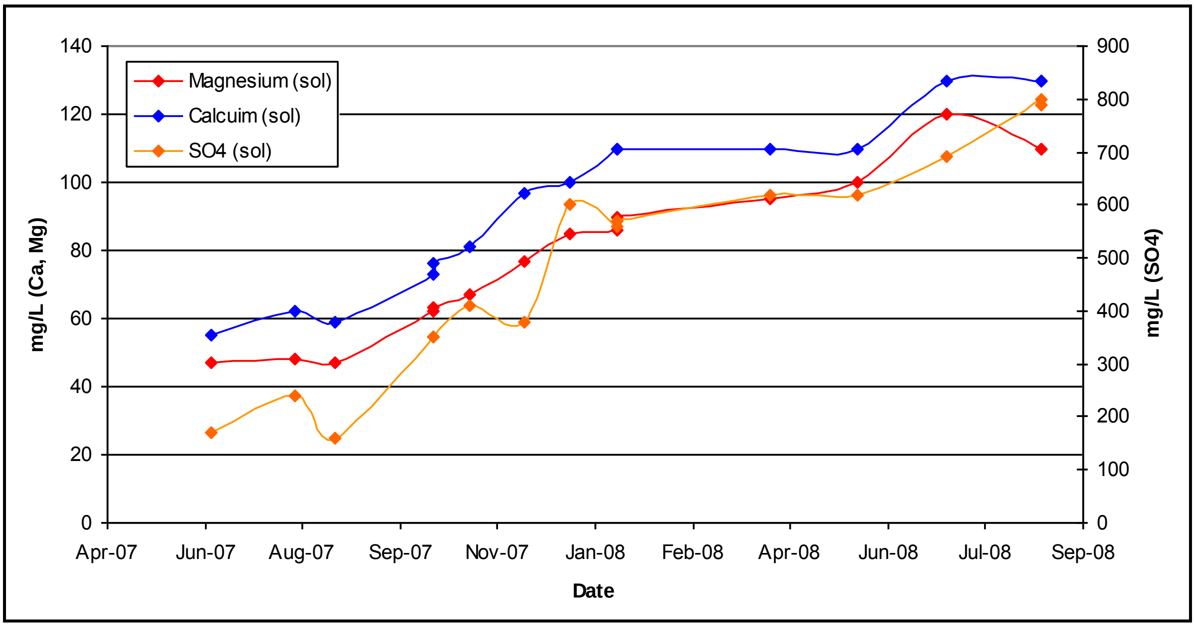

Figure 49 Increases in calcium, magnesium and sulfate concentrations in the intermediate outflow bore (MGP_b)

Our data suggests that groundwater in the shallow zone of the aquifer on the western side of the lake is recharged locally by rainfall and that inputs from the lake are minimal. Water samples from MGP_c show no evidence of evaporative concentration in Na^+, Cl^- or TDS concentrations, and water levels and the Piper diagram indicate only minor if any connection to lake water. Ca^{2+} and Mg^{2+} concentrations in this watertable bore show a clear seasonal cycle, which is lacking in the other bores. This suggests that rainfall has a greater influence on this zone of the aquifer than the lake does, and again that there is only limited or no connection to the lake or other sampled zones of the aquifer. It is likely that the low permeability of the lake bed sediments limits the interaction of shallow groundwater and the lake in this region. Concentrations of SO_4^{2-}, Fe and SO_4^{2-}/Cl^- ratios again suggest oxidation of acid sulfate soils in this zone, although pH values are neutral at the watertable west of the lake.

Concentrations of total Zn, Ni, Cr, Cd and As are all significantly higher at the base of the aquifer on the down-gradient (western) side of the lake (MGP_a) than in other zones. There is a sharp change in hydrochemical properties between MGP_a and the other deep bore (MT1D). Trends in the concentrations of these metals correlate to trends in total suspended solids, suggesting that the elevated metals are likely to be a result of sediment in the water sample, rather that geochemical processes. Water from the underlying Poison Hill Greensand could however be affecting metal concentrations in this bore, as there is no confining layer between the silty, heavy metal rich Poison Hill Greensand and the overlying Tamala Limestone.

Numerical analysis and hydrochemical modelling would allow a more definitive and quantitative determination of the processes which are affecting water quality in the Lake Mariginiup area.

6 Implications for ecological values

The results of the shallow groundwater systems investigation have provided an improved understanding of the local hydrogeology at Lake Mariginiup (Section 5). This understanding can be applied to the ecological trends observed at the lake (Section 2.4) and this, combined with local area modelling, will inform our management recommendations.

6.1 Monitoring infrastructure

The monitoring infrastructure installed for this investigation has improved our ability to monitor water levels and water quality in and around at Lake Mariginiup. However, measuring the Ministerial criteria at the staff gauge may not be possible if water levels at Lake Mariginiup continue to decline. Alternatively, bore MS10 could be used to measure the Ministerial criteria when the lake is dry, but it is not appropriate to apply the staff gauge criteria to MS10 due to the increasing detachment of the watertable.

A correlation between groundwater and surface water levels between 1995 and 2009 (representing the most recent relationship) shows that despite the increasing detachment of the groundwater from the lake, a reasonably strong correlation exists ($R^2 = 0.94$) (Figure 50). Using the regression equation, the equivalent groundwater level at bore MS10 to meet the spring peak surface water ecological water requirement (41.5 m AHD) is 41.14 m AHD. When relating groundwater levels to vegetation at the transect, newly established bore MGP_c should be used.

6.2 Ecological implications

A significant finding of this investigation is that the watertable has become increasingly detached from the lake. A smaller contribution of groundwater to the lake is possibly why Ministerial criteria have not been met and surface water levels have been below Froend et. al. (2004b) ecological water requirements in the last ten years. The low water levels have been exacerbated by a smaller contribution of rainfall to the lake. The consequence has been declining richness of macroinvertebrates, encroachment of sedge species into the wetland basin, and reduced wading habitat for waterbirds.

While groundwater levels remain slightly above the Froend et al. (2004) ecological water requirements for wetland vegetation, summer groundwater levels may not be high enough to support shallow rooted species (*Typha orientalis* and *Baumea articulata*) on the upper slopes of the lake (Figure 51). For similar dampland vegetation on the Gnangara Mound, Farrington et al. (1989) calculated that summer groundwater use was 266 mm. While the deeper rooted *Eucalyptus rudis* may be able to obtain some of this from groundwater, the shallow rooted vegetation will be relying on water available in the soil above the watertable. The sandy soil recorded at the vegetation transect is likely to have a low storage capacity (roughly 2%[2]) and the plant available water in the soil above the summer watertable is estimated to be roughly

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[2] Determined from similar soil types on the Southern Swan Coastal Plain (Bill Moulden pers. comm.)

40 mm[3]. It is unlikely that this will be enough to sustain the shallow rooted vegetation, particularly over a dry summer. In combination with physical distrurbance, this would partly explain the weediness and declining health of sedges on the upper slopes of the vegetation transect and encroachment of sedges into the wetland basin where the groundwater in summer is more accessible.

Water quality is probably the most immediate threat to the ecological values of Lake Mariginiup. Water levels are below the Froend et al. (2004) ecological water requirements for sediment processes which is consistent with the oxidation of acid sulfate soils in the lake sediment shown through this investigation. Combined with the inflow of acidic groundwater from the east, Lake Mariginiup is now considered to be permanently acidified.

An increase in the acidity of an aquatic ecosystem can be considered a stressor which is directly toxic to aquatic ecosystems (ANZECC 2000). As pH levels in the lake are generally below trigger levels for freshwater ecosystems and wetlands in south-western Australia, acidity is likely to be contributing to declining richness of macroinvertebrates. Furthermore, high heavy metal concentrations, which are known to be directly toxic to aquatic ecosystems are probably exacerbating the decline in ecosytem health (ANZECC 2000). Concentrations of Al^{3+} and Zn^{2+} found entering the lake and in the lake and in groundwater discharging into the lake from the east breached national triggers for freshwater ecosystems. Al^{3+} is of particular concern, as it can be highly toxic to fish in an acidic environment (ANZECC 2000). This puts the Swan River goby in Lake Mariginiup, at significant risk.

The high level of nutrients in the lake are likely to harm the lake ecology. NH_4, TN and TP exceed trigger levels for freshwater ecosystems and wetlands in south-western Australia. NH_4 can be directly toxic to aquatic ecosystems, particularly fish, and excessive P and N can indirectly affect the ecosystem by causing algal growth and cyanobacterial blooms.

