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

*Securing Western Australia's water future*

# Perth Shallow Groundwater Systems Investigation

## North Lake

Hydrogeological record series

Report no. HG42
May 2015

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# Preface

This report is based on work conducted as part of the Perth shallow groundwater systems investigation. This was a four-year (2007–10) program undertaken by the Groundwater Review Section of the Water Resource Assessment Branch within the Department of Water. Program funding was provided by the Department of Water and the Australian Government’s Water Smart Australia initiative.

The investigation focused on wetlands on the Gnangara and Jandakot groundwater mounds, which are significant sources of groundwater for the Perth metropolitan area. The groundwater mounds sustain ecosystems dependent on shallow groundwater. Many of these ecosystems are stressed by land-use changes, increased groundwater abstraction and a shift to a drier climate, resulting in the deterioration of their social, cultural, economic and environmental values.

The formulation of the Perth shallow groundwater systems investigation arose from outcomes of a groundwater resource review conducted in 2006 (McHugh & Bourke 2007). This review summarised the then 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 for 28 wetlands on the Swan Coastal Plain, prioritised according to a combination of ecological significance, management issues and geomorphic setting.

The objectives of the Perth shallow groundwater systems investigation were:

- 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 identify the interactions and connectivity of surface water and groundwater.
- Investigate the chemistry of wetlands and wetland sediments to give a detailed understanding of the capacity 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

North Lake is situated approximately 14 kilometres south-west of Perth on the Jandakot Mound, an important groundwater resource for the surrounding metropolitan area. The lake is a conservation category wetland and is protected under the Environmental Protection (Swan Coastal Plain Lakes) Policy 1992 (Government of Western Australian 1992). The lake is one of 23 sites on the Jandakot Mound for which the Minister for the Environment established water level criteria to manage the development of groundwater abstraction for public water supply and the expected growth in private licensed groundwater. Falling surface water levels have resulted in ongoing breaches of the water level criteria and have prompted further research to better understand the lake's hydrogeology.

The lake was chosen as one of 28 sites in the Perth shallow groundwater systems (SGS) investigation to improve understanding of relationships between wetland hydrogeology, chemistry and ecosystem function. This understanding is crucial for the improved management of water levels in relation to the Ministerial water level criteria and ecological condition.

In 2008, the groundwater monitoring network at North Lake was upgraded by installing a cluster of groundwater monitoring bores along the western (downgradient) and eastern (upgradient) margins of the lake. A water table monitoring bore was also installed further east of the lake where vegetation surveys are carried out. A 12 month sampling program was conducted between June 2007 and June 2008 to improve our hydrogeological understanding of the lake. Two additional rounds of groundwater sampling were conducted in May and September 2012 to complement earlier sampling.

At North Lake, the Superficial aquifer intercepts the ground surface, creating a groundwater dependent ecosystem. The lake's ecological values include its use as a drought refuge for waterbirds, its fringing vegetation and its uniqueness as an urban habitat for freshwater sponges. These values are affected by falling groundwater levels and deteriorating groundwater quality. Reduced rainfall and groundwater abstraction have caused groundwater level decline and the seasonal drying of North Lake. This has led to encroachment of vegetation into the wetland basin and the loss of some waterbird habitat. Falling groundwater levels and poor groundwater quality near the water table may be contributing to the declining condition of the lake's fringing vegetation.

North Lake, located in an inter-dunal depression of the Spearwood and Bassendean dune systems, is underlain by Bassendean Sand. Lake bed sediments consist of organic-rich silts and diatomite up to a combined thickness of 9.5 m. These sediments can store up to five times more soil moisture than Bassendean Sand and may be important in supporting the ecology within the lake basin.

The hydrology of North Lake is dominated by groundwater through-flow. Groundwater flows into the lake from the south-east and out to the north-west. The lake has dried over the summer/autumn period since the mid-1990s and is now a seasonal wetland. Groundwater contours suggest the lake interacts with the upper 20 m (about half) of the Superficial aquifer. When the lake is dry the water table is within the lake bed sediments.

The lake's water quality has changed: pH has fallen since 2007 (pH 3.01 was recorded in May 2012 in sampling outside the investigation period) and aluminium has been detected in surface water and groundwater, indicating acidification processes. Arsenic concentrations measured during the investigation period in the middle of the Superficial aquifer to the east of the lake were commonly higher than Department of Health non-potable groundwater use guidelines (DEC 2010). However these concentrations may have been overestimated because total metals were measured rather than dissolved (soluble) concentrations. Groundwater sampling in 2012 measured soluble concentrations, which were significantly lower than concentrations measured during the investigation and were below Department of Health non-potable groundwater use guidelines.

North Lake is not located in a public drinking water source protection area and the Superficial aquifer beneath North Lake is not used as a source of potable water. Furthermore, the area around North Lake is not considered suitable for installation of new domestic groundwater garden bores (DoW 2011). Despite this, the findings of this study reinforce the need for users of untreated groundwater from domestic bores to test the quality of groundwater to ensure it is suitable for its intended use and where necessary have it appropriately treated[1].

The lake is at risk of acidification due to the oxidation of iron sulfide minerals in lake bed sediments and underlying soils as water levels decline. Metals and metalloids stored in organic silts of the lake bed sediments, as well as acidity, could be flushed into the lake and groundwater during re-wetting of the sediments. Acidification is likely to have detrimental effects on the aquatic ecology by affecting the lake's macroinvertebrate abundance and assemblages and may affect surrounding vegetation. To reduce these risks, lake levels need to be managed to limit the number and length of seasonal drying events.

Murdoch Drain was a historical source of nutrients to the lake. Nutrient concentrations in the lake however were expected to have decreased since this drain was blocked. This investigation found nutrient concentrations higher than ANZECC guidelines for lakes and wetlands in south-west Western Australia. Unblocking Murdoch Drain may help improve lake levels but would likely increase nutrient input

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[1] Additional information on appropriate use and testing of garden bores can be found at:

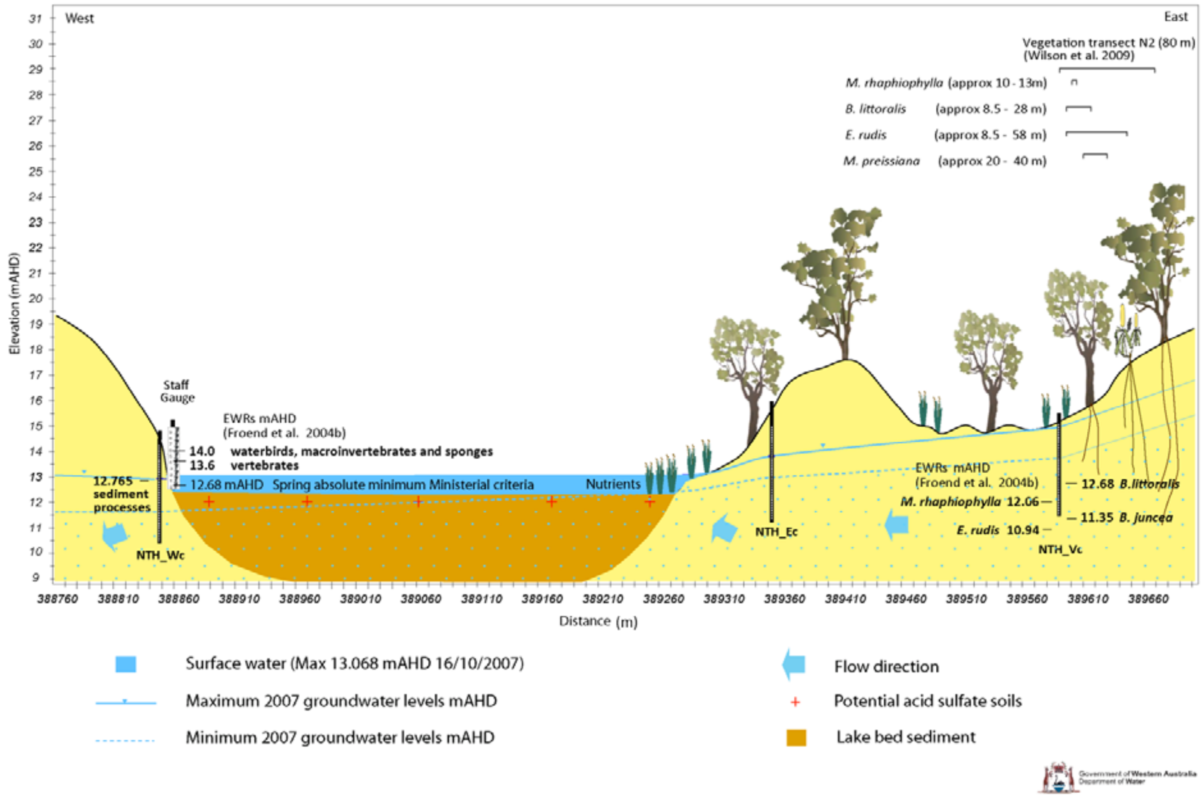
- DoH advice on bore water (www.public.health.wa.gov.au/3/658/2/bore_water.pm)
- Contaminated groundwater— could my garden bore be affected? (www.der.wa.gov.au/your-environment/contaminated-sites/60-fact-sheets-and-technical-advice)

unless drainage water was carefully managed to ensure nutrients were removed before reaching North Lake.

This investigation has improved our understanding of the lake's hydrogeology and has upgraded the monitoring network. North Lake bore (61410726) should be used to measure water level criteria given in Ministerial Statement 688 when the lake is dry. A groundwater level of 12.25 m AHD at the bore is equivalent to the current absolute minimum surface water level criterion. When relating groundwater levels to the ecological condition of vegetation at the transect, the newly established bore NTH_VC should be used.

To maintain and improve the ecological condition of North Lake, management could focus on raising water levels. This would help retain the lake's value as a summer refuge for waterbirds and its fringing vegetation. Higher levels would also limit the number and length of seasonal drying events and reduce the risk of acidification. Reducing private licensing of groundwater near the lake could improve water levels and support ecological values. Improvements to the design and management of urban water drainage in the area could also help raise levels. If raised groundwater levels cannot be achieved, slowing the rate of decline would still be beneficial to the lake's ecology. This would at least slow the rate of acidification and potentially mitigate water quality issues.

An improved conceptual model of the relationships between the hydrogeology, chemistry and the wetland ecosystem of North Lake was developed in this study (see below and Figure 53). The conceptual model shows groundwater flowing towards the lake from the east and down and out of the lake on the west. The conceptual model also shows different water levels at the lake, the approximate thickness of lake bed sediments and the presence of iron sulfide minerals in lake bed sediments that have the potential to acidify when oxidised. This model is discussed in detail in Section 6, with some recommendations detailed in Section 7 to provide a basis for improved management of North Lake.



*Conceptual model of the relationships between the hydrogeology, chemistry and the wetland ecosystem of North Lake*

# 1 Introduction

## 1.1 Context and justification

North Lake is a conservation category wetland, which is the highest priority for wetland conservation identified in the former Department of Environment and Conservation's geomorphic wetlands dataset and is protected under the Environmental Protection (Swan Coastal Plain Lakes) Policy 1992 (Government of Western Australian 1992).

The lake is one of 23 sites on the Jandakot Mound where the Minister for the Environment established water level criteria, set in Ministerial Statement 688, to manage the development of groundwater abstraction for public water supply and the expected growth in private licensed groundwater use (Government of Western Australia 2005).

Declining surface water levels have resulted in ongoing breaches of the water level criteria and have prompted further research to better understand the hydrogeology of North Lake. A groundwater resource review recommended that site-specific data be collected and analysed to assess the lake's current status in terms of groundwater–surface water connectivity and groundwater quality. The review highlighted the need to investigate whether North Lake bore provides a suitable representation of groundwater levels in relation to ecological condition and recommended the installation of a new shallow monitoring bore at the vegetation transect (McHugh & Bourke 2007).

## 1.2 Investigation objectives

The objectives of the investigation at North Lake were to:

1. Upgrade the groundwater monitoring network.
2. Improve our hydrogeological understanding of the lake.
3. Assess the distribution of acid sulfate soils in and around the lake, and their effects on water quality.
4. Develop a conceptual model of the relationships between wetland hydrogeology, chemistry and ecosystem function to provide a basis for improved management strategies.

# 2 Background

## 2.1 Location

North Lake is located on the Jandakot Mound in the City of Cockburn, approximately 14 kilometres south-west of Perth, Western Australia (Figure 1).

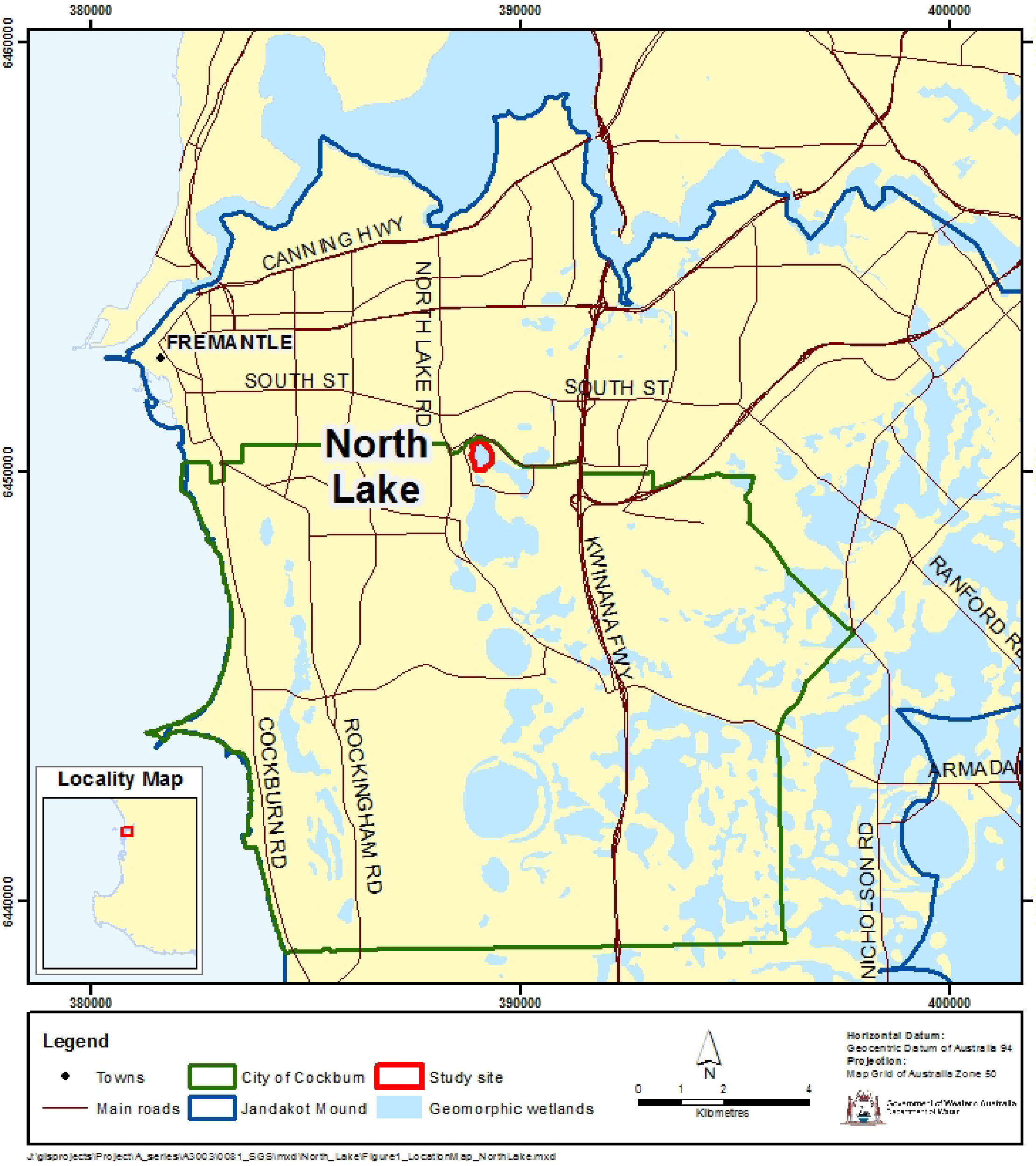


*Figure 1 Regional location of North Lake*

## 2.2 Climate

The climate is Mediterranean with hot dry summers and mild wet winters. Mean annual rainfall (1908 – 2008) for this period was just over 800 mm/year, however annual rainfall in the Perth region has declined since the 1970s (Figure 2). Annual rainfall from 1998 to 2008 was ~700 mm/year.

Perth's annual potential evaporation exceeds annual rainfall with pan evaporation at Perth airport close to 2000 mm/year during 2007 and 2008. Evaporation is highest during summer and lowest in winter with an average daily pan evaporation rate of 5.5 mm recorded during 2007–08.

The closest weather station to North Lake is Jandakot aero (station no. 9172). Monthly rainfall throughout the study (April 2007 to June 2008) is presented in Figure 3. Rainfall followed a typical Mediterranean pattern apart from some unseasonal rainfall in December 2007 and February 2008.

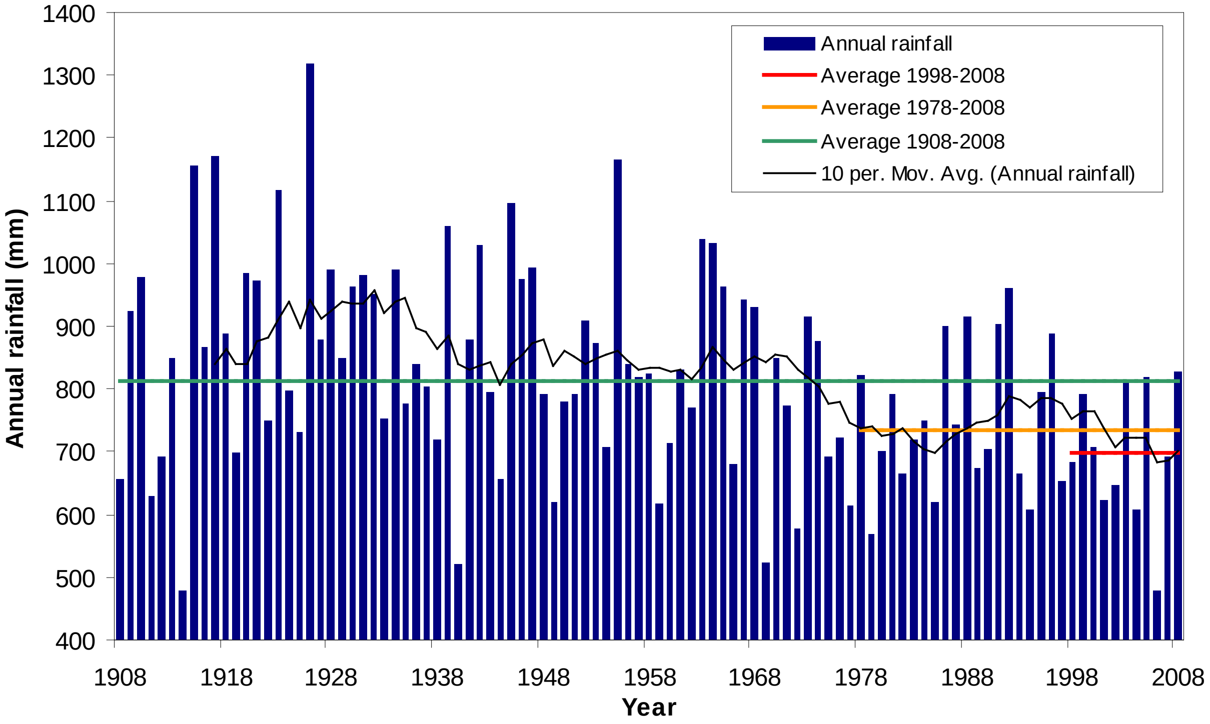


*Figure 2 Annual rainfall at Perth Airport station*

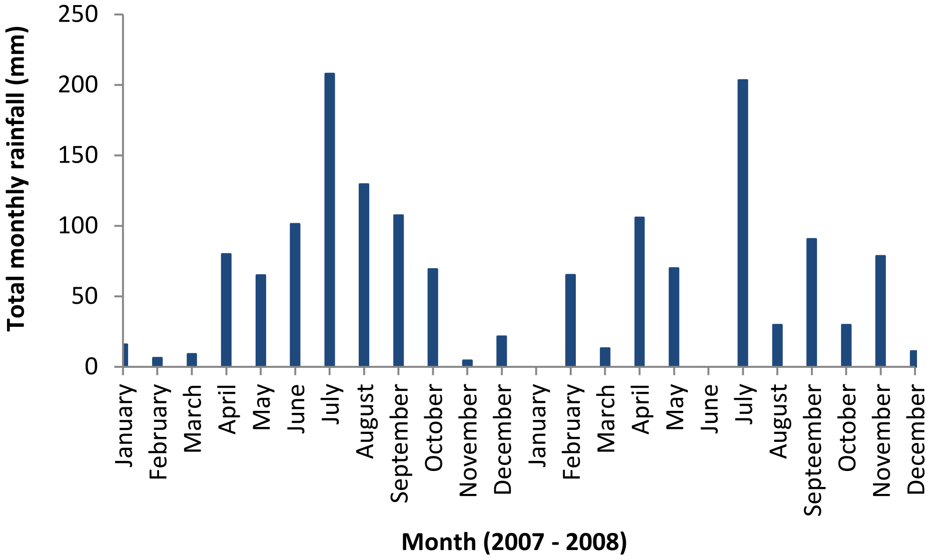


*Figure 3 Monthly rainfall at Jandakot aero station in 2007-2008. Note: No data available for June 2008.*

## 2.3 Geology

### Regional geology and geomorphology

North Lake is located on the Swan Coastal Plain within the Perth Basin. The Swan Coastal Plain is characterised by four geomorphic units which trend sub-parallel to the present day coast (Gozzard 2007). The oldest is the Pinjarra Plain to the east, abutting the Darling Fault (Figure 4). Adjacent to the Pinjarra Plain is a series of shoreline dune systems that decrease in age from east to west. These are, from oldest to youngest, the Bassendean Dunes, the Spearwood Dunes and the Quindalup Dunes.

The Perth Basin contains a thick sedimentary sequence deposited on the down-thrown block associated with the faulting that formed the Darling Scarp. The youngest Cainozoic sediments are collectively referred as the superficial formations. These include the Ascot Formation, Yoganup Formation, Bassendean Sand, Guildford Formation/Clay, Tamala limestone and Safety Bay Sand (Figure 4).

North Lake is underlain by Bassendean Sand and is part of the north-south oriented chain of lakes that lie in the inter-dunal depression between the Bassendean Dunes and the Spearwood Dunes (the Bibra Suite of Wetlands, Hill et al. 1996). The Bassendean Dunes comprise Bassendean Sand. Bassendean Sand mainly comprises highly leached quartz sand, some microcrystalline pyrite and very little clay. Bassendean Sand is highly susceptible to acidification because it is very poorly buffered and unable to resist changes in pH following oxidation of sulfide minerals (Prakongkep et al. 2012).

The Spearwood Dunes are formed from the weathering of Tamala Limestone, which comprises leached sands and calcarenite (Davidson 1995). Beneath these dune systems is the older Tertiary Ascot formation of shelly sands and limestone (Davidson 1995).

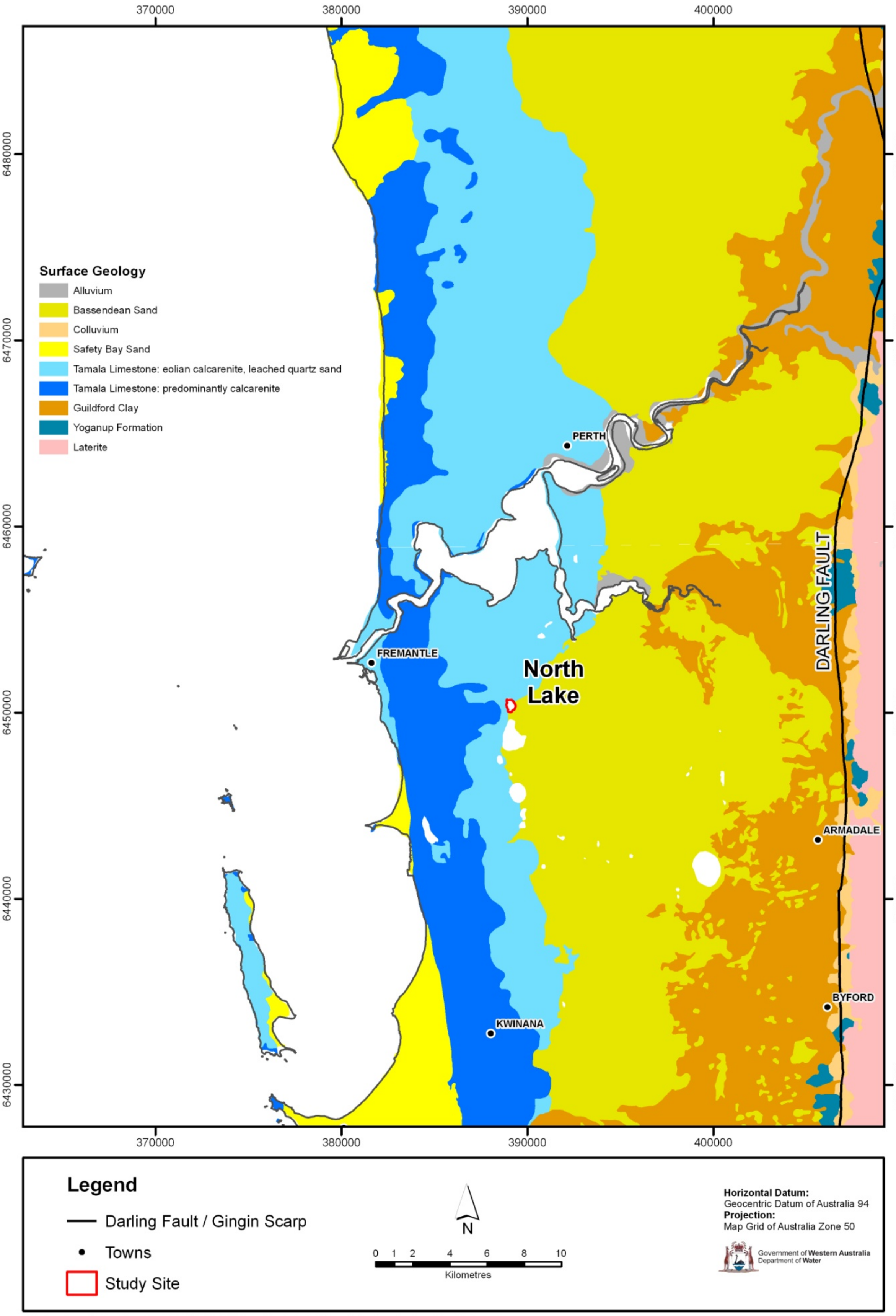
The superficial formations in the North Lake area are underlain by the Kardinya Shale Member of the Osborne Formation (Davidson 1995). This member consists of dark green to black inter-bedded siltstones and shales and is often puggy and glauconitic and near North Lake is approximately 120 m thick (Davidson 1995). The Kardinya Shale separates the superficial formations from the Leederville Formation in this area.

## Acid sulfate soils

Acid sulfate soils (ASS) are a significant management issue on the Swan Coastal Plain, particularly for wetlands like North Lake that are situated on highly leached, poorly buffered, base cation depleted Bassendean Sand. Acid sulfate soils contain iron sulfide minerals such as pyrite. Iron sulfide minerals are stable under anaerobic conditions but when exposed to oxygen release sulfuric acid triggering acidification processes in soil, sediment and groundwater. Oxidation of iron sulfide minerals can result from water table decline caused by reduced rainfall or groundwater abstraction or from dewatering and excavation as part of construction activities.

The term ASS in this report includes materials containing both potential and actual acidity. Sediments with potential acidity are referred to as potential acid sulfate soils (PASS) and contain iron sulfide minerals in an undisturbed anaerobic environment. Sediments that are acidic (i.e. $pH \leq 4$) are referred as actual acid sulfate soils (AASS).

The vulnerability of Bassendean Sand on the Swan Coastal Plain to acidification has been studied by the former Department of Environment and Conservation (DEC). An acid sulfate soil mapping program, conducted in 2008–2010, assessed 200 sediment cores, mainly in Bassendean Sand, in the Perth metropolitan area. This work showed very low levels of sulfidic acidity (< 0.03%S) can cause significant pH decline ($pH < 3.0$) in poorly buffered Bassendean Sand (Singh et al. 2012). More detailed mineralogical investigations which included identification of nano-crystalline pyritic particles has also been conducted in Bassendean Sand. These pyrite particles are smaller than the more traditionally understood framboidal pyrite structure. These smaller pyrite particles have a higher surface area to volume ratio and therefore react more efficiently with sediment upon oxidation (Prakongkep et al. 2012).



J:\gisprojects\Project\A_series\A3003\0081_SGS\mxd\North_Lake\Figure3_SurfaceGeology_NorthLake.mxd

*Figure 4 Regional surface geology, Swan Coastal Plain*

## 2.4 Hydrogeology

The Superficial aquifer south of the Swan River in the Perth metropolitan area is referred to as the Jandakot Mound (Figure 5). The Jandakot Mound is bound by the Darling Fault to the east, Swan River to the north, the Indian Ocean to the west and other groundwater flow systems such as the Stakehill Mound and the Safety Bay Mound to the south. Groundwater is recharged primarily by rainfall and flows radially from the crest of the Jandakot Mound towards its hydraulic boundaries (Figure 5).

The Superficial aquifer in the North Lake area has a saturated thickness of about 35 m (Davidson 1995). The horizontal hydraulic conductivities vary: Bassendean Sand 10– > 50 m/day, Tamala Limestone 100–1000 m/day and Ascot Formation estimation ~ 8 m/day (Davidson 1995).

The Jandakot groundwater system refers to the unconfined Superficial aquifer as well as the deeper Leederville and Yarragadee aquifers. The Superficial aquifer is underlain by the Leederville aquifer, with the Kardinya Shale forming a confining layer between the two (Davidson 1995). The Kardinya Shale, approximately 120 m thick near North Lake, has a vertical hydraulic conductivity of ~ $1 \times 10^{-6}$ (m/day), so leakage of any significance is unlikely (Davidson 1995).

A general understanding of historical water quality in the Jandakot Mound can be inferred from data obtained from production bores screened in the Superficial aquifer in 1992 (Davidson 1995). Water is of sodium chloride type, classified fresh (low total dissolved solids/salinity, typically less than 500 mg/L), with near neutral pH and well buffered (Table 1). The water quality data provides an indication of water quality in the lower half of the Superficial aquifer, because this is where production bores are screened. When this data is compared to the quality of groundwater at the water table it illustrates how groundwater near the water table is more susceptible to change due to geochemical interactions associated with land use and water table fluctuations.

*Table 1 Groundwater quality in the lower half of the Superficial aquifer, upgradient of North Lake(Davidson 1995)*

| Parameter | Range in concentration (mg/L) |
|---|---|
| Salinity (TDS) | 178 – 713 |
| Alkalinity | 42 – 217 |
| Sulfate | 2 – 67 |
| Chloride | 48 – 260 |
| Dissolved iron | 0.2 – 5.67 |
| Nitrate | < 0.02 |
| pH | 6.0 – 7.4 |

North Lake is located west of the crest of the Jandakot Mound in the Bibra suite of wetlands. The Bibra suite of wetlands also includes Bibra Lake, Lake Yangebup, Lake Kogalup, Lake Coogee and Thompsons Lake.

Water level records at North Lake extend back to 1972 when a regular monitoring regime was implemented in anticipation of the Jandakot Mound groundwater abstraction scheme. There was an upward trend in water levels during the 1970s and 1980s and a downward trend since the early 1990s. North Lake had a maximum water level of ~ 3.0 m in winter, which declined to < 1.6 m in summer (Bayley et al. 1989). North Lake has dried regularly since the mid-1990s and has dried each summer since 2006.

Previous studies have linked the thickness and composition of lake bed sediments and bathymetry in ascertaining interactions between groundwater and surface water. Lake bed sediments at North Lake are thick: recorded up to 9.5 m thick in this investigation. This is in comparison with Lake Mariginiup, a wetland similar to North Lake, also located in an inter-dunal depression between the Spearwood and Bassendean Dunes, with sediments up to 2 m thick (Searle et al. 2010). Thicker lake bed sediments slow the movement of groundwater and can inhibit surface water–groundwater interaction (Bayley et al. 1989).

## 2.5 Land use

North Lake is one of 19 lakes that comprise the Beeliar Regional Park and is the main water body in James Paterson Park, a recreational park used by the local community. Land use around the park is predominantly urban.

Urbanisation around the North Lake area intensified throughout the 1970s. In response to increased local recharge caused by the clearing of native vegetation and urbanisation throughout the 1970s and 1980s groundwater levels around the lake rose by about 2 m (Megirian 1982). During the 1970s two drains were also deepened and provided water discharge into North Lake (Megirian 1982).

There may have been some previous recreational use of North Lake. Bayley et al. (1989) state that during the course of their study, children were observed paddling in the lake and using home-made rafts. There is no contemporary evidence of recreational use of North Lake itself though the surrounding park and native bushland are commonly used for walking and other recreational activities.

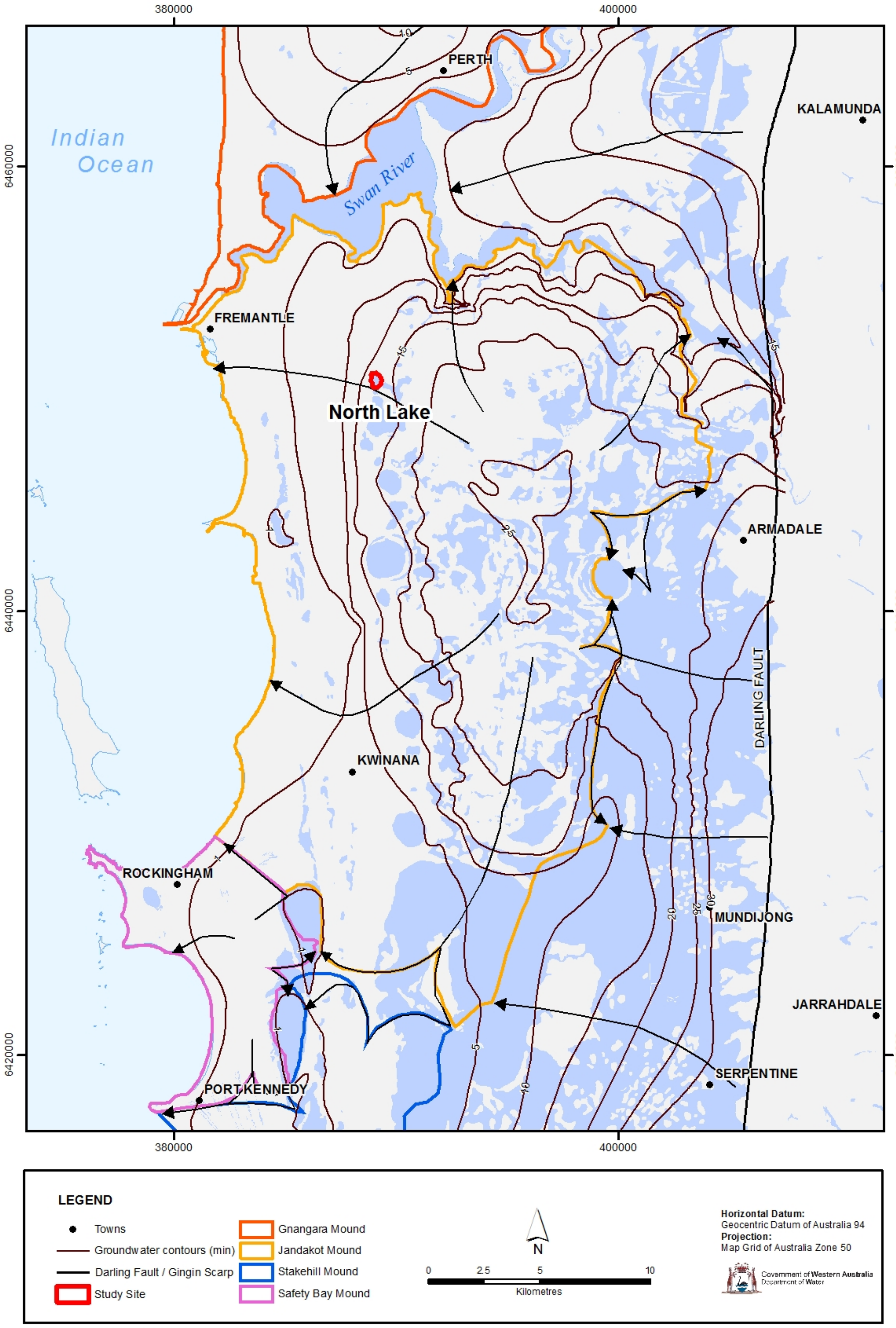


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*Figure 5 Regional groundwater flow on the Jandakot Mound*

## 2.6 Groundwater use

The Department of Water has the statutory authority to manage Western Australia's water resources. The two main tools used to manage groundwater use are allocation limits and groundwater licences. Allocation limits guide individual licensing decisions. They set out how much water is available from a particular resource or area and consider how much water needs to remain in the system for the environment. Allocation limits consider recharge estimates, environmental objectives and benefits of groundwater use.