As discussed in Section 5.4, the chemisty of the groundwater has also changed. The high acidity of the groundwater on the eastern side of the lake and the risk of acidity on the western side, pose a threat to the riparian vegetation. In particular, the mobilisation of Al^{3+} into the groundwater may put the vegetation at risk of ‘acid toxicity’. Acid toxicity occurs when the mobilisation of Al^{3+} induces a reduction of the molar Ca/Al and Mg/Al ratios in the groundwater which reduces root growth, inhibits the uptake of Ca^{2+} and Mg^{2+} by fine roots, and reduces the water conductivity of the roots (Caspary 1991). This is compounded by further depeletion of Ca^{2+} and Mg^{2+} from sediment by acidic groundwater. It is possible that acid toxicity is partially responsible for the declining health of riparian vegetation at Lake Mariginiup. This highlights the fact that groundwater quality, in addition to compliance with criteria levels and ecological water requirements, should be assessed when assigning causes to changes in ecological condition.

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[3] Plant available water in the soil between the surface and the watertable was calculated by multiplying the distance between the surface and the summer minimum watertable (in mm) by 2%.

While changes to groundwater chemisty at depth may not directly affect ecosystems, there are social implications. Concentrations of Fe and Cr breach irrigation water guidelines, which is a concern for horticulturalists using groundwater from around the lake. Although the department advises against untreated bore water being used for drinking, in the Mariginiup area groundwater is used to irrigate domestic vegetable gardens, as well as inside the home. Groundwater in this area has been shown to breach the drinking water guidelines for total concentrations of As, Cr and Ni, as well as soluble Al and Fe.

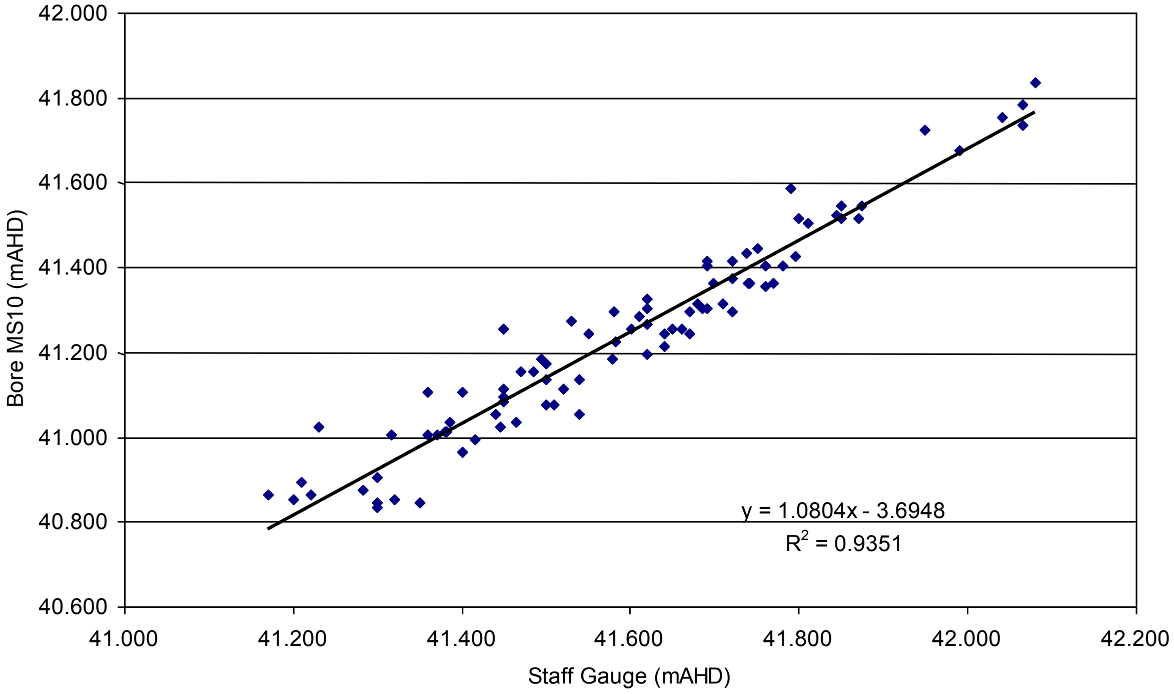


Figure 50 Correlation between groundwater and surface water levels (1995–2009)

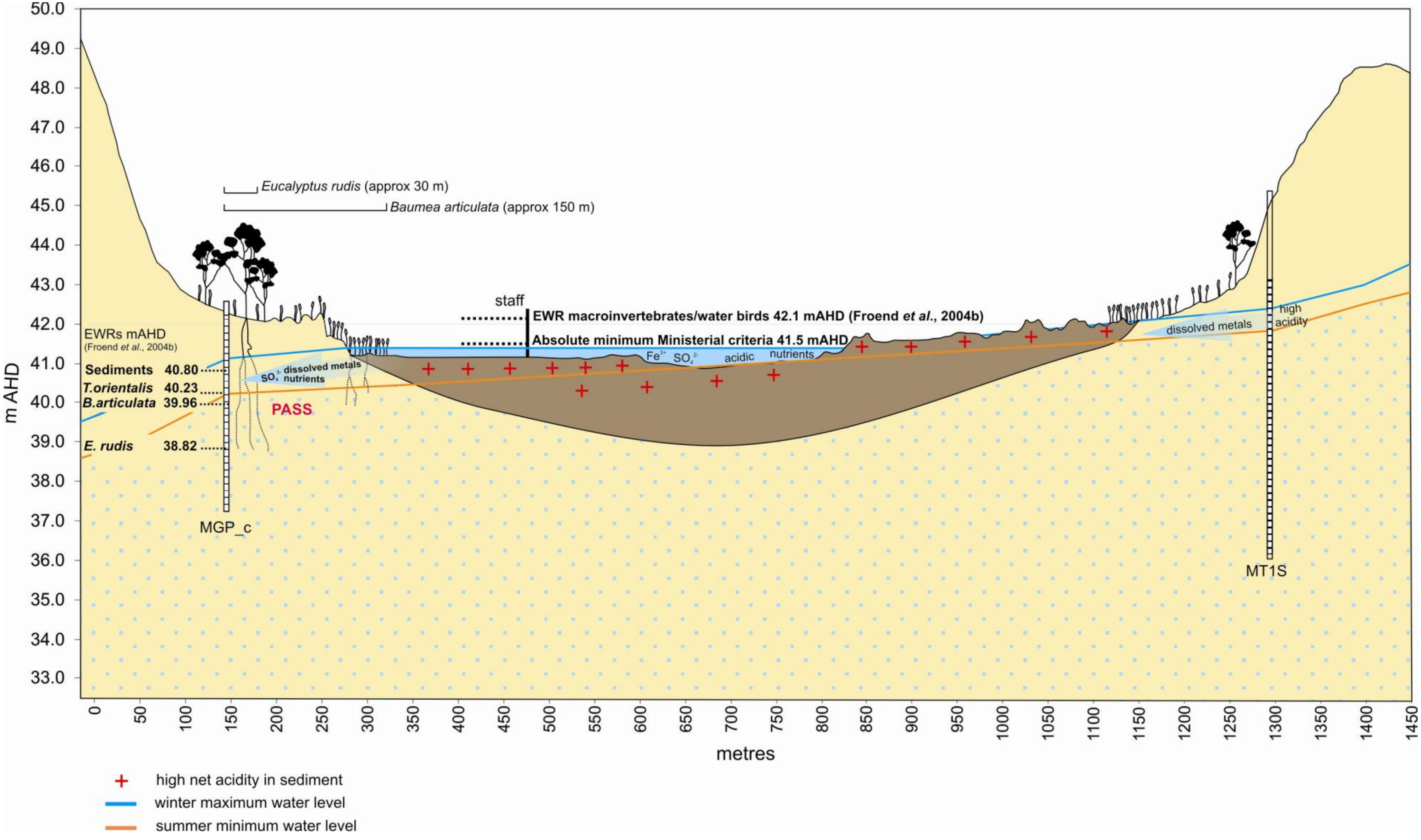


Figure 51 Ecological water requirements for groundwater-dependent ecosystems at Lake Mariginiup

6.2.1 Land and water use

In order to improve the ecological condition of groundwater-dependent ecosystems at Lake Mariginiup, water levels need to increase. Local-scale numerical modelling predicted that the land-use scenario which yielded the greatest gains in water levels was the combined effect of pine clearing and urbanisation. The modelling predicted an increased summer minimum and winter maximum by 0.2 m and 0.6 m in the lake by 2031, respectively (Figure 5). Groundwater levels on the western side of the lake were predicted to rise by approximately 0.5m (Bourke 2009).