The Department of Water manages three main types of groundwater use from the Jandakot groundwater system:

- Water licensed for private supply, including to local government for watering of public open spaces.
- Water licensed to the Water Corporation for public supply through the Integrated Water Supply Scheme.
- Unlicensed domestic garden bore use.

The Department of Water manages groundwater resources by dividing regions into subareas. North Lake is located in the City of Cockburn subarea within the Perth South groundwater area (Figure 6). The City of Cockburn subarea is bound by the City of Melville subarea of the Perth South groundwater area to the north and the Airport subarea of the Jandakot groundwater area to the east. Water use from these subareas, especially from draw points located close to North Lake, has the potential to affect groundwater levels at the lake. Groundwater licensing from the City of Cockburn, City of Melville and Airport subareas is summarised below. Of these subareas, only the Airport subarea has water licensed for public supply.

### *Groundwater licensed for private supply*

Private licensed entitlements in the area are from the Superficial aquifer only. Private licensed entitlements around North Lake are shown in Figure 6.

In 2008–09, private licensed entitlements from the City of Cockburn subarea (Figure 6) totalled 0.54 GL, and were below the allocation limit of 1 GL set for the Superficial aquifer in this subarea.

In 2008–09 private licensed entitlements from the City of Melville subarea (Figure 6) totalled 4.01 GL, and were below the allocation limit of 5.5 GL set for the Superficial aquifer in this subarea.

In 2008–09 private licensed entitlements from the Airport subarea (Figure 6) totalled 1.36 GL, and together with public supply entitlements were below the allocation limit of 4.29 GL set for the Superficial aquifer in this subarea.

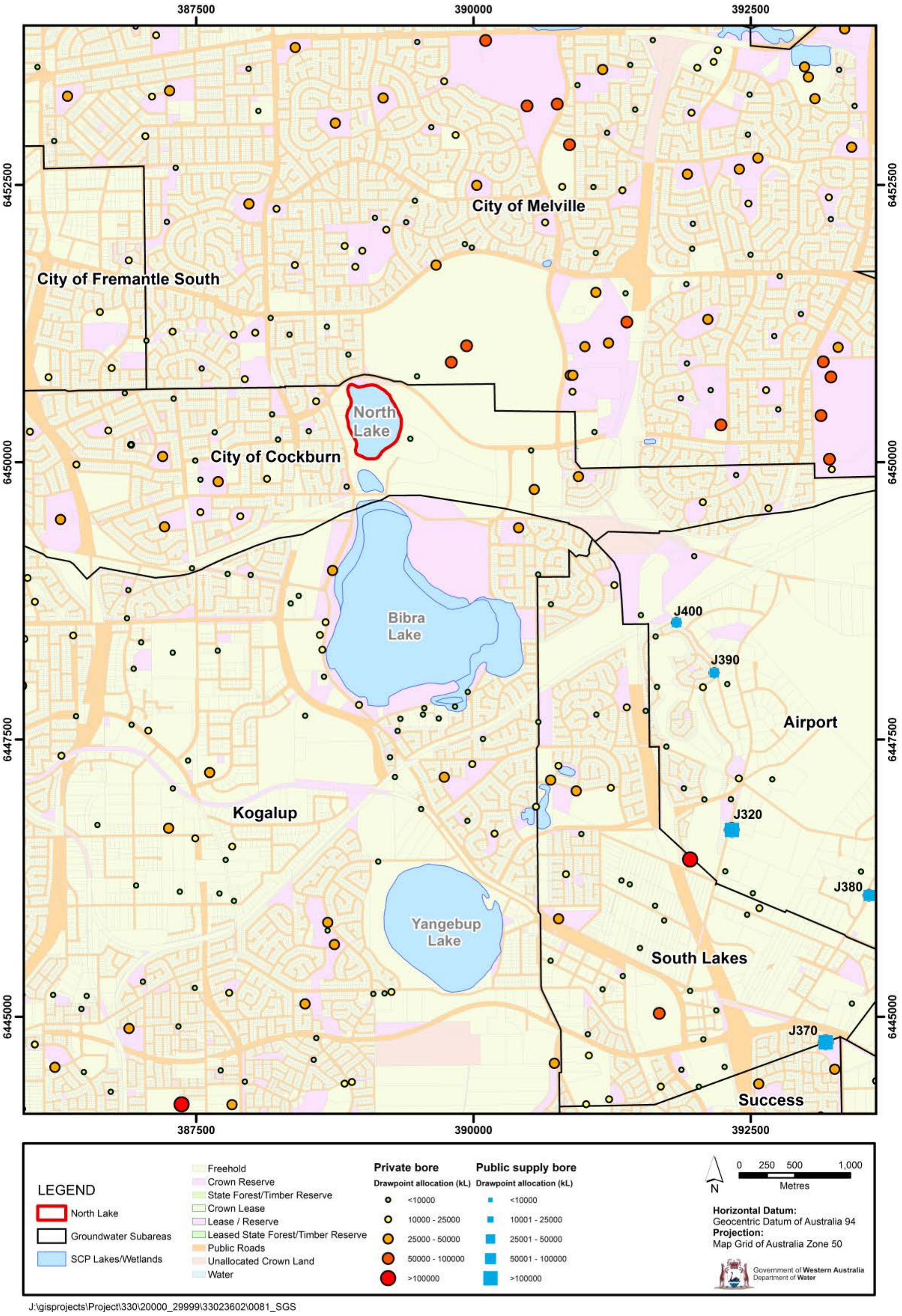

*Figure 6 Groundwater licensed for private and public supply around North Lake (in kL per annum, 1 000 000 kL = 1 GL)*

### *Groundwater licensed for public supply*

Licensed entitlements from the Jandakot groundwater system for public supply are mostly from the Superficial and Leederville aquifers (Figure 7). Groundwater abstraction for public water supply from the Jandakot bore field commenced in 1979–80. Groundwater abstraction for public supply has eased in the Superficial aquifer since about 1995 while volumes of groundwater abstracted from the deeper Leederville aquifer has increased since about 2007 (Figure 7). Total abstraction for public water supply from the Jandakot groundwater system in 2008–09 was 10.90 GL; 4.04 GL from the Superficial aquifer and 6.86 GL from the Leederville aquifer (DoW 2009).

In 2008–09, licensed entitlements for public supply from the Superficial aquifer in the Airport subarea totalled 1.32 GL.

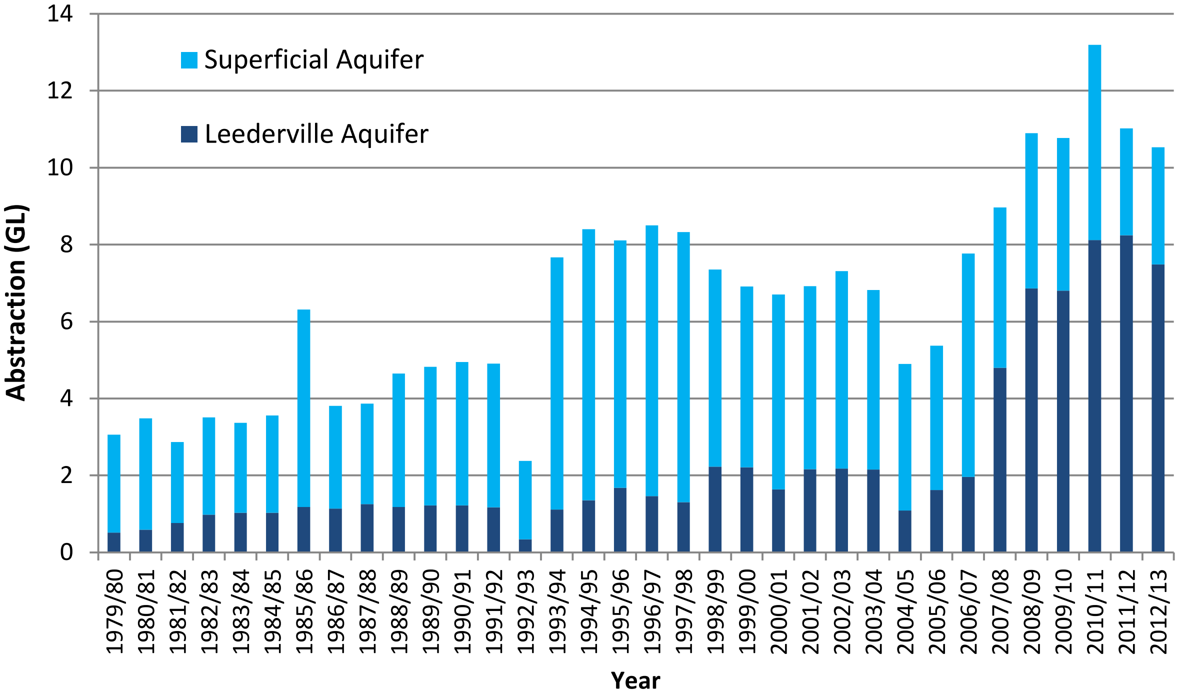

*Figure 7 Groundwater abstraction for public supply under the IWSS from the Jandakot groundwater system*

### *Unlicensed domestic garden bore use*

Groundwater is also abstracted from the Superficial aquifer through domestic garden bores that do not require a licence. Garden bore use is estimated using Australian Bureau of Statistics data and Water Corporation household use data. In 2011, the Department of Water published a map of the Perth metropolitan area indicating areas suitable and unsuitable for installing garden bores. This map was based on parameters including depth to groundwater, groundwater level trends, salinity, contaminated sites and geology.

## 2.7 Drainage

There is currently no managed drainage flowing into or out of North Lake, although water still flows through an open cut channel into the north-east of the lake during wetter months (Tim Fisher, DEC, pers. comm.).

Historically, two drains discharged into North Lake. The Kardinya Drain was constructed in 1977 and flowed into the north-west of the lake. The Murdoch University Veterinary Farm Drain was cleared and deepened in 1975 and discharged through a swamp in the south-east corner of the lake (Bayley et al. 1989). The Murdoch Veterinary Farm Drain was a source of nutrients into the lake. The Murdoch and Kardinya drains were blocked to prevent inflow to North Lake because of nutrient enrichment problems (WAWA 1994).

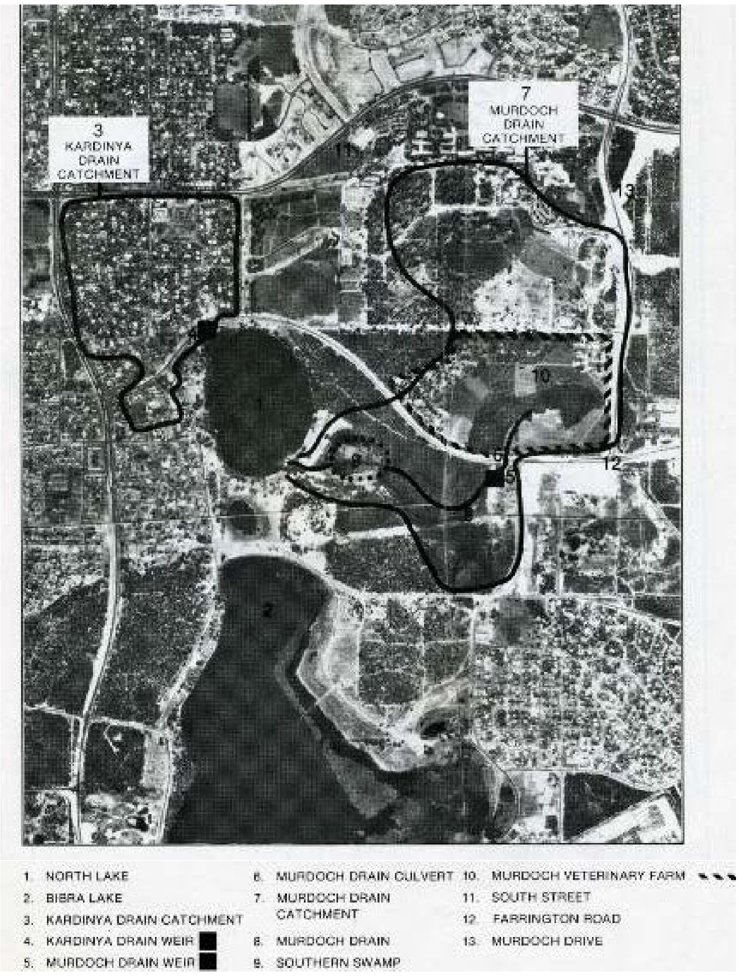

*Figure 8 North Lake historic drainage (after Bayley et al. 1989)*

## 2.8 Cultural significance

Wetlands across the Swan Coastal Plain are known to be of cultural and spiritual significance to indigenous groups and were used extensively in traditional times (Big Island 2007). There are four Registered Sites of Significance at North Lake that are protected under the Aboriginal Heritage Act 1972. The lake is listed as a mythological site and as a camping and hunting place (3709). The other sites are artefact/scatter sites (3294, 3295, 4106).

## 2.9 Ecology

North Lake has previously been described as a permanent wetland (Froend et al. 2004b). However, since the mid-1990s the lake has dried more often and has dried every year since 2006. The value of North Lake as a summer refuge for waterbirds has declined (Froend et al. 2004b), however the lake is the only known urban wetland supporting freshwater sponges, and the surrounding bushland supports significant flora, bird and mammal species. North Lake is also valued for its fringing vegetation which includes extensive *Melalucea rhaphiophylla* and *Banksia articulata* stands (Froend et al. 2004b).

The existing ecological and water regime management objectives for North Lake are designed to protect its key ecological values. These are (WAWA 1991):

- Periodic inundation of *Melaleuca* species
- Water levels remain within the historic range (Note: range from 1980 to 1990 was 13.2–15.5 m AHD)
- Maintain aesthetics of the lake.

Protection of ecological values at North Lake began in the early-1990s through a water level criteria set by the Minister for the Environment. Criteria levels were based on ecological water requirements (EWRs), which are the water regimes necessary to maintain a low level of risk to ecological values (WRC 2000). The criteria set for North Lake were originally designed to protect fringing vegetation and the lake’s value as waterbird drought refuge (WAWA 1991).

In a review of the environmental conditions for the Jandakot Mound in 2001, it was acknowledged that lake levels had fallen since drainage input into North Lake was reduced to lower nutrient inflow (WRC 2001).

The current water level criteria for North Lake, given in Ministerial Statement 688, state that water levels should not fall between 12.68 m AHD and 13.29 m AHD (with the absolute minimum criterion being 12.68 m AHD) and that water levels should not decline at a rate greater than 0.1 m/year. The absolute minimum criterion is a summer minimum water level that is measured on staff gauge 6142521 (Government of Western Australia 2005; Figure 9).

Water levels in North Lake have fallen below the absolute minimum criterion every year since 2005–06. In eight of the last 10 years the lake has dried (the lake dries at 12.38 m AHD).

Declining water levels have led to native vegetation encroaching into the basin where it was previously inundated, declines in the condition and health of fringing vegetation (including declines in condition and health of mature *E. rudis*) and exotic vegetation threatening to become dominant in some areas (Froend et al. 2004b). The encroaching vegetation at the lake has resulted in some loss of muddy shorelines and shallows that form important habitat for waterbirds (Froend et al. 2004b).

In 2004, the ecological values of North Lake were re-assessed and new EWRs were proposed (Froend et al. 2004b). Five new EWRs were proposed for wetland vegetation, waterbirds, sponges and macroinvertebrates, aquatic vertebrates and sediment processes, as outlined below. These EWRs have not been adopted as water level criteria, but are used by the Department of Water to assess possible impacts of current groundwater levels on ecological values.

1. To meet the minimum water requirements of all wetland vegetation, groundwater levels should not fall below the mean maximum depth to groundwater of the most susceptible species. A groundwater level at the end of autumn of 12.68 m AHD will support groundwater dependent vegetation at North Lake.

2. A peak surface water level of 13.26 m AHD would inundate *Melaleuca* species on both sides of the wetland. This inundation would prevent the spread of sedges and exotics into the basin, thereby maintaining habitat for waterbirds (Froend et al. 2004a).

3. A peak surface water level of 14.0 m AHD is required to meet the EWRs of the lake’s sponges and macroinvertebrate species (Froend et al. 2004a).

4. A peak surface water level of 13.6 m AHD is needed to retain surface water for sufficient periods to meet water requirements of aquatic vertebrates including frogs and turtles (Froend et al. 2004a).

5. To maintain sediment processes and prevent oxidation of acid sulfate soils, surface water levels should not drop below 12.76 m AHD (Froend et al. 2004a).

For the past 10 years surface water levels have failed to meet the EWRs of the lake’s sponges and macroinvertebrates and in nine of the last 10 years levels have failed to meet the EWRs for turtles, frogs and sediment processes. In four of the last five years the lake levels have not met the waterbird EWR (Froend et al. 2004b; Figure 10).

Although recent groundwater levels have met the wetland vegetation EWR, some encroachment of native vegetation into the lake bed and declines in the condition of mature *E. rudis* have been observed at North Lake (Froend et al. 2004a). Despite these declines, North Lake still supports values related to the extensive stands of *M. rhaphiophylla* and *B. articulata* surrounding the lake.

The ecological values of North Lake are at risk from groundwater level decline, acidification and fire. Falling groundwater may cause further losses of fringing vegetation, lower lake levels which will lead to further encroachment of vegetation into the lake bed, reduced waterbird habitat and reduced macroinvertebrate family richness. Falling lake levels will also adversely affect the lake's sponges and aquatic vertebrates. Lake acidification could change the lake's aquatic communities, cause deaths of sensitive species, lower richness and abundance of macroinvertebrates and reduce fringing vegetation (DEC 2009b). Fire is likely to cause oxidation of acid sulfate soils and contribute to, or accelerate, acidification.

Relationships between ecological function, geology (Section 4), hydrogeology and chemistry (Section 5) are discussed in Section 6.

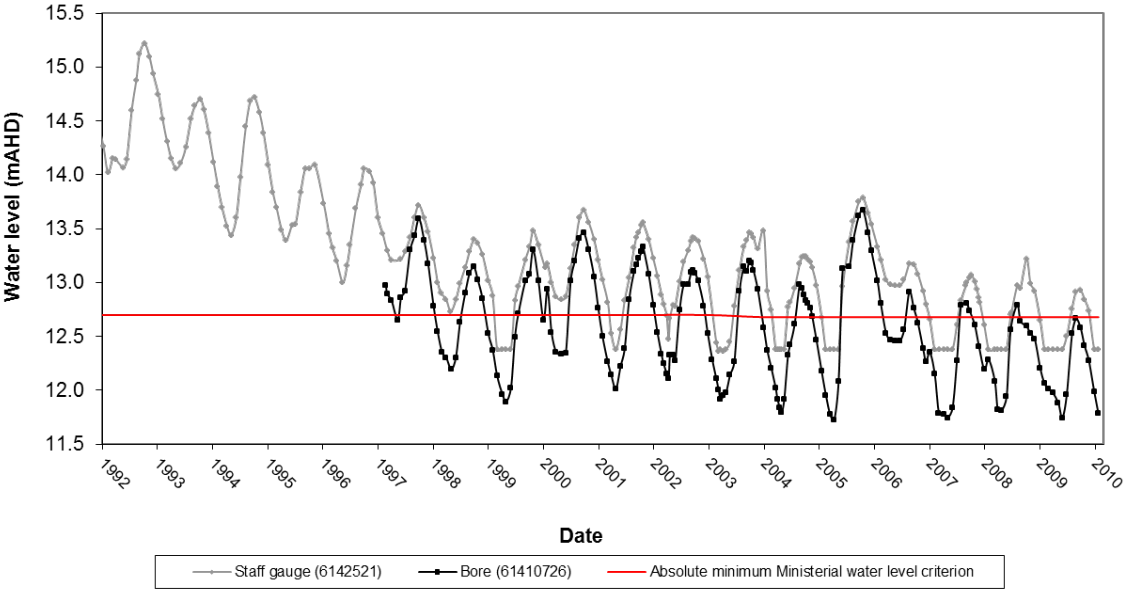

*Figure 9 Hydrograph of groundwater and surface water levels at North Lake*

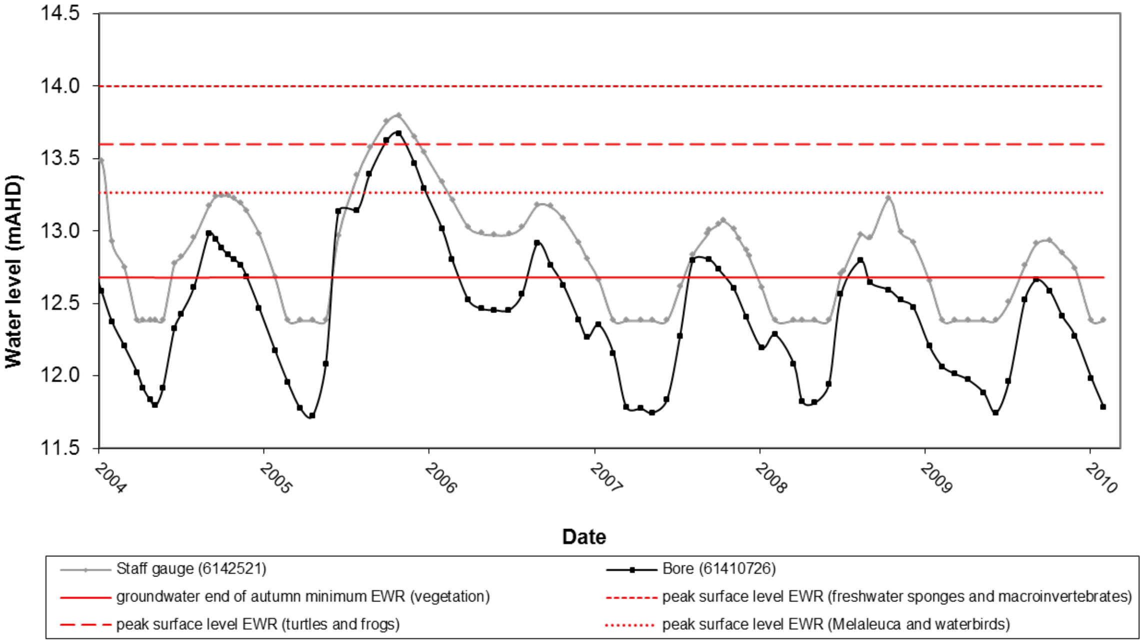

*Figure 10 Hydrograph of North Lake showing Froend et al. (2004b) EWRs*

## 2.10 Previous investigations

Megirian (1982) completed a thesis in 1982 about the hydrogeology of North Lake and Bibra Lake. North Lake was shown to be a groundwater dependent flow-through lake, with groundwater flowing in a westerly direction, based on October 1982 groundwater level data.

The City of Cockburn collected pH data between 1994 and 2009 as part of a midge monitoring program (Figure 11). This data suggests higher pH before 2007. Since 2007, low pH has occasionally been recorded. This indicates a decline in buffering capacity and acidification processes in the lake. The blue circles in the diagram represent pH values measured in the lake in this Perth SGS investigation and also suggest lower pH values than recorded throughout the 1990s. Water pH can fluctuate before longer-term acidification. The results suggest North Lake, currently a seasonal wetland, is at risk of long-term acidification.

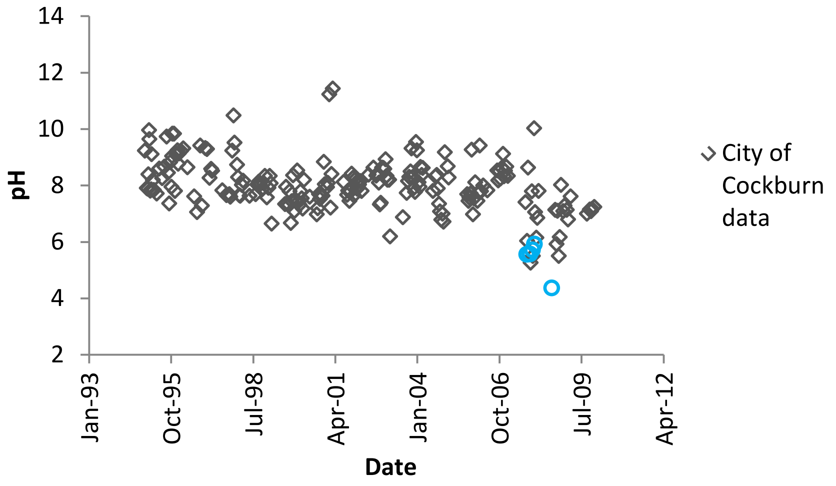

*Figure 11 Surface water pH in North Lake 1994-2009Note: The blue dots represent data obtained from this Perth SGS investigation.*

Water samples collected in surface water at North Lake between 1970 and 1982 recorded total dissolved solids (TDS) between 290 and 1060 mg/L (Megirian 1982). Samples were collected twice a year, after summer and winter. This indicates the water to be generally fresh, with lower salinity after winter and higher salinity with lower water levels and higher rates of evaporation after summer.

# 3 Investigation program

A groundwater resource review (McHugh & Bourke 2007) highlighted the need for site-specific information about wetland function to appropriately manage North Lake. The investigation program included drilling and construction of seven groundwater monitoring bores, lake and groundwater chemistry sampling over 12 months from May 2007 to June 2008. Two additional rounds of groundwater sampling were completed in 2012. Monthly lake and groundwater level measurements were taken throughout the investigation. An acid sulfate soil investigation, involving lakebed sediment coring, was undertaken during drilling and construction of new bores.

## 3.1 Groundwater bore construction

Seven groundwater monitoring bores were installed during this investigation (Table 2). Two clusters of three groundwater monitoring bores were installed at the western and eastern edges of North Lake, screened at different depths of the Superficial aquifer. An additional groundwater monitoring bore was installed at the water table near the vegetation transect (NTH_VC) on the north-eastern margin of Frog Swamp (Figure 12). The bore construction and lithological logs are presented in Appendix A.

*Table 2 Groundwater bores installed during the investigation at North Lake*

| Depth | AWRC Name | AWRC Number | Drilled depth (m BNS) | Screened interval (m BNS) |
|---|---|---|---|---|
| Shallow | NTH_WC | 61410454 | 7.1 | 0.03–4.03 |
| Intermediate | NTH_WB | 61410455 | 24.0 | 19.81–21.81 |
| Deep | NTH_WA | 61410456 | 39.0 | 33.84–35.84 |
| Shallow | NTH_EC | 61410457 | 5.9 | 0.62–4.62 |
| Intermediate | NTH_EB | 61410458 | 21.0 | 16.88–18.88 |
| Deep | NTH_EA | 61410459 | 39.0 | 30.62–32.62 |
| Shallow | NTH_VC | 61410460 | 5.9 | 0.0–3.84 |

## 3.2 Sediment investigation

### Acid sulfate soil testing

Field testing for acid sulfate soils (ASS) was conducted on sediment cores retrieved during the installation of shallow groundwater monitoring bores and lake bed sediments (Figure 12 & Table 3).

Field testing comprised pH ($pH_F$) and hydrogen peroxide pH testing ($pH_{FOX}$). Field pH ($pH_F$) is an assessment of existing acidity, measuring pH in water (1 part sediment: 5 parts water ratio). This indicates the presence of actual acid sulfate soils (AASS) which are defined as having $pH_F$ less than 4.0. Measured $pH_{FOX}$ indicates potential acidification under optimal oxidising conditions and indicates the presence of potential acid sulfate soil (PASS) which is characterised as sediment containing iron sulfide minerals such as pyrite and may reduce pH < 3.0.

Selected sediment samples were tested in the laboratory to confirm field testing and assess sulfidic acidity. Samples were submitted to the National Measurement Institute (NMI) laboratory and analysed for the SPOCAS suite of assessments, the chromium reducible sulfur assessment and metals/metalloids.

*Table 3 Locations of lake bed sediment cores*

| Core ID | Easting | Northing | Drill depth (m) |
|---|---|---|---|
| NTH_L01 | 389224 | 6450566 | 8.9 |
| NTH_L02 | 389140 | 6450398 | 13.1 |
| NTH_L03 | 389018 | 6450371 | 10.7 |

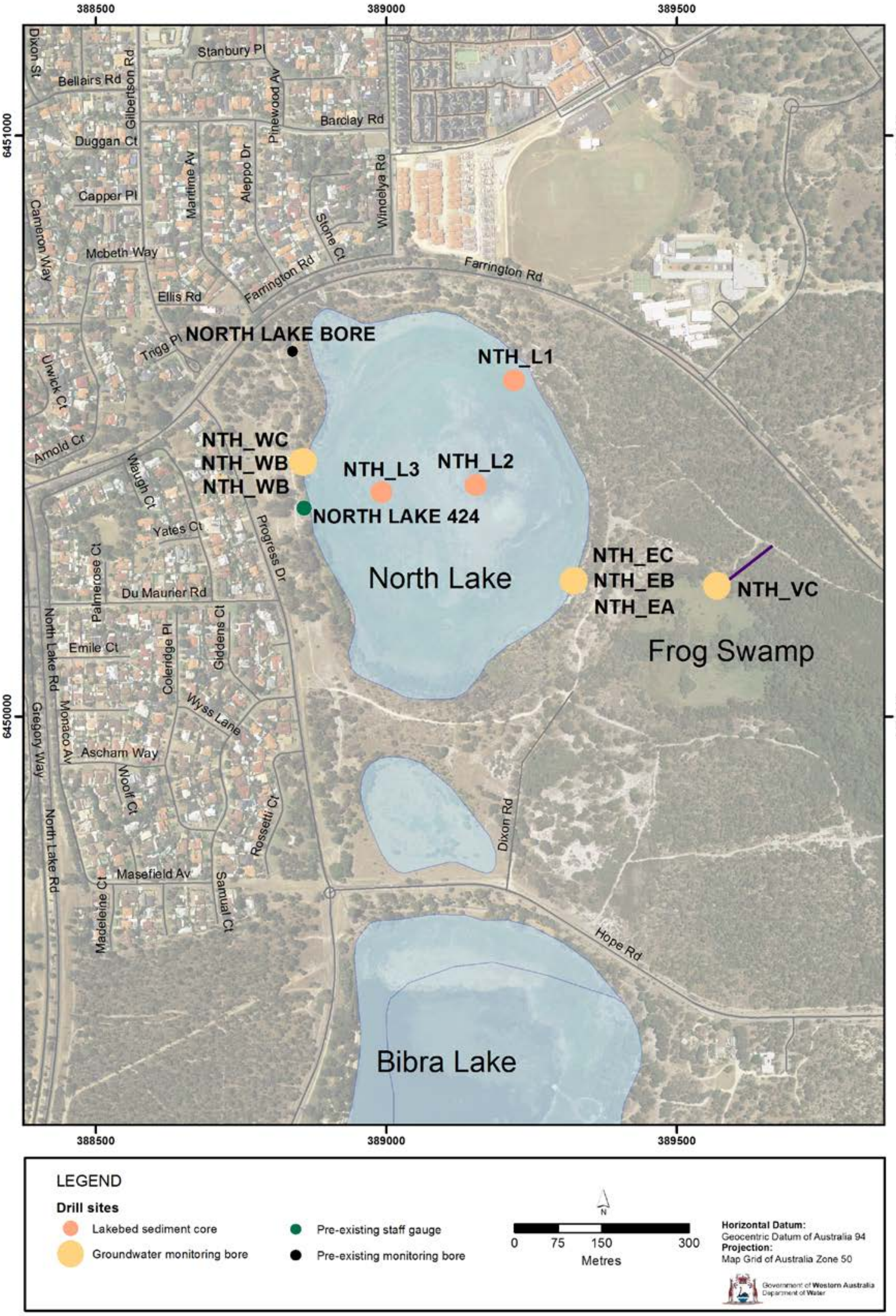

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*Figure 12 Groundwater monitoring bore and sediment sample locations at North Lake*

## 3.3 Groundwater investigation

Groundwater monitoring for water quality and water levels was conducted each month for the 12-month sampling program May 2007 to June 2008. Additional water quality samples were also collected in May and October 2012. Groundwater and surface water levels were recorded monthly in the 2007–2008 monitoring period as well as the two sampling events in 2012. Groundwater levels have been monitored monthly at the water table bore near the vegetation transect since the Perth SGS sampling concluded in 2008.

Groundwater quality monitoring was conducted using a low flow bladder pump. Field parameters were recorded every 5 minutes for at least 20 minutes or until readings stabilised before collecting samples in laboratory-supplied containers. Field readings included pH, temperature, electrical conductivity, oxidation-reduction potential and dissolved oxygen. Laboratory parameters are shown in Table 4. In this study, herbicides, pesticides and nutrients were monitored at a lower frequency than other parameters. Herbicides and pesticides were not included in 2012 sampling.

Groundwater sampling methods are detailed in Appendix B.

*Table 4 Laboratory parameters submitted to National Measurement Institute*

| Parameters analysed by the National Measurement Institute | |
|---|---|
| Total metals | Al, As, Cd, Cr, Fe, Hg, Mn, Ni, Se, Zn |
| Dissolved metals | Al, B, Fe |
| Base cations | Ca, Mg, Na, K |
| Base anions | Cl, $SO_4$, $CO_3$, HCO |
| Nutrients | NOx, TKN, total N, $NH_3$-N/ $NH_4$-N, dissolved P, total P, $PO_4$-P |
| Herbicides and pesticides | Chlordane, Chlordane (Tech: a+g), DDD-p,p, DDE-P,P, DDT-P,P, Dieldrin<br>OCs, OPs, Diuron, total Endosulfate, Endosulf-a, Diazinon, Endosulf-b<br>Endrin, Ethion, HCH (BHC) a, b, d, HCH (BHC), Heptachlor<br>Heptachlor epoxide, Heptachlor obenzene, Hexazinon, Bromophos-ethyl |
| Other parameters | pH, total acidity as $CaCO_3$, total alkalinity as $CaCO_3$, EC, DOC<br>TSS, TDS, DON |

## 3.4 Surface water sampling

Surface water was sampled at the staff gauge at the western edge of North Lake throughout the 2007–2008 sampling program, when water levels permitted. Surface water samples were collected on four occasions in this period and on one occasion in 2012 (September). Additional surface water samples were also collected from the south-eastern part of the lake in 2012. In May 2012 (S1), a surface water sample was collected from a pool of water when the lake was mainly dry, and dry at the staff gauge. In September 2012 another sample was collected from a similar location in the south-eastern part of the lake (S2) when the lake was full; this sample was collected in conjunction with a sample from the staff gauge at the western edge of the lake (North Lake 424).

Surface water sample locations, shown in Figure 13, were assessed for the same parameters as groundwater samples (Table 4).

## 3.5 Rainfall

Rainfall is a primary source of recharge to the Superficial aquifer. The chemical composition of rain is important in interpreting the chemical composition of groundwater near the water table and potential changes in chemical composition that happen during infiltration through the unsaturated zone to groundwater. A rainfall sample was collected in an open bucket adjacent to the vegetation transect for a 24 hour period on 28 July 2008.

## 3.6 Quality assurance

Decontamination procedures in the field included using new tubing for each groundwater bore, using disposable filters for sampling at each bore and decontaminating each element of the low-flow bladder pump after pumping each bore. Decontamination of the low-flow pump included rinsing in tap water, followed by a mixture of Decon 90 and tap water and a final rinse in distilled water. Field duplicates were collected at an approximate rate of 1:20 samples. The success of decontamination procedures was confirmed by the collection of rinseate samples, also at an approximate rate of 1:20 samples.

Samples were delivered to the laboratory within holding times, except for pH which has a holding time of six hours. It is often not practical for samples to be delivered and analysed by the laboratory within six hours from the point of sample collection. Field pH data is considered more representative of aquifer and lake conditions. Laboratory measured pH was generally higher than pH measured in the field (Figure 14). This may be due to precipitation of bicarbonate in the lab sample.