Under this best case scenario, water levels in the lake would be above absolute minimum Ministerial criteria levels by 2014 and continue to increase to just below the preferred criteria by 2029 (Figure 51). Due to the 'two-in-six years' rule, Lake Mariginiup would still technically be non-compliant, but as water levels increase, and eventually approach 42.1 m AHD, there may be some improvement to macroinvertebrate and waterbird communities. However, this will depend on whether the ecosystem, in its current state, can persist until water levels improve. It will also depend greatly on whether water quality improves. This may not be evident until 2025 when the lake will be wet enough in summer to reduce acid sulfate soil oxidation, or may not occur at all, as poor quality groundwater will still be entering the lake from the eastern side. More work into the diffusion rates of oxygen (and other oxidants) in organic-rich silty sediments is required to fully understand the rates of acid sulfate soil oxidation, the formation of products and the depths of water levels required to keep acid sulfate soil bearing sediments from oxidising.

A 0.5 m rise in groundwater level should ensure that the deeper species (*E. rudis*) on the upper slopes and sedges (*B.articulata* and *T. orientalis*) on the lower slopes will persist. Again, this will depend on groundwater quality. Shallow rooted species on the upper slopes are unlikely to survive, particularly if groundwater doesn't rise until 2030.

The implication of watertable rebound on water quality is uncertain. Raising water levels will help prevent further oxidation of acid sulfate soils, and increase water availability to the ecosystem. However, it could also mobilise more metals into the system. Our data suggests some seasonal flushing of metals into the groundwater as the watertable rises over winter, but the rates of all contributing reactions are not fully understood. Watertable rebound is likely to mobilise more Al^{3+} from previously desiccated soils, into the groundwater and eventually the lake, along with metals released by oxidation of acid sulfate soils. It is unclear how long the impacts of acidification will persist in the system. PHREEQCE geochemical modelling could provide a better understanding of these processes.

The urbanisation and pine clearing scenario yields some positive results, although different climate regimes were not included in the modelling scenarios. All scenarios used a simulated climate based on average rainfall for 1996 to 2007 (Bourke 2009). Perth is expected to experience a drier climate into the future (IPCC 2007) which is likely to affect groundwater levels across the Gnangara Mound. Regional-scale groundwater models have shown that a drier climate could lower the watertable in the east Wanneroo area by up to 2 m (Bourke 2009).

The scenarios used in the local-scale modelling were based on land-use change, and did not specifically look at the effects of groundwater abstraction on the system (Bourke 2009). In addition to climate change, private abstraction is thought to be the greatest factor influencing water levels at Lake Mariginiup (Yesertener 2007). One aim of the *Gnangara groundwater areas allocation plan* (DoW 2009a) is to reduce private abstraction in the area by 20% (See Section 2.6 of that plan). Modelling using the Perth regional aquifer modelling system has estimated that this could increase groundwater levels in the east Wanneroo area by up to 1.5m (Bourke 2009). There may also be some benefit from a regional reduction in abstraction from the integrated water supply scheme (as indicated in the Gnangara allocation plan), but this has not yet been quantified.

It is possible that the decrease in groundwater and surface water levels caused by declining rainfall could outweigh the increase in groundwater level gained by reduced abstraction at Lake Mariginiup. In this case, the minor benefits seen under the urbanisation and pine clearing scenario might be negated. However, it is not appropriate to make this assumption due to the highly uncertain nature of regional model predictions at local scales. It is recommended that the local-scale model be used to assess the effects of declining rainfall and reduced abstraction on water levels at Lake Mariginiup.

7 Recommendations

The following recommendations are made in this report:

- The Department of Water should continue to endorse the Forest Products Commission pine harvesting schedule, but with the inclusion of water chemistry monitoring of the watertable. This is because, to improve the ecological condition of Lake Mariginiup, water levels need to increase, and this is most likely to be achieved under the combined pine plantation clearing and urbanisation scenario.
- Support the development of water sensitive urban design in the East Wanneroo area.
- Measure the Ministerial criteria level at bore MS10 when the lake is dry. The revised level of 41.14 m AHD should be used.
- Measure groundwater levels at the newly installed bore MGP_c when relating the watertable to the ecological condition of the vegetation transect.
- Develop hydrochemical triggers and management actions for the next water reform plan and initiate a hydrochemical monitoring program for the bore MGP_c site. It is recommended that quarterly hydrochemical sampling (major ions, metals, nutrients) and analysis should be undertaken at bores MGP_c, MGP_b, MGP_a, and MT1S. Monthly hydrochemical sampling of the lake should be undertaken when surface water is present.
- Review data from the hydrochemical monitoring program every two years to assess whether management objectives set out in this plan are being met and whether trigger levels need improvement.
- Inform irrigators of the potential effects of high concentrations of heavy metals in groundwater around Lake Mariginiup.
- By 2030 reduce private abstraction in the area by 20%, as per the *Gnangara Sustainability Strategy* (DoW 2009b)
- Undertake further local area modelling and include drier climate and reduced abstraction scenarios. Further chemical modelling of acidification processes is also required.