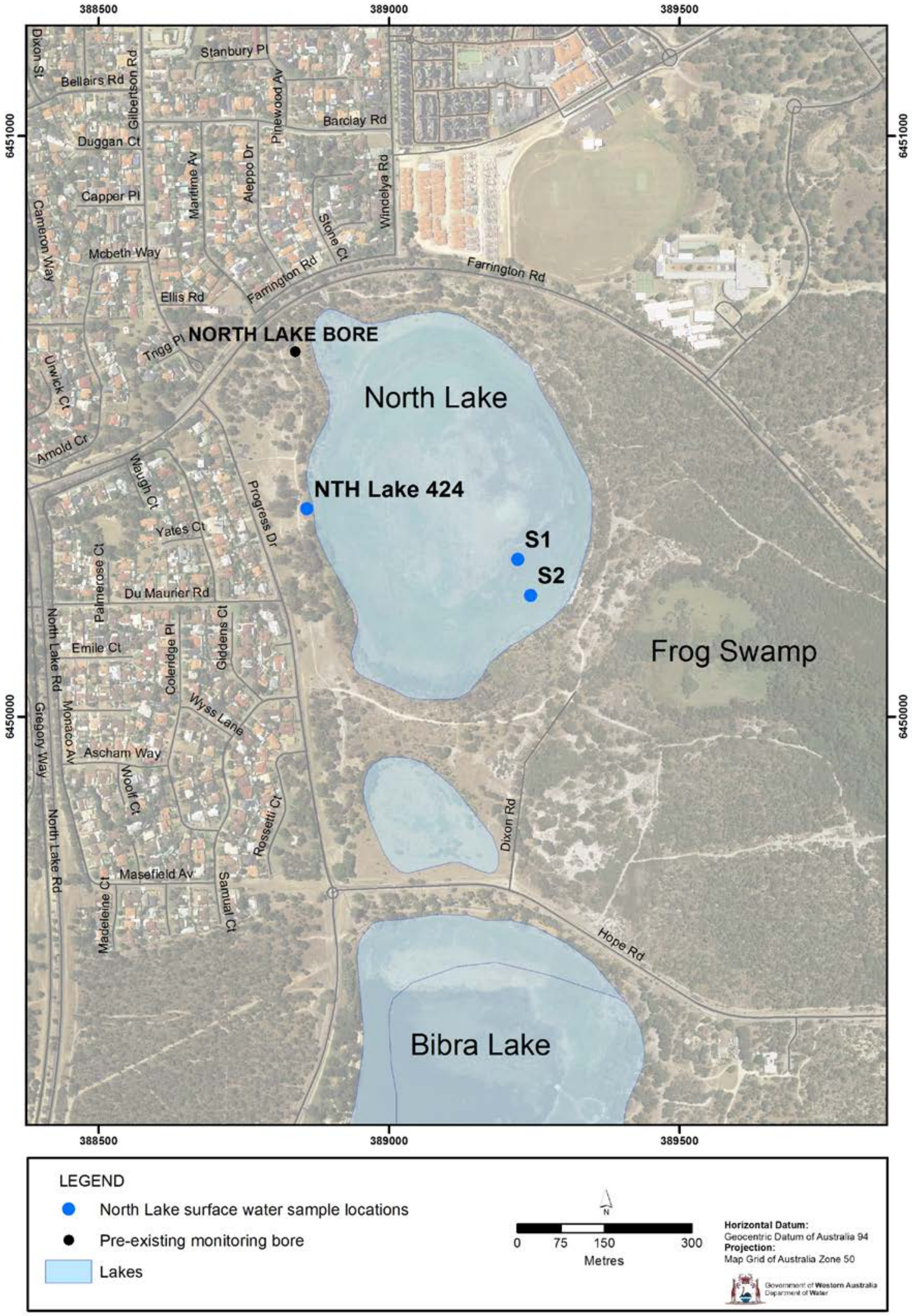

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*Figure 13* Surface water sample locations

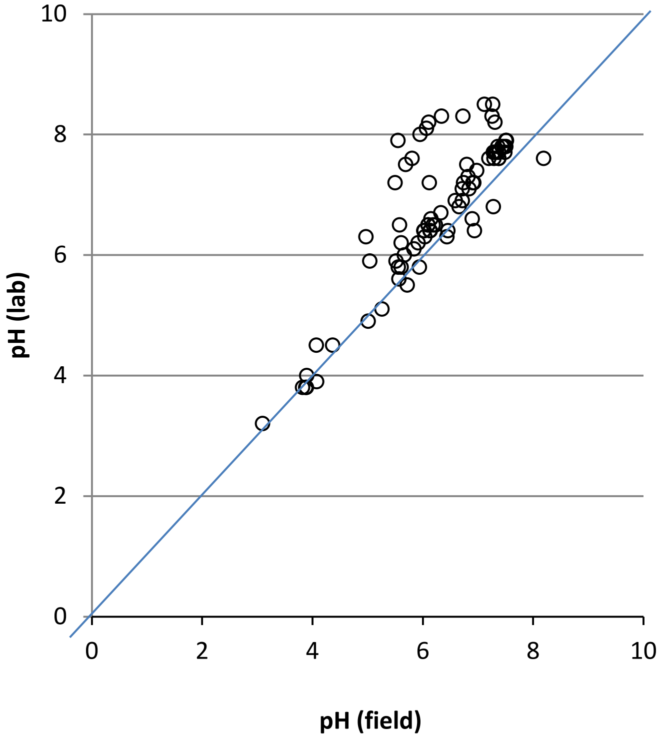

*Figure 14 Comparison of field pH and laboratory measured pH*

Laboratory quality assurance procedures include analysis of duplicate samples, blanks and calculation of the ion (electrical) balance. Groundwater samples should be electrically neutral (e.g. anion-cation balance should be 0%). The ion balance is an assessment of satisfactory laboratory analysis. An ion balance within 5% is considered acceptable and management decisions and conclusions can be based on data with confidence (Hounslow 1995). Further investigation or justification may be required to consider samples with ion balances greater than 5%.

Ion balances were calculated using six cations (Ca, K, Mg, Na, Al, Fe) and four anions ($HCO_3$, Cl, $NO_3$ $SO_4$). Total organic nitrogen (TON) was used as a surrogate for $NO_3$, under the assumption that TON is 98–99% $NO_3$ given the high volatility of $NO_2$. To calculate ion balances, results need to be converted into meq/L:

$$\text{meq/L} = \frac{\text{mg/L} * \text{valency}}{\text{formula weight}}$$

Ion balances were calculated for 58 samples using the formula:

$$EB = \left( \frac{\sum cations - \sum anions}{\sum cations + \sum anions} \right) 100$$

Sodium was not assessed in the first four rounds of sampling and therefore ion balances are only calculated for 58 samples out of a total of 87 samples. Ion balances were greater than 5% for 6 of these 58 samples and had range 5.1–23.1%. Two samples with an electrical balance greater than 10% were:

- NTH_WA on 14/2/2008 with 11.1%, meaning a surplus of anions or a deficiency in cations
- NTH_WC on 8/5/2008 with 23.1%, meaning a surplus of cations or deficiency in anions.

In some cases, acidic water may affect ion balances as $H^+$ ions are not included (Hounslow 1995). Nitrate was not included in the assessment of ion balances; however, nitrate was not detected in either NTH_WA or NTH_WC on 14/2/2008 or 8/5/2008 respectively. In general, the results are acceptable to form conclusions regarding the quality of groundwater and surface water around North Lake, and base recommendations for improved management.

## 3.7 Data interpretation

Geological cross sections based on lithology intersected during bore installation and lake bed core retrieval were constructed. The cross section is drawn according to the transect line in Figure 15.

Water level data was analysed using hydrograph analysis and interpretation of water level contours. Maps of the water table and cross sections were produced using water level contours to infer groundwater flow paths in the context of local geology. Water table maps and cross sections of water level contours were constructed for seasonal maximum water levels (October 2007) and seasonal minimum water levels (March 2008). Groundwater contours on the water table maps were interpolated based on 11 bores using kriging in ArcMap using the 3D analyst extension. Final contours were hand drawn to account for surface water bodies, such as North Lake and Bibra Lake.

A number of assumptions were made to fill gaps in the data set. Water levels were not measured in October in NTH_VC and the maximum water level for this bore is taken from September (10/07/07). North Lake bore recorded its maximum water level in September but the October water level was used to ensure the data was as synoptic as possible. The minimum water level in the North Lake bore was recorded in May 2008, but the March water level is used in maps and cross sections. Water levels in the water table bore on the east of the lake (NTH_EC) were not measured between 12 February and 20 May 2008. Water levels at NTH_EC and NTH_EB are assumed to maintain similar readings and March 2008 is used for seasonal minimum water levels at NTH_EC.

Hydrogeochemical data was analysed using Piper and Stiff diagrams, chloride profile and time series plots. In some cases regression coefficients were also calculated.

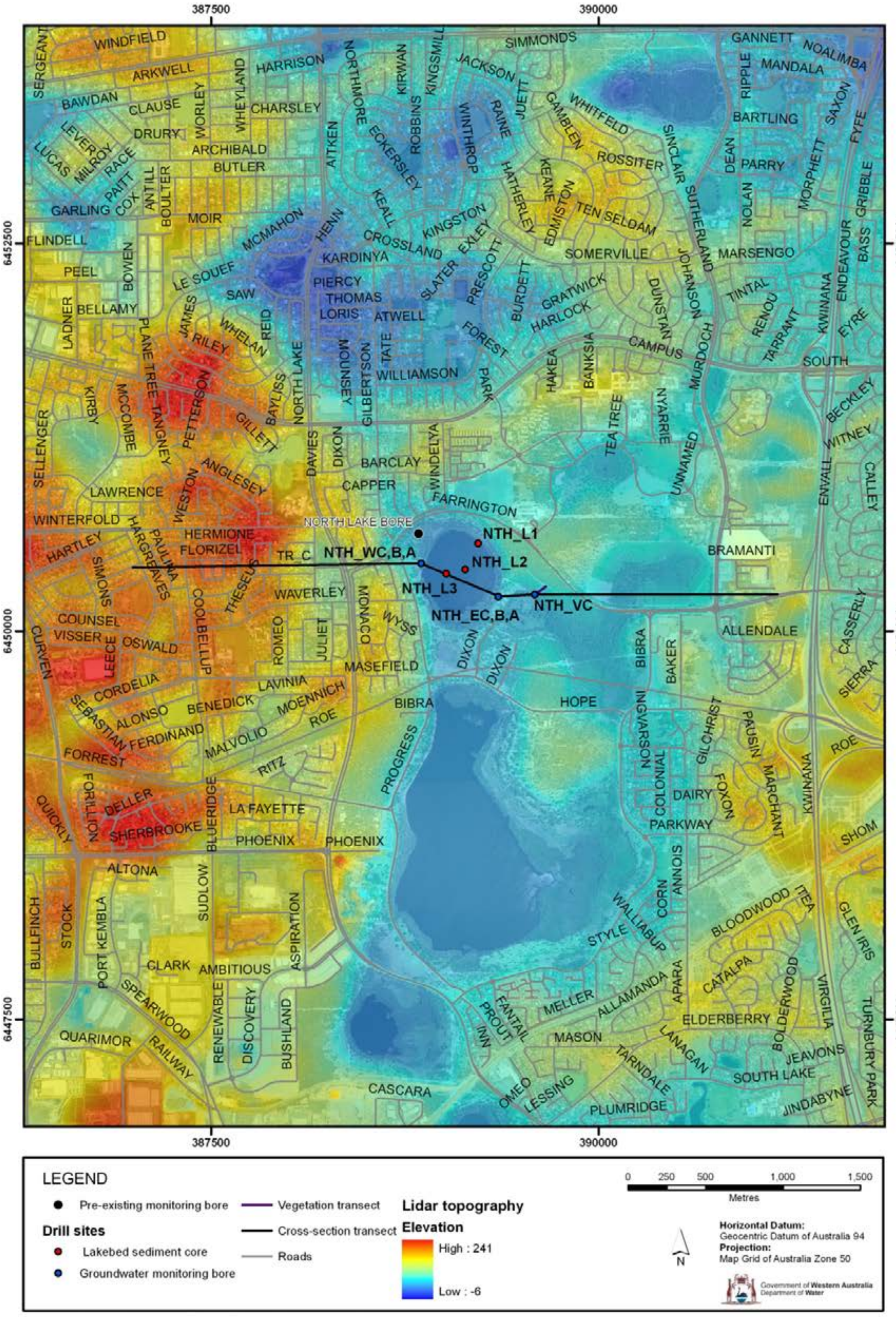

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*Figure 15 Map of cross section transect through North Lake. This section is shown in Figure 19.*

# 4 Geology results

## 4.1 Superficial formations

In this study Bassendean Sand and the Ascot Formation comprised the superficial formations around North Lake (figures 16–18). Bassendean Sand was recorded to 27 m below ground level (bgl) at the western edge of the lake and to 21 m bgl at the eastern edge of the lake. The Ascot Formation underlies Bassendean Sand and varies in thickness between 9 m at the western edge and 17 m at the eastern edge of the lake. The Ascot Formation overlies the Kardinya Shale which acts as a confining unit between the Superficial aquifer and the deeper Leederville aquifer.

Sediment cores at NTH_W and NTH_E were located approximately 50 m from the lake basin. Both cores appear similar (figures 16 & 17). Bassendean Sand was predominantly grey and brown, fine to coarse-grained quartz sand with variable silt content. The Ascot Formation in this area consists of calcarenite and coarse–very coarse shelly sands and gravel.

The geology interpreted from our results differs from previous studies. North Lake is located near the boundary of Tamala Limestone and Bassendean Sand. Previous studies show North Lake to be located in the inter-dunal depression, where Tamala Limestone is mapped at the western edge of the lake and Bassendean Sand east of the lake (Davidson 1995). Residual sands of Tamala Limestone have also been reported surrounding the lake (Megirian 1982; Davidson 1983). The rise in topography to the west of the lake (Figure 16) is thought to represent the transition from Tamala Limestone to Bassendean Sand. Sands in the immediate study area around North Lake appear to represent Bassendean Sand.

A previous mineralogical study suggests sands in inter-dunal depressions represent a mixture of sands from the two adjacent dunes (Bastian 1996). In the case of North Lake this would be mixture of Bassendean Sands to the east and sands of the Tamala Limestone to the west (Davidson 1995). This investigation did not look at the geology beyond the inter-dunal depression. It is likely that in some areas sands represent a mineralogical mixture of Bassendean Sand and Tamala Limestone.

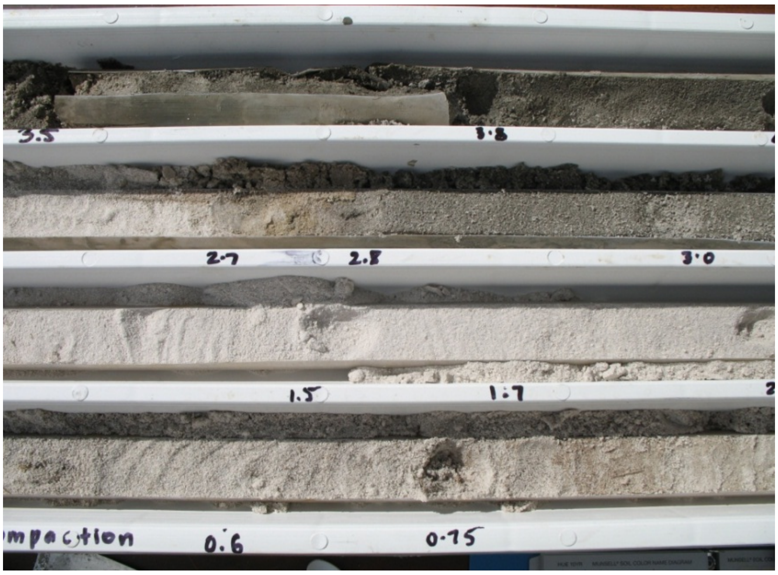

*Figure 16 NTH_WC (Bassendean Sand) grey sand near the water table (Groundwater level 2.7 m bgl on 18 April 2007)*

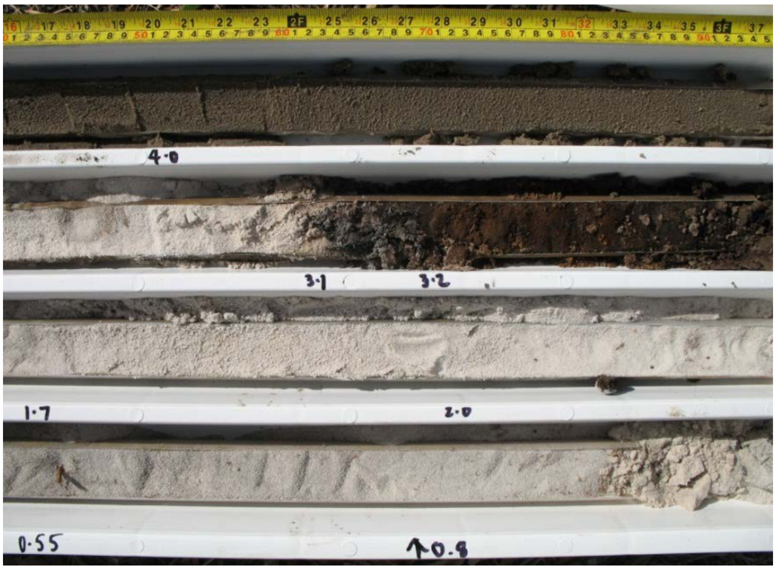

*Figure 17 NTH_EC (Bassendean Sand) sharp change to ferruginised sand near the water table(Groundwater level 2.6 m bgl on 17 April 2007)*

*Figure 18 NTH_VC (Bassendean Sand) grey leached sand with some iron mottling near the watertable (Groundwater level 1.4 m bgl on 16 April 2007). Note: Core not retrieved between 2 m and 3 m bgl*

## 4.2 Cretaceous formations

The Kardinya Shale Member of the Osborne Formation was intersected at 36 m bgl beneath the western edge of the lake and at 38 m bgl beneath the eastern edge of the lake. These sediments consisted of black cohesive sandy silt. Drilling ceased once the Cretaceous formations were intersected and the thickness of the Kardinya Shale is assumed to extend well beyond the 2 m intersected during this study. Davidson (1995) suggests Kardinya Shale is about 120 m thick beneath North Lake.

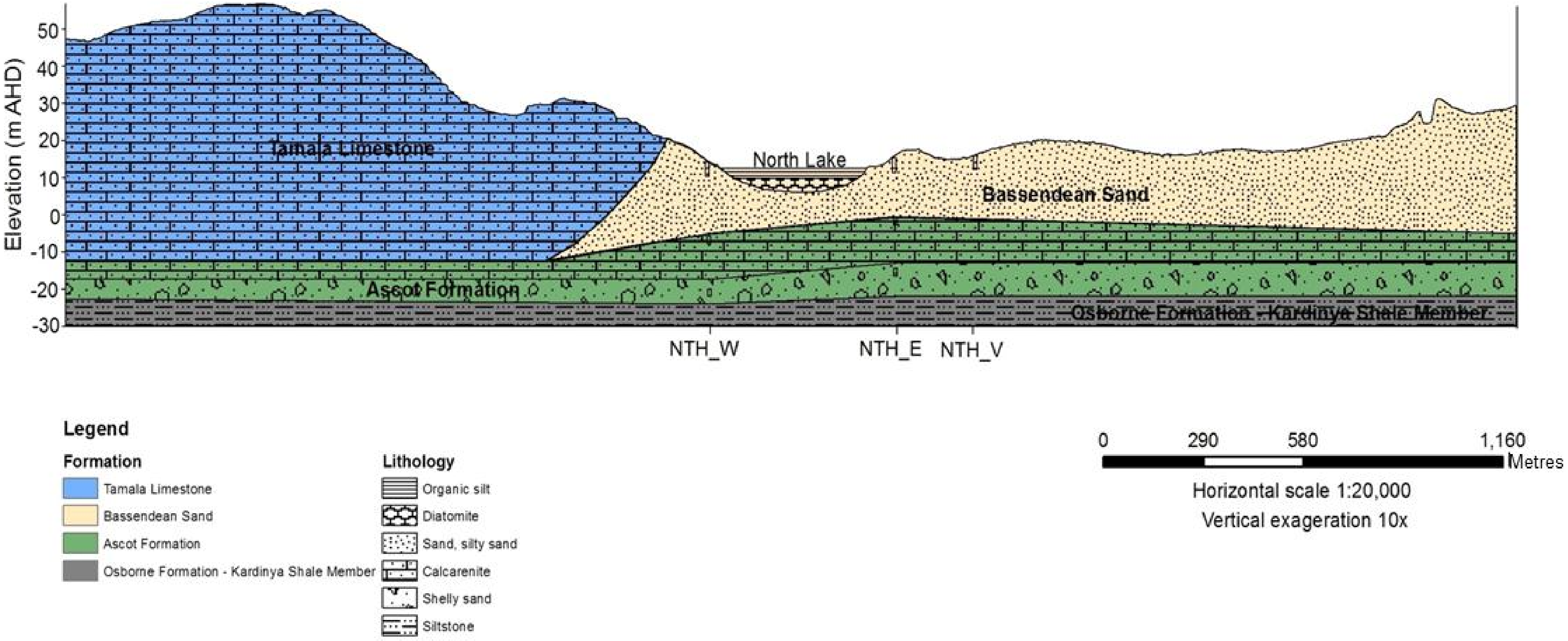

*Figure 19 Geological cross section through North Lake*

## 4.3 Lake bed sediments

Lake bed sediments have been described by Megirian (1982) as being predominantly clays of variable organic content, laminated in places, with lenses of pale yellow diatomite and charcoal fragments. Megirian (1982) interprets this sequence to suggest the lake bed sediments were deposited in three cycles of sedimentation which comprise saprocol diatomite, consolidated organic matter and clay with the thickest deposits in the centre of the lake. These sediments would act to inhibit the movement of water (Bayley et al. 1989). Water movement will be more inhibited by thicker sediments.

Three sediment cores were retrieved from the lake bed during this drilling program (locations shown in Figure 12). Sediments varied in thickness from 0.6 m at NTH_L01 to 9.5 m at NTH_L03. Sediments comprised organic silt, diatomite and sand (Table 5). Lake bed sediments are underlain by Bassendean Sand.

*Table 5 Lithology of lake bed sediment cores*

| Core ID | From (m bgl) | To (m bgl) | Lithology | Description |
|---|---|---|---|---|
| NTH_L01 | 0.0 | 0.6 | Organic silt | Black organic rich silt, abundant macro organic matter, very minor sand component. |
| | 0.6 | 8.9 | Sand | Grey fine to medium quartz sand |
| NTH_L02 | 0.0 | 2.3 | Organic silt | Black organic rich silt, abundant macro organic matter, very minor sand component. |
| | 2.3 | 3.5 | Diatomaceous silt | Brown diatomaceous organic silt with minor sand |
| | 3.5 | 4.0 | Herbaceous peat | Black organic rich silt |
| | 4.0 | 5.9 | Diatomite | Grey-brown, homogenous, stiff diatomite, minor sand |
| | 5.9 | 13.1 | Sand | Grey fine to medium quartz sand |
| NTH_L03 | 0.0 | 2.4 | Organic silt | Black organic rich silt, abundant macro organic matter, very minor sand component. |
| | 2.4 | 9.5 | Diatomite | Grey-brown, homogenous, stiff diatomite with variable organic content and minor sand |
| | 9.5 | 10.1 | Sand | Grey fine to medium quartz sand |

## 4.4 Acid sulfate soils

### Acid sulfate soil field testing

Actual acid sulfate soil (AASS; $pH_F < 4$) was recorded in the black organic-rich sediment at the surface of the lake bed at NTH_L01, with potential acid sulfate soil beneath this layer (Figure 20). The other two lake bed sediment cores were not investigated for sulfidic acidity. AASS was recorded between 0.25 m and 0.75 m bgl at NTH_VC, while potential acid sulfate soil (PASS) was recorded from 1.75 m to the end of the investigated core (Figure 20).

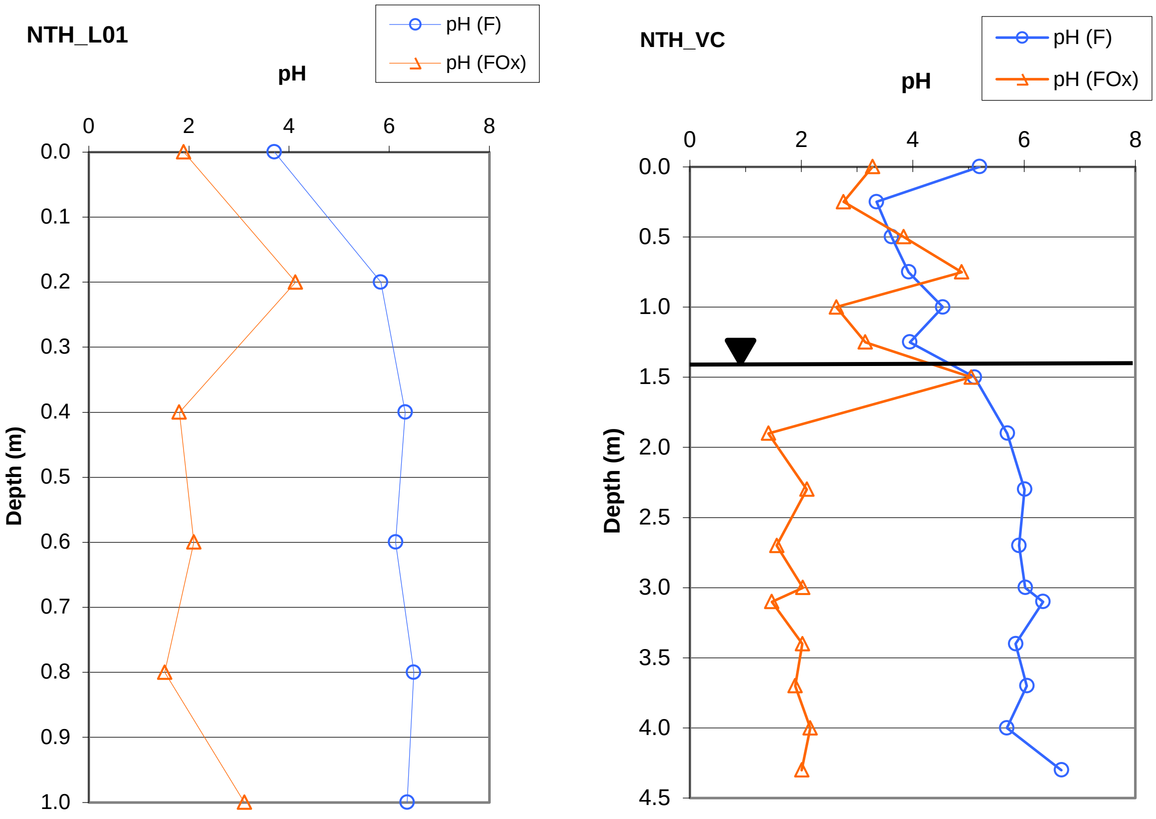

*Figure 20 Acid sulfate soil pH testing at NTH_L01 and NTH_VC*

PASS was recorded on both sides of North Lake at NTH_WC and NTH_EC (Figure 21). Groundwater levels at the time core was retrieved are also noted on the diagrams, which highlights a significant store of potential acidity beneath the water table, which could be liberated if groundwater levels decline.

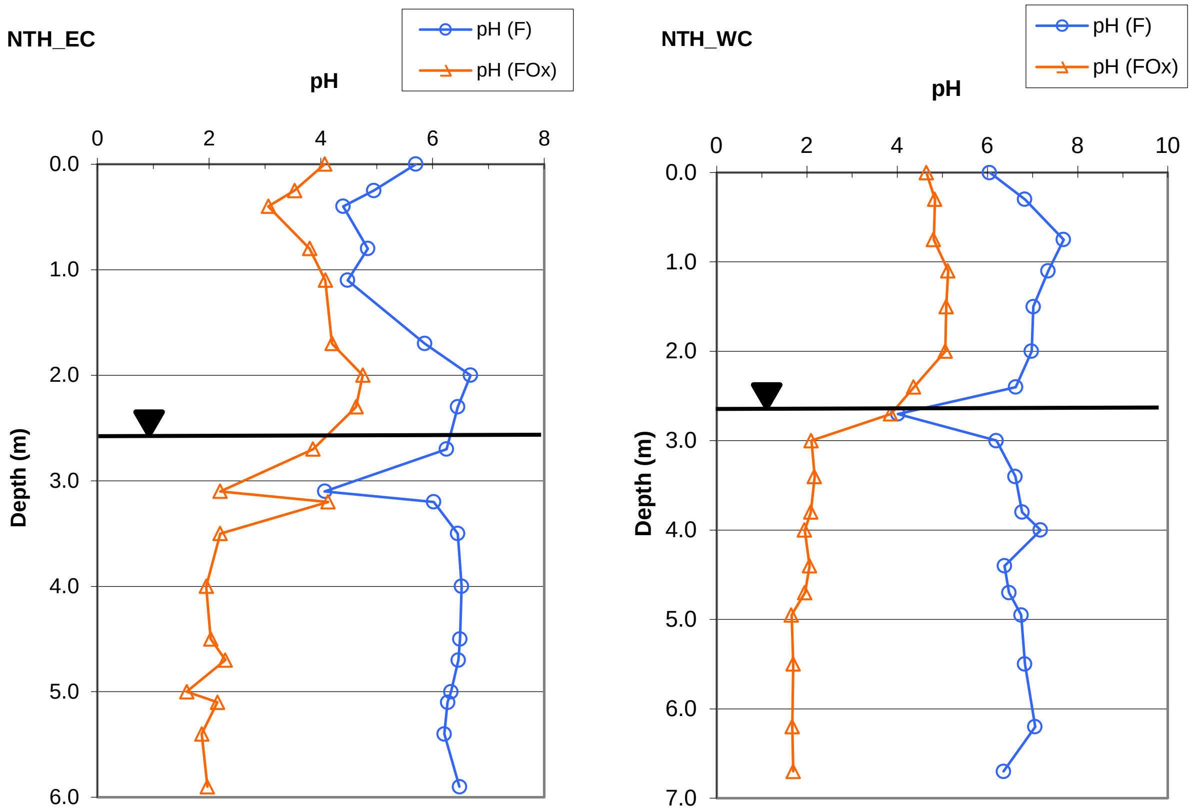

*Figure 21 Acid sulfate soil pH testing at NTH_EC and NTH_WC*

The data shows a high risk of acidification from the oxidation of pyrite, as $pH_{FOX} < 2$ was recorded in each investigated sediment profile.

## Acid sulfate soil laboratory analysis

Laboratory analysis supports the results of field testing showing the presence of actual and potential acid sulfate soils at North Lake and provides an assessment of organic and inorganic sulfidic acidity, providing greater detail for assessing the magnitude of the acidification risk.

The difference in field and laboratory pH is often due to sample preparation before laboratory analysis and as a result field pH values are considered more reliable. Sample preparation involves drying, crushing and grinding the sample. Smaller particle size and greater surface area to volume ratios encourage more efficient reactions with carbonaceous material resulting in a higher pH than under field conditions. $pH_{FOX}$ values are generally lower than $pH_{OX}$ which may also reflect the influence of sample preparation procedure. When $pH_F$ is greater than $pH_{KCl}$, it may reflect the time taken for laboratory samples to be analysed and the oxidation of sediment, causing some acidification.

$S_{POS}$ values include organic and inorganic sulfidic acidity while $S_{CR}$ measures only inorganic sulfidic acidity. Inorganic sulfidic acidity is generally pyrite oxidation and organic acidity is a less efficient acidification process. To place these figures in context, the national management criterion for acid sulfate soils if disturbance is proposed is 0.03%S. However this criterion was selected on soil conditions in New South Wales and Queensland. An acid sulfate soil mapping program conducted in the Swan Coastal Plain in the Perth region provided evidence to suggest this criterion should be lowered to about 0.01%S in poorly buffered Bassendean Sand (Singh et al. 2012).

This acid sulfate soil investigation at North Lake showed most of the potential acidity is inorganic and probably due to the presence of iron sulfide minerals such as pyrite. The highest potential sulfidic acidity was measured in the lake bed sediment (NTH_L01), recording 1.60%$S_{CR}$ and 1.90% $S_{POS}$ suggesting about 0.30% is organic acidity and 1.60% is inorganic acidity, sourced from pyrite. The potential sulfidic acidity measured at North Lake was considerably higher than that measured in similar investigations at Lake Mariginiup (Searle et al. 2010) and Lake Gwelup (Clohessy 2012). Low $pH_{FOX}$ values confirm a high level of stored acidity that may be released upon oxidation of currently stable and reduced iron sulfide minerals such as pyrite, emphasising the acidification risk at North Lake (Table 6).

*Table 6 Acid sulfate soils field and laboratory analysis*

| Site | Depth | $pH_F$ | $pH_{Fox}$ | $pH_{KCl}$ | $pH_{OX}$ | TAA % | $S_{POS}$ % | $S_{Cr}$ % |
|---|---|---|---|---|---|---|---|---|
| NTH_L01 | 0.0 | 3.7 | 1.9 | 4.0 | 2.4 | 0.529 | 0.85 | 0.43 |
| | 0.4 | 6.3 | 1.8 | 5.9 | 2.3 | 0.022 | 1.90 | 1.60 |
| | 0.8 | 6.5 | 1.5 | 5.8 | 2.6 | 0.032 | 0.22 | 0.07 |
| NTH_VC | 2.3 | 6.0 | 2.1 | 5.3 | 2.7 | <0.002 | 0.04 | 0.08 |
| | 3.7 | 6.1 | 1.9 | 5.4 | 3.1 | 0.003 | 0.04 | 0.05 |
| | 4.3 | 6.7 | 2.0 | 5.4 | 2.7 | <0.002 | 0.05 | 0.08 |
| NTH_EC | 3.1 | 4.1 | 2.2 | 5.3 | 3.7 | 0.003 | <0.01 | <0.01 |
| | 3.5 | 6.5 | 2.2 | 5.8 | 3.5 | 0.003 | 0.08 | 0.07 |
| | 4.5 | 6.5 | 2.0 | 5.5 | 2.8 | <0.002 | 0.04 | 0.06 |
| NTH_WC | 4.1 | 7.2 | 2.0 | 5.7 | 2.8 | <0.002 | 0.05 | 0.08 |
| | 6.7 | 6.4 | 1.7 | 5.2 | 2.3 | 0.002 | 0.20 | 0.23 |

## Metals and metalloids in sediment

Oxidation of acid sulfate soils is often accompanied by the release of metals and metalloids (Al, As, Cr, Cd, Fe) into the water column (Appleyard et al. 2006). Sediment samples recorded elevated levels of aluminium and iron. This analysis shows a store of aluminium and iron which may be released into groundwater given various chemical processes. The store of these metals and metalloids measured at North Lake is higher than stores measured in similar investigations at Lake Mariginiup (Searle et al. 2010) and Lake Gwelup (Clohessy 2012). Acidification, for example, will release metals and metalloids into the groundwater and surface water.

Arsenic concentrations appear to be correlated with sulfide content (Figure 22). This is significant because if arsenic is associated with iron minerals in high sulfide layers, the oxidation of these may lead to the mobilisation of arsenic. This presents a further management issue with respect to the maintenance of water levels, ecological values and water quality.

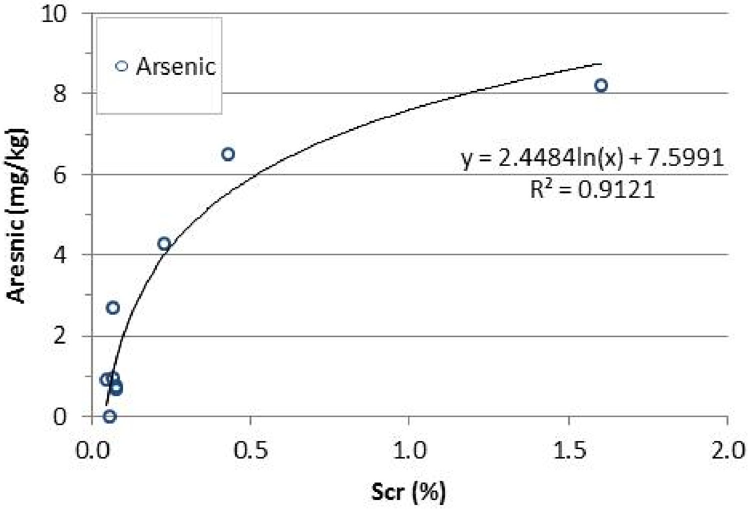

*Figure 22 Relationship between arsenic, iron and chromium reducible sulfur in sediment*

*Table 7 Metal and metalloid concentrations in soils. Note: Ecological investigation level (EIL), DEC 2010*

| Site | Depth | Al | As | Cd | Cr | Fe | Mn | Ni | Se | Zn |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | mg/kg | | | | |
| *EIL guideline* | | | *20* | *3* | | | *500* | *60* | | *200* |
| NTH_L01 | 0 | 6760 | 6.5 | <0.5 | 30 | 16 900 | 43 | 12 | 5.1 | 110 |
| | 0.4 | 10 700 | 8.2 | <0.5 | 37 | 20 100 | 21 | 4 | 5.7 | <0.5 |
| | 0.8 | 26 000 | 2.7 | <0.5 | 77 | 3210 | 16 | 3.9 | 4.4 | <0.5 |
| NTH_VC | 2.3 | 150 | 0.7 | <0.5 | 1.1 | 1030 | 0.78 | <0.5 | <0.5 | <0.5 |
| | 3.7 | 5570 | 0.91 | <0.5 | 5.4 | 690 | 2 | 0.81 | 0.53 | <0.5 |
| | 4.3 | 2890 | 0.67 | <0.5 | 4.2 | 820 | 2.2 | 0.6 | <0.5 | <0.5 |
| NTH_EC | 3.1 | 2740 | <0.5 | <0.5 | 3.1 | 330 | 0.95 | <0.5 | <0.5 | <0.5 |
| | 3.5 | 12 000 | 0.95 | <0.5 | 16 | 1360 | 2.9 | 1.9 | <0.5 | <0.5 |
| | 4.5 | 560 | <0.5 | <0.5 | 1.7 | 830 | 0.92 | <0.5 | <0.5 | <0.5 |
| NTH_WC | 4 | 240 | 0.75 | <0.5 | 2.8 | 1200 | 2.9 | <0.5 | <0.5 | <0.5 |
| | 6.7 | 170 | 4.3 | <0.5 | 1.7 | 3330 | 3.4 | 1.7 | <0.5 | <0.5 |

# 5 Hydrogeology results

## 5.1 Surface water levels

Water level records at North Lake extend back to 1972 when a regular monitoring regime was implemented in anticipation of the Jandakot Mound groundwater abstraction scheme. Water levels show an upward trend from this time to the late 1980s, and are followed by a downward trend to the late 1990s. Since the 1990s water levels have remained low and the lake routinely dries in the summer months (Figure 24). The lake has changed from being a permanent surface water body to being a seasonally inundated wetland.