Appendices

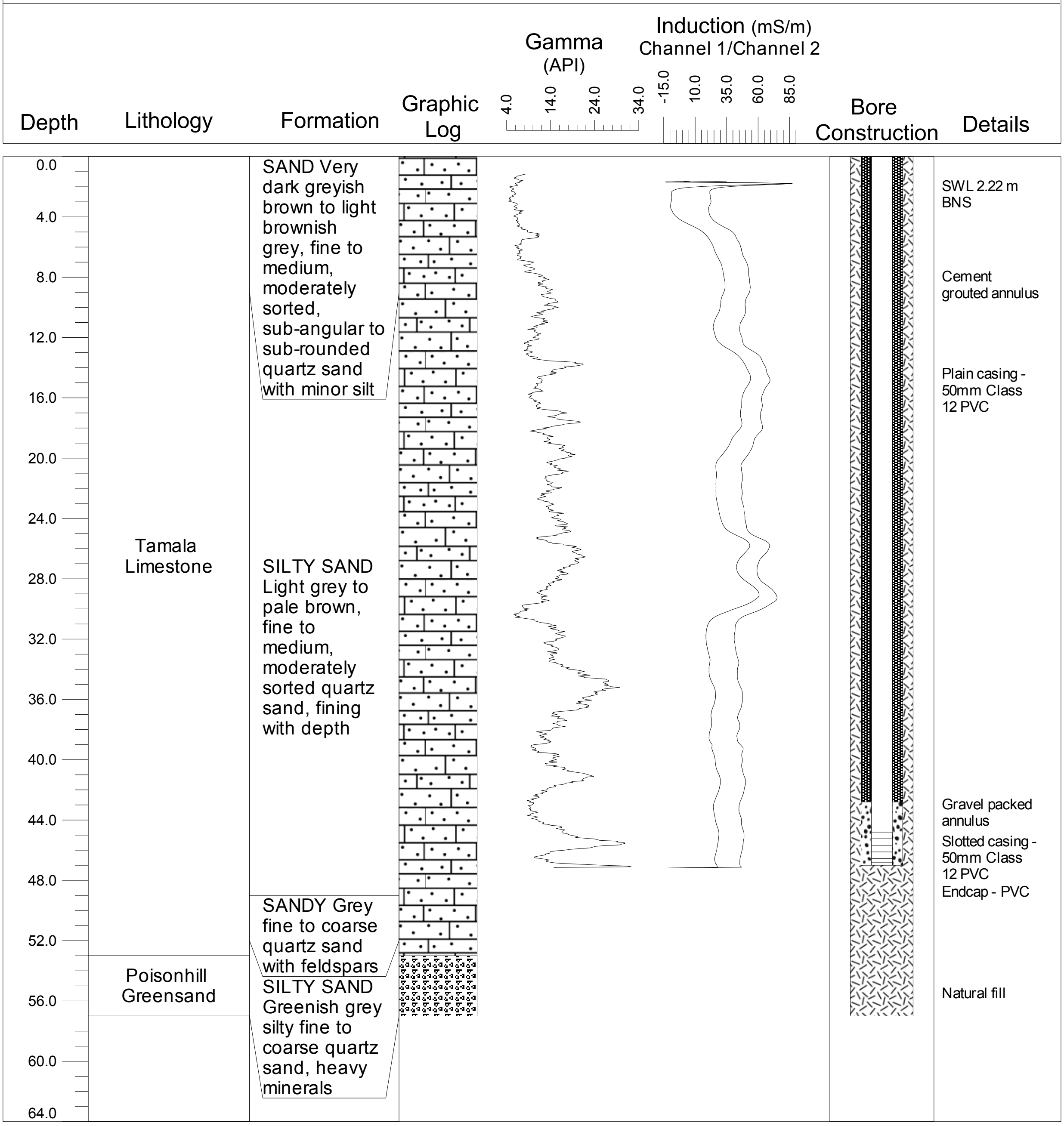
Appendix A — Construction diagrams

BORE COMPLETION DETAILS Department of Water Government of Western Australia

Perth Shallow Groundwater Systems Investigation - Stage 1

AWRC Name: **MGPa**

AWRC Number: **61611442**



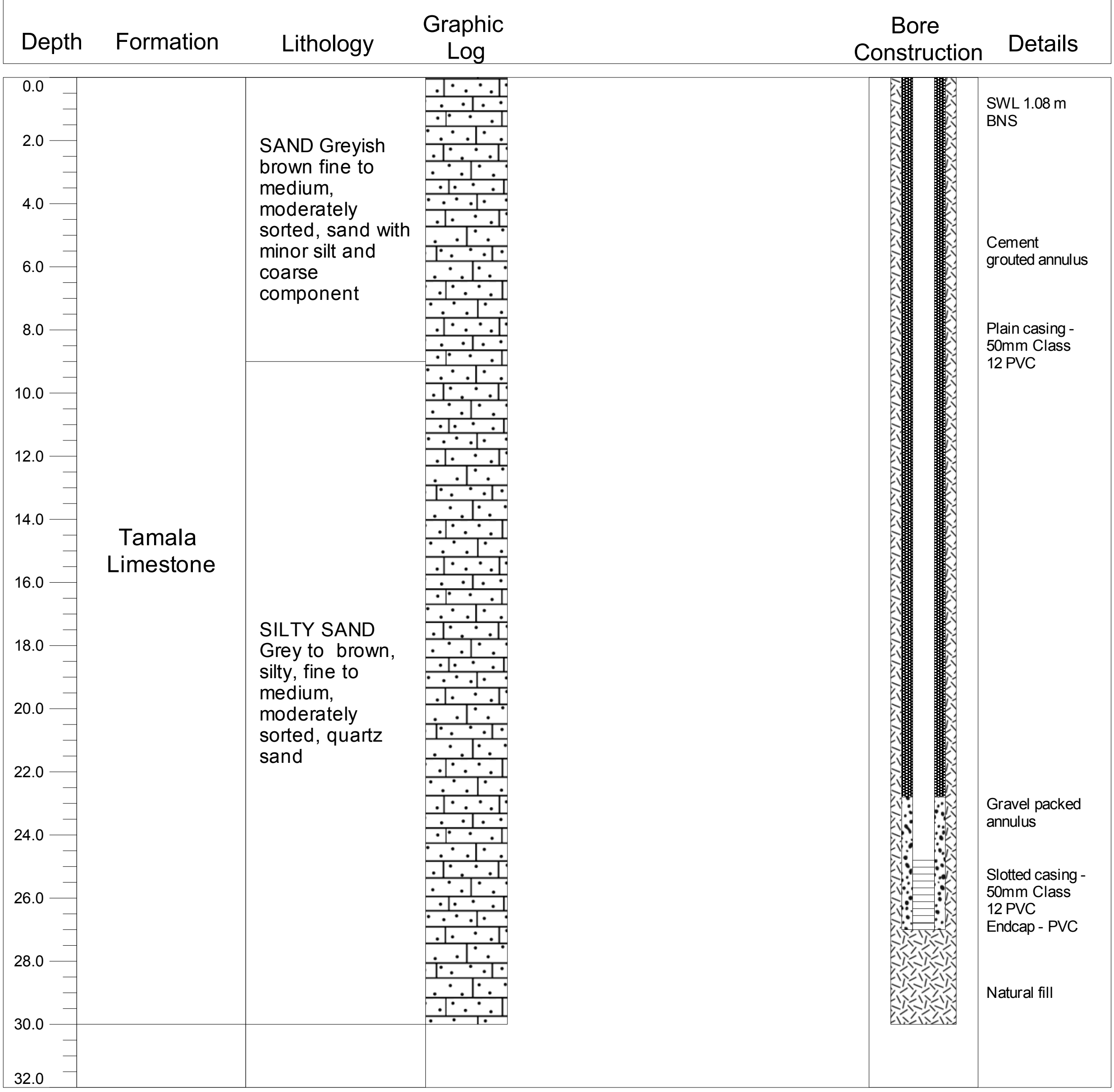
Drilled by:	Great Southern Drilling	Northing (Z50):	6489047.163	Screens (m BNS):	44.80 - 46.80
Date drilled:	6/7/07	Easting (Z50):	387426.524	SWL (m BNS):	2.22
Logged by:	Sarah Bourke	Surface (m AHD):	42.203	EC (mS/cm):	1.494
Aquifer:	Superficial	Drill depth (m BNS):	57	pH:	7.15

BORE COMPLETION DETAILS

Perth Shallow Groundwater Systems Investigation - Stage 1

Department of Water
Government of Western Australia

AWRC Name: **MGPb**
AWRC Number: **61611441**



SAND Greyish brown fine to medium, moderately sorted, sand with minor silt and coarse component

SILTY SAND Grey to brown, silty, fine to medium, moderately sorted, quartz sand

SWL 1.08 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC
Endcap - PVC

Natural fill

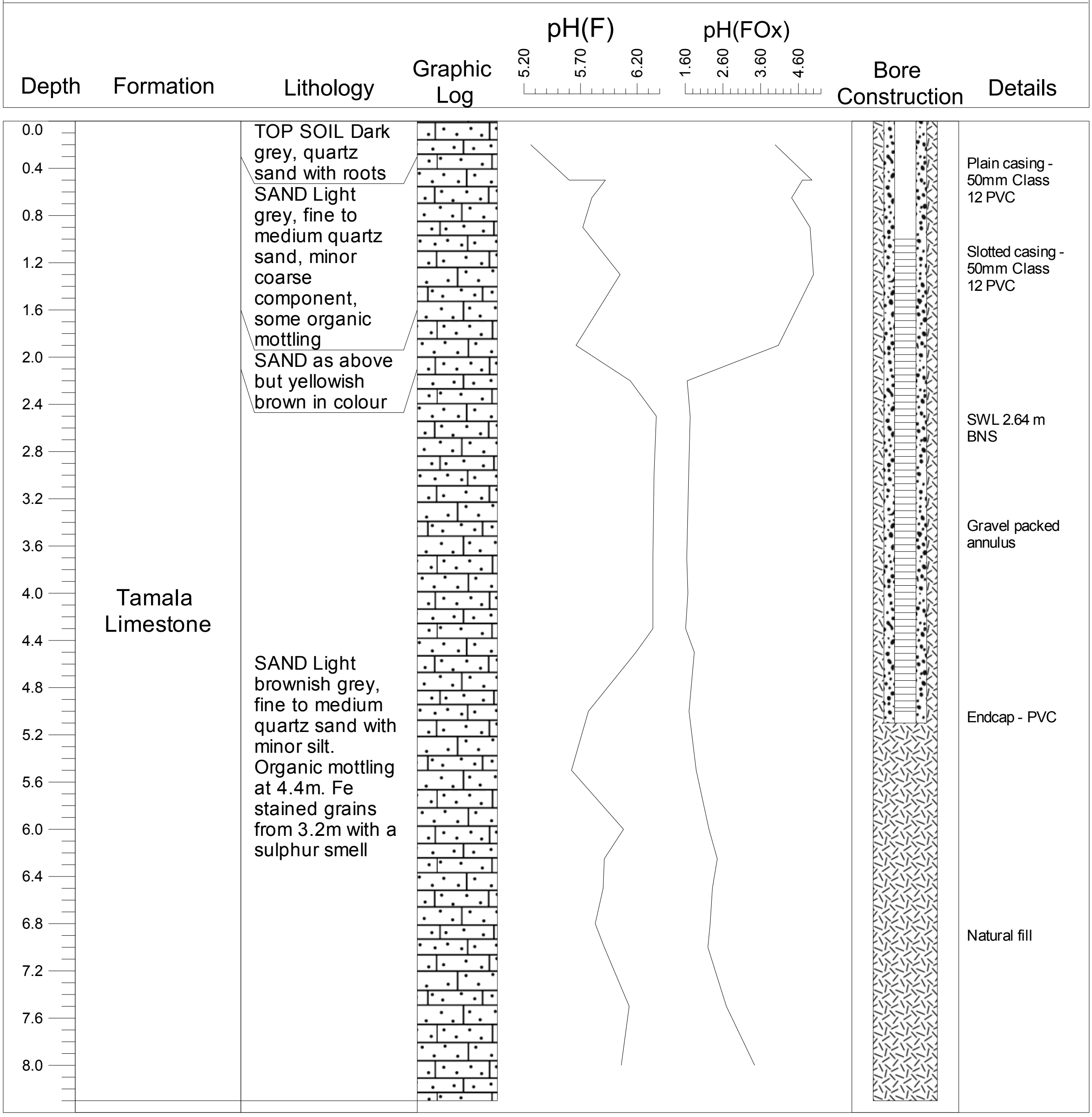
Drilled by:	Great Southern Drilling	Northing (Z50):	6489099.73	Screens (m BNS):	24.81 - 26.81
Date drilled:	6/12/07	Easting (Z50):	387428.09	SWL (m BNS):	1.08
Logged by:	Sarah Bourke	Surface (m AHD):	42.132	EC (mS/cm):	2.09
Aquifer:	Superficial	Drill depth (m BNS):	30	pH:	7.21

BORE COMPLETION DETAILS

Perth Shallow Groundwater Systems Investigation - Stage 1

Department of Water
Government of Western Australia

AWRC Name: **MGPc**
AWRC Number: **61611440**



TOP SOIL Dark grey, quartz sand with roots

SAND Light grey, fine to medium quartz sand, minor coarse component, some organic mottling

SAND as above but yellowish brown in colour

SAND Light brownish grey, fine to medium quartz sand with minor silt. Organic mottling at 4.4m. Fe stained grains from 3.2m with a sulphur smell

Drilled by:	Great Southern Drilling	Northing (Z50):	6489095.298	Screens (m BNS):	0.95 - 4.95
Date drilled:	5/24/07	Easting (Z50):	387423.739	SWL (m BNS):	2.64
Logged by:	Sarah Bourke	Surface (m AHD):	42.244	EC (mS/cm):	0.897
Aquifer:	Superficial	Drill depth (m BNS):	8.3	pH:	6

Appendix B — 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 within the water column and surrounding materials, possibly 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

- Ensure all equipment is washed and decontaminated.
- All instrumentation and equipment (pumping equipment, hoses, and standing water level recorders) is to be decontaminated prior to and after sampling at each site location. Decontamination is conducted by firstly rinsing with a mixture of Decon-910® and Perth scheme water. A second thorough rinse is performed using just Perth scheme water, and then a final very thorough rinse is conducted using the standard laboratory purchased deionised water.
- Use new (disposable) air and water tubing for each sampling event.
- Ensure water quality meters are functional and calibrated.
- Dip bore for groundwater level and record.
- Identify screen depth from records and lower low flow bladder pump to midway between screened interval. If sampling a shallow bore (full length screen) lower pump to 0.5 m below groundwater level.
- Connect air tubing to air supply.
- Connect water outlet tubing to instrument flow cell.
- Apply air to pump, adjust air supply and discharge time to commence pumping.
- Note other field observations such as interesting sample colour, presence of large quantities of particulate matter, and smell.
- Measure groundwater quality for the in situ field parameters pH, conductivity, temperature, redox and dissolved oxygen using multiprobe sensors installed in a flow cell. Record measurements every five minutes until the parameters stabilise then record a final value.
- Record results a field observation form for submission to Department of Water database.

- Once physical in situ field parameters have stabilised and been recorded, collect samples for laboratory analysis. All sample bottles should be filled to the shoulder of the bottle leaving a small airspace at the top of the bottle.
- Collect surface water samples by wading close to staff gauges, flushing bottles three times with lake water and filling from 10 cm below the surface. Record in situ field parameters and surface water levels.

In situ water quality parameters were monitored with Hydrolab test equipment (Quanta and multiprobe sensors).

Field pH testing methods

These were modified from those of Ahern et al. (1998), as described in Draft identification and investigation of acid sulfate soils (Department of Environment 2006).

Field pH testing

Before sampling:

- Set up clean, dry beakers in rack designed to measure pHf on the right and pHfox on the left.
- Calibrate pH measuring equipment using appropriate solutions.
- Adjust the pH of around 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.
- Collect sediment cores and return to 'field laboratory' setup to perform field tests before oxidation of sediments is able to occur.

Field pH_f and pH_{fox} testing

- Take ½ teaspoon sized sample of sediment approximately every 25 cm or when a lithology change is noted (which ever is lesser), noting the depth of the sample.
- Place into beaker used for pHf tests and add 12 ml of water from a clean syringe (marked pHf) to make a 1:5 soil:water solution and shake well.
- Take another ½ teaspoon sized sample of sediment from the same place as the previous sample used for the pHf measurement, and place into a beaker used for measuring pHfox.
- Add 12 ml of pH adjusted 30% hydrogen peroxide using a second syringe (marked pHfox) to make a 1:5 soil:peroxide solution, and shake well.
- Repeat above steps until entire core has been sampled.
- Shake all beakers well and leave for approximately 1 hour (during which time logging of cores can be done).
- Regularly shake (i.e. every 5 to 10 minutes) all beakers to ensure maximum amount of sediment goes into solution.
- After 1 hour record pHf and pHfox readings, taking all pHf measurements first (to ensure no contamination with peroxide and also to allow maximum time for

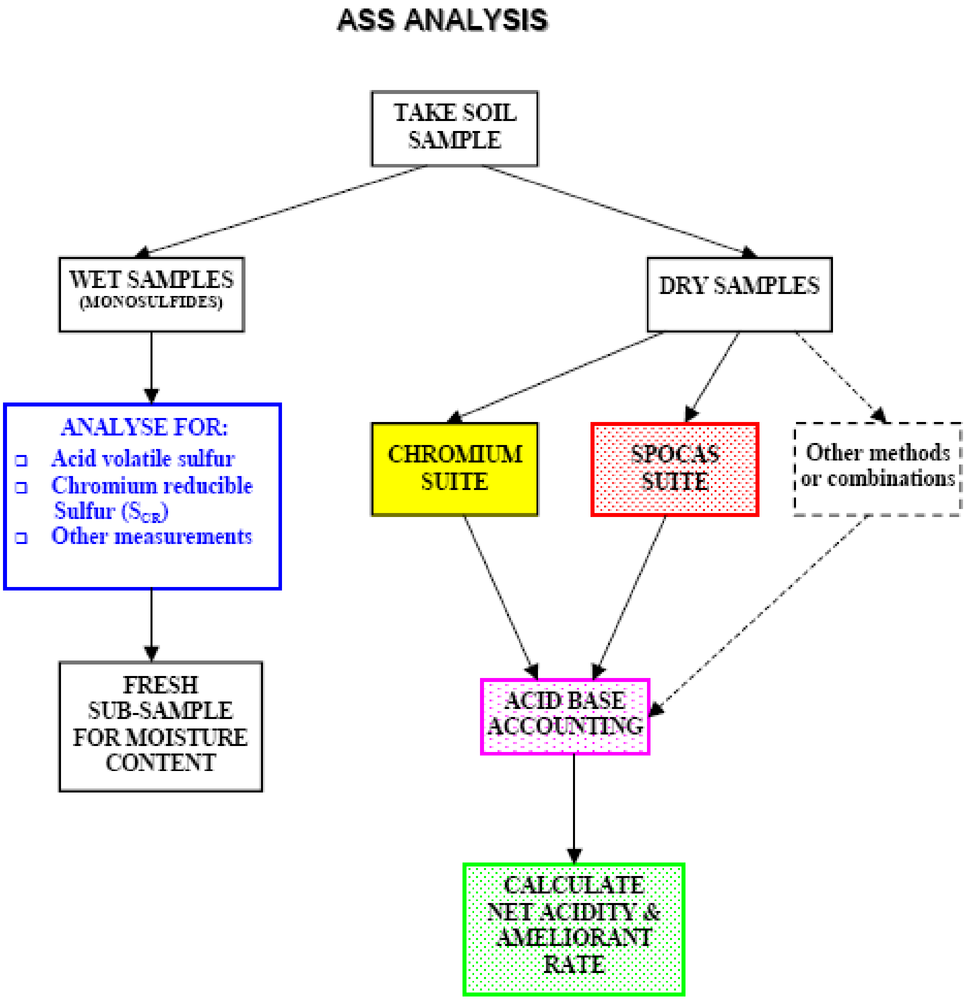
peroxide to react with the sediments). Clean pH probe with distilled water between each reading.