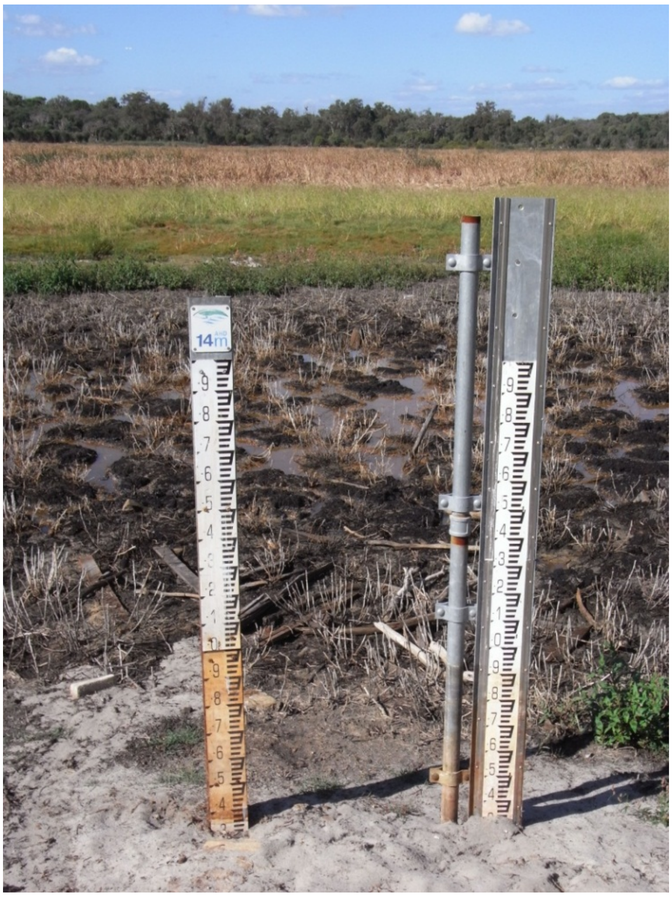

*Figure 23 Staff gauge used to measure water levels at North Lake (North Lake 424)*

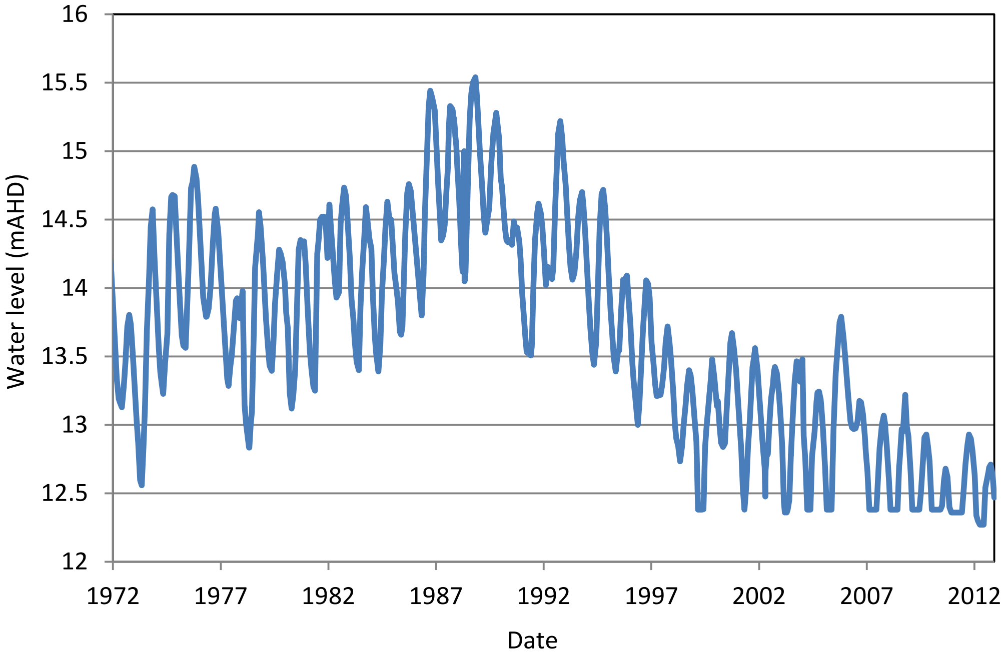

*Figure 24 Water levels at the North Lake staff gauge(North Lake 424). Note: 12.38 m AHD represents a dry lake.*

## 5.2 Groundwater levels

Seasonal maximum water levels were recorded in October 2007 and seasonal minimum in March 2008. Water levels across the site were between 11.4 m AHD (NTH_WB) and 14.9 m AHD (NTH_VC) during the sampling period (Figure 25). Groundwater levels were higher east of the lake (NTH_VC and NTH_E) and lower west of the lake (NTH_W), characteristic of a groundwater flow-through wetland.

Water level fluctuations between seasonal maximum and minimum water levels can be important for the ecology of the lake and its fringing vegetation. The difference between seasonal maximum and seasonal minimum at the water table was 1.3 m at the western edge of the lake (NTH_WC), 1.1 m at the eastern edge of the lake (NTH_EC) and 1.2 m at the vegetation transect (NTH_VC). Water levels in the original criterion bore (North Lake bore) varied by 0.65 m between maximum (October 2007) and minimum (March 2007) values.

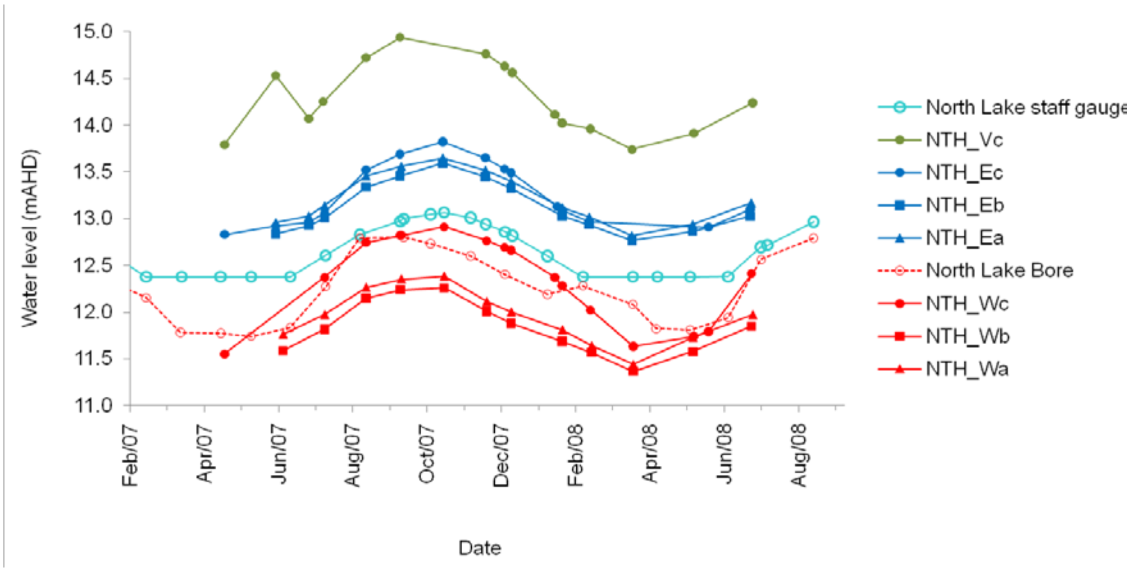

*Figure 25 Hydrograph of groundwater and surface water levels*

## 5.3 Surface water-groundwater interaction

Surface water–groundwater interaction increases with rising water levels in North Lake. The difference in groundwater levels between shallow bores and intermediate bores reflects this change. The difference in groundwater levels between the water table monitoring bore and the underlying intermediate bore was greatest at the western edge of the lake compared to the eastern edge (Figure 25). This indicates a greater component of vertical groundwater flow at the western edge of the lake. Groundwater levels at NTH_WC were up to 0.6 m higher than NTH_WB when surface water levels at North Lake were at their peak. The vertical distance between NTH_WC and NTH_WB is 19 m, this gives a hydraulic gradient of 0.03. This downward gradient suggests either downward flow and/or the presence of an aquitard. Although there was a silty/clay layer at around 12 m depth the vertical gradient is absent in summer when the lake is dry. This suggests the elevated water levels are related to outflow from North Lake and are not induced by a low-permeability layer.

A strong correlation is shown between groundwater levels (measured at the North Lake bore) and surface water levels at the staff gauge between 1997 and 2009 ($R^2$ = 0.89; Figure 26) [Note – staff gauge levels of 12.38 m AHD recorded when the lake was dry and associated bore levels were removed when determining the relationship]. Using the linear relationship equation, the equivalent groundwater level to be measured on North Lake bore to meet the Ministerial summer minimum surface water level criterion is 12.25 m AHD.

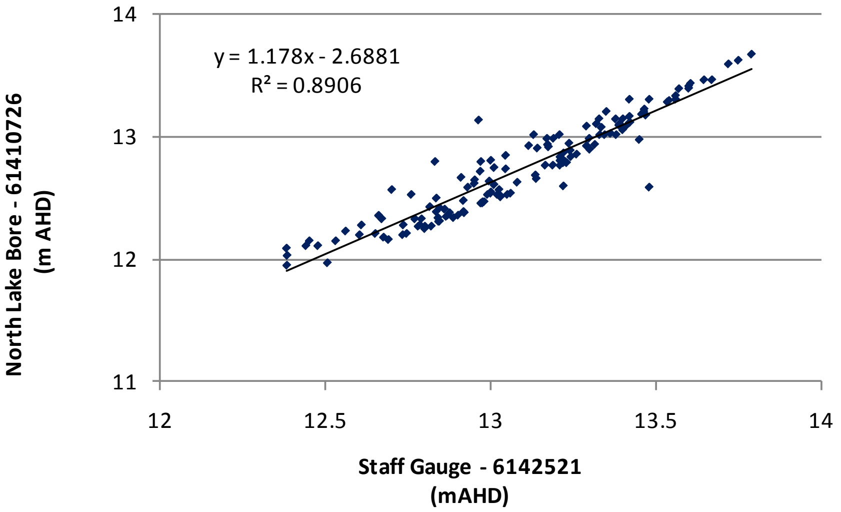

*Figure 26 Correlation between groundwater and surface water levels (1997–2009)*

## 5.4 Groundwater flow

### Lateral groundwater flow

Groundwater flows in a north-westerly direction through North Lake. Groundwater flow near the water table in October 2007 and March 2008 is shown in figures 27 and 28. When North Lake holds water the flow lines bend into the lake on the east and away from the lake on the west, reflecting groundwater inflow on the east and outflow on the west.

In March 2008 North Lake was dry and groundwater flow lines are drawn across the lake. Bibra Lake still held water at this time and so groundwater flow is shown entering the lake on the east and leaving the lake on the west.

Hydraulic gradients are consistent with the generalised model of a flow-through lake (Townley & Trefry 2000) with lateral flow from east to west through the lake (figures 27 & 28).

Hydraulic gradients (dimensionless) are calculated from the ratio of the change in hydraulic head (h) over the distance between the two measurement points (s);

$I = \Delta h / \Delta s$

Hydraulic gradients can be a reflection of groundwater flow (advection) as groundwater flows from high hydraulic head (or pressure) to low hydraulic head. Alternatively, in heterogeneous systems, hydraulic gradients can be induced by a barrier to flow that causes a higher pressure on one side, creating the observed difference in water levels.

The hydraulic head decreases as you move from east to west across the study site. The east-west change in hydraulic head across the site is about 2 m, over a distance of 800 m, a hydraulic gradient of 0.0025.

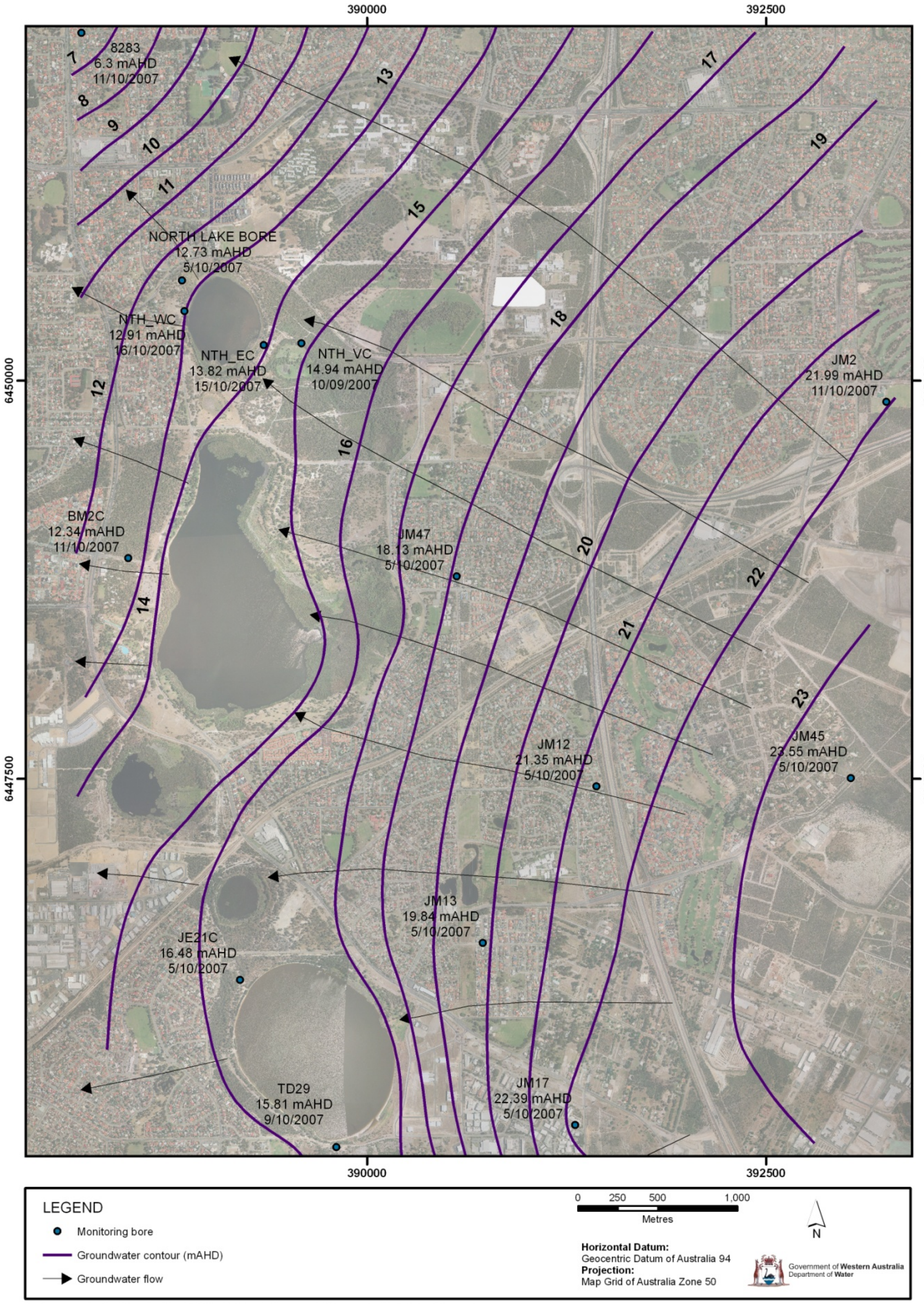

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*Figure 27 Groundwater contours and flow direction at seasonal maximum water levels (October 2007)*

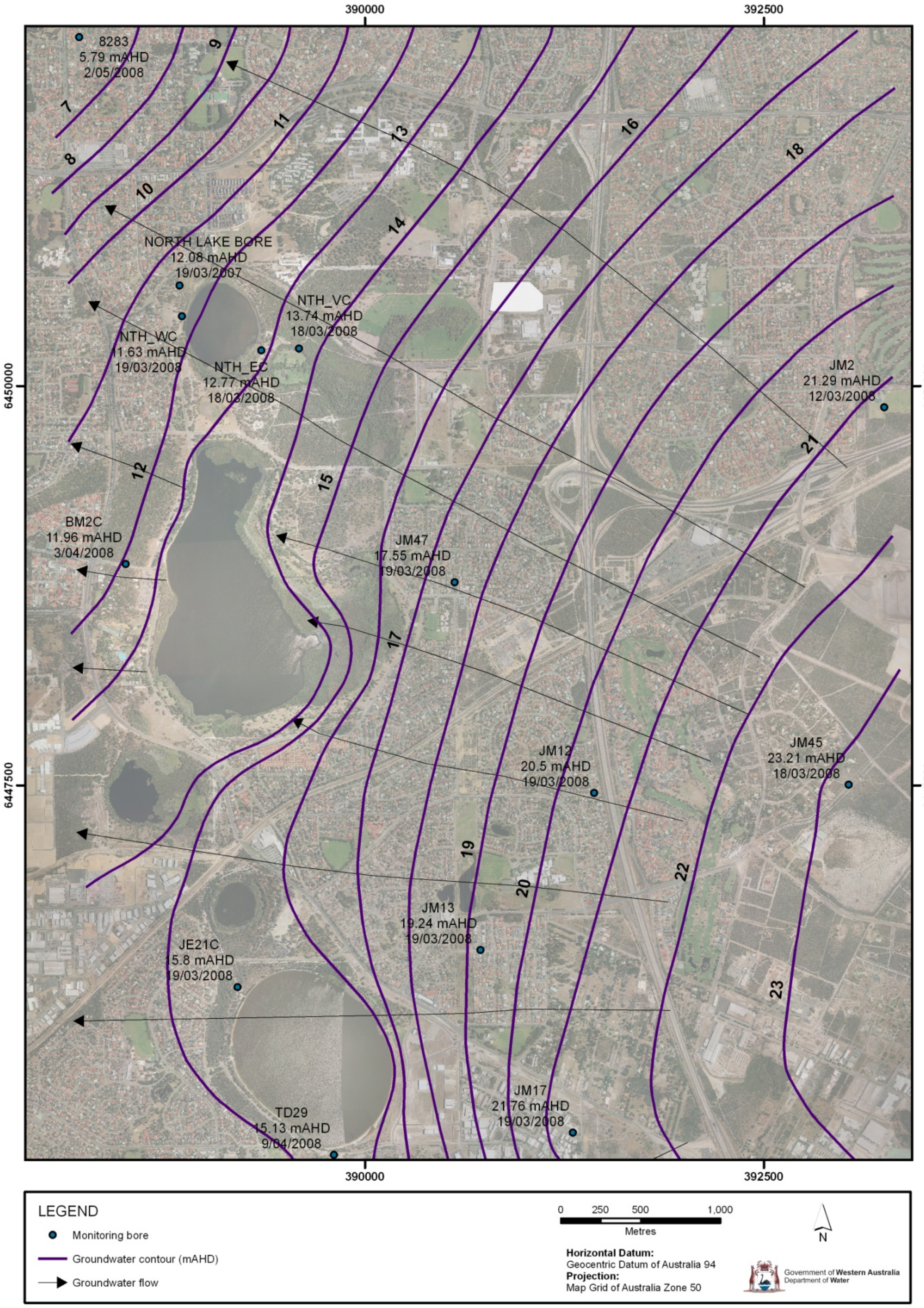

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*Figure 28 Groundwater contours and flow direction at seasonal minimum water levels (March 2008)*

## Vertical groundwater flow

North Lake is a flow-through, groundwater-dependent wetland when the lake contains water. Groundwater flows upwards towards the lake on the upgradient eastern side of the lake and downwards out of the lake on the downgradient western edge of the lake. North Lake interacts with about half the vertical extent of the Superficial aquifer when the lake contains water (Figure 29). When the lake dries, this interaction ceases, and groundwater flow is mainly horizontal for the entire vertical extent of the aquifer (Figure 30).

Vertical groundwater gradients are greater than horizontal gradients at the water table. This vertical hydraulic gradient was 0.2 m of head difference over 16 m depth (from NTH_EC to NTH_EB) or 0.0125 at its maximum. This gradient was largest at maximum water levels and ceased when the lake dried.

Bassendean Sand and the Ascot Formation comprise the sediments of the Superficial aquifer. The Kardinya Shale Member of the Osborne Formation is an aquiclude, or barrier to flow and the top of the Kardinya Shale defines the base of the Superficial aquifer (figures 29 and 30).

At seasonal minimum water levels when the lake is dry the water table is within the lake bed sediments. These sediments are low permeability, comprised of peat, silt and diatomite. Lake bed sediments influence groundwater flow by encouraging flow slightly downwards, away from the zone of low hydraulic conductivity.

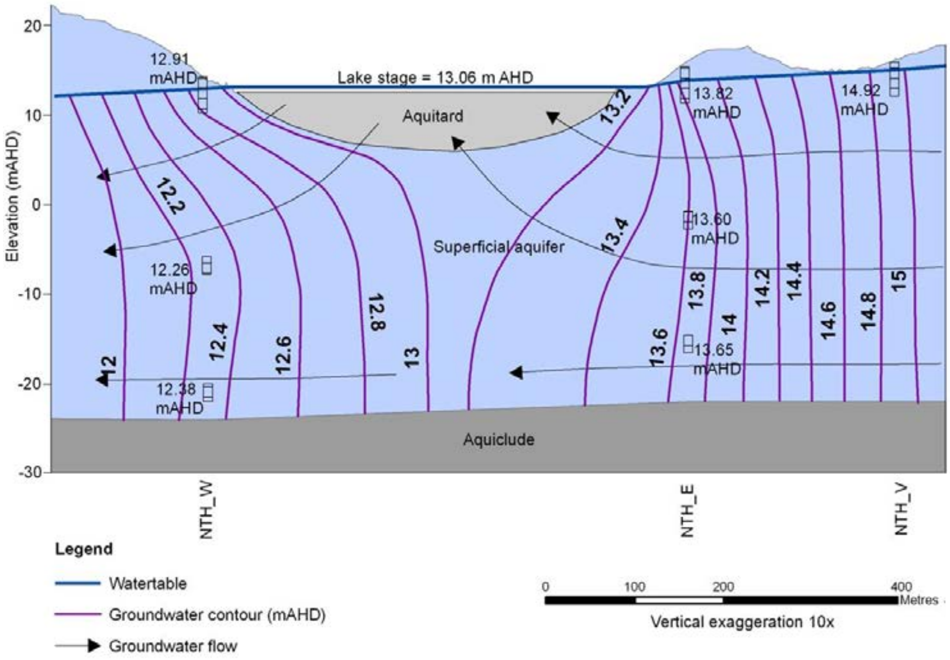


*Figure 29 Cross section of groundwater contours and flow paths at maximum levels (when the lake is full)*

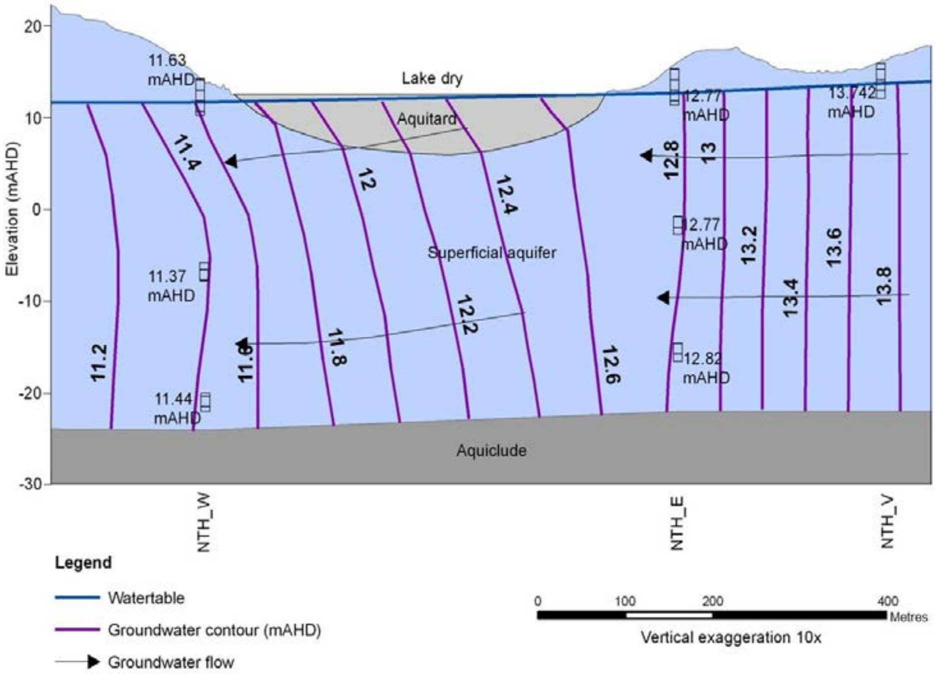


*Figure 30 Cross section of groundwater contours and flow paths at minimum levels (when the lake is dry)*

## 5.5 Hydrogeochemistry

### Salinity

Salinity is assessed in terms of total dissolved solids (TDS) and electrical conductivity (EC). Water quality measured as salinity (TDS) in surface water at North Lake ranged between marginal (930 mg/L in October 2007) and moderately saline (2870 mg/L) near the staff gauge (North Lake 424). In May 2012, when the lake was mainly dry, salinity in a pool of surface water at the south eastern part of the lake (NTH_S1) was 6150 mg/L; this is saline (Figure 31). These highly variable salinity figures are at least in part due to the amount of evaporation associated with fluctuating water levels in the lake.

Salinity in groundwater near the middle and base of the Superficial aquifer was consistent throughout the monitoring period, similar to trends in chloride concentrations (Figure 31). Groundwater is fresh near the middle and base of the Superficial aquifer beneath North Lake (Figure 31). Higher salinity near the water table is mainly due to higher rates of evaporation and geochemical interactions exacerbated with water table fluctuations.

The largest seasonal variation in salinity was recorded at NTH_WC where the water is also acidic. Salinity was between 990 mg/L (October 2007) and 2240 mg/L (November 2007) for the monitoring period April 2007–June 2008. This difference may at least in part be due to rainfall in the week (about 15 mm) prior to sampling in

October 2007 and dry conditions in the month leading up to the November 2007 sampling event.

Salinity at NTH_WC also rose significantly as measured in the two rounds of monitoring in May and September 2012: 5320 mg/L and 7070 mg/L respectively. These increases are probably also associated with increased acidity releasing other major ions such as calcium, magnesium and sulfate.

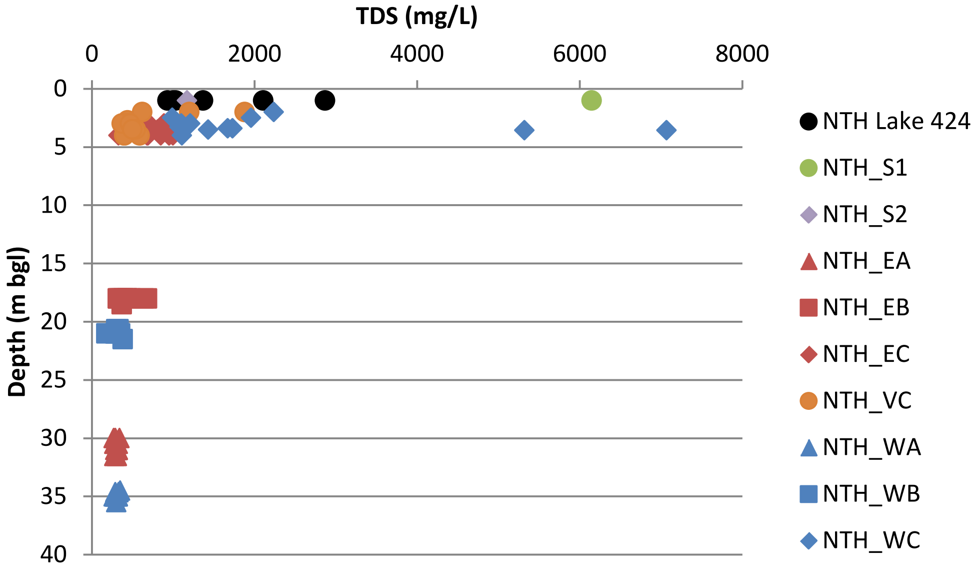


*Figure 31 Salinity in groundwater and surface water at North Lake*

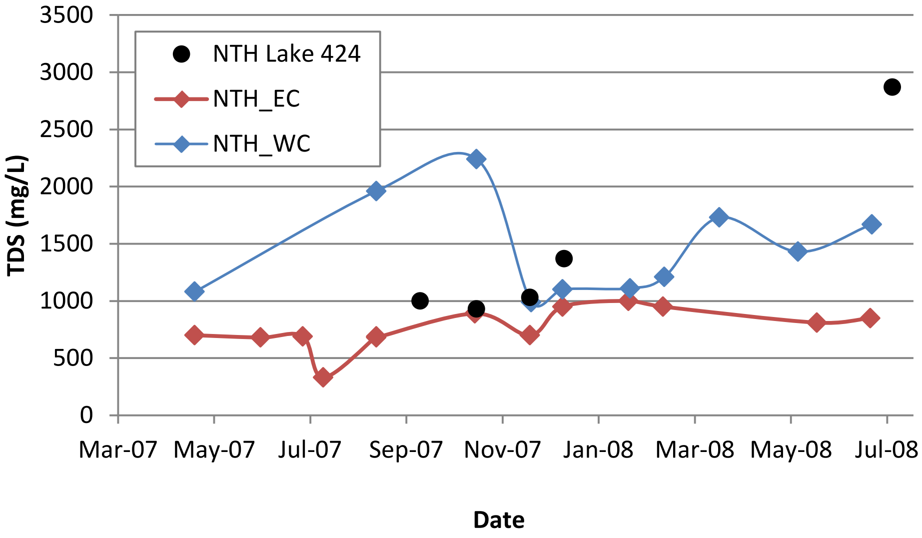


*Figure 32 Salinity in groundwater near the watertable and surface water at the western edge of the lake*

## Major ions

A Piper diagram (Figure 33) provides a visual summary comparing major ion compositions from different locations and depths. The bottom left triangle represents the cations and the bottom right triangle the anions. Samples collected between September 2007 and June 2008 were included in the Piper diagram. Monitoring between May 2007 and August 2007 did not include analysis of sodium and is not plotted on the Piper diagram. Sampling results from May and September 2012 are not included in the Piper (Figure 33).

Surface water in North Lake (North Lake 424) is dominated by chloride (Cl) and sulfate ($SO_4$) with no dominant cation. High sulfate levels and sulfate to chloride ratios indicate sulfide oxidation and is likely to be the main source of acidity at North Lake.

The ionic compositions of groundwater vary between bores. Groundwater near the water table (NTH_EC, NTH_VC, NTH_WC) plots close to lake water. Water in intermediate and deep bores has higher levels of calcium (Ca) and bicarbonate ($HCO_3$) than surface water in North Lake and plots closer to the centre of the Piper diagram (Figure 33). The similar ionic compositions of water in shallow groundwater and surface water in the lake suggest some interaction, consistent with the interpretation of a flow-through lake. The differences in ionic composition of groundwater at greater depths of the Superficial aquifer may also indicate the nature of groundwater flow paths and that groundwater in the upper half of the aquifer is somewhat separated from groundwater at the base of the aquifer.

The presence of Ca and $HCO_3$ suggests the influence of carbonate rock-types. Calcarenite and shelly sands of the Ascot Formation were intersected at the base of the Superficial aquifer during this study and are the likely source of this carbonate material in the groundwater at depth.

The ionic compositions of water samples can also be compared using Stiff diagrams (Figure 35). These provide a visual summary of ionic composition of a single water sample at one sampling time. The Stiff diagram (Figure 35) shows the ionic composition of water in North Lake and each groundwater bore in October 2007. The horizontal axis shows the concentrations of each ion in milli-equivalents per litre (meq/L). This axis is symmetrical with cations plotted towards the left and anions towards the right.

These plots illustrate the different ionic profiles in groundwater near the water table and lake water compared to groundwater at greater depths. These differences result from groundwater acidification processes near the water table and a low buffering capacity. The higher proportions of magnesium and sulfate in NTH_WC and NTH_VC indicate dissolution and oxidation processes.

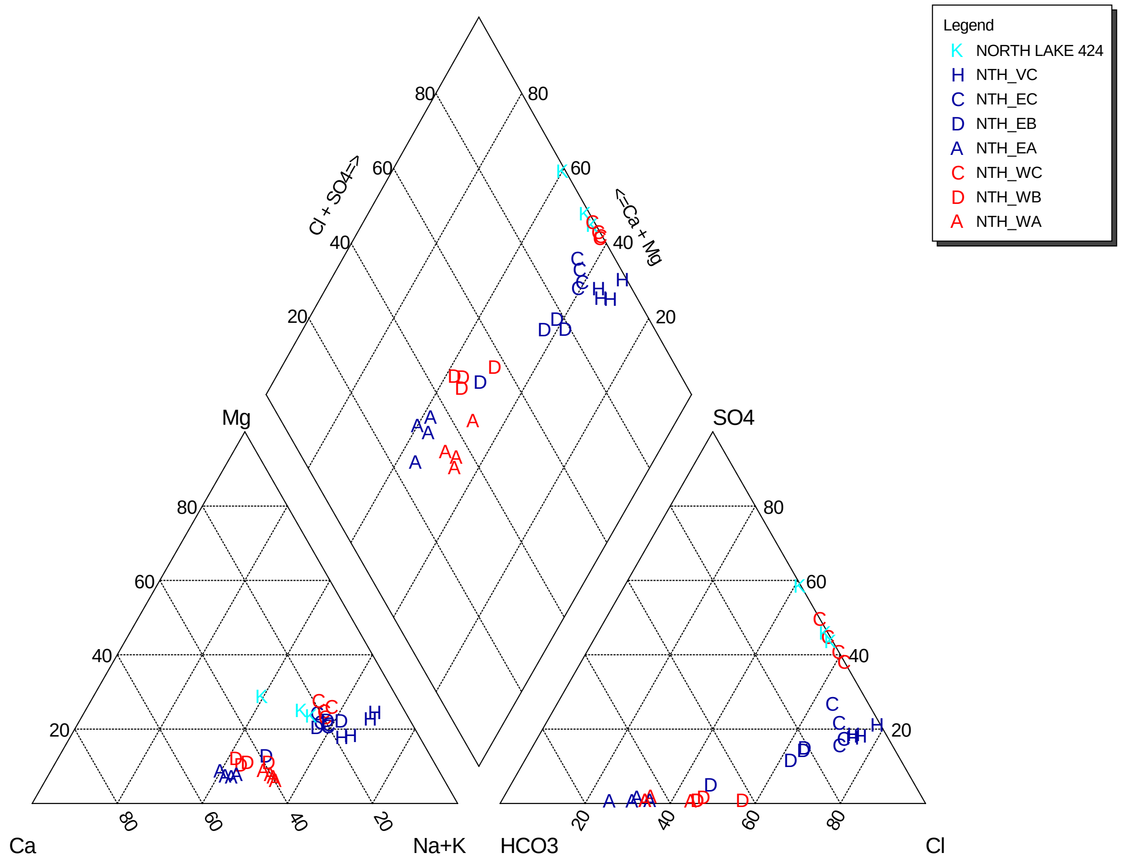


*Figure 33 Piper diagram, 2007–08 data*

The intermediate bore east of the lake (NTH_EB) shows a greater dominance of Na and Cl ions than other deeper bores. This could be due to groundwater flow from Frog Swamp, reflect a lack of carbonate material from acidification processes or a higher rate of evaporation, rather than additional sodium and chloride input.

### *Chloride in groundwater and surface water*

Lake water is subject to evapoconcentration which increases chloride concentration which is highest when lake water levels are at a minimum. Chloride concentrations in surface water ranged from 230 mg/L (September 2007) to 570 mg/L (July 2008) at the western edge of the lake (North Lake 424). In May 2012 the lake was mainly dry and in September 2012 chloride concentration was at 360 mg/L.

Chloride concentrations in groundwater near the middle and the base of the Superficial aquifer are similar (Figure 34). Chloride concentrations, like salinity, vary near the water table due to evaporation and were higher in groundwater flowing out and away from North Lake (to the west) than in water recharging or flowing towards the lake from the east (Figure 34).