- Dispose of solutions into an appropriate container (although hydrogen peroxide rapidly decomposes to water and oxygen so is not harmful to the environment) and thoroughly clean all beakers, syringes and other equipment using Decon (detergent) and water.

Laboratory methods

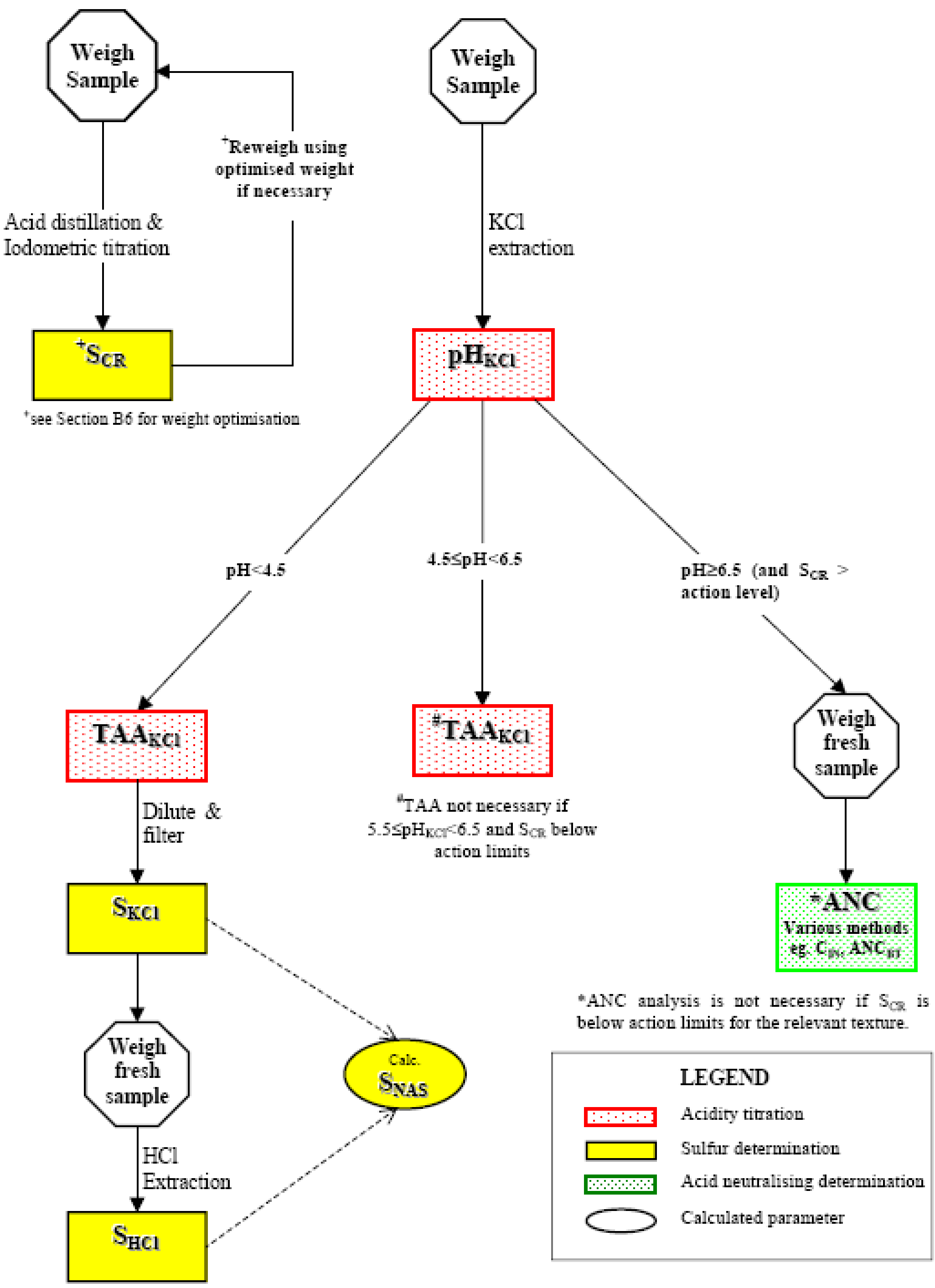
These are described in *Acid sulfate soils laboratory methods guidelines* (Ahern et al. 2004).

The following flow diagram (from Ahern et al. 1998)represents the process followed when analysing acid sulfate soils.



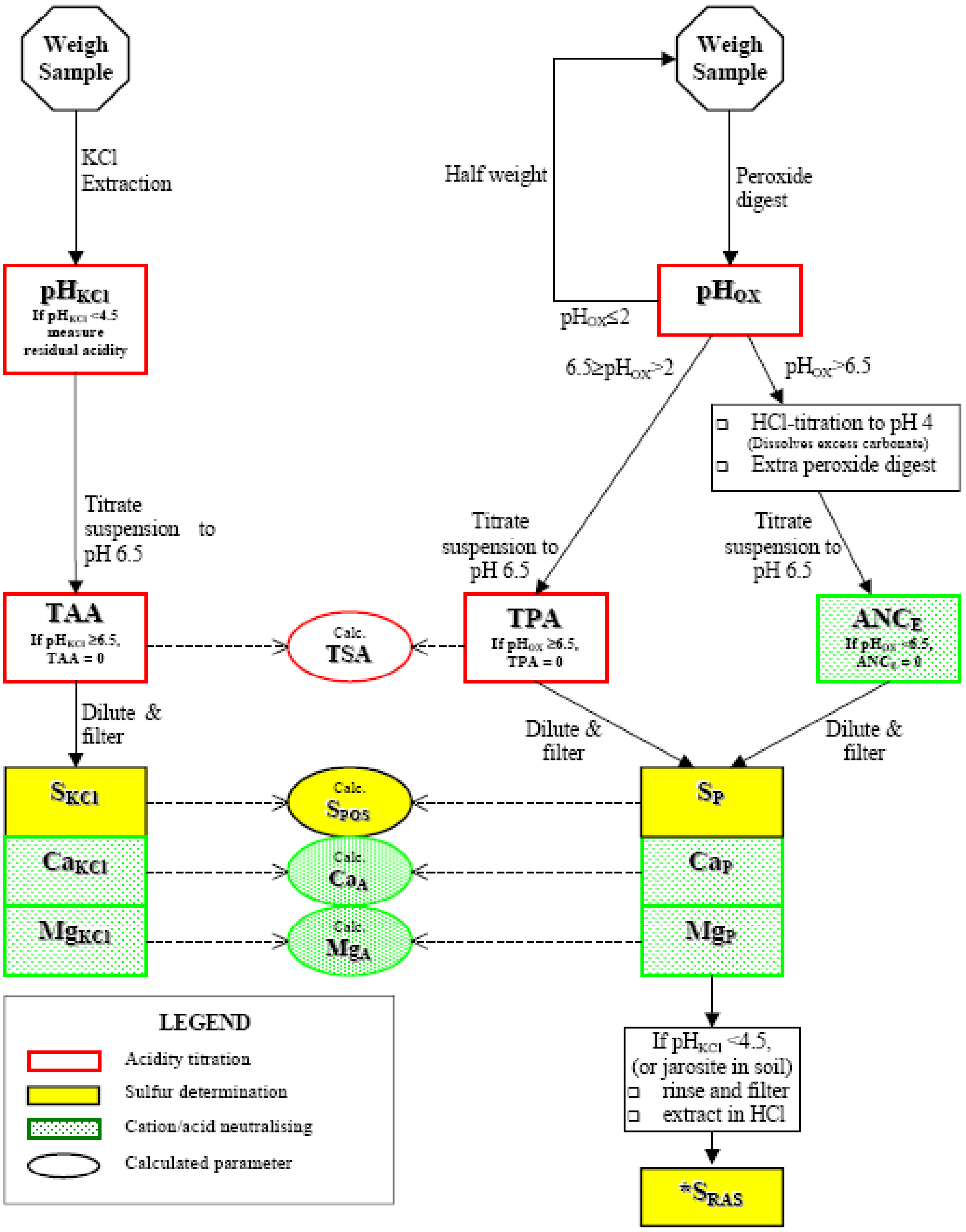
The following flow diagram (from Ahern et al. 1998) represents the process involved using the chromium suite.

CHROMIUM SUITE



The following flow diagram (from Ahern et al. 1998) represents the process involved in analysis using the SPOCAS suite.

SPOCAS: FLOW DIAGRAM



Appendix C — Historical lithology logs

LAKE MARIGINIUP MT1D

Depth m	Description
0 - 4 WT 3	Sand; off-white, fine to coarse, poorly sorted, sub-angular to rounded, frosted quartz and abundant organic material.
4 - 7	Sand; Brown, iron oxide cemented (coffee rock), medium-grained, poorly to moderately sorted, sub-angular to rounded quartz.
7 - 8	Sand; pale brown, fine to coarse, moderately sorted sub-angular to rounded quartz with some iron oxide staining.
8 - 27	Sand; white becoming very pale brown with depth, trace clay, fine to coarse-grained, poorly sorted, sub-angular to rounded, frosted, quartz trace scattered black heavy minerals.
27 - 45	Sand; very pale brownish-white, fine to coarse, poorly sorted, sub-angular to rounded, frosted quartz and trace scattered black heavy minerals.
45 - 48	Sand; pale greyish-white, trace clay, fine-grained to granular, minor small pebbles, sub-angular to rounded, some with high sphericity (bimodal), poorly sorted quartz and common black heavy minerals trace weathered feldspar.
- - - - - - - - - - - - - -	UNCONFORMITY - - - - - - - - - - - - - - -
48 - 52	Sand; greyish-green, clayey, fine to coarse (48 m fine to medium; 52 m coarse) well sorted (48 m), poorly sorted (52 m) sub-angular to rounded quartz, abundant green glauconite, common black heavy minerals.

<u>Probable Stratigraphy</u>

0 - 48 m; Superficial sediments

48 - 52 m; ? Poison Hill Greensand

LAKE MARIGINIUP

~~MANGINIUP~~ MT 2D

0-3 WT ✓	Sand:	yellow, fine-medium, moderately sorted quartz rounded to well rounded, possibly frosted; contains rare heavy mineral grains.
3-10	Sand:	white, fine-medium moderately sorted, quartz subangular (fine) and rounded to well rounded (medium) contains common heavy mineral grains.
10-14	Sand:	brown (?coffee rock).
14-28	Sand:	light grey, fine-coarse, variable, poor to moderately sorted, quartz angular (fine) to well rounded and frosted (coarse); contains rare grains of felspar, scattered heavy minerals and thin clay interbeds at about 16-20 m.
28-40	Sand:	light grey, coarse to very coarse, slightly felspathic moderately sorted, quartz rounded to well rounded with a high sphericity felspar partially kaolinized.
40-?46.5	Sand:	light grey-brown, medium-coarse, felspathic, poor-moderately sorted quartz rounded to well rounded (coarse) subangular (fine-medium); contains scattered heavy mineral and fine well rounded pebbles.
46.5-47	Siltstone:	light brown, sandy; contains scattered medium-very coarse well rounded quartz grains.
47-55	Sand:	light felspathic grey at top to grey at base, variable, medium to very coarse, quartz subangular (fine and medium) to well rounded with high sphericity (coarse); contains partially kaolinized felspar grains, rare heavy mineral grains, and rare well rounded pebbles of quartz.
55-58	Gravel:	grey, very sandy fine (0.2 cm) to coarse (2.5 cm) poorly sorted, pebbles, rounded to well rounded quartz; sand as for 47-55.
58-60	Sand:	light green-grey, slightly silty, bimodal, very fine to very coarse, quartz subangular (fine) to well rounded with a high sphericity (coarse); contains scattered glauconite and layer of black shiny (phosphatic) pebbles at base including ammonite fragment.
		UNCONFORMITY
60-61.5 TD	Sand:	dark grey green, silty, glauconitic medium to very coarse, tending to be bimodal quartz subangular to subrounded (fine and medium) to well rounded with a high sphericity (coarse)

Logged by A.D. Allen 79

ADA:YM

February 27 1979.

LAKE MARIGINIUP MT 3D

Depth (m)	Description
0 - 6	Sand; creamy white, fine to medium, some coarse, moderately sorted, sub-angular to rounded, frosted quartz.
6 - 9 WT 6	Sand; chocolate brown, very weakly cemented (coffee rock) ferruginous, medium grained, some coarse, sub-rounded to rounded, limonitic stained quartz.
9 - 12	Sand; pale brown, fine to coarse, predominantly medium, moderately sorted, some grains limonitic stained, sub-angular to rounded, frosted quartz and common black heavy minerals.
12 - 18	Sand; creamy white, fine to coarse, predominantly medium, moderately sorted, sub-angular to rounded, frosted quartz and common black heavy minerals.
18 - 28	Sand; creamy white, very slightly clayey, fine to coarse, predominantly medium, moderately sorted, sub-angular to rounded, frosted quartz, common black heavy minerals and scattered weathered feldspar.
28 - 36	Sand; creamy white, fine to coarse, moderately to poorly sorted, sub-angular to rounded, frosted ~~quality~~ quartz scattered weathered feldspar and trace black heavy minerals.
36 - 50	Sand; pale creamy brown becoming browner with depth and more clayey with depth. Trace black heavy minerals at top of section. Fine to coarse, predominantly medium, sub-angular to rounded, moderately sorted quartz and scattered weathered feldspar.
50 - 57.5	Sand; dark grey, slightly clayey, fine to very coarse, scattered pebbles, (bimodal) sub-angular to rounded, coarse with high sphericity, 50-54 m very clayey.
	- - - - - - - - - - - - - - - UNCONFORMITY - - - - - - - - - - - - - - -
57.5 -61	Sand; dark green becoming bright green with depth, very clayey, glauconitic, fine to coarse, poorly sorted, sub-angular to rounded quartz.

Appendix D – Acid sulfate soils field and laboratory results

Field results

Bore name	MGP_c
Date	24/05/07
Easting	387423.739
Northing	6489095.3
pH Cal (4.01)	4.02 @ 18.4
pH H_2O_2	5.21 @ 18.1
SWL	2.64m

	Field pH				
Depth m	pH$_F$	PH$_{FOX}$	Δ pH	Sample sent to lab?	Soil texture
0.2	5.26	3.98	-1.28	Yes	Block OM with light grey quartz sand
0.5	5.60	4.96	-0.64	Yes	light grey quartz sand
0.9	5.72	4.91	-0.81	Yes	as above
1.3	6.05	5.00	-1.05		as above
0.5	5.92	4.71	-1.21	Yes	as above, some silt and org. mottling
0.7	5.80	4.42	-1.38		yellowish brown quartz sand, silty Fe, org. mottling
1.9	5.66	4.07	-1.59	Yes	as above, decrease in silty and Fe. Organic mottling
2.2	6.14	1.65	-4.49		light brownish grey f to c quartz sand
2.5	6.37	1.73	-4.64	Yes	as above
3.0	6.35	1.69	-4.66	Yes	as above
3.7	6.34	1.64	-4.70		as above
4.0	6.34	1.67	-4.67	Yes	as above
4.3	6.34	1.61	-4.73		as above
4.5	6.19	1.84	-4.35		greyish brown m to c silty quartz sand
5.0	5.77	1.70	-4.07	Yes	as above
5.5	5.62	1.89	-3.73		as above
6.0	6.08	2.23	-3.85	Yes	as above
6.3	5.91	2.45	-3.46		as above
6.5	5.90	2.32	-3.58		as above
6.8	5.83	2.26	-3.57		as above
7.0	5.91	2.20	-3.71	Yes	as above
7.5	6.13	2.69	-3.44		as above
8.0	6.06	3.44	-2.62	Yes	as above