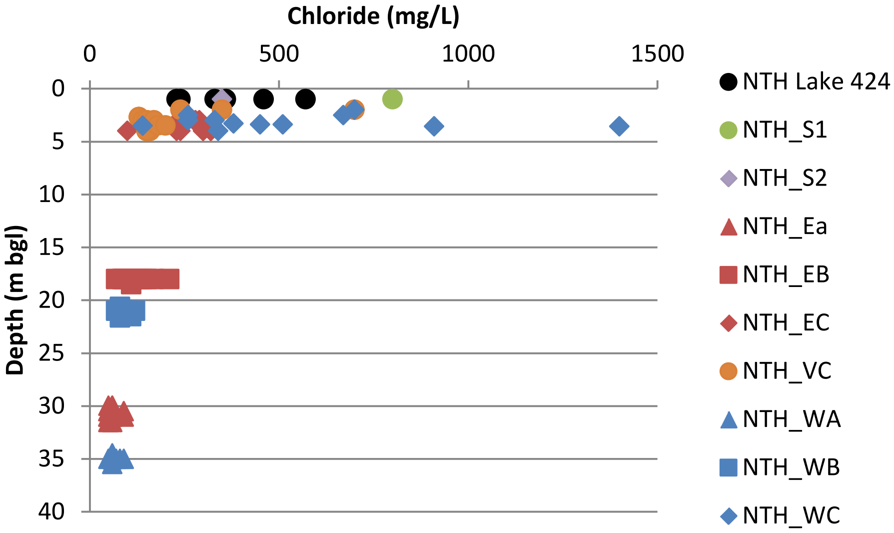


*Figure 34 Chloride in groundwater and surface water*

### *Chloride and groundwater flow*

Chloride is a non-reactive ion commonly used as a conservative tracer to assist interpretation of groundwater flow (Turner & Townley 2006).

A cross section created using average chloride values from this investigation shows the vertical gradient with lowest concentrations at the base of the Superficial aquifer (Figure 36). The highest concentrations are in the water table bore west of the lake (NTH_WC) suggesting outflow of evapoconcentrated water from the lake is restricted to the top half of the Superficial aquifer.

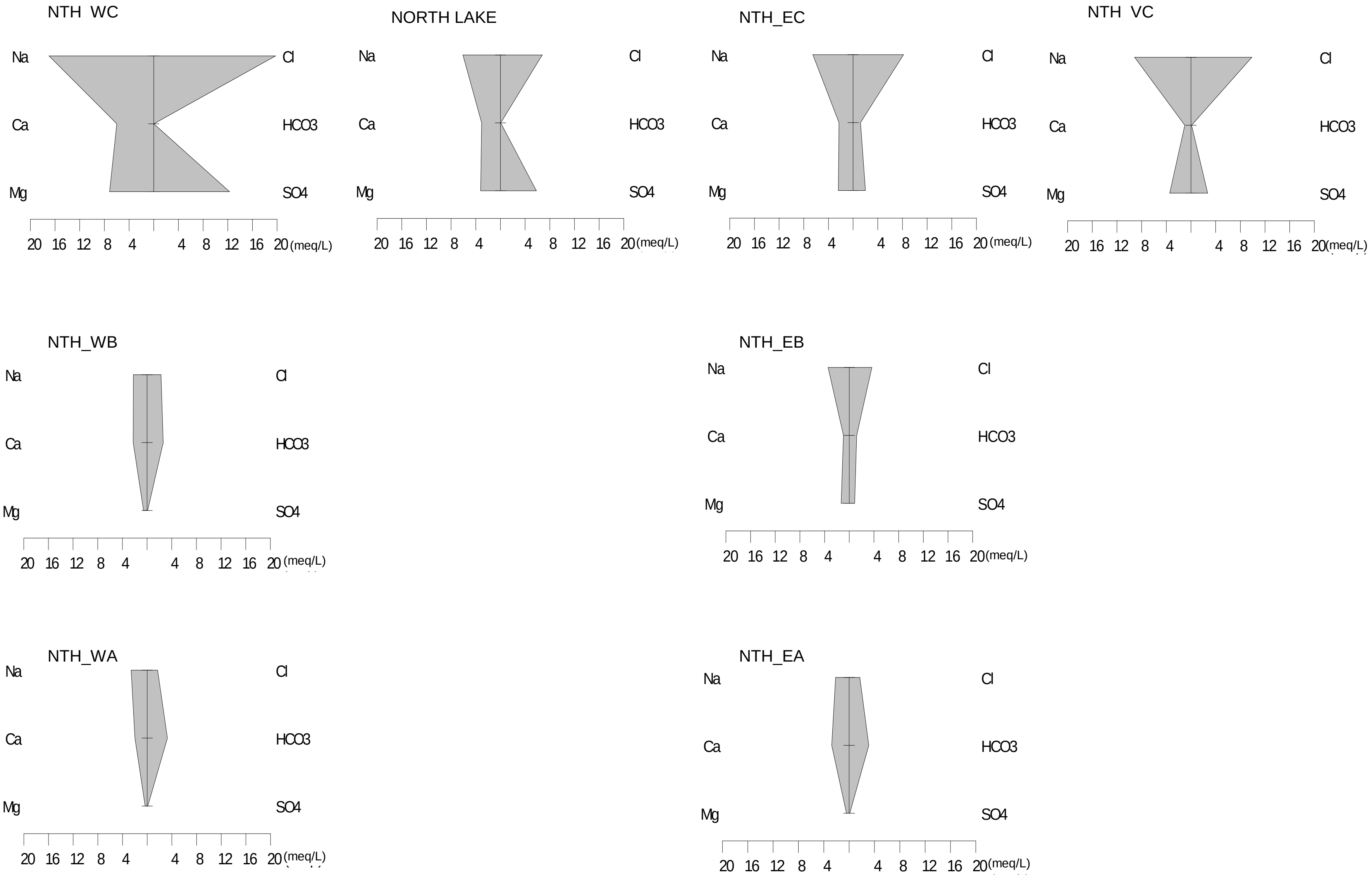


*Figure 35* *Stiff diagrams of North Lake and groundwater monitoring bores (October 2007)*

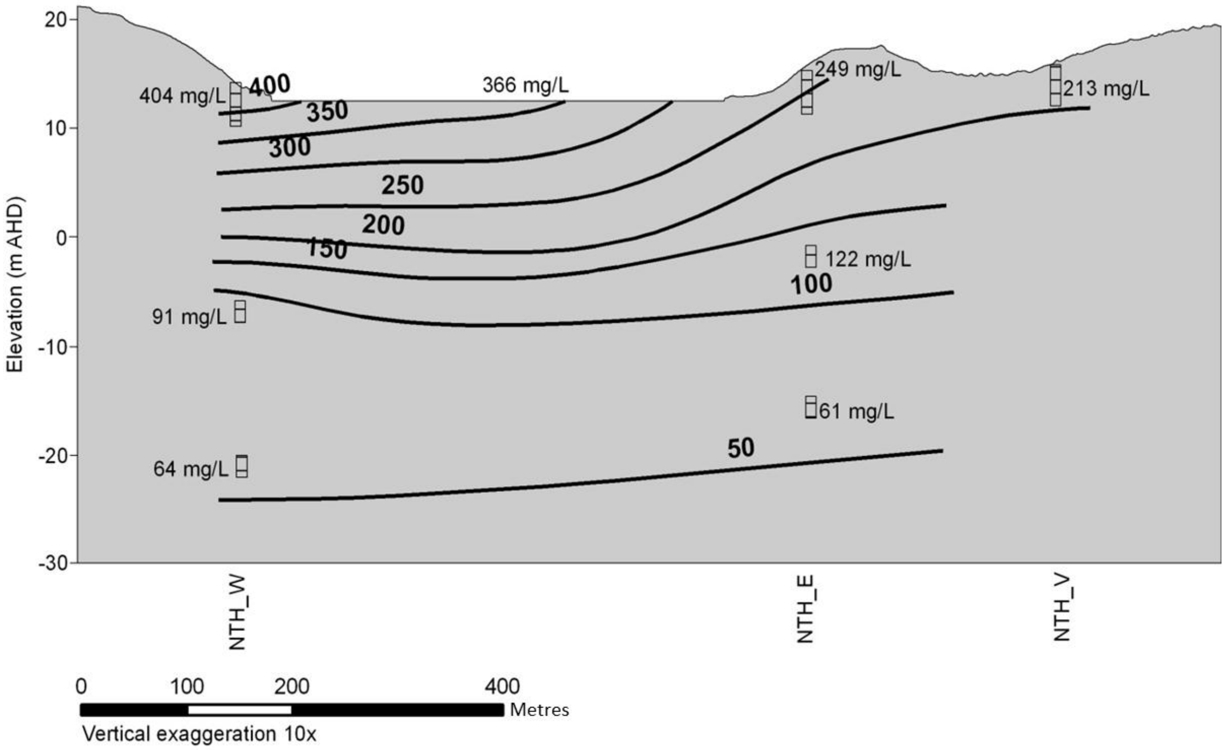


Figure 36 Cross section of chloride concentrations in groundwater

### Sulfate

Sulfate concentrations were highest in surface water at North Lake and in groundwater near the water table. Sulfate concentrations were low and generally not detected in groundwater near the middle and base of the Superficial aquifer (Figure 37). These differences indicate two main processes in groundwater:

1. Groundwater near the water table and surface water at North Lake is oxidising, converting sulfide minerals to sulfate minerals.
2. Groundwater near the middle and the base of the aquifer beneath North Lake is reducing, with sulfate minerals converted to sulfide minerals.

Sulfate concentrations in surface water at North Lake ranged between 280 mg/L (NTH Lake 424, October 2007) and 2700 mg/L (NTH_S2, May 2012). Sulfate concentrations vary with time and location in the lake, highlighting that the chemistry of surface water is not the same for the entire lake and multiple monitoring points are required for better site characterisation.

Groundwater near the water table also contained high concentrations of sulfate. Sulfate levels were generally higher at the western downgradient edge of the lake than at the eastern upgradient edge of the lake, although the highest levels of sulfate were recorded at NTH_VC. For the 2007–08 monitoring period, sulfate concentrations at the water table were between 14 mg/L (NTH_EC, July 2007) and 600 mg/L (NTH_VC, August 2007).

Sulfate concentrations had significantly increased at NTH_WC in 2012 monitoring compared with data from 2007–08: 2000 and 2700 mg/L in May and September 2012, respectively. This trend was not observed at NTH_VC while NTH_EC could not be sampled in 2012 due to a blockage in the monitoring bore. This increase at NTH_WC was due to oxidation processes liberating sulfate from previously reduced and stable sulfide minerals in lake sediments and groundwater. This process is exacerbated by the seasonal drying of the lake.

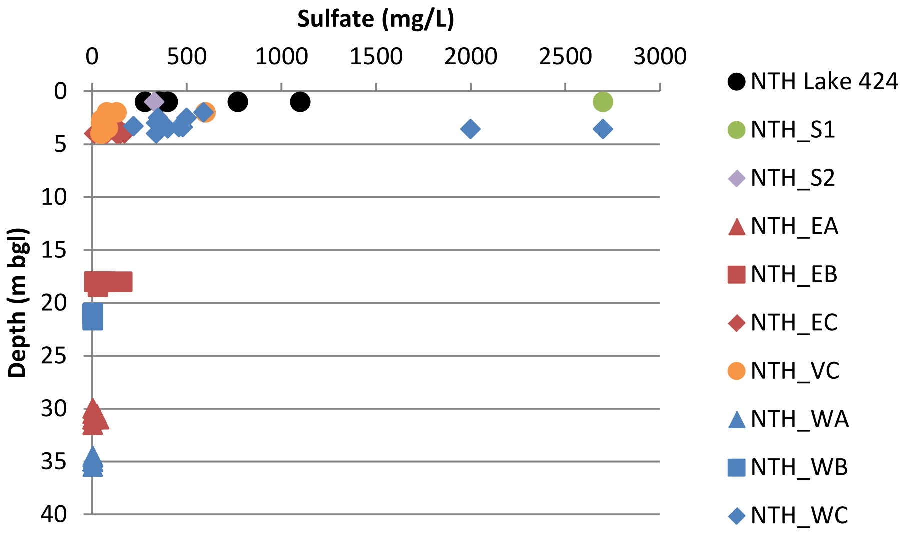


*Figure 37 Sulfate concentrations in surface water and groundwater*

### *Sulfate to chloride ratios*

Sulfate to chloride ratios greater than 0.5, with elevated levels of aluminium and iron, indicate pyrite oxidation (Mulvey 1993; DEC 2010). Sulfate to chloride ratios in surface water at North Lake and the shallow groundwater monitoring bore (NTH_WC) were greater than 0.5 in every sample collected between 2007 and 2012 (Figure 38). Sulfate to chloride ratios from NTH_EC and NTH_VC were near 0.5 regularly, but greater than 0.5 on one occasion at each location.

Higher levels of sulfate were probably detected at NTH_WC than NTH_VC and NTH_EC because of oxidation processes associated with water table fluctuations. Furthermore, the oxidation of lake sediments, when the lake is dry, is likely to act as a source of sulfate at NTH_WC, because when the lake is full, groundwater flows out of the lake in a westerly direction.

Sulfate to chloride ratios at NTH_WC in 2007–08 were between 0.58 (April 2007) and 2.86 (May 2008) and also high in in 2012: 2.20 and 1.93 in May and September 2012 respectively.

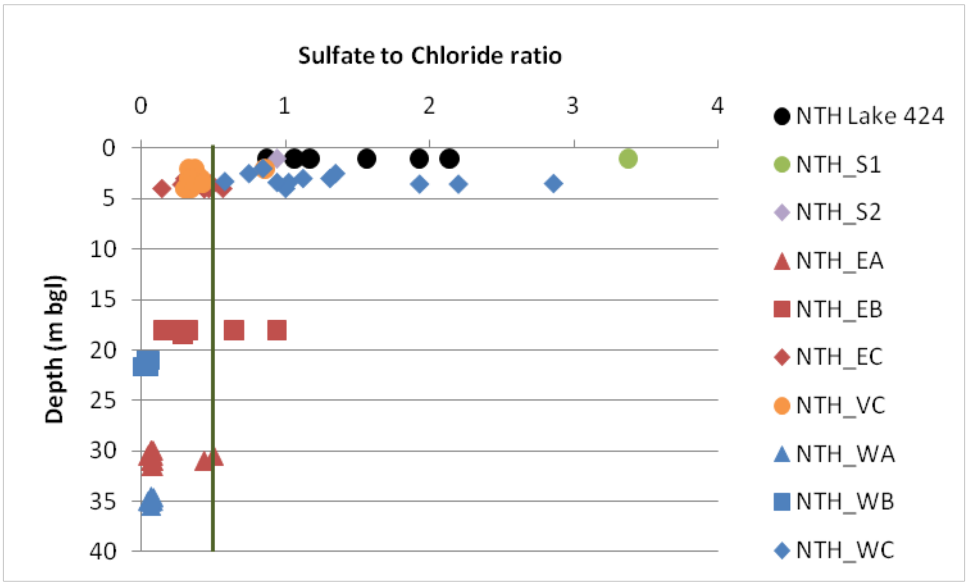


*Figure 38 Sulfate/chloride ratios of North Lake and adjacent watertable bores. Note: vertical line indicates 0.5, sulfate to chloride ratio.*

## Alkalinity, acidity and pH

North Lake appears to be on the verge of permanent acidification, similar to Lake Mariginiup (Searle et al. 2010) in Perth's northern suburbs. Surface water in the lake has no buffering capacity, therefore no ability to resist changes in pH, and highly sensitive to pyrite oxidation, exacerbated by the seasonal drying of the lake.

North Lake water had acidic pH values during the monitoring period, although they were not stable and varied over time: 4.37 (July 2008) and 5.92 (December 2007) at the western edge of the lake, when the lake contained water. When the lake was largely dry, surface water ponding was sampled at the south-eastern part of the lake, where pH was 3.01 (Figure 39). Throughout monitoring 2007–12, the lake lacked any available acid buffering capacity, indicated from very low alkalinity levels which ranged from < 1 mg/L (July 2008) to 7 mg/L (December 2007; Figure 39).

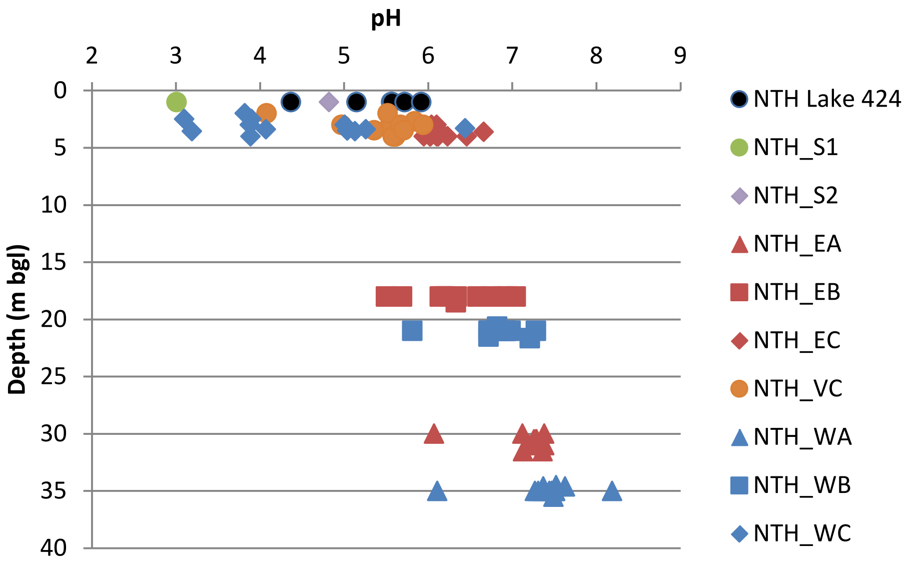


*Figure 39 pH in surface water and groundwater*

The Swedish Environmental Protection Agency (Swedish EPA) published guidance discussing the risk of acidification with respect to alkalinity levels and suitable buffering capacity to resist changes in pH. The Swedish EPA states alkalinity concentrations less than 60 mg/L with pH less than 7.5 are insufficient to maintain stable and acceptable pH in areas with a high susceptibility to acidification (Swedish EPA 2002). Alkalinity levels less than 30 mg/L with pH less than 6.0 are also insufficient to maintain stable and acceptable pH (Swedish EPA 2002). North Lake is similar to Lake Mariginiup, located on the Gnangara Mound north of Perth, and is a good example of how wetlands in leached, poorly buffered, base cation-depleted Bassendean Sand are highly susceptible to acidification.

Following the guidance of the Swedish EPA, groundwater near the base of the aquifer beneath North Lake is suitably buffered to resist changes in pH. While pH is lower near the middle than at the base of the Superficial aquifer, alkalinity levels are above 60 mg/L at NTH_EB and above 100 mg/L at NTH_WB and is not at current risk of acidification. Alkalinity levels are dynamic and change over time subject to chemical processes in sediments and groundwater.

There is a sharp contrast in the quality of groundwater at NTH_WC and NTH_WB. Acid generating processes are clearly indicated at NTH_WC but are not evident at NTH_WB. Further investigation is required to assess the vertical migration of the acidification front beneath the western portion of North Lake.

Acidification processes are evident at NTH_VC and is highly susceptible to acidification given low buffering capacity (Figure 40).

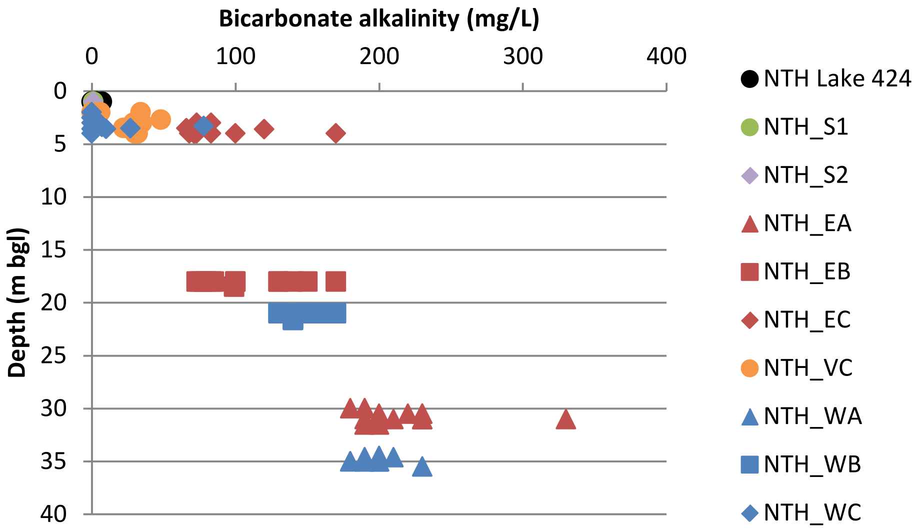


*Figure 40 Alkalinity in surface water and groundwater*

Total acidity concentrations are generally low but acidity needs to be viewed in context with alkalinity. Low levels of acidity can cause significant pH decline in poorly buffered sediment and groundwater. This is the case for surface water at the western edge of North Lake (North Lake 424). Total acidity was recorded between 10 mg/L (November 2007) and 13 mg/L (July 2008) in 2007/2008, despite generating pH values as low as 4.37. Monitoring in September 2012 found similar levels of total acidity (15 mg/L) and a corresponding pH value of 4.70.

To emphasise the need to monitor multiple points of a wetland for suitable characterisation to see the varied spatial distribution of water chemistry, very high levels of total acidity were also recorded at the south-eastern part of North Lake. Total acidity was recorded at 630 mg/L (NTH_S1, May 2012) and 42 mg/L (NTH_S2, September 2012), with pH of 3.01 and 4.50 respectively.

High sulfate to chloride ratios appeared to correlate with higher levels of acidity further emphasising the occurrence of pyrite oxidation at NTH_WC. Total acidity was recorded up to 580 mg/L at NTH_WC with a corresponding pH of 3.6 and sulfate to chloride ratio of 2.2.

## Oxidation-reduction potential

### *Background*

The oxidation–reduction potentials (redox) can provide an indication of various chemical processes in water. A negative redox potential suggests reducing conditions and a positive redox potential suggests oxidising conditions. Instantaneous redox measurements are difficult to interpret as most natural waters are not in equilibrium and can only be considered to provide a qualitative indication of redox condition (Appelo & Postma 2005).

Oxidation and reduction reactions generally occur in a particular sequence which can be used to predict the next chemical process. The typical reduction sequence from a higher redox to a more reducing environment is according to the following:

Oxygen reduction → nitrate reduction → reduction of manganese oxides → reduction of iron oxides → sulfate reduction → methanogenesis.

The typical oxidising sequence is according to the following from a lower redox value to a more oxidising environment:

Oxidation of organic matter → sulfide oxidation → oxidation of ferrous iron → nitrification → oxidation of manganese.

It should also be noted that a reduction reaction may proceed in conjunction with any oxidation reaction that is located at a lower redox. For example, sulfate reduction can be combined with the oxidation of organic matter but not the oxidation of ferrous iron (Appelo & Postma 2005). This also indicates higher levels of sulfate may also occur in conjunction with elevated levels of iron and vice versa, given the influence of oxidation reduction potentials on chemical reactions in groundwater.

#### *Oxidation–reduction potentials at North Lake*

Surface water had positive oxidation reduction potentials, indicative of oxidising conditions while groundwater near the watertable fluctuated between positive and negative oxidation reduction potentials. Redox conditions in the middle and base of the aquifer beneath North Lake were highly reducing.

It is evident that very low levels of sulfate and iron in the lower half of the aquifer at near neutral pH values are a result of sulfate reduction and reduction of iron oxides. In groundwater near the water table there are higher levels of sulfate and iron in association with higher redox values and therefore some sulfide oxidation and the oxidation of ferrous iron.

The presence of organic matter and/or dissolved organic carbon is also significant in driving reactions in conjunction with the redox environment. In groundwater, elevated levels of dissolved organic carbon, up to 140 mg/L in NTH_VC, could be driving sulfate reduction (and iron sulfide formation) under anoxic conditions. The presence of organic carbon drives bacterial growth and can lead to reducing conditions, with a shift in dominant oxidation state of iron from Fe (III) to Fe (II), and pyrite formation (Appleyard et al. 2006; Degens 2009).

## Metals and metalloids

### Overview

A range of guideline values for metals and metalloids in water has been defined by the Australian and New Zealand Environment and Conservation Council (ANZECC 2000) and the National Health and Medical Research Council (NHMRC 2004; Table 8). These values are incorporated into guidelines for Western Australia published by the Department of Environment and Conservation (DEC 2010).

*Table 8 Guideline levels for metals and metalloids*

| Species | Freshwater | Drinking water | Irrigation water |
|---|---|---|---|
| | | (mg/L) | |
| Al (sol) | *0.055* | *0.2* | *5* |
| As (tot) | *0.024 (AsIII)*<br>*0.013 (AsV)* | *0.007* | *0.1* |
| B (sol) | *0.37* | *0.3* | *0.5* |
| Cd (tot) | *0.0002* | *0.002* | *0.01* |
| Cr (tot) | *0.001* | | *0.1* |
| Fe (sol) | | *0.3*# | *0.2* |
| Mn (tot) | *1.9* | *0.5* | *0.2* |
| Ni (tot) | *0.011* | *0.02* | *0.2* |
| Se (tot) | *0.005* | *0.01* | *0.02* |
| Zn (tot) | *0.008* | *3* | *2* |

*#Guideline for aesthetic qualities*

This investigation identified aluminium, iron and manganese as the main metals in surface water and groundwater at North Lake. The presence of these species is illustrated in this section. The processes involved in their release into groundwater and surface water are discussed in more detail in Section 6 – Key findings. Table 9 summarises the surface water and groundwater species above investigation levels. A conservative freshwater guide has been used for surface water while an irrigation guide has been used for groundwater. Groundwater is used for irrigation through domestic bores. The Department of Health domestic non-potable groundwater use guide (DoH 2006) is also relevant when using untreated groundwater. This is generally a factor of 10 greater than the drinking water guideline.

Cadmium and zinc were identified at concentrations exceeding guidelines at least once in this study (Table 9). Cadmium was recorded at very low concentrations and only exceeded the freshwater guide once in surface water at North Lake. Zinc exceeded freshwater guidelines in each lake sample at North Lake and further investigation may be required into the presence of zinc to assess its risk to the environment.

*Table 9 Summary of trigger value breaches of metal and metalloid concentrations in North Lake and adjacent groundwater (ANZECC 2000 & DEC 2010)*

| Site | Al (sol) | As (tot) | Cd (tot) | Cr (tot) | Fe (sol) | Mn (tot) | Zn (tot) |
|---|---|---|---|---|---|---|---|
| | | | | (mg/L) | | | |
| NTH LAKE 424 | X | | X$^{+}$ | | X | | X |
| *Freshwater trigger* | *0.055* | *0.024 (AsIII),*<br>*0.013 (AsV)* | *0.0002* | *0.001* | | *1.9* | *0.008* |
| NTH_VC | X | | | | X | X | |
| NTH_EC | | X | | | X | X | |
| NTH_EB | X | X | | | X | | |
| NTH_EA | | | | | X | | |
| NTH_WC | X | | | | X | X | |
| NTH_WB | X | X | X* | X* | X | | |
| NTH_WA | | | | | X | | |
| *Irrigation water trigger* | *5.0* | *0.1* | *0.01* | *0.1* | *0.2* | *0.2* | *2* |
| *DoH (2006)* | *2.0* | *0.07* | *0.02* | *0.5* | *3.0* | *5.0* | *30* |

$^{+}$ Equal to the trigger value

* Related to high TSS

### *Aluminium*

The release of aluminium may be triggered by low or high pH, or mechanisms associated with organic complexes. Aluminium toxicity poses a risk to the health of vegetation and the ecological value of North Lake.

Dissolved aluminium in surface water at the western edge of North Lake (NTH Lake 424) ranged between 0.01 mg/L (December 2007) and 0.15 mg/L (July 2008). Higher levels of aluminium were recorded in surface water at the south-eastern portion of North Lake. In May 2012, dissolved aluminium concentration was at 43 mg/L (NTH_S1) when the lake was largely dry and 0.25 mg/L (NTH_S2) in September 2012. The presence of aluminium varies between locations in North Lake and its release in high concentrations is controlled by pH.

Higher levels of aluminium were generally found near the water table and in surface water than in groundwater deeper in the Superficial aquifer (Figure 43) and were associated with lower pH at NTH_WC (Figure 41). The biggest range of aluminium concentrations was in NTH_WC, with concentrations up to 27 mg/L (not shown in Figure 41 as right off the scale of the graph). Elevated levels were also found in groundwater near the middle of the aquifer beneath the western edge of the lake.

Dissolved aluminium at NTH_VC varied between 0.07 mg/L (April 2007) and 5.1 mg/L (August 2007). This variation should be considered when assessing the health of vegetation in the area. The release of aluminium near the water table may be associated with the oxidation of pyrite with acid attack on aluminosilicate minerals, while the mobilisation of aluminium near the middle of the aquifer beneath the western edge of North Lake may be due to movement of micro-fine clays.

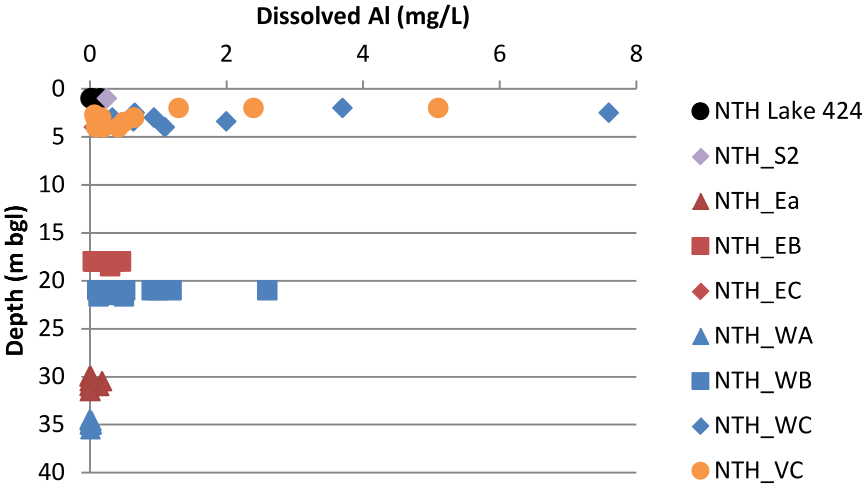


*Figure 41 Dissolved aluminium in surface water and groundwater. Note: NTH_S1 recorded Al: 43 mg/L*

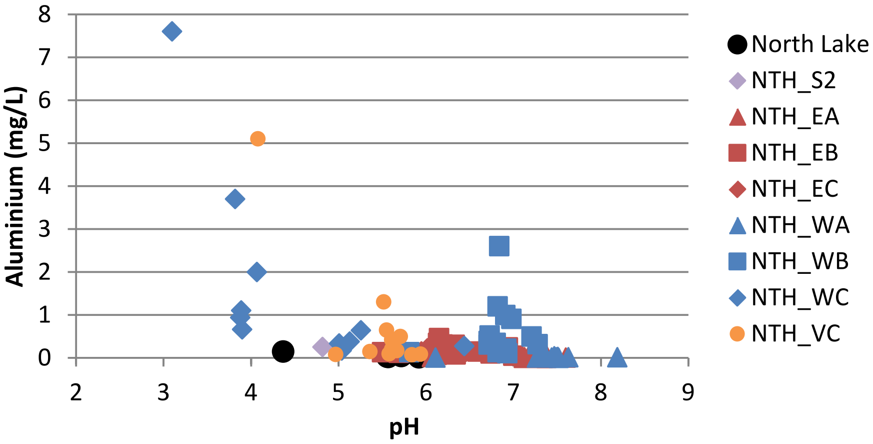


*Figure 42 Relationship between dissolved aluminium and pH*

### *Iron*

Dissolved iron levels were higher in groundwater near the water table and in surface water than in groundwater deeper in the aquifer. The range in dissolved iron was also greater in shallow groundwater than in deeper groundwater (figures 43 and 44).

Dissolved iron in groundwater near the water table was between 0.053 mg/L (NTH_EC, May 2007) and 170 mg/L (NTH_WC, May 2012). Elevated levels of iron were consistently recorded near the water table at the western edge of North Lake. Elevated levels (> 1 mg/L) were also recorded at the base of the Superficial aquifer beneath North Lake (Figure 44).

The mechanisms for iron release in groundwater beneath North Lake are discussed in detail in Section 6 – Key findings.

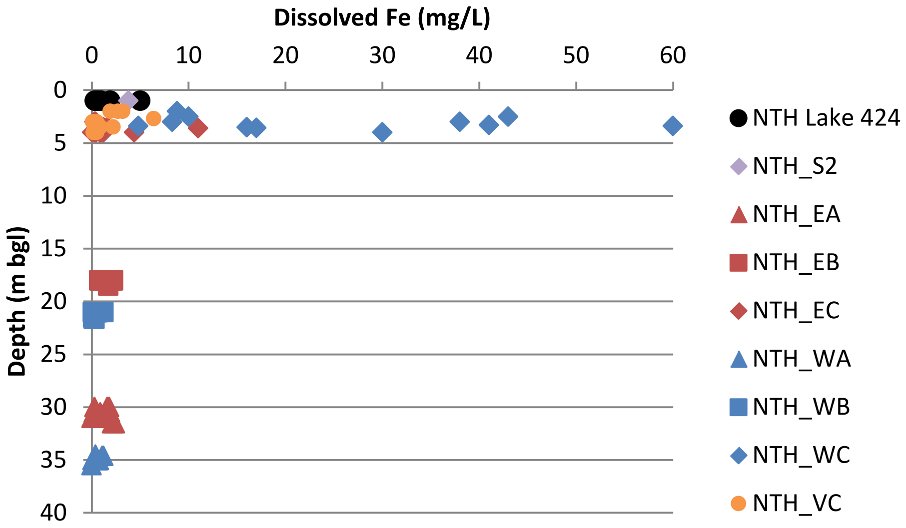


*Figure 43 Dissolved iron in surface water and groundwater at North Lake. Note: NTH_WC recorded dissolved iron at 170 mg/L in May 2012, but this is not included in the figure due to scale.*

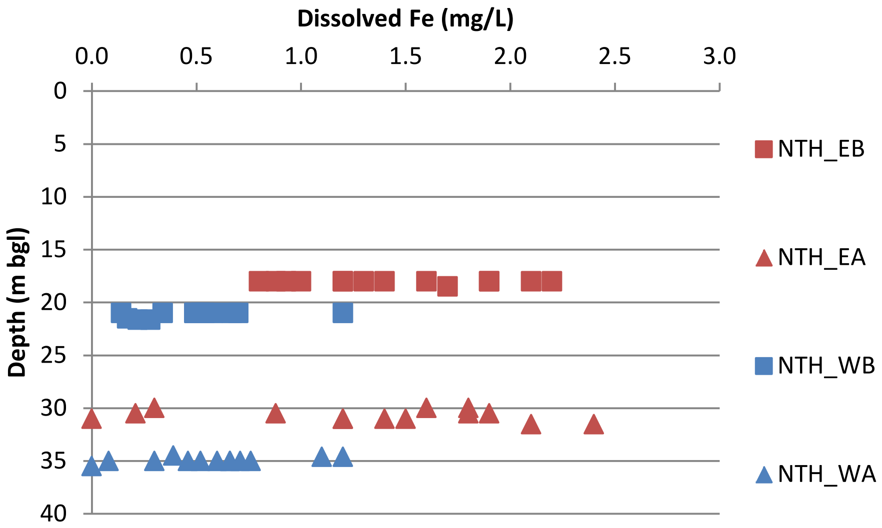


*Figure 44 Dissolved iron in groundwater near the middle and base of the Superficial aquiferbeneath North Lake*

### *Arsenic*

Very low concentrations (< 0.001–0.0018 mg/L) of arsenic were recorded in surface water. Even when pH at NTH_S1 was very low (pH 3.01), arsenic levels were very low (0.0018 mg/L). These concentrations in surface water do not indicate a risk to environmental values or human health (DoH 2006; DEC 2010).

Elevated levels of arsenic were found in groundwater near the water table at NTH_EC and throughout the middle of the aquifer beneath the lake (Figure 45). Arsenic in groundwater near the water table and middle of the aquifer beneath the eastern edge of the lake, ranged between < 0.001 mg/L (NTH_EB) and 0.38 mg/L (NTH_EB, September 2007). Arsenic concentrations in these bores commonly exceed Department of Health non-potable groundwater use guideline of 0.07 mg/L (DEC 2010).

Elevated arsenic levels are associated with evidence of particulate iron in the samples and may be more concentrated than soluble arsenic within the aquifer. Particulate iron was indicated by total iron being greater than soluble iron, particularly in the middle of the aquifer (NTH_EB). Particulate iron within bores can adsorb and concentrate arsenic as groundwater flows through and result in total arsenic concentrations being higher than soluble arsenic in groundwater. The particulate material may have been dislodged from the bores during sampling contributing to over-estimation of arsenic in the samples obtained. Elevated arsenic concentrations can be a by-product of pyrite oxidation and/or may also be released under reductive dissolution processes at near neutral pH values, which is likely the case for mid-aquifer groundwater beneath the eastern edge of the lake (NTH_EB).

This investigation measured arsenic in total concentrations, meaning samples were not filtered through a 0.45 µm filter. So, depending on the level of suspended particulates in water sampled from bores, arsenic concentrations in terms of significance to environmental and health values may be overestimated. Later samples taken outside the investigation period in 2012 were field filtered enabling determination of soluble arsenic, rather than total concentrations. This found concentrations of soluble arsenic less than 0.016 mg/L, almost an order of magnitude less than sampling during the investigation period, and were within Department of Health non-potable groundwater use guideline of 0.07 mg/L (DEC 2010).

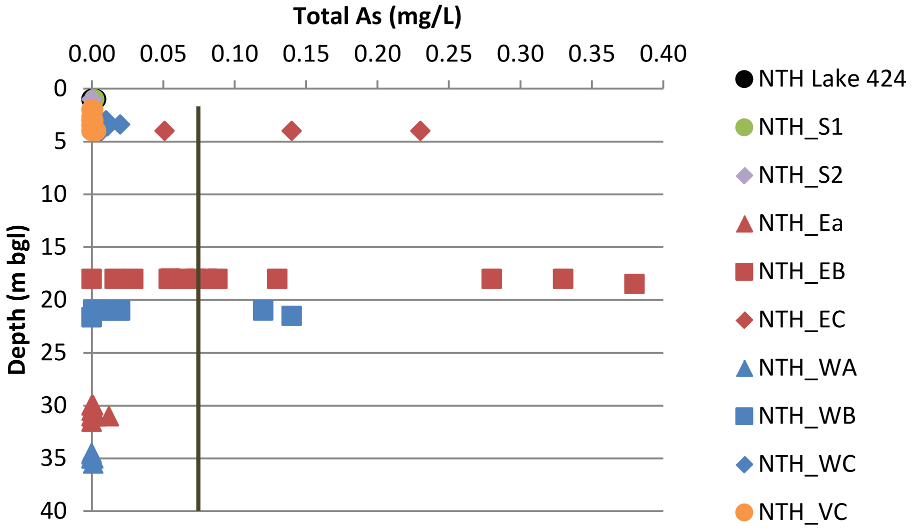


*Figure 45 Arsenic in surface water and groundwater. Note: Vertical line indicates DoH (2006) non-potable groundwater use guide for arsenic of 0.07 mg/L.*

*Manganese*

In this investigation manganese was measured in total concentrations, meaning samples were not filtered through a 0.45 µm filter; therefore, depending on the level of total suspended solids, the concentrations may be overestimated in terms of significance to environmental and health values. During groundwater sampling in May and September 2012 manganese was measured as dissolved concentrations.

Similar to trends in pH, acidity, alkalinity and other metals, over the sampling period manganese had the widest range in concentrations near the water table and in surface water. Manganese levels were generally higher near the water table and in surface water than in groundwater near the middle and base of the Superficial aquifer (Figure 46).

The highest concentration of manganese (1.9 mg/L) was recorded at NTH_S1, in a highly acidic (pH 3.01) sample. All other samples had manganese concentrations lower than the freshwater guidelines (ANZECC 2000). Manganese in surface water at the western edge of the lake (NTH Lake 424) ranged between 0.22 mg/L (November 2007) and 0.6 mg/L (September 2012).

Manganese in groundwater near the water table varied between 0.007 mg/L (NTH_EC, November 2007) and 0.78 mg/L (NTH_WC, April 2007) and concentrations were fairly similar upgradient and downgradient of the lake.

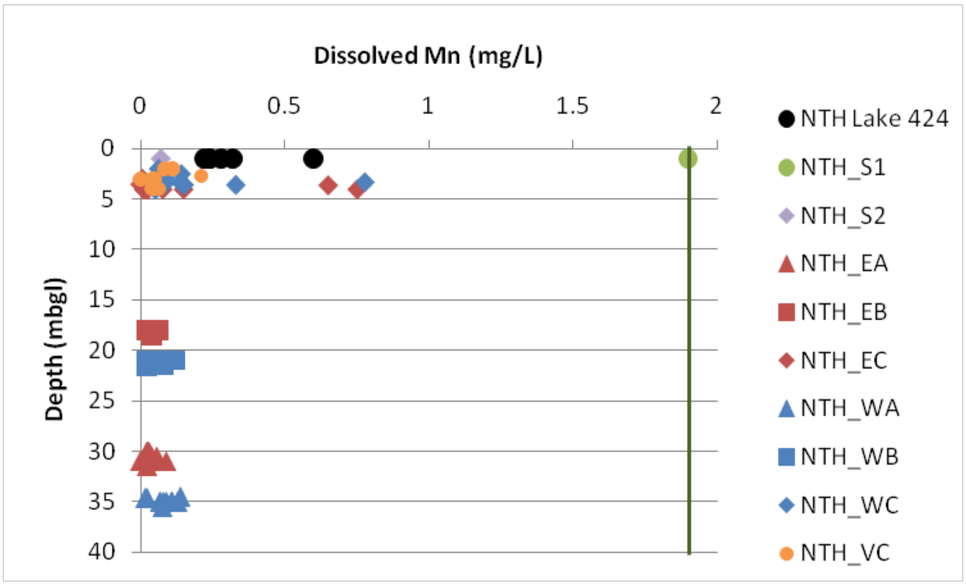


*Figure 46 Manganese in surface water and groundwater. Note: Vertical line indicates fresh water guideline for manganese is 1.9 mg/L (DEC 2010).*

*Other metals and metalloids*

This investigation also included assessments of other metals and metalloids in groundwater and surface water, such as cadmium, chromium, nickel, selenium and zinc. These species were generally recorded at low limits and not considered a significant risk to environmental values and human health. The results of all water quality data is in Appendix D.

## Nutrients (nitrogen and phosphorus)

The following nitrogen compounds were assessed as part of this Perth SGS investigation:

- Total nitrogen (TN)
- Total oxidised nitrogen (TON)
- Ammonia/ium
- Total Kjeldahl nitrogen
- Dissolved organic nitrogen (DON).

### *Total nitrogen*

Total nitrogen (TN) is a measured value that includes both reduced and oxidised forms of nitrogen. Higher levels of total nitrogen were generally recorded in surface water and in groundwater at the water table. Nearly all the investigation’s samples collected from surface water and shallow groundwater recorded total nitrogen at levels greater than 1.5 mg/L: the guideline for wetlands in the south-west of Western Australia (ANZECC 2000). Total nitrogen levels were higher in shallow groundwater at the western downgradient edge of the lake than at the eastern upgradient edge of the lake.

Total nitrogen in groundwater near the water table on either side of North Lake was between 1.1 mg/L (NTH_EC, July 2007) and 4.7 mg/L (NTH_WC, August 2007). Elevated levels were also recorded in groundwater at the water table at NTH_VC: between 0.98 mg/L (February 2008) and 4.00 mg/L (September 2012; Figure 47).

Lower levels of TN were also found in groundwater deeper in the Superficial aquifer, where concentrations were more consistent over the study period than in groundwater near the water table (Figure 47). Total nitrogen up to 6.5 mg/L was measured at NTH_WB. As this was recorded with no variation in $NO_x$ or ammonia it likely represents a high organic nitrogen concentration.

The total nitrogen composition in groundwater and surface water at North Lake is generally derived from ammonia/ium and dissolved organic nitrogen rather than nitrate.

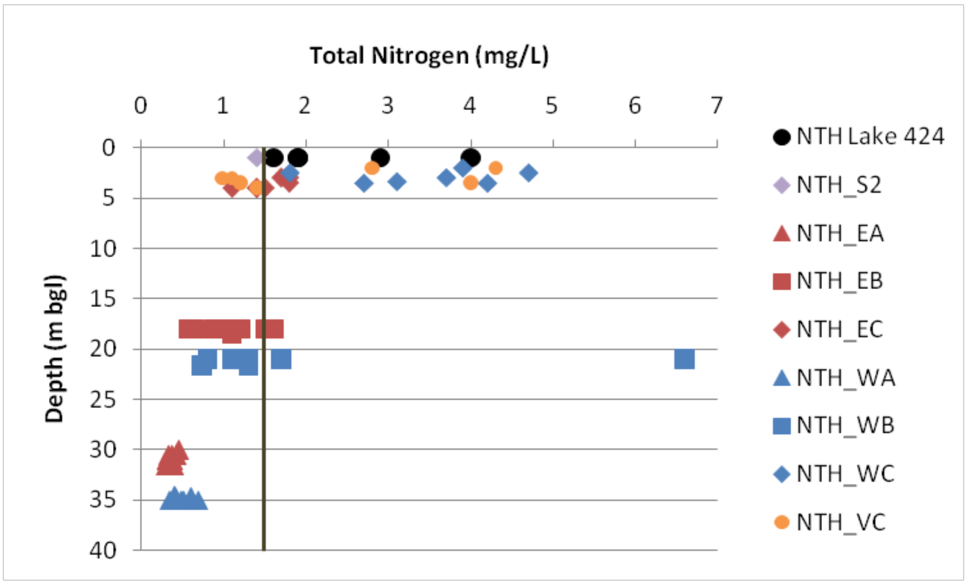


*Figure 47 Total nitrogen in surface water and groundwater. Note: vertical line at 1.5 mg/L, the TN guide for wetlands in south-western Australia*

### *Total oxidised nitrogen*

Total oxidised nitrogen (TON) is a measure of inorganic nitrite ($NO_2$) and nitrate ($NO_3$) and may be referred to as $NO_x$ to reflect this species composition. $NO_2$ is commonly an intermediate product and TON is generally dominated by $NO_3$, particularly where it is exposed to oxygen. The presence of TON is largely controlled by the oxidation-reduction potentials of groundwater. For example, TON is stable under oxidising conditions and low concentrations or not detectable in groundwater under reducing conditions.

NOx concentrations in groundwater and surface water were low. All concentrations were below the south-western Australia guideline of 0.1 mg/L for wetlands (ANZECC 2000), except at NTH_WC where nitrate was up to 0.83 mg/L (June 2008).

### *Ammonia/ium*

Ammonia ($NH_3$) and ammonium ($NH_4$) are measured collectively and reported as one value that includes both species and referred to as ammonia/ium. Ammonia/ium is a reduced nitrogen compound and is generally identified in groundwater under reducing conditions (negative oxidation reduction potentials). Guidelines for water quality in wetlands of south-western Australia are 0.04 mg/L (ANZECC 2000).

Levels of ammonia/ium are highly variable; for example, ammonia/ium ranged between 0.014 mg/L (July 2008) and 0.27 mg/L (September 2007) in surface water at the western edge of the lake (NTH Lake 424). However, in the acidic pool of water sampled in May 2012, at the south-eastern part of the lake, it was up to 48 mg/L (not shown in Figure 48 due to scale).

Ammonia/ium levels were higher (up to 2.0 mg/L) in groundwater near the water table at the western edge of the lake (NTH_WC) than in bores screened at the water table east of the lake (NTH_EC and NTH_VC).

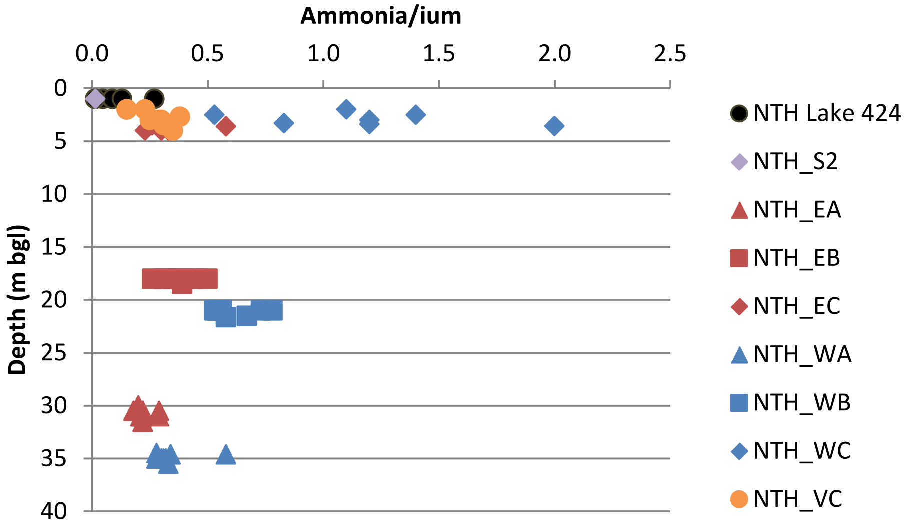


*Figure 48 Ammonia/ammonium in surface water and groundwater*

### *Dissolved organic nitrogen*

Dissolved organic nitrogen (DON) is calculated by subtracting the dissolved ammonia/ium and $NO_x$ concentrations from the total nitrogen concentration in a filtered sample. DON was higher in surface water and groundwater near the water table than in groundwater deeper in the Superficial aquifer (Figure 49).

The majority of the nitrogen is made up of organic nitrogen, with smaller portions of ammonia/ium and nitrate. The presence of organic nitrogen and organic carbon is probably driving nitrate reduction processes in groundwater.

### *Phosphorus*

Total phosphorus (TP) concentrations in groundwater were up to 0.35 mg/L and 0.13–0.17 mg/L in North Lake during this study (Figure 50).These concentrations are an order of magnitude higher than ANZECC guidelines for lakes (0.01 mg/L) and twice the guideline concentration for wetlands (0.06 mg/L). TP concentration in the intermediate bore west of the lake was higher in July 2007, similar to TN in this bore. The guide for total phosphorus in wetlands of south-western Australia is 0.6 mg/L (ANZECC 2000). All groundwater samples collected in this investigation have total phosphorus less than these guidelines (Figure 50).

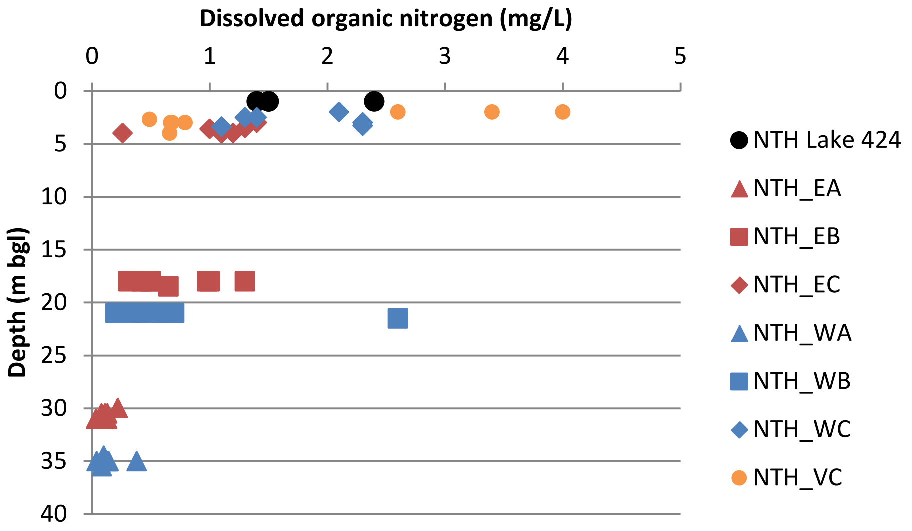


*Figure 49 Dissolved organic nitrogen in surface water and groundwater*

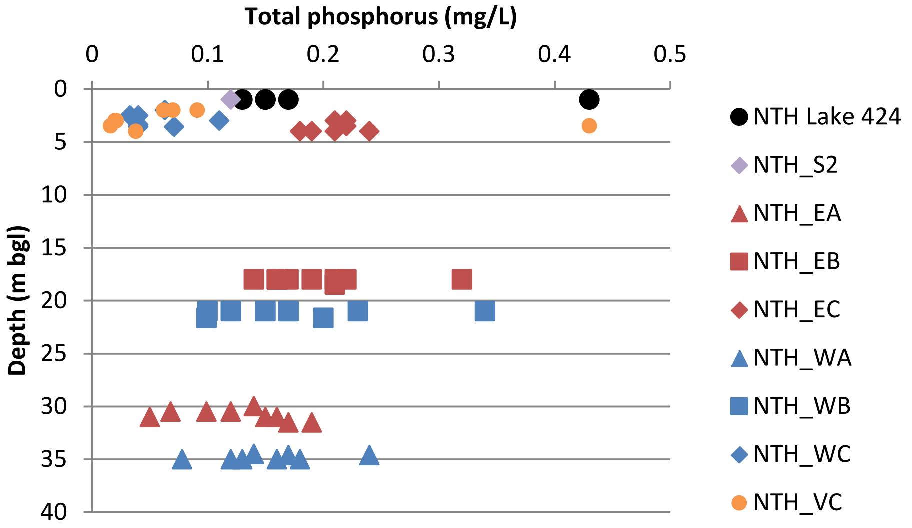


*Figure 50 Phosphorus in surface water and groundwater*

## Dissolved organic carbon

Dissolved organic carbon (DOC) concentrations were higher in groundwater near the water table and in surface water than in groundwater near the middle and base of the Superficial aquifer beneath North Lake (Figure 51). Higher levels were generally detected beneath the western edge of North Lake (NTH_WC and NTH_WB) than in groundwater beneath the eastern edge of the lake (NTH_EC and NTH_EB).

Dissolved organic carbon up to 140 mg/L was measured at NTH_VC in October 2007; this bore also had the widest range in concentrations throughout the monitoring period. The source of DOC is unclear but there is a linear relationship between DON and DOC suggesting similar processes are driving these parameters. Under reducing conditions the presence of organic carbon could drive reduction of oxidants like sulfate and the formation of pyrite. Decreases in DOC with depth may indicate consumption by bacteria within the aquifer (Appleyard et al. 2006).

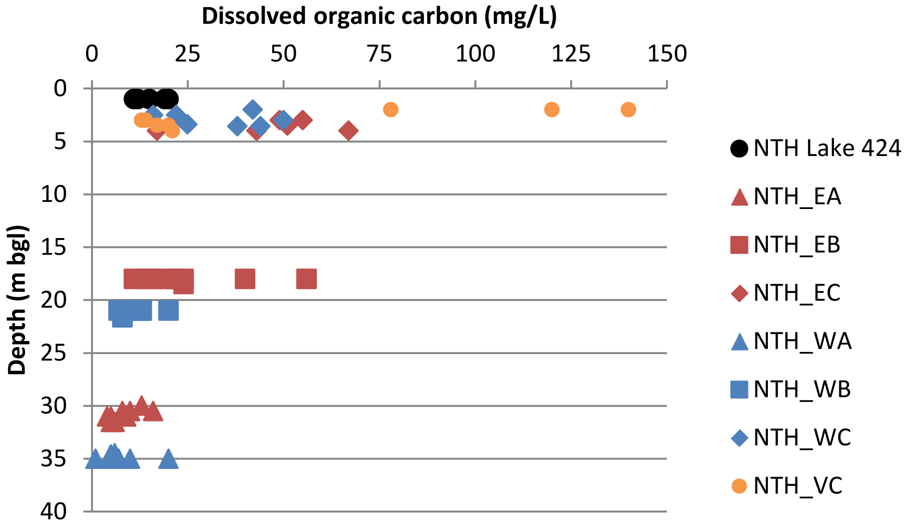


*Figure 51 Dissolved organic carbon in surface water and groundwater*

## Pesticides and herbicides

Water samples were analysed for a range of pesticides and herbicides (see Appendix B for full list of analytes) once during the study period. No pesticides or herbicides were detected in the lake or groundwater.

# 6 Key findings

## 6.1 Water movement at North Lake

### Surface water-groundwater interaction

This study confirmed North Lake is a groundwater dependent flow-through wetland located in the inter-dunal depression of the Spearwood and Bassendean Dune Systems. North Lake is underlain by the poorly buffered Bassendean Sand with the well buffered calcareous Tamala Limestone to the west of the lake. Groundwater flows in a south-east to north-west direction through North Lake. When the lake holds water, groundwater from the upper half (approximately 20 m) of the Superficial aquifer flows up to the lake on the east (upgradient edge of the lake) and down and out of the lake on the west (downgradient edge of the lake; figures 29 & 52). When the lake is dry, the water table is present within lake bed sediments and groundwater flow is horizontal with minimal vertical groundwater flow (Figure 29). The quality of groundwater at the western edge of the lake (NTH_WC) is highly influenced by the quality of water in lake outflow.

### Lake bed sediments

The lake bed sediments consist of organic silts and extensive diatomaceous deposits up to 9.5 m thick (NTH_L03). These sediments are underlain by Bassendean Sand. Diatomite has a high moisture retention capacity which likely explains the observations of pools of surface water during dry summer months. An example of the soil moisture capacity of diatomite using a neutron probe was found in the Yeal area (50 km north of Perth); it showed diatomite can contain 40–60% soil moisture by weight. Bassendean Sand has a much lower water retention capacity and may contain only 5–10% soil moisture by weight (Antao 2009a, b).

The thickness of lake bed sediments at North Lake varies from 0.6 m (NTH_L01) to 9.5 m (NTH_L03). This investigation showed lake water levels are consistently lower than the water table on the eastern inflow side of the lake and higher than the water table on the western outflow side of the lake. This highlights the dependence of the lake on regional groundwater levels.

Lake bed sediments are a significant store of acidity, metals and metalloids (Figure 52). Sediment investigations recorded high levels of potential acidity ($S_{CR}$ up to 1.6% and $pH_{FOX}$ down to 1.5), aluminium and iron. When the lake dries, there is a potential for the release of acidity, metals and metalloids into surface water and subsequently groundwater, downgradient of the lake. There is evidence of this in groundwater near the water table at the western edge of the lake (NTH_WC).

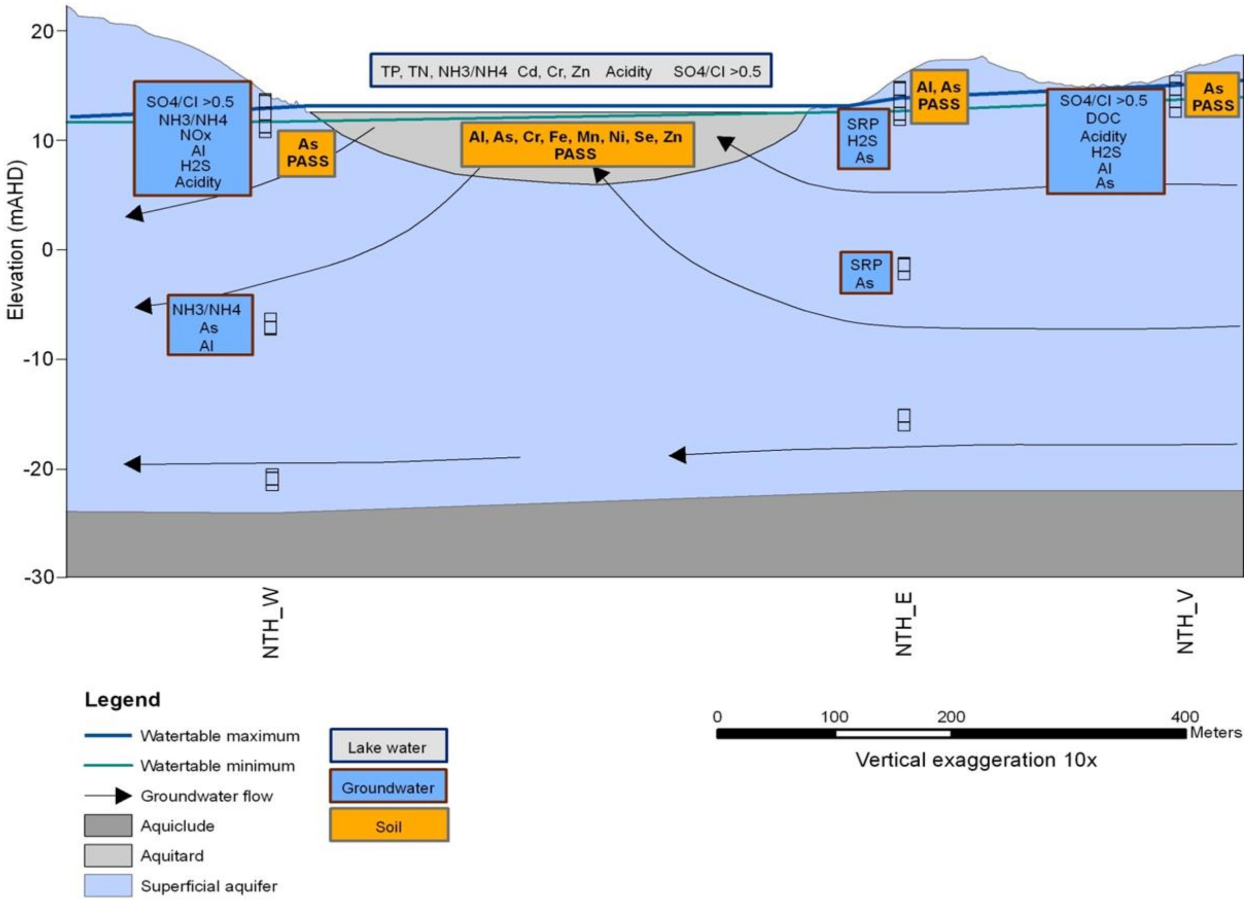


*Figure 52 Conceptual diagram of surface water-groundwater interaction and the main chemical parameters in groundwater. Note: screened intervals of bores shown.*

## 6.2 Water levels, water quality and ecological implications at North Lake

### Water levels

At North Lake groundwater and surface water levels have declined since the late 1980s. Groundwater level decline is due to reduced rainfall and groundwater abstraction. In the late 1990s the lake dried for the first time since records began in 1972. Since 2006 North Lake has seasonally dried each year.

The seasonal drying is threatening ecological values. Recent surface water levels have failed to meet Ministerial water level criteria and ecological water requirements recommended by Froend et al. (2004b) for macroinvertebrates, sponges, frogs, turtles, waterbirds and sediment processes. Water levels have been non-compliant with the absolute summer minimum criterion since 1999–2000 and have also mostly failed to be high enough to inundate *Melaleuca* species on both sides of the wetland and to prevent the spread of sedges and exotics into the basin.

North Lake dries at an elevation of 12.38 m AHD. In recent years the lake has been dry for approximately five months each summer/autumn. This is likely to have caused declines in macroinvertebrate family richness and the loss of the lake's freshwater sponges which are thought to require permanent water (Froend et al. 2004b). The protracted dry periods may be reducing the survival of frog eggs and tadpoles, thereby affecting recruitment success of frogs at and around the lake. The dry periods may also be adversely affecting long-necked turtles at North Lake (WRM 2007). Although long-necked turtles can survive in wetlands which are dry for up to 6 months of the year, they prefer near permanent surface water (Froend et al. 2004b) as their diet consists mainly of tadpoles, fish and aquatic invertebrates which are only available when open water is present (WRM 2007).

The drying of the lake, encroachment of vegetation and loss of muddy shore areas have contributed to fewer waterbirds using the lake as summer refuge or visiting the lake (Froend et al. 2004b).

### Acidification and pyrite oxidation

Acidification processes in surface water and groundwater near the water table are largely attributed to pyrite oxidation. This is supported through identification of actual acid sulfate and potential acid sulfate soil at North Lake. Surface water and groundwater near the water table show very low levels of alkalinity, high sulfate to chloride ratios (> 0.5) and elevated levels of aluminium and iron.

Pyrite oxidation can be summarised by the following (Appelo & Postma 2005):

$$2FeS_2 + 15/2O_2 + 5H_2O \rightarrow 2FeOOH + 4SO_4^{2-} + 8H^+$$

Pyrite oxidation is a very efficient acid-generating process where one mole of pyrite ($FeS_2$) may produce up to four moles of acidity ($H^+$). Acidification processes such as pyrite oxidation can be triggered from sediment disturbance or fluctuating water levels. Declining water levels expose iron sulfide minerals, such as pyrite, previously stable under anaerobic conditions.

Pyrite oxidation has lowered alkalinity levels in surface water and groundwater near the water table. North Lake is periodically acidic and on occasions pH values were low (down to 4.37 in July 2008 and 3.01 in pools of surface water in the lake in May 2012). pH values are below freshwater ecosystem values (pH 6.5) for wetlands in south-west Australia and acidity is likely affecting the lake's ecology.

There is very little buffering capacity in the lake water. Alkalinity levels less than 60 mg/L with a corresponding pH less than 6.0 are not sufficient to maintain stable and acceptable pH values (Swedish EPA 2002). Lake water consistently recorded alkalinity levels less than 10 mg/L as $CaCO_3$ and is unable to buffer against pH changes and is highly susceptible to acidification.

The oxidation of lake bed sediments (when the lake dries) has affected the quality of water recharging the Superficial aquifer at the western edge of the lake. This is shown by very low alkalinity levels, low pH and higher aluminium, iron and sulfate to chloride ratios at the western edge of the lake compared to other bores screened at the water table.

Pyrite oxidation appears limited to surface water and groundwater near the water table and is not evident in groundwater near the middle or base of the Superficial aquifer beneath North Lake. Reducing conditions and very low levels of sulfate in the lower half of the Superficial aquifer support this.

North Lake is at risk of permanent acidification, similar to Lake Mariginiup. Lake Mariginiup recorded episodic acidification, evident from fluctuating pH values between 2002 and 2007. However after alkalinity reserves were exhausted from continued acidification and continued acidic groundwater input, the lake has been permanently acidic since 2008 (Searle et al. 2010). Acidification at Lake Mariginiup is due to circumstances similar to North Lake. Both lakes are located in the inter-dunal depression of the Bassendean and Spearwood dune systems and both have dried at an increased frequency due to declining groundwater levels as a result of lower rainfall and groundwater abstraction. Furthermore, the oxidation of pyrite is considered the primary cause of acidification.

## Release of metals and metalloids in water

Aluminium, iron, manganese and arsenic were the main species of concern in groundwater around North Lake. Relevant mechanisms for ion release include low pH, oxidation and reductive dissolution processes. Organic matter is important in catalysing some of these processes

### Aluminium in surface water and groundwater

Elevated levels of aluminium were found in groundwater near the water table and in surface water at North Lake, mainly due to acidification processes and low pH. Elevated levels of aluminium were also recorded near the middle of the Superficial aquifer beneath the western edge of North Lake but as a result of different chemical processes as pH values are near neutral and highly reducing (–ve oxidation reduction potential).

The speciation of aluminium is important for ecological health considerations because monomeric aluminium is more toxic than aluminium bound to organic complexes (Kerven et al. 1989). Water hardness also plays a role in the toxicity of aluminium. Aluminium is less toxic when concentrations of calcium and magnesium are high (ANZECC 2000).

When pH falls below 4.5 aluminium solubility increases, and the more toxic monomeric aluminium ($Al^{3+}$) can be released (Appelo & Postma 2005). From sampling conducted between 2007 and 2012 surface water had pH less than 4.5 on three occasions. These low pH values coincided with higher levels of aluminium. In groundwater near the water table low pH values found west of the lake (NTH_VC) are likely a result of acidification from pyrite, and aluminium in the monomeric form is considered likely. However, in groundwater at the eastern edge of the lake (NTH_EC), aluminium is likely to be in a less toxic form, bound to organic complexes, given slightly higher pH values. There is also evidence to suggest pyrite oxidation at NTH_EC; however, this acid-generating process is yet to lower alkalinity levels to cause significant pH decline that would ultimately affect the species of aluminium present in groundwater. It should also be noted that as bore NTH_EC is blocked, it has not been sampled since 2008 this is not a contemporary understanding of groundwater chemistry at this location.

Acid toxicity can result in the loss of sensitive fringing vegetation, proliferation of invasive species and terrestrialisation. Acid toxicity is more likely when the mobilisation of aluminium induces lower calcium to aluminium molar ratios. Low calcium to aluminium molar ratios pose higher risks to ecological values, including reduction in root growth, inhibition of calcium and magnesium uptake by fine roots, and a reduction in the water conductivity of roots (Caspary 1991). The loss of calcium from soils, such as through leaching or acidification processes can lead to a progressive decline in the health of both woodland and wetland ecosystems and the loss of plant and animal species (DEC 2009b).

In groundwater near the middle of the Superficial aquifer beneath the western edge of the lake, the release of aluminium may be due to some kind of reductive dissolution processes. Reducing conditions are supported by highly negative oxidation–reduction potentials and very low sulfate concentrations, indicating sulfate reduction. Sediments at the screened interval of NTH_WB have high clay content and are described as ‘silty sand’. Sediments in bores screened at the water table are medium grained quartz sand (Appendix A). Dissolved organic carbon was not recorded at higher levels in the middle of the aquifer at NTH_WB compared to others, so based on the data the release of aluminium associated with organic complexes was not considered a likely reason. More detailed investigation into the release of aluminium may be required at this location.

### *Iron throughout the vertical extent of the Superficial aquifer*

Elevated concentrations of iron are evident throughout the entire vertical extent of the Superficial aquifer which includes Bassendean Sand (shallow and intermediate bores) and the Ascot Formation (deep bores). Groundwater beneath the lake generally had higher levels of iron throughout the entire vertical extent of the Superficial aquifer than were identified in similar investigations conducted at Lake Mariginiup (Searle et al. 2010) and at the Egerton Seepage (McHugh et al. 2011). However, iron in groundwater beneath North Lake was lower than concentrations found in highly degraded groundwater east of Lake Gwelup (Clohessy 2012).

Iron levels varied most near the water table, particularly in the iron-enriched groundwater at the western edge of the lake. The groundwater quality near the water table often varies and is subject to change over time given a fluctuating water table initiates and promotes many geochemical interactions. These concentrations highlight the difference in groundwater chemistry near the water table compared with groundwater near the middle of the aquifer. Iron near the water table is likely being released through oxidation processes, a contention also supported by low pH, high sulfate levels and high sulfate to chloride ratios.

Ferrous iron ($Fe^{2+}$) is the dominant form of iron in the pH range 5–8 (Appelo & Postma 2005) and this is likely the form of iron in most areas of North Lake and its groundwater environment. Where conditions are more acidic, as in surface water at various times and in groundwater near the water table at the western edge of the lake, the mix is also likely to include ferric iron ($Fe^{3+}$).

Elevated levels of iron in the middle and base of the Superficial aquifer varied over time throughout the monitoring period. Iron is likely being released through reductive dissolution processes, given the reducing oxidation-reduction potentials and very low concentrations of sulfate, indicating sulfate reduction.

### *Arsenic in the Superficial aquifer*

Elevated levels of arsenic, up to 0.38 mg/L (NTH_EB), were detected in the middle of the Superficial aquifer; they were commonly higher than Department of Health non-potable groundwater use guidelines (DEC 2010). However, as discussed previously, sampling conducted in 2007 – 2008 measured total arsenic, which may have overestimated the potential significance to the environment or human health.

North Lake is not located in a public drinking water source protection area and the Superficial aquifer in the area is not a source of potable water. The Department of Water recommends the area around North Lake is not suitable for installation of new garden bores (DoW 2011). Despite this, the findings of the study reinforce the need for users of untreated groundwater from domestic bores to test the quality of groundwater to ensure it is suitable for its intended use.

In Gwelup, elevated levels of arsenic have been recorded near the base and middle of the Superficial aquifer (Appleyard et al. 2006; Clohessy 2012). Similar groundwater conditions were identified beneath North Lake: highly reducing conditions with elevated levels of iron and high levels of bicarbonate alkalinity ($HCO_3$). The main difference between the quality of groundwater near the base and middle of the aquifer in Gwelup and North Lake is sulfate concentrations. Gwelup groundwater is enriched with iron and sulfate (Appleyard et al. 2006; Clohessy 2012), while the investigation at North Lake found very low to non-detectable levels of sulfate. The mechanism for arsenic release in Gwelup groundwater and beneath North Lake may be through the reductive dissolution of iron minerals by organic matter (represented as $CH_2O$) and may be described by the following:

$CH_2O + 4FeOOH + 7H^+ \rightarrow 4Fe^{2+} + HCO_{3-} + 6H_2O$ (Appelo & Postma 2005).

This process was thought to be a possible cause for the release of low concentrations of arsenic in the lower half of the Superficial aquifer in the Gwelup area (5–15 µg/L; Appleyard et al. 2006).

Arsenic was generally not detected or detected at low concentrations in deeper groundwater monitoring bores at the base of the Superficial aquifer and screened in the Ascot Formation. This shows the possible effect of reductive dissolution processes in groundwater in Bassendean Sand near the middle of the aquifer is not evident in similar reducing conditions in the Ascot Formation. This highlights the influence of chemical composition of sediments on chemical processes in groundwater.

## Nutrients

Total nitrogen (TN) and total phosphorus (TP) measured in groundwater near the water table and in surface water were generally higher than ANZECC guidelines for nutrients in freshwater ecosystems (lakes and wetlands) in south-west Australia (figures 52 & 53). The historic source of phosphorus may have been direct input from the Murdoch drain. High concentrations of these nutrients can damage aquatic environments by stimulating the growth of algae and cyanobacteria which can then dominate and change the dynamics of the system (ANZECC 2000). Some species of cyanobacteria are toxic and can have directly lethal effects on waterbirds and large invertebrates (Davis & Froend 1999). High concentration of nutrients can also allow the proliferation of midges and mosquitoes (Arnold 1990), and create conditions that encourage the growth of the bacterium *Clostridium botulinum* (botulism) which produces a toxin that causes paralysis and death in waterbirds (DEC 2009b).

# 7 Recommendations

Recommendations are subject to Department of Water priorities and resource availability.

## Management actions

- The Ministerial criterion level should be measured at North Lake bore (61410726) when the lake is dry. A groundwater level of 12.25 m AHD at the bore is equivalent to the current Ministerial absolute minimum surface water level criterion.
- Groundwater levels should be measured at bore NTH_VC (60410460) when relating the water table to the ecological condition of the vegetation transect.
- Groundwater level monitoring in water table bores should be maintained to identify longer-term trends.
- Local area groundwater modelling could be used to calculate the change in water levels under reduced abstraction scenarios or altered drainage.