Laboratory results for samples from bore MGP_c

Depth m	Moisture %	pH_{KCl}	pH_{Ox}	TAA	TPA	TSA	S_{KCl}	S_p	S_{POS}	S_{Cr}	S_{RAS}	S_{NAS}	Ca_{KCl}	Ca_p	Ca_A	Mg_{KCl}	Mg_p	Mg_A
0.1	93.0	4.6	3.0	11	84	73	<0.01	0.23	0.23	<0.01			<0.1	0.2	0.1	<0.1	<0.1	<0.1
0.5	99.7	5.5	4.2	<1	<1	<1	<0.01	<0.01	<0.01	<0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1.0	99.2	5.6	4.1	<1	<1	<1	<0.01	<0.01	<0.01	<0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
1.5	98.5	5.4	3.9	<1	<1	<1	<0.01	<0.01	<0.01	<0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2.0	85.1	5.8	3.6	<1	<1	<1	<0.01	<0.01	<0.01	<0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2.5	85.2	5.8	3.6	<1	5	5	<0.01	0.01	<0.01	0.02			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
3.0	85.8	5.7	3.3	<1	2	2	<0.01	<0.01	<0.01	<0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
4.0	86.0	5.7	3.2	<1	3	3	<0.01	<0.01	<0.01	0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
5.0	87.4	5.9	3.0	<1	9	9	<0.01	0.02	0.01	0.02			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
5.0 (duplicate)		5.5	3.0	<1	8		<0.01	0.01		0.02			<0.1	<0.1		<0.1	<0.1	
6.0	85.8	5.7	3.3	<1	1	1	<0.01	<0.01	<0.01	<0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
7.0	86	5.8	3.6	<1	<1	<1	<0.01	<0.01	<0.01	<0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
8.0	86.1	5.8	3.7	<1	<1	<1	<0.01	<0.01	<0.01	<0.01			<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Depth m	Al mg/kg	As mg/kg	Cd mg/kg	Cr mg/kg	Fe mg/kg	Mn mg/kg	Ni mg/kg	Se mg/kg	Zn mg/kg
0.1	2710	1.8	<0.5	5.9	450	2.3	0.5	0.71	3.7
0.5	170	<0.5	<0.5	<0.5	42	0.61	<0.5	<0.5	1.1
1.0	120	<0.5	<0.5	<0.5	37	<0.5	<0.5	<0.5	1.1
1.5	130	<0.5	<0.5	<0.5	33	0.64	<0.5	<0.5	<0.5
2.0	94	<0.5	<0.5	<0.5	140	1.3	<0.5	<0.5	<0.5
2.5	75	<0.5	<0.5	<0.5	260	1.5	<0.5	<0.5	<0.5
3.0	79	<0.5	<0.5	<0.5	200	1.7	<0.5	<0.5	<0.5
4.0	270	<0.5	<0.5	<0.5	180	1.2	<0.5	<0.5	<0.5
5.0	290	<0.5	<0.5	<0.5	240	1.6	<0.5	<0.5	1.3
6.0	280	<0.5	<0.5	<0.5	150	2.2	<0.5	<0.5	<0.5
7.0	240	<0.5	<0.5	<0.5	130	3.1	<0.5	<0.5	<0.5
8.0	250	<0.5	<0.5	0.6	130	4.6	<0.5	<0.5	<0.5

Shortened forms

AHD	Australian height datum
DNRA	Dissimilatory nitrate reduction to ammonium
TAA	Titratable actual acidity
TDS	Total dissolved salts
TPA	Titratable peroxide acidity
TSA	Titratable Sulfidic acidity
TSS	Total suspended solids

Glossary

Abstraction	The withdrawal of water from any water resource.
Acid sulfate soils	Naturally occurring, these are soils containing significant quantities of reduced sulfur (pyrite and other sulfides). When these soils are disturbed the reduced sulfur is oxidised resulting in the release of acidity and often toxic metals.
Acid-buffering capacity	A measure of the resistance to changes in pH following the addition of an acid.
Acidification	The process by which soil, or water becomes more acidic (decreasing pH).
AHD	Australian height datum, which is equivalent to: mean sea level (MSL) + 0.026 m, low water mark Fremantle (LWMF) + 0.756 m.
Algal blooms	The rapid excessive growth of algae, generally caused by high nutrient levels and favourable conditions. Can result in water column deoxygenation when the algae die.
Alkalinity	A measure of a solution’s ability to resist changes in pH due to the addition of an acid. In natural waters this usually relates to the amount of bicarbonate, carbonate and hydroxide compounds present in the water.
Allocation limit	The volume of water set aside for annual licensed use.
AMG	Australian map grid
Anthropogenic	Originating from the activity of humans.
Aquifer	A geological formation or group of formations able to receive, store and/or transmit large amounts of water.
Assessment level	Guideline concentrations of analytes adopted to indicate the potential presence of contamination and to trigger requirement for further investigation and assessment of risk at a site.
Bore	A narrow, normally vertical hole drilled into a geological formation to monitor or withdraw groundwater from an aquifer (*see also* Well).

Buffer	A solution which resists changes in pH when a small amount of strong acid or base are added
Buffering capacity	A measure of the ability of a solution to resist changes in pH.
Confined aquifer	A permeable bed saturated with water and lying between an upper and a lower confining layer of low permeability, the hydraulic head being higher than the upper surface of the aquifer.
Confining bed	Sedimentary bed of very low hydraulic conductivity.
Conformably	Sediments deposited in a continuous sequence without a break.
Contaminants	A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful effects to humans or the environment.
Cretaceous	Final period of Mesozoic era, 65–144 million years ago.
Dewatering	Short-term abstraction of groundwater to lower the watertable and permit the excavation of 'dry' sediment.
Dissolution	The process of dissolving a solid to produce a solution.
Drawdown	The difference between the elevation of the initial piezometric surface and its position after pumping or gravitational drainage.
Ecological water requirement	The water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk).
Equilibrium	The condition of a system or reaction in which competing influences are balanced.
Eutrophication	An excess of nutrients (nitrogen and phosphorus) in an ecosystem, often resulting in excessive primary production.
Evapotranspiration	The combined loss of water by evaporation and transpiration. Includes water evaporated from the soil surface and water transpired by plants.
Fault	A fracture in rocks or sediments along which there has been an observable displacement.

Flux	Flow
Formation	A group of rocks or sediments that have certain characteristics in common, were deposited about the same geological period, and that constitute a convenient unit for description.
Glauconitic	Of the mineral glauconite, which is an iron potassium phyllosilicate (mica group) mineral of characteristic green color.
Groundwater	Water that occupies the pores within the rock or soil profile.
Groundwater-dependent ecosystem	An ecosystem that depends on groundwater for its existence and health.
Holocene age	The geological period that started approximately 10 000 years ago and extends to the present.
Hydraulic	Pertaining to water motion.
Hydraulic gradient	The rate of change of total head per unit distance of flow at a given point and in a given direction.
Hypoxic	Water with a low concentration of oxygen (typically 1–30% of oxygen saturation).
Ion	An atom which has lost or gained electrons and therefore carries an electrical charge.
Lacustrine	Pertaining to, produced by, or formed in a lake.
Leach	Remove soluble matter by percolation of water.
Metalloid	An element whose properties are between those of metals and non-metals.
Mineralisation	The breakdown or conversion of organic matter into carbon dioxide.
Neutralisation	The chemical reaction in which an acid and a base react to produce salt and water.

Oxidation	A process resulting in the loss of electrons from a chemical species accompanied by an increase in oxidation state. This process does not necessarily require the presence of oxygen.
Permian	An era of geological time, 225–280 million years ago.
pH	The negative logarithm of the concentration of hydrogen ions.
PHREEQCE	A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations
Quaternary	Relating to the most recent period in the Cainozoic era, from 2 million years to present.
Redox	In aqueous solutions, the reduction potential is the tendency of the solution to either gain or lose electrons and is measured in volts (V), millivolts (mV) or Eh. 1 Eh = 1 mV, because the absolute potentials are defined relative to the standard hydrogen electrode which is arbitrarily given a potential of 0.00 V.
Redox potential	In aqueous solutions, the reduction potential is the tendency of the solution to either gain or lose electrons and is measured in volts (V), millivolts (mV), or Eh (1 Eh = 1 mV mV). Because the absolute potentials are difficult to accurately measure, reduction potentials are defined relative to the standard hydrogen electrode which is arbitrarily given potential of 0.00 V.
Reduction	A process resulting in the gain of electrons by a chemical species accompanied by a decrease in oxidation state.

Salinity	A measure of the concentration of total dissolved solids in water. 0–500 mg/L fresh 500–1500 mg/L fresh to marginal 1500–3000 mg/L brackish > 3000 mg/L saline
Scarp	A line of cliffs (steep slopes) produced by faulting or by erosion.
SPOCAS	An acronym standing for Suspension Peroxide Oxidation Combined Acidity and Sulfur method.
Stressor	An agent, condition or other stimulus that causes stress to an organism or ecosystem.
Sulfate reduction	In the aquatic environment, the microbially catalysed process which converts sulfate to sulfide.
Surficial	Pertaining to the surface.
Terrestrial	Refers to an organism (or ecosystem) being of land origin.
Tertiary	The first period of the Cainozoic era, 2–65 million years ago.
Toxicity	The degree to which a substance is able to damage an exposed organism.
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.
Transpiration	The loss of water vapour from a plant, mainly through the leaves.

Trigger level	Concentrations of key indicators, above or below which there is a risk of adverse biological effects
Unconfined aquifer	A permeable bed only partially filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure.
Watertable	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.
Well	An opening in the ground made or used to obtain access to underground water. This includes soaks, wells, bores and excavations.

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