## Options for future monitoring and investigation

- A continuous, long term groundwater and surface water quality monitoring program could be implemented to assess the impacts of water level decline on water quality. The results of this investigation suggest future water quality monitoring should focus on (in priority order): pH, metals and metalloids, major ions and nutrients. Such a program would assist in drawing conclusions regarding the risk of deteriorating water quality on ecological values.
- Further assessment of the presence and extent of acid sulfate soils would help clarify the magnitude of the risk of water level decline on sediment and water quality. This could include:
    - Investigation of the rates of acidification and buffering processes.
    - Measurement of the storage and release of metals and metalloids within the lake bed sediments.
    - Delineation of the plume of sulfate- and iron-enriched acidic groundwater discharging from the western edge of the lake.

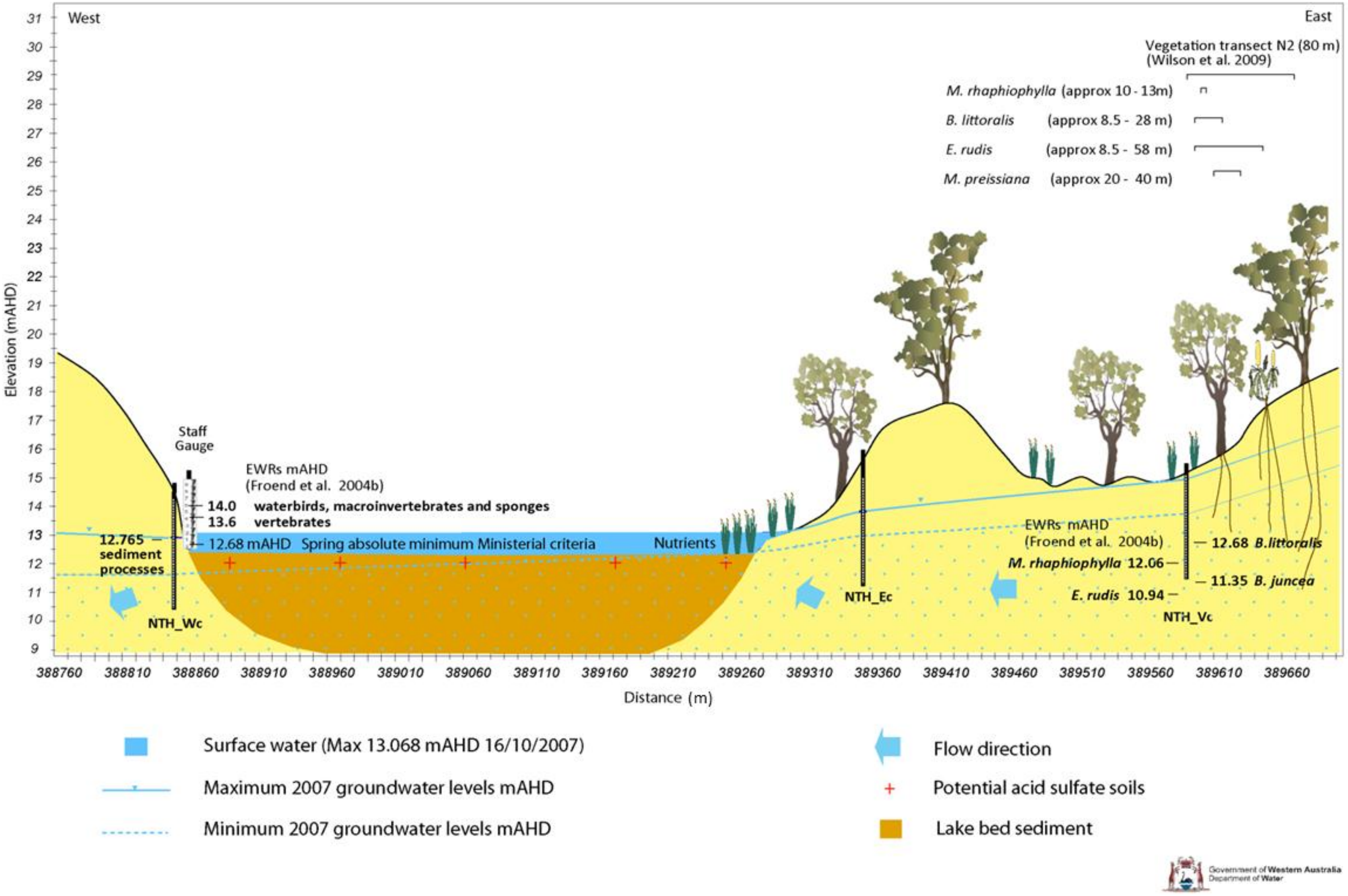
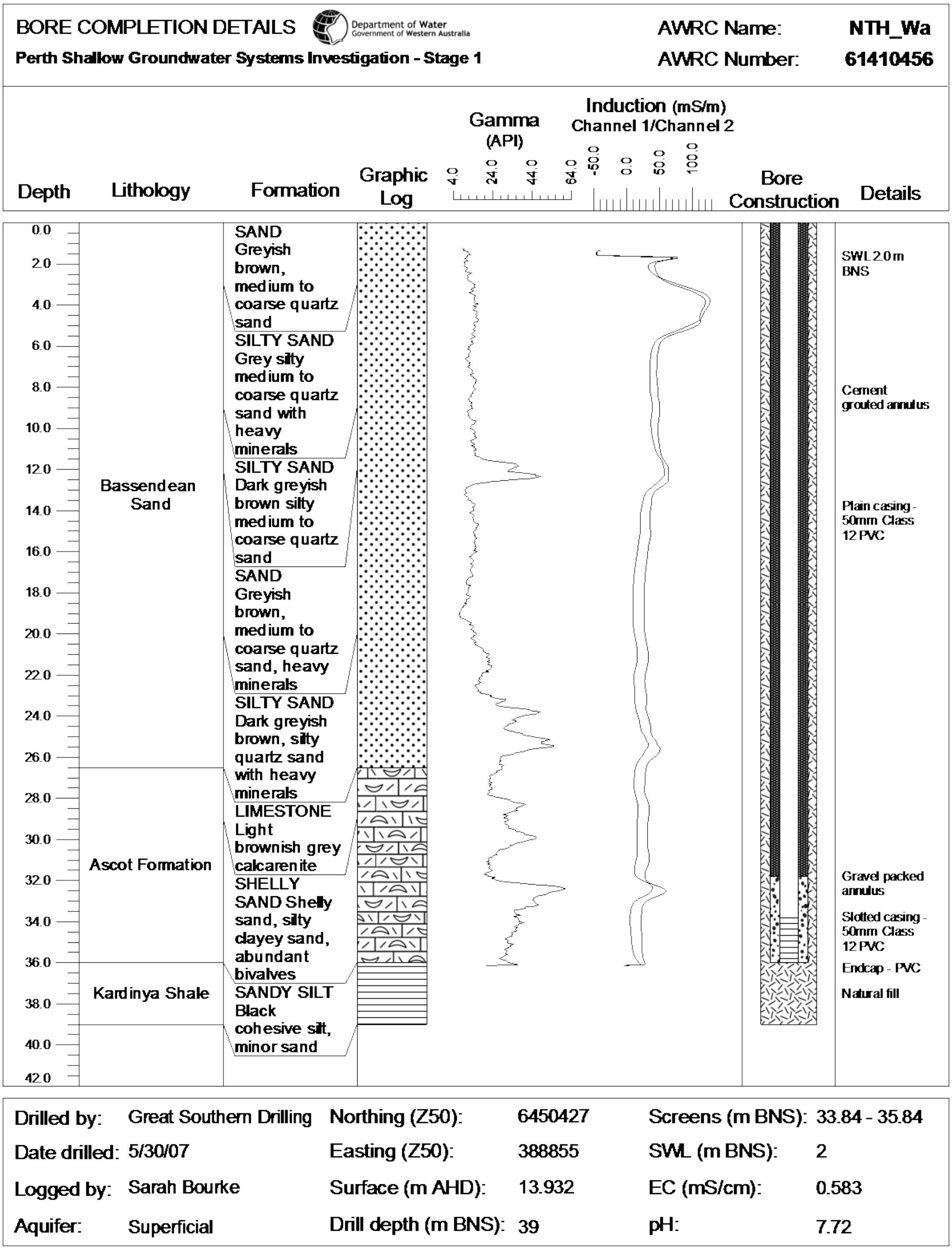


*Figure 53 Conceptual diagram of the relationships between the hydrogeology, chemistry and the wetland ecosystem of North Lake*

# Appendices

## Appendix A – Bore construction and lithology



**BORE COMPLETION DETAILS**

**Perth Shallow Groundwater Systems Investigation - Stage 1**

AWRC Name: **NTH_Wa**
AWRC Number: **61410456**

| Depth | Lithology | Formation |
|---|---|---|
| 0.0 | Bassendean Sand | SAND Greyish brown, medium to coarse quartz sand |
| | | SILTY SAND Grey silty medium to coarse quartz sand with heavy minerals |
| | | SILTY SAND Dark greyish brown silty medium to coarse quartz sand |
| | | SAND Greyish brown, medium to coarse quartz sand, heavy minerals |
| | | SILTY SAND Dark greyish brown, silty quartz sand with heavy minerals |
| | Ascot Formation | LIMESTONE Light brownish grey calcarenite |
| | | SHELLY SAND Shelly sand, silty clayey sand, abundant bivalves |
| | Kardinya Shale | SANDY SILT Black cohesive silt, minor sand |

Details:
SWL 2.0 m BNS
Cement grouted annulus
Plain casing - 50mm Class 12 PVC
Gravel packed annulus
Slotted casing - 50mm Class 12 PVC
Endcap - PVC
Natural fill

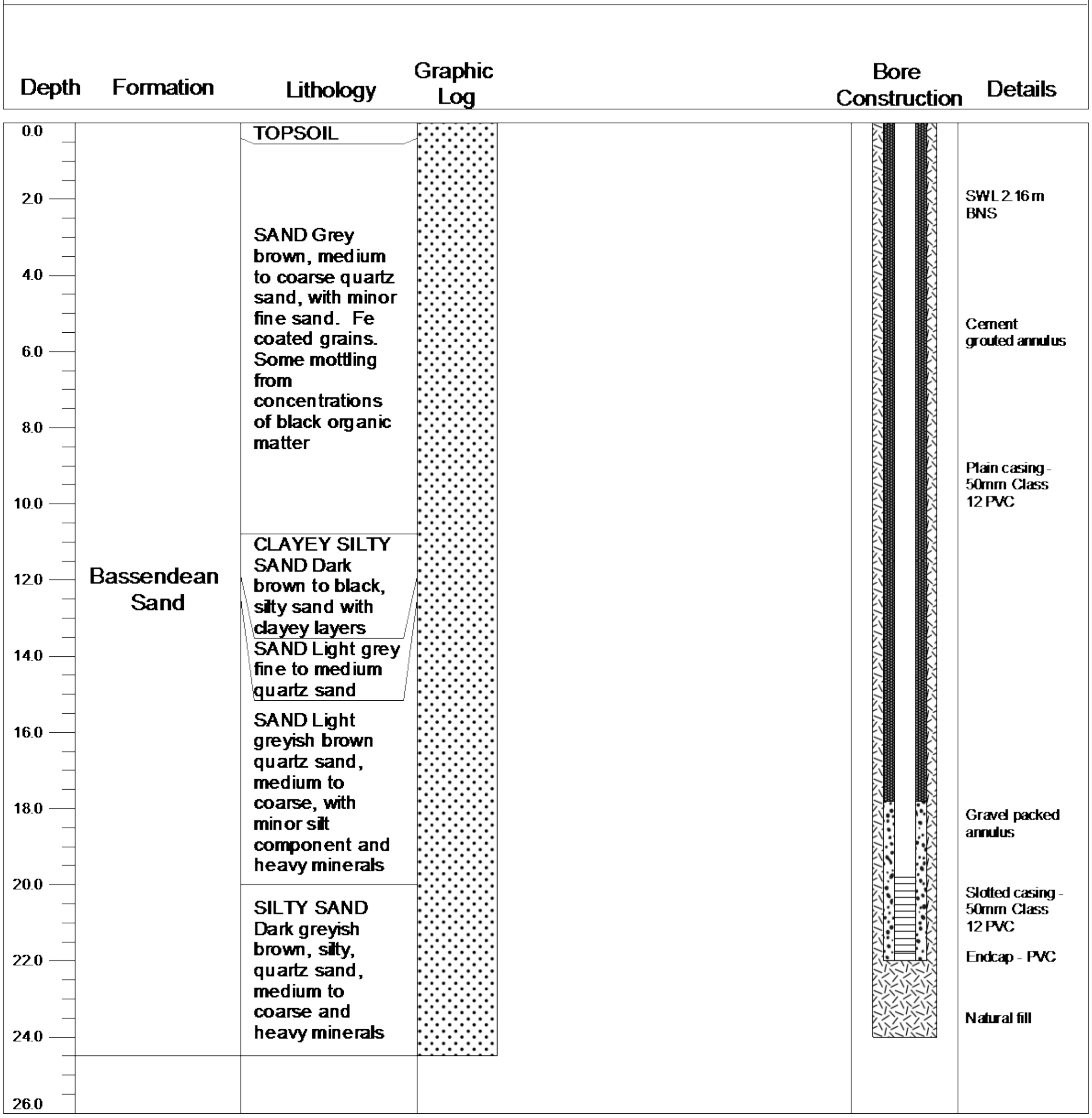
| | | | | | |
|---|---|---|---|---|---|
| Drilled by: | Great Southern Drilling | Northing (Z50): | 6450427 | Screens (m BNS): | 33.84 - 35.84 |
| Date drilled: | 5/30/07 | Easting (Z50): | 388855 | SWL (m BNS): | 2 |
| Logged by: | Sarah Bourke | Surface (m AHD): | 13.932 | EC (mS/cm): | 0.583 |
| Aquifer: | Superficial | Drill depth (m BNS): | 39 | pH: | 7.72 |

## BORE COMPLETION DETAILS

**Perth Shallow Groundwater Systems Investigation - Stage 1**

Department of Water
Government of Western Australia

| | |
|---|---|
| AWRC Name: | **NTH_Wb** |
| AWRC Number: | **61410455** |



TOPSOIL

SAND Grey brown, medium to coarse quartz sand, with minor fine sand. Fe coated grains. Some mottling from concentrations of black organic matter

CLAYEY SILTY SAND Dark brown to black, silty sand with clayey layers

SAND Light grey fine to medium quartz sand

SAND Light greyish brown quartz sand, medium to coarse, with minor silt component and heavy minerals

SILTY SAND Dark greyish brown, silty, quartz sand, medium to coarse and heavy minerals

SWL 2.16 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC

Endcap - PVC

Natural fill

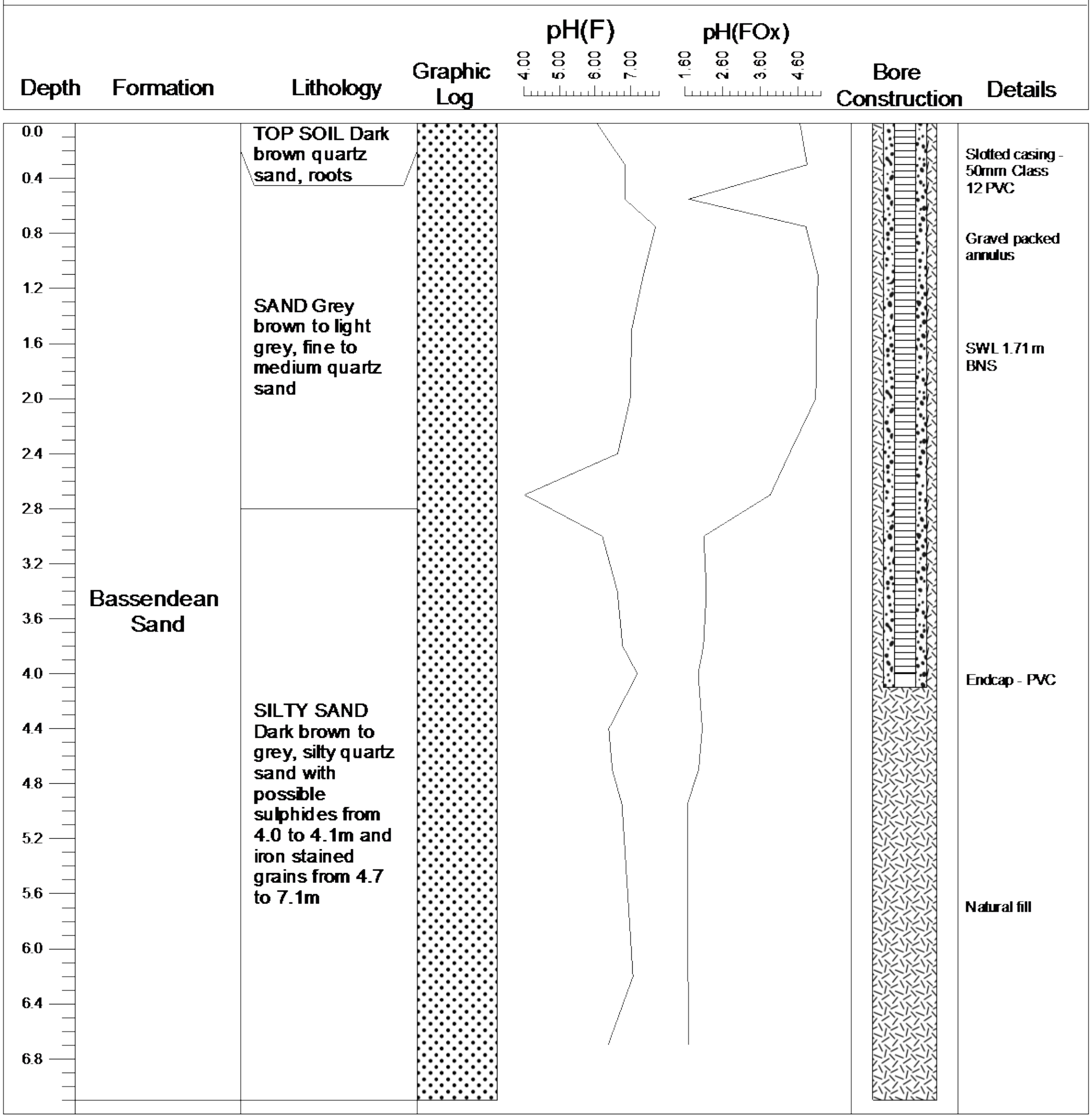
| | | | | | |
|---|---|---|---|---|---|
| Drilled by: | Great Southern Drilling | Northing (Z50): | 6450430 | Screens (m BNS): | 19.81 - 21.81 |
| Date drilled: | 5/31/07 | Easting (Z50): | 388854 | SWL (m BNS): | 2.16 |
| Logged by: | Sandie McHugh | Surface (m AHD): | 13.932 | EC (mS/cm): | 0.648 |
| Aquifer: | Superficial | Drill depth (m BNS): | 24 | pH: | 7.41 |

## BORE COMPLETION DETAILS

**Perth Shallow Groundwater Systems Investigation - Stage 1**

Department of Water
Government of Western Australia

AWRC Name: **NTH_Wc**
AWRC Number: **61410454**



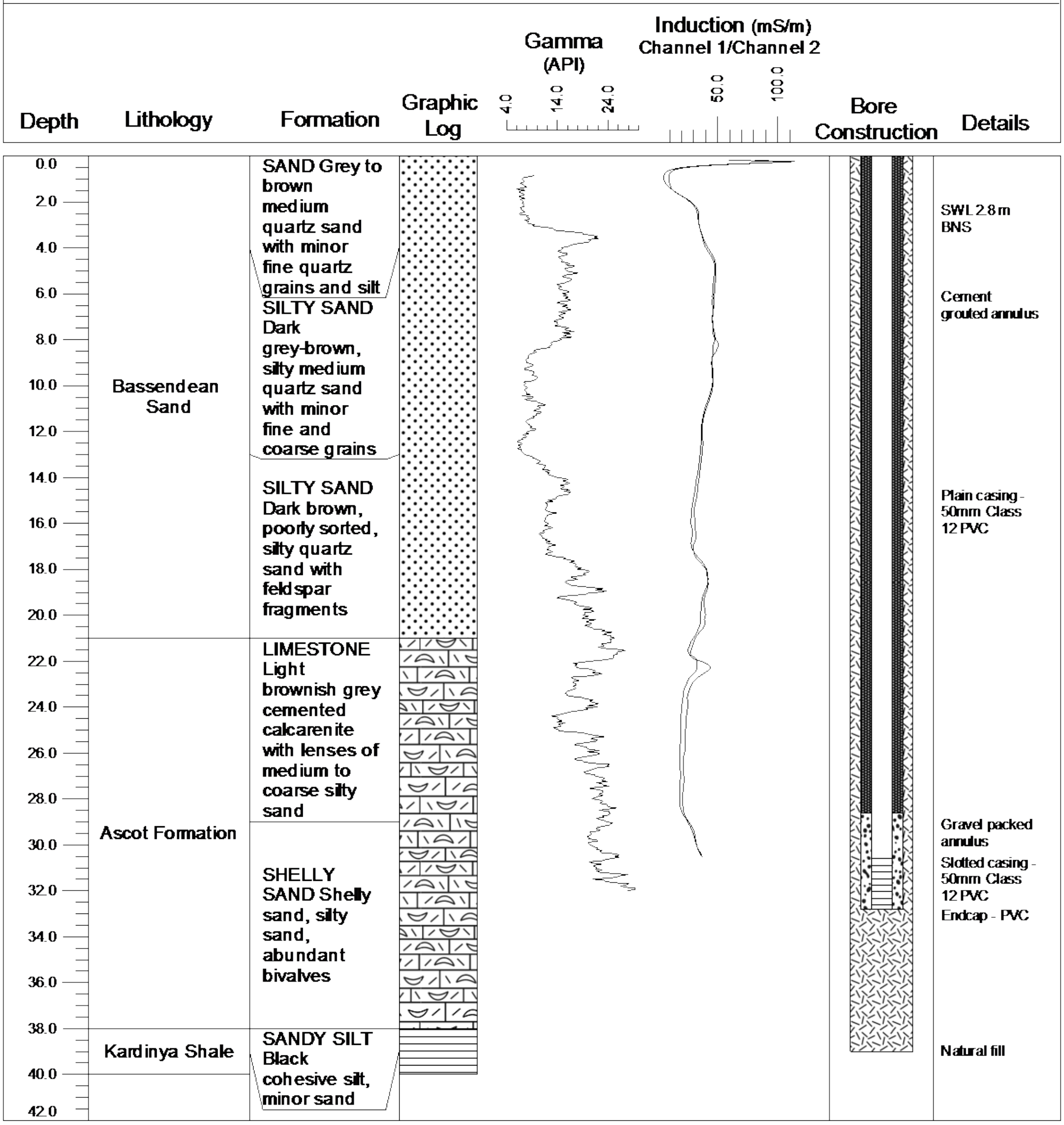
| | | | | | |
|---|---|---|---|---|---|
| **Drilled by:** | Great Southern Drilling | **Northing (Z50):** | 6450436 | **Screens (m BNS):** | 0.03 - 4.03 |
| **Date drilled:** | 4/18/07 | **Easting (Z50):** | 388853 | **SWL (m BNS):** | 1.71 |
| **Logged by:** | Sandie McHugh | **Surface (m AHD):** | 14.043 | **EC (mS/cm):** | 2.06 |
| **Aquifer:** | Superficial | **Drill depth (m BNS):** | 7.1 | **pH:** | 6.35 |

**BORE COMPLETION DETAILS** Department of Water Government of Western Australia

**Perth Shallow Groundwater Systems Investigation - Stage 1**

AWRC Name: **NTH_Ea**

AWRC Number: **61410459**



| | | | | | |
|---|---|---|---|---|---|
| Drilled by: | Great Southern Drilling | Northing (Z50): | 6450224 | Screens (m BNS): | 30.62 - 32.62 |
| Date drilled: | 5/29/07 | Easting (Z50): | 389354 | SWL (m BNS): | 2.8 |
| Logged by: | Sandie McHugh | Surface (m AHD): | 15.848 | EC (mS/cm): | 0.624 |
| Aquifer: | Superficial | Drill depth (m BNS): | 39 | pH: | 8.24 |

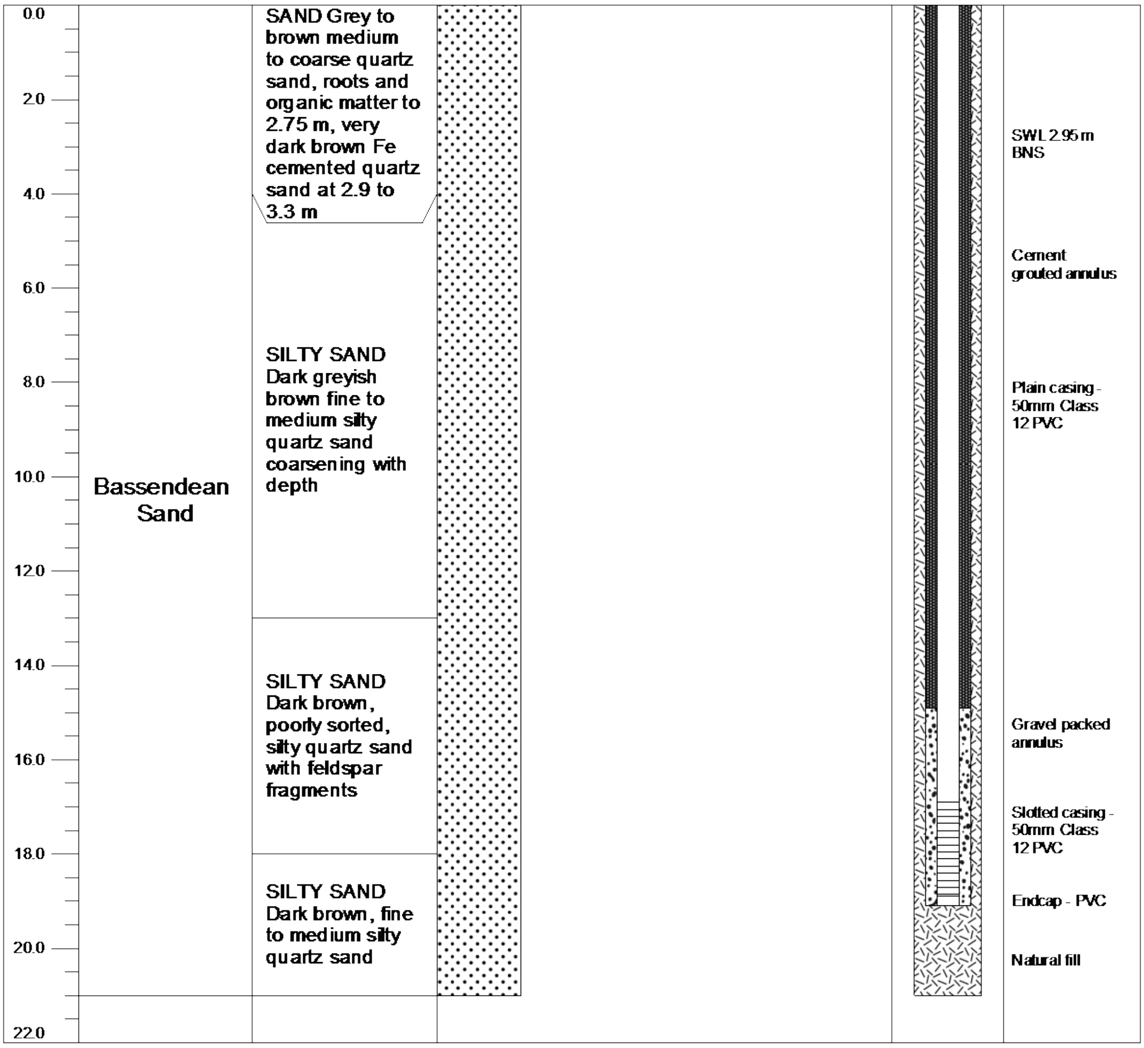
## BORE COMPLETION DETAILS

**Perth Shallow Groundwater Systems Investigation - Stage 1**

Department of Water
Government of Western Australia

AWRC Name: **NTH_Eb**
AWRC Number: **61410458**

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



Bassendean Sand

SAND Grey to brown medium to coarse quartz sand, roots and organic matter to 2.75 m, very dark brown Fe cemented quartz sand at 2.9 to 3.3 m

SILTY SAND Dark greyish brown fine to medium silty quartz sand coarsening with depth

SILTY SAND Dark brown, poorly sorted, silty quartz sand with feldspar fragments

SILTY SAND Dark brown, fine to medium silty quartz sand

SWL 2.95 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC

Endcap - PVC

Natural fill

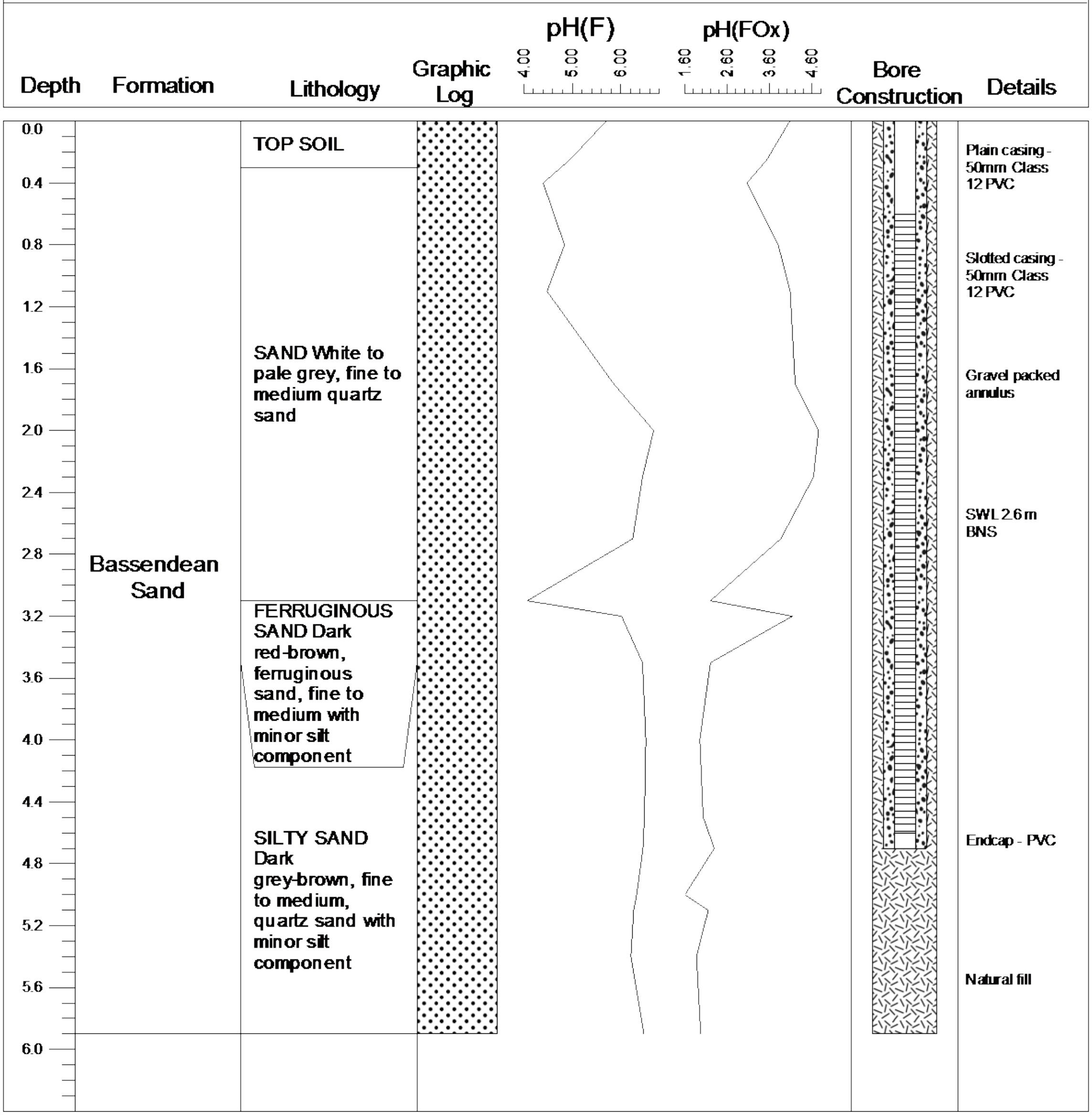
| | | | | | |
|---|---|---|---|---|---|
| **Drilled by:** | Great Southern Drilling | **Northing (Z50):** | 6450220 | **Screens (m BNS):** | 16.88 - 18.88 |
| **Date drilled:** | 5/30/07 | **Easting (Z50):** | 389354 | **SWL (m BNS):** | 2.95 |
| **Logged by:** | Sandie McHugh | **Surface (m AHD):** | 15.906 | **EC (mS/cm):** | 0.551 |
| **Aquifer:** | Superficial | **Drill depth (m BNS):** | 21 | **pH:** | 7.69 |

BORE COMPLETION DETAILS

**Perth Shallow Groundwater Systems Investigation - Stage 1**

Department of Water
Government of Western Australia

AWRC Name: **NTH_Ec**
AWRC Number: **61410457**



TOP SOIL

SAND White to pale grey, fine to medium quartz sand

FERRUGINOUS SAND Dark red-brown, ferruginous sand, fine to medium with minor silt component

SILTY SAND Dark grey-brown, fine to medium, quartz sand with minor silt component

Plain casing - 50mm Class 12 PVC

Slotted casing - 50mm Class 12 PVC

Gravel packed annulus

SWL 2.6 m BNS

Endcap - PVC

Natural fill

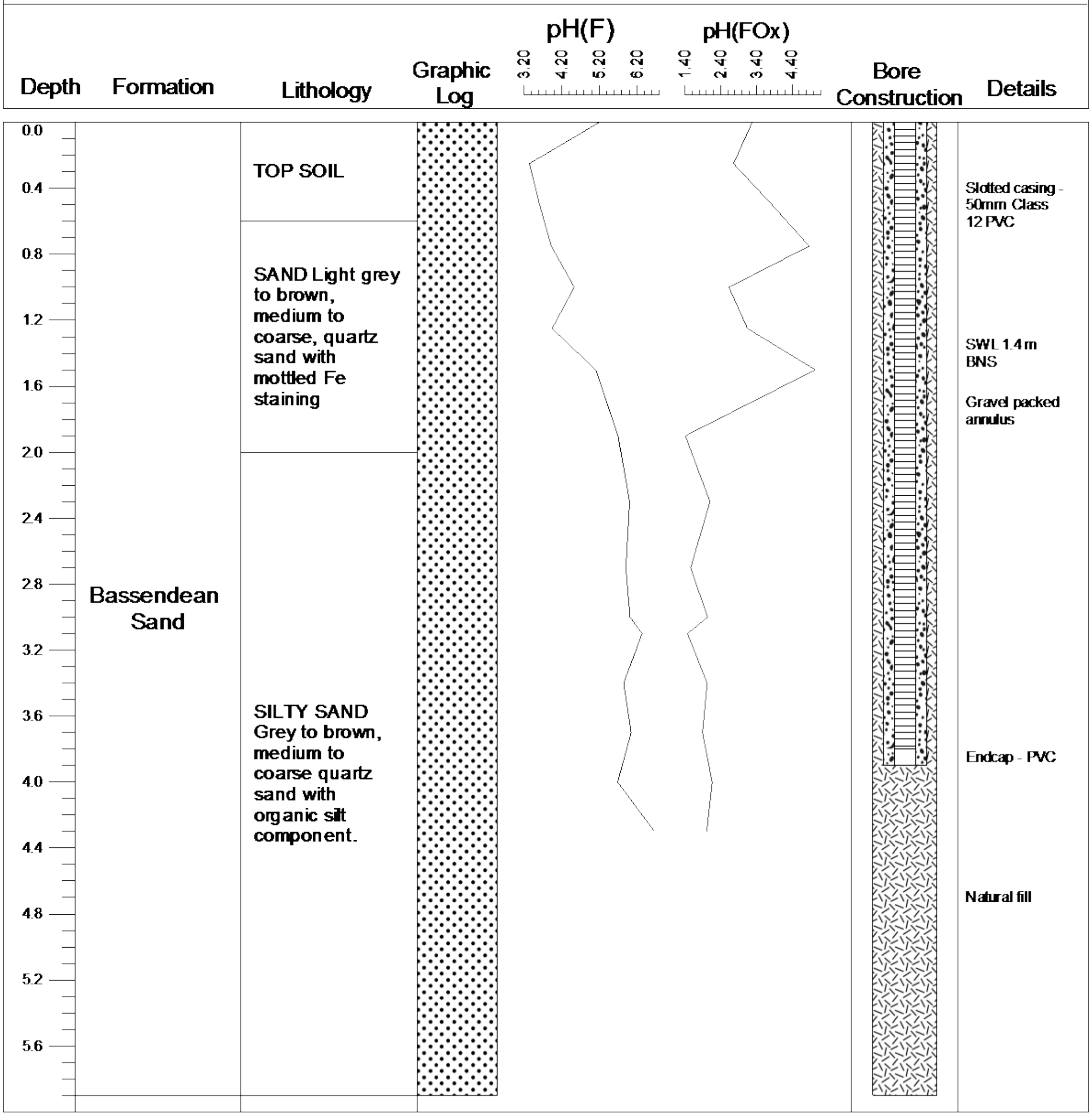
| | | | | | |
|---|---|---|---|---|---|
| Drilled by: | Great Southern Drilling | Northing (Z50): | 6450223 | Screens (m BNS): | 0.62 - 4.62 |
| Date drilled: | 4/17/07 | Easting (Z50): | 389351 | SWL (m BNS): | 2.6 |
| Logged by: | Sandie McHugh | Surface (m AHD): | 15.648 | EC (mS/cm): | 0.964 |
| Aquifer: | Superficial | Drill depth (m BNS): | 5.9 | pH: | 6.12 |

## BORE COMPLETION DETAILS

**Perth Shallow Groundwater Systems Investigation - Stage 1**

Department of Water
Government of Western Australia

AWRC Name: **NTH_Vc**
AWRC Number: **61410460**



TOP SOIL

SAND Light grey to brown, medium to coarse, quartz sand with mottled Fe staining

SILTY SAND Grey to brown, medium to coarse quartz sand with organic silt component.

Slotted casing - 50mm Class 12 PVC

SWL 1.4 m BNS

Gravel packed annulus

Endcap - PVC

Natural fill

| | | | | | |
|---|---|---|---|---|---|
| Drilled by: | Great Southern Drilling | Northing (Z50): | 6450234 | Screens (m BNS): | 0.0 - 3.84 |
| Date drilled: | 4/16/07 | Easting (Z50): | 389587 | SWL (m BNS): | 1.4 |
| Logged by: | Sandie McHugh | Surface (m AHD): | 15.691 | EC (mS/cm): | 0.683 |
| Aquifer: | Superficial | Drill depth (m BNS): | 5.9 | pH: | 6.35 |

# Appendix B – Sampling methodology

## Equipment

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 water quality parameters stabilise. Once stabilised, in-situ readings can be recorded and samples collected for laboratory analysis. This method requires smaller volumes of water to be withdrawn than conventional techniques and potentially reduces the aeration or degassing of samples collected. It also minimises the disturbance within the water well column and surrounding materials, potentially 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. In-situ water quality parameters were monitored with Hydrolab test equipment (Quanta and multiprobe sensors).

## Low-flow bladder pump and water quality procedures

- Ensure all equipment is washed and decontaminated.
- All instrumentation and equipment (i.e. pumping equipment, hoses, and standing water level recorders) is to be decontaminated before and after sampling at each 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 the bore, measure the groundwater level and record.
- Identify screen depth from records and lower low-flow bladder pump to midway along 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 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, electrical conductivity, temperature, redox and dissolved oxygen using multiprobe sensors installed in a flow cell. Record measurements every five minutes until the parameters stabilise and then record a final reading.
- Record results on a Field Observation Form for submission to Department of Water database.

- Take samples for laboratory analysis once physical in-situ field parameters have stabilised and have been recorded.

### *Acid Sulfate Soil Testing*

Conduct sediment pH and pH peroxide tests in-situ immediately after extracting sediment cores.

Procedural outline – field $pH_F$ test

- Calibrate field pH meter.
- Prepare the test tubes in the test tube rack. Make sure the rack is marked with the depths so there is no confusion about the top and bottom of the profile. Use of separate racks for the $pH_F$ and $pH_{FOX}$ tests is recommended as contamination may occur when the $pH_{FOX}$ reactions are violent.
- Conduct tests at soil profile intervals of 0.25 m or at least one test per horizon whichever is smaller.
- Remove approximately 1 teaspoon of soil from the profile. Place approximately ½ teaspoon of the soil into the $pH_F$ test tube and ½ teaspoon of the soil into the $pH_{FOX}$ test tube for the corresponding depth test. It is important that these 2 subsamples come from the same depth and they are similar in characteristics. For example, DO NOT take ½ teaspoon of soil from the 0–0.25 m depth that is grey mud, while selecting ½ teaspoon from the same depth that is a yellow mottled sample. These will obviously give different results independent of the type of test conducted.
- Place 10 mL of deionised water (pH 5.5) in the $pH_F$ test tube.
- In some instances, in less than five minutes, monosulfidic material may start to oxidise and substantially affect the $pH_F$ results.
- Immediately place the spear point electrode (preferred method) into the test tube, ensuring that the spear point is totally submerged. Never stir the paste with the electrode as this will damage the semi-permeable glass membrane.
- Measure the $pH_F$ using a pH meter with spear point electrode.
- Wait for the reading to stabilise and record the pH measurement. Record all measurements and pH calibration on a field data sheet.

Procedural outline – Field pH peroxide test

- Caution: PPE required – Safety glasses, nitrile gloves, long-sleeved shirt
- Adjust and record the pH of the hydrogen peroxide before going into the field. Add a few drops of NaOH at a time, checking the pH with the electrode regularly. NaOH is highly caustic so exercise safety precautions. Note that as NaOH raises the pH quickly, monitor pH while adding. Do NOT buffer a large volume of hydrogen peroxide at one time. Only buffer the amount to be used in the field. Usually a couple of months supply is adequate. Keep in a fridge, well labelled and take only small volumes into the field at one time. This will ensure the longevity of the peroxide. Further, over time, the pH of already buffered peroxide may change. Check the pH of the peroxide in the morning before departing for the field. Have a small volume of NaOH in the field kit so the peroxide can be buffered if required.

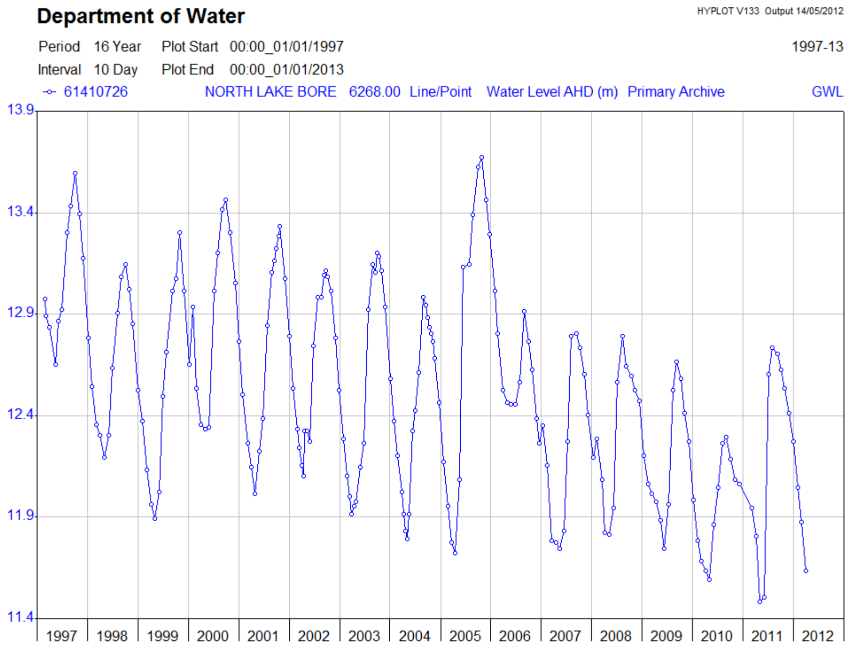
- Calibrate field pH meter.
- Prepare the test tubes in the test tube rack as for $pH_F$ test. Make sure the rack is marked with the depths so there is no confusion about the top and bottom of the profile. Use separate racks for the $pH_F$ and $pH_{FOX}$ tests to avoid contamination when the $pH_{FOX}$ reactions are violent.
- Conduct $pH_F$ tests at 0.25 m intervals of the soil profile or at least one per horizon whichever is smaller.
- Remove approximately 1 teaspoon of soil from the profile. Place approximately ½ teaspoon of that soil into the $pH_F$ test tube and ½ teaspoon into the $pH_{FOX}$ test tube for the corresponding depth test. Make sure these 2 subsamples come from the same depth and that they are similar in characteristics. For example, DO NOT take ½ teaspoon of soil from the 0-0.25m depth that is grey mud while selecting ½ teaspoon from the same depth that is a yellow mottled sample. These will obviously give different results independent of the type of test conducted.
- Add 10 mL of 30% $H_2O_2$ adjusted to pH 4.5–5.5 to the soil in a heat-resistant test tube and stir the mixture. Do NOT add more than a few drops at a time. This will prevent overflow and wastage of peroxide. Ideally, allow approximately 20 minutes for any reactions to occur. If substantial sulfides are present, the reaction will be vigorous and may occur almost instantly. In this case, it may not be necessary to stir the mixture.
- Wait for the soil/peroxide mixture to cool (may take up to 10 minutes). The reactions often exceed 90 °C. Placing an electrode into these high temperature situations may result in physical damage and inaccurate readings as most pH meters are set to record a result for an ambient temperature of approximately 25 °C.
- Use an electronic pH meter (preferred method) to measure the $pH_{FOX}$. Place a spear point electrode into the test tube, ensuring that the spear point is totally submerged in the soil/peroxide mixture. Ensure that the plastic soil sleeve that exposes the spear point totally is used on the end of the electrode in preference to the protective pronged sleeve that almost totally conceals the spear point. This will ensure good contact with the soil. Never stir the mixture with the electrode. This will damage the semi-permeable glass membrane.
- Rate the reaction using a LMHXV scale.
- Wait for the reading to stabilise and record the $pH_{FOX}$ measurement.
- Record all measurements and pH calibration measurements on a data sheet.

### **Soil Core Analysis***:*

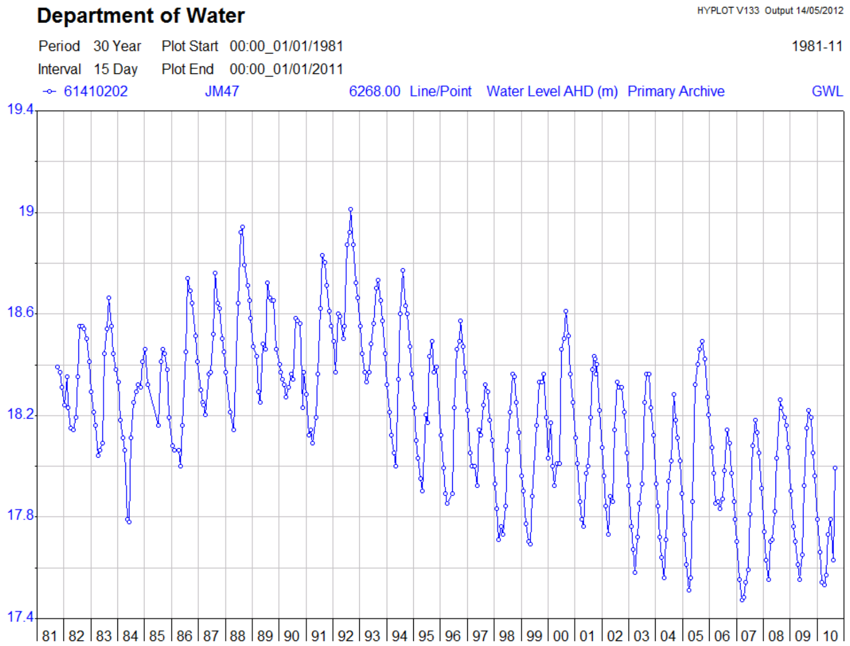
Using the above field analysis to identify possible soil profiles of concern, core samples were collected and sent to the laboratory for further analysis. Samples were analysed using either the SPOCAS suite and/or Chromium reducible sulphur suite of analyses to conduct acid base accounting (ABA). Analysis for the following metals and non-metals was also conducted: As, Al, Fe, Cr, Cd, Mn, Ni, Zn and Se.

# Appendix C – Hydrographs

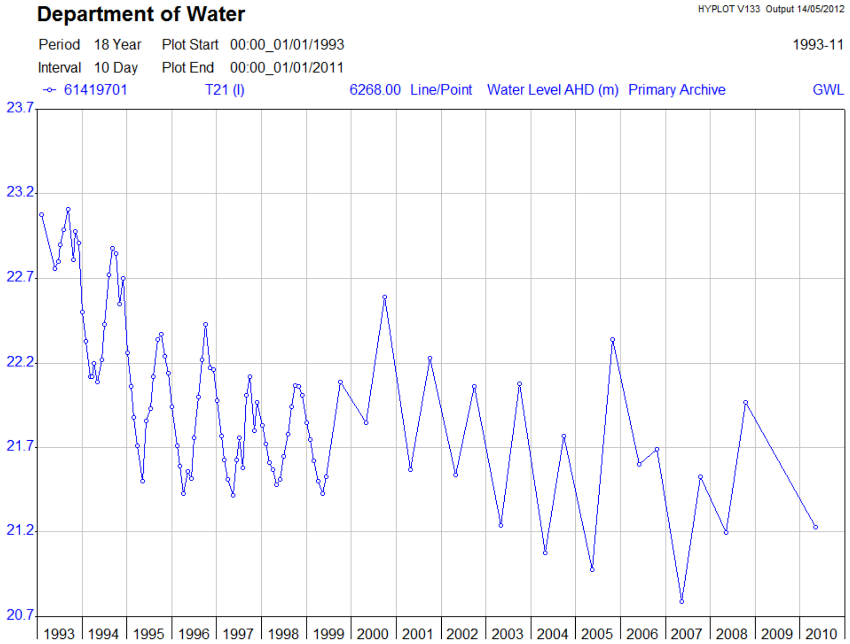
## Hydrographs of selected groundwater monitoring bores near North Lake



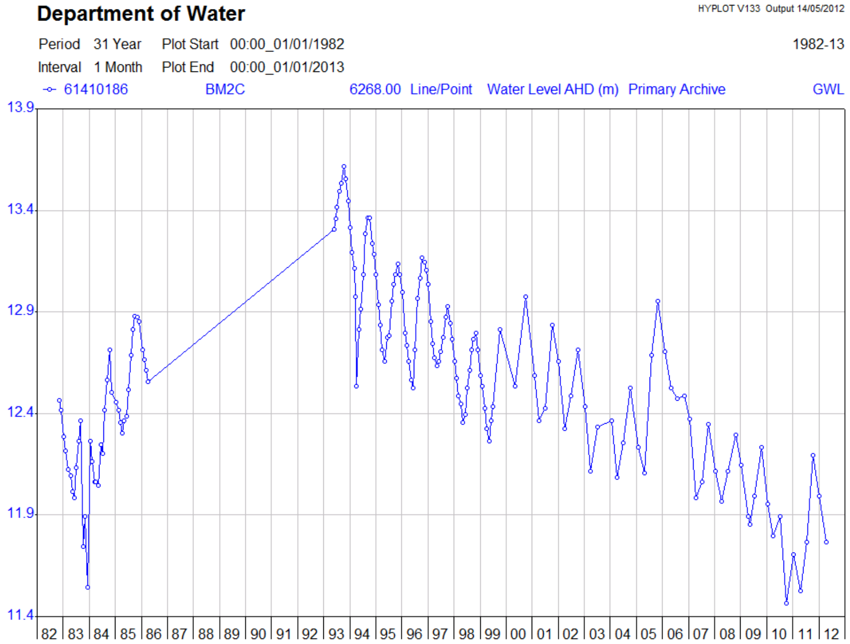
*North Lake Bore (AWRC Ref: 61410726)*



*JM47 (AWRC Ref: 61410202)*



*T21 (I) (AWRC Ref: 61419701)*



*BM2C (AWRC Ref: 61410186)*

# Appendix D – Groundwater Quality Data, 2012

## May 2012 – Groundwater monitoring

### Field groundwater quality data collected May 2012

| Bore ID | Sample date | pH | Temp (°C) | EC (mS/cm) | Redox (mV) | DO (%) | DO (mg/L) | SWL (m btoc) | Sample depth (m bgl) |
|---|---|---|---|---|---|---|---|---|---|
| NTH_Wc | 1/05/2012 | 3.19 | 20.87 | 5.78 | 24 | 15.2 | 1.35 | 2.96 | 3.56 |
| NTH_Wb | 1/05/2012 | 6.82 | 20.08 | 0.533 | -212 | 1.6 | 0.15 | 2.88 | 20.64 |
| NTH_Wa | 1/05/2012 | 7.37 | 20.59 | 0.537 | -180 | 7 | 0.72 | 2.76 | 34.63 |
| NTH_Vc | 1/05/2012 | 5.36 | 19.28 | 0.789 | -113 | 2.1 | 0.17 | 2.38 | 3.48 |
| NTH_Ec | 2/05/2012 | | Not sampled – bore blocked | | | | | | |
| NTH_Eb | 1/05/2012 | 6.22 | 20.09 | 1.018 | -192 | 1.5 | 0.14 | 3.72 | 18.00 |
| NTH_Ea | 2/05/2012 | 7.13 | 20.18 | 0.545 | -176 | 16.3 | 1.49 | 3.6 | 31.53 |

### Laboratory analysis for groundwater samples collected May 2012

| Bore ID | Sample date | pH | EC (mS/m) | TDS (mg/L) | TSS (mg/L) | Alkalinity (mg/L) | Acidity (mg/L) |
|---|---|---|---|---|---|---|---|
| NTH_Wc | 1/05/2012 | 3.6 | 574 | 5320 | < 1 | < 1 | 580 |
| NTH_Wb | 1/05/2012 | 7.2 | 53 | 330 | 220 | 140 | 21 |
| NTH_Wa | 1/05/2012 | 7.7 | 53 | 330 | 89 | 210 | 6 |
| NTH_Vc | 1/05/2012 | 5.8 | 78 | 540 | < 1 | 28 | 78 |
| NTH_Vc (dup) | 1/05/2012 | 5.9 | 79 | 520 | | 27 | 84 |
| NTH_Ec | 2/05/2012 | | | Not sampled – bore blocked | | | |
| NTH_Eb | 1/05/2012 | 6.6 | 100 | 680 | 26 | 85 | 35 |
| NTH_Ea | 2/05/2012 | 7.6 | 54 | 310 | 30 | 200 | 6 |

### Laboratory analysis for groundwater samples collected May 2012 – Major ions

| Bore ID | Sample date | Sulfate (mg/L) | Chloride (mg/L) | $SO_4$:Cl | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) |
|---|---|---|---|---|---|---|---|---|
| NTH_Wc | 1/05/2012 | 2000 | 910 | 2.20 | 360 | 220 | 540 | 28 |
| NTH_Wb | 1/05/2012 | 4 | 80 | 0.05 | 44 | 7 | 50 | 3 |
| NTH_Wa | 1/05/2012 | 4 | 60 | 0.07 | 38 | 5 | 60 | 5 |
| NTH_Vc | 1/05/2012 | 68 | 180 | 0.38 | 21 | 19 | 90 | 8 |
| NTH_Vc (dup) | 1/05/2012 | 70 | 180 | 0.39 | 21 | 19 | 90 | 8 |
| NTH_Ec | 2/05/2012 | | | Not sampled – bore blocked | | | | |
| NTH_Eb | 1/05/2012 | 160 | 170 | 0.94 | 55 | 33 | 90 | 7 |
| NTH_Ea | 2/05/2012 | 4 | 60 | 0.07 | 46 | 5 | 50 | 5 |

## Laboratory analysis for groundwater samples collected May 2012 – Metals and metalloids

| | | Dissolved metals/metalloids | | | | | | | Total metals | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bore ID | Sample date | Al | Fe | As | Mn | Cu | Cr | Ni | Al | Fe |
| | | (mg/L) | | | | | | | | |
| NTH_Wc | 1/05/2012 | 27 | 170 | 0.011 | 0.33 | 0.02 | 0.0072 | 0.0069 | 31 | 180 |
| NTH_Wb | 1/05/2012 | 0.13 | 0.28 | < 0.001 | 0.022 | < 0.001 | 0.0018 | < 0.001 | 10 | 4.1 |
| NTH_Wa | 1/05/2012 | 0.028 | 1.2 | < 0.001 | 0.024 | < 0.001 | 0.0011 | < 0.001 | 1.4 | 4 |
| NTH_Vc | 1/05/2012 | 0.15 | 0.89 | < 0.001 | 0.047 | < 0.001 | 0.0029 | < 0.001 | 0.17 | 1.5 |
| NTH_Vc (dup) | 1/05/2012 | 0.14 | 1.2 | < 0.001 | 0.043 | < 0.001 | 0.0016 | < 0.001 | 0.15 | 0.89 |
| NTH_Ec | 2/05/2012 | Not sampled - bore blocked | | | | | | | | |
| NTH_Eb | 1/05/2012 | 0.12 | 1.2 | < 0.001 | 0.022 | < 0.001 | < 0.001 | < 0.001 | 1.2 | 2.3 |
| NTH_Ea | 2/05/2012 | 0.011 | 2.4 | < 0.001 | 0.024 | 0.015 | < 0.001 | < 0.001 | 0.44 | 3.4 |

## Laboratory analysis for groundwater samples collected May 2012 – Nutrients

| Bore ID | Sample date | $NH_3$-N | FRP | ON | TKN | TN | TON | TP | DOC |
|---|---|---|---|---|---|---|---|---|---|
| | | (mg/L) | | | | | | | |
| NTH_Wc | 1/05/2012 | 2 | 0.063 | 2 | 4.2 | 4.2 | 0.018 | 0.071 | 38 |
| NTH_Wb | 1/05/2012 | 0.58 | 0.098 | 0.41 | 1.3 | 1.3 | < 0.01 | 0.2 | 8 |
| NTH_Wa | 1/05/2012 | 0.58 | 0.035 | 0.17 | 0.59 | 0.6 | < 0.01 | 0.24 | 5 |
| NTH_Vc | 1/05/2012 | 0.33 | 0.013 | 0.87 | 1.2 | 1.2 | < 0.01 | 0.016 | 17 |
| NTH_Vc (dup) | 1/05/2012 | 0.32 | 0.012 | 0.86 | 1.2 | 1.2 | < 0.01 | 0.016 | 16 |
| NTH_Ec | 2/05/2012 | Not sampled – bore blocked | | | | | | | |
| NTH_Eb | 1/05/2012 | 0.4 | 0.18 | 0.61 | 1 | 1 | < 0.01 | 0.21 | 16 |
| NTH_Ea | 2/05/2012 | 0.22 | 0.029 | 0.15 | 0.39 | 0.39 | < 0.01 | 0.19 | 6 |

## September 2012 – Groundwater monitoring

### Field groundwater quality data collected September 2012

| Bore ID | Sample date | pH | Temp (°C) | EC (mS/cm) | Redox (mV) | DO (%) | DO (mg/L) | SWL (m btoc) | Sample depth (m bgl) |
|---|---|---|---|---|---|---|---|---|---|
| NTH_Wc | 27/09/2012 | 5.13 | 16.57 | 8.71 | 107 | 24.7 | 2.32 | 2 | 3.56 |
| NTH_Wb | 27/09/2012 | 7.21 | 19.43 | 0.545 | –149 | 1.8 | 0.17 | 2.46 | 21.64 |
| NTH_Wa | 27/09/2012 | 7.63 | 19.3 | 0.548 | –197 | 6.4 | 0.59 | 2.34 | 34.63 |
| NTH_Vc | 27/09/2012 | 5.71 | 16.74 | 0.888 | –8 | 22.8 | 2.2 | 1.66 | 3.48 |
| NTH_Ec | | | | Not sampled – bore blocked | | | | | |
| NTH_Eb | 27/09/2012 | 7.04 | 19.35 | 0.748 | –98 | 49 | 4.49 | 3.31 | 18 |
| NTH_Ea | 28/09/2012 | 7.36 | 19.22 | 0.557 | –191 | 5 | 0.47 | 3.1 | 31.53 |

### Laboratory analysis for groundwater samples collected September 2012

| Bore ID | Sample date | pH | EC (mS/m) | TDS (mg/L) | TSS (mg/L) | Alkalinity (mg/L) | Acidity (mg/L) |
|---|---|---|---|---|---|---|---|
| NTH_Wc | 27/09/2012 | 5.0 | 844 | 7070 | 2 | 10 | 140 |
| NTH_Wb | 27/09/2012 | 7.1 | 54 | 300 | 65 | 140 | 26 |
| NTH_Wa | 27/09/2012 | 7.7 | 54 | 290 | 1 | 190 | 9 |
| NTH_Vc | 27/09/2012 | 5.7 | 89 | 500 | 2 | 22 | 98 |
| NTH_Ec | | Not sampled – bore blocked | | | | | |
| NTH_Eb | 28/09/2012 | 7.0 | 75 | 430 | 14 | 130 | 28 |
| NTH_Ea | 27/09/2012 | 7.6 | 55 | 280 | 15 | 190 | 11 |

### Laboratory analysis for groundwater samples collected September 2012 – Major ions

| Bore ID | Sample date | Sulfate (mg/L) | Chloride (mg/L) | $SO_4$:Cl | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) |
|---|---|---|---|---|---|---|---|---|
| NTH_Wc | 27/09/2012 | 2700 | 1400 | 1.93 | 470 | 290 | 910 | 25 |
| NTH_Wb | 27/09/2012 | < 5 | 80 | 0.01 | 44 | 6 | 50 | 2 |
| NTH_Wa | 27/09/2012 | < 5 | 60 | 0.08 | 40 | 5 | 60 | 4 |
| NTH_Vc | 27/09/2012 | 85 | 200 | 0.43 | 19 | 20 | 110 | 10 |
| NTH_Ec | | | Not sampled – bore blocked | | | | | |
| NTH_Eb | 28/09/2012 | 71 | 110 | 0.65 | 52 | 17 | 70 | 5 |
| NTH_Ea | 27/09/2012 | 4 | 50 | 0.08 | 51 | 5 | 50 | 5 |

## Laboratory analysis for groundwater samples collected September 2012 – Metals and metalloids

| | | Dissolved metals/metalloids | | | | | | | Total Metals | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bore ID | Sample date | Al | Fe | As | Mn | Cu<br>(mg/L) | Cr | Ni | Al | Fe |
| NTH_Wc | 27/09/2012 | 0.38 | 17 | 0.01 | 0.15 | 0.0015 | <0.001 | < 0.001 | 0.39 | 17 |
| NTH_Wb | 27/09/2012 | 0.5 | 0.22 | < 0.001 | 0.02 | < 0.001 | 0.0024 | < 0.001 | 1.9 | 2.3 |
| NTH_Wa | 27/09/2012 | 0.01 | 1.1 | < 0.001 | 0.018 | < 0.001 | < 0.001 | < 0.001 | 0.019 | 1.2 |
| NTH_Vc | 27/09/2012 | 0.5 | 2.2 | < 0.001 | 0.045 | 0.0014 | 0.0021 | 0.0012 | 0.52 | 2.2 |
| NTH_Ec | | Not sampled – bore blocked | | | | | | | | |
| NTH_Eb | 27/09/2012 | 0.046 | 2.1 | 0.016 | 0.028 | 0.0012 | 0.0011 | < 0.001 | 0.12 | 2.2 |
| NTH_Ea | 28/09/2012 | 0.006 | 2.1 | < 0.001 | 0.023 | < 0.001 | < 0.001 | < 0.001 | 0.061 | 2.4 |

## Laboratory analysis for groundwater samples collected September 2012 – Nutrients

| Bore ID | Sample date | $NH_3$-N | FRP | ON | TKN<br>(mg/L) | TN | TON | TP | DOC |
|---|---|---|---|---|---|---|---|---|---|
| NTH_Wc | 27/09/2012 | 0.32 | 0.018 | 2.3 | 2.6 | 2.7 | 0.035 | 0.04 | 44 |
| NTH_Wb | 27/09/2012 | 0.58 | 0.099 | 0.14 | 0.72 | 0.73 | < 0.01 | 0.099 | 8 |
| NTH_Wa | 27/09/2012 | 0.34 | 0.12 | 0.065 | 0.4 | 0.41 | < 0.01 | 0.17 | 5 |
| NTH_Vc | 27/09/2012 | 0.13 | 0.066 | 1.3 | 4 | 4 | < 0.01 | 0.43 | 20 |
| NTH_Ec | | Not sampled – bore blocked | | | | | | | |
| NTH_Eb | 28/09/2012 | 0.31 | 0.16 | 0.26 | 0.57 | 0.58 | 0.016 | 0.16 | 11 |
| NTH_Ea | 28/09/2012 | 0.22 | 0.16 | 0.067 | 0.29 | 0.3 | < 0.01 | 0.17 | 5 |

# Appendix E – Surface Water Quality Data, 2012

Field surface water quality data collected at North Lake in 2012

| Bore ID | Sample date | pH | Temp (°C) | EC (mS/cm) | Redox (mV) | DO (%) | DO (mg/L) |
|---|---|---|---|---|---|---|---|
| NTH_S1 | 2/05/2012 | 3.01 | 17.47 | 7.32 | 379 | 152.5 | 14.41 |
| NTH_S2 | 28/09/2012 | 4.82 | 19.25 | 1.89 | 222 | 39.9 | 3.66 |
| NTH LAKE 424 | 27/09/2012 | 5.15 | 18.06 | 2.97 | 267 | 102.8 | 9.47 |

Laboratory analysis for surface water samples collected at North Lake in 2012

| Bore ID | Sample date | pH | EC (mS/m) | TDS (mg/L) | TSS (mg/L) | Alkalinity (mg/L) | Acidity (mg/L) |
|---|---|---|---|---|---|---|---|
| NTH_S1 | 2/05/2012 | 3.3 | 657 | 6150 | 69 | < 1 | 630 |
| NTH_S2 | 28/09/2012 | 4.5 | 185 | 1170 | 84 | < 1 | 42 |
| NTH LAKE 424 | 27/09/2012 | 4.7 | 291 | 2110 | 67 | 2 | 15 |

Laboratory analysis for surface water samples collected at North Lake in 2012 – Major ions

| Bore ID | Sample date | Sulfate (mg/L) | Chloride (mg/L) | SO4:Cl | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) |
|---|---|---|---|---|---|---|---|---|
| NTH_S1 | 2/05/2012 | 2700 | 800 | 3.38 | 460 | 280 | 510 | 10 |
| NTH_S2 | 28/09/2012 | 330 | 350 | 0.94 | 110 | 43 | 190 | 11 |
| NTH LAKE 424 | 27/09/2012 | 770 | 360 | 2.14 | 150 | 60 | 250 | 17 |

Laboratory analysis for surface water samples collected at North Lake in 2012– Metals and metalloids

| Bore ID | Sample date | Al | Fe | As | Mn | Cu | Cr | Ni | Al | Fe |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | (mg/L) | | | | |
| NTH_S1 | 2/05/2012 | 43 | 120 | 0.0018 | 1.9 | 0.0096 | 0.0069 | 0.072 | 44 | 120 |
| NTH_S2 | 28/09/2012 | 0.25 | 3.8 | < 0.001 | 0.07 | < 0.001 | < 0.001 | < 0.001 | 0.46 | 13 |
| NTH LAKE 424 | 27/09/2012 | 0.042 | 5 | 0.0017 | 0.6 | < 0.001 | < 0.001 | < 0.001 | 0.043 | 5.8 |

Laboratory analysis for surface water samples collected at North Lake in 2012 – Nutrients

| Bore ID | Sample date | NH3-N | FRP | ON | TKN | TN | TON | TP | DOC |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | (mg/L) | | | | |
| NTH_S1 | 2/05/2012 | 48 | 0.033 | 12 | 60 | 60 | 0.013 | 0.23 | 54 |
| NTH_S2 | 28/09/2012 | 0.02 | 0.022 | 0.72 | 1.4 | 1.4 | < 0.01 | 0.12 | 18 |
| NTH LAKE 424 | 27/09/2012 | 0.13 | 0.066 | 1.3 | 4 | 4 | < 0.01 | 0.43 | 20 |

# Glossary

| | |
|---|---|
| Abstraction | The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality. |
| 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. |
| 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 | Annual volume of water set aside for use from a water resource. |
| Aquiclude | An impermeable geological formation through which zero groundwater flow occurs. |
| Aquifer | A geological formation or group of formations able to receive, store and/or transmit large amounts of water. |
| Aquitard | A geological formation that restricts/retards groundwater flow. |
| Biodiversity | Biological diversity or the variety of organisms, including species themselves, genetic diversity and the assemblages they form (communities and ecosystems). Sometimes includes the variety of ecological processes within those communities and ecosystems. |
| 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 layer | Sedimentary bed of very low hydraulic conductivity. |
| 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. |
| Correlation | Indicates the strength and direction of the linear relationship between two random variables. |
| Cretaceous | Final period of Mesozoic era; 65–144 million years ago. |
| Decline | The difference between the elevation of the initial watertable and its position after a decrease in recharge (i.e. rainfall). |
| Dewatering | Short-term abstraction of groundwater to lower the watertable and permit the excavation of 'dry' sediment. |
| Discharge | The water that moves from the groundwater to the ground surface or above, such as a spring. This includes water that seeps onto the ground surface, evaporation from unsaturated soil, and water extracted from groundwater by plants (see Evapotranspiration) or engineering works (see Groundwater pumping). |
| Drawdown | The difference between the elevation of the initial piezometric surface and its position after pumping or gravitational drainage. |
| Dissolved oxygen | The concentration of oxygen dissolved in water normally measured in milligrams per litre (mg/L). |
| Ecological water requirement (EWR) | The water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk. |
| Ecological values | The natural ecological processes occurring within water-dependent ecosystems and the biodiversity of these systems. |

| | |
|---|---|
| Ecosystem | A community or assemblage of communities of organisms, interacting with one another, and the specific environment in which they live and with which they also interact, e.g. lake, to include all the biological, chemical and physical resources and the interrelationships and dependencies that occur between those resources. |
| Environmental water provisions | The water regimes that are provided as a result of the water allocation decision-making process taking into account ecological, social, cultural and economic impacts. They may meet in part or in full the ecological water requirements. |
| Equilibrium | The condition of a system or reaction in which competing influences are balanced. |
| Evapotranspiration | The combined loss of water by evaporation and transpiration. Includes water evaporated from the soil surface and water transpired by plants (Water and Rivers Commission 2001a). |
| Fault | A fracture in rocks or sediments along which there has been an observable displacement. |
| 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. |
| Geomorphic | Pertaining or related to the form of the Earth or its surface features. |
| Gradient | The rate of change of total head per unit distance of flow at a given point and in a given direction. |
| Groundwater | Water that occupies the pores within the rock or soil profile. |
| Groundwater area | Are the boundaries that are proclaimed under the *Rights in Water and Irrigation Act* and used for water allocation planning and management. |
| Groundwater dependent ecosystem | An ecosystem that is dependent on groundwater for its existence and health. |
| Groundwater level | An imaginary surface representing the total head of groundwater. Defined by piezometer readings. |
| Groundwater mound | A mound shaped water table that develops in areas where the rate at which rainwater infiltrates vertically is greater than the rate at which groundwater flows horizontally. |
| Groundwater | The rate at which infiltration water reaches the |

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|---|---|
| recharge | watertable. |
| Groundwater subarea | Areas defined by the Department of Water within a Groundwater area, used for water allocation planning and management. |
| Guidelines | Values or ranges of acceptable or unacceptable levels of a chemical, beyond which management response is usually triggered. |
| Head | The height of the free surface of a body of water above a given subsurface point. |
| Hydraulic | Pertaining to water motion. |
| Hydrogeology | The hydrological and geological science concerned with the occurrence, distribution, quality and movement of groundwater, especially relating to the distribution of aquifers, groundwater flow and groundwater quality. |
| Hydrograph | A graph showing the height of a water surface above an established datum plane for level, flow, velocity, or other property of water with respect to time. |
| Inter-dunal | Between dunes. |
| Ion | An atom which has lost or gained electrons and therefore carries an electrical charge. |
| Leach | Remove soluble matter by percolation of water. |
| LOR | Limit of reporting. The lower limit of reliability given by the laboratory responsible for carrying out the analysis. Greater than the limit of detection (LOD). |
| Mesozoic | An era of geological time between 250 and 65 million years ago (Ma). It included the Triassic, Jurassic and Cretaceous periods. |
| Metalloid | An element whose properties are between those of metals and non-metals. |
| Neutralisation | The chemical reaction in which an acid and a base react to produce salt and water ($H_2O$). |
| Organism | Is a living system. In at least some form, all organisms are capable response to stimuli, reproduction, growth and development, and maintenance of homeostasis as a stable whole. |
| 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. |

| | |
|---|---|
| Palaeoclimatology | The study of climate through geological time. |
| pH | A measure of the acidity or basicity of an aqueous solution. Solutions with a pH less than 7 are said to be acidic and solutions with a pH greater than 7 are basic or alkaline. Pure water has a pH very close to 7. |
| Precipitate | The solid formed when mixing two ionic solutions produces an insoluble product. |
| Quaternary | Relating to the most recent period in the Cainozoic era, from 2 million years to present. |
| Recharge | Water that infiltrates into the soil to replenish an aquifer. |
| 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). 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. Water classified as fresh (0–500 mg/L); fresh to marginal (500–1500 mg/L); brackish (1500–3000 mg/L); saline >3000 mg/L. |
| Screen | A special form of bore liner used to stabilise the aquifer or gravel pack, while allowing the flow of water through the bore into the casing and permitting the development of the screened formation by an appropriate process. |
| 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 small pores on the underside of leaves. |
| 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. |
| Volumetric | Relating to measurement by volume. |
| 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